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Anchorage loss and root resorption associated with two anchorage reinforcement methods in a dog model

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A thesis submitted to University of Dublin in partial fulfillment of the requirements for the degree of

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DECLARATION

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Summary

Intra–oral anchorage reinforcement methods are crucial for the success and outcome of orthodontic treatment. This thesis reports on the efficacy of two different types of intra-oral anchorage reinforcement methods; Nance appliance and miniscrews, and their effect on orthodontically induced inflammatory root resorption (OIIRR).

The aim of the first study was to examine the amount of anchorage loss (AL) and desired tooth movement (DM) found in the Nance appliance group compared with the control group (conventional molar anchorage) at 3 time points (5, 10 and 15 weeks). Four beagle dogs were fitted with a custom made Nance appliance and bands on the mandibular fourth (PM_4) and second (PM_2) premolar, respectively. The control beagle dogs (n=3) were fitted with bands on the PM_2 and PM_4. Reference miniscrews were placed mesial to the PM_2 to measure the amount of tooth movement. The PM_2 was retracted over 15 weeks in both groups (Nance and control) and the amount of PM_4 (AL) and PM_2 (DM) movement was recorded at each time point. The mean amount of DM was significantly ($p=0.03$) more in the Nance group than the control group at 10 weeks, but was not different after 15 weeks. The mean percentage of AL to the total space closure in the Nance group was 28.8%. The Nance appliance had 16.9% less AL than the control group after 15 weeks ($p=0.03$). Most of the Nance appliance's AL (80%) occurred over the first 10 weeks.

In the second study, the mean AL and DM, at 3 time points (5, 10 and 15 weeks), was compared between the miniscrew anchorage reinforcement group and the control group (conventional molar anchorage). Beagle dogs (n=6) were fitted with custom made bands on the mandibular PM_2 and PM_4. Reference miniscrews were used as described earlier to measure the amount of movement at the different time points. In the miniscrew group (n=3), active miniscrews were placed buccal and mesial to the PM_4 to apply distal traction to the PM_2. The mean amount of DM was significantly ($p=0.03$) more in the miniscrew than the control group at 10 weeks, but was not different after 15 weeks. The mean percentage of AL in the miniscrew group (miniscrew movement) was 15.7% of the total movement. The mean amount of AL was 0.92 mm. The miniscrew group had 30% less AL than the control group ($p<0.01$). Most of the miniscrews' AL (70%) occurred over the first 5 weeks.

Finally, the OIIRR associated with the different anchorage methods (control, Nance appliance and miniscrew) was assessed. The animals in the previous studies were

sacrificed after 15 weeks and the PM_2 (n=20) and PM_4 (n=20) were examined under light microscopy. A grid was superimposed on each root and the total root resorption (RR) ratio and the number of squares with RR at the different root surfaces (mesial, distal and apical) was recorded. The type of anchorage had a significant influence on the total RR ratio ($p<0.01$), with the miniscrew group having the least total RR ratio. The type of tooth was also significant ($p<0.01$), as PM_2 had a smaller total RR ratio than PM_4. When the total RR ratio for each tooth type was compared between the different anchorage methods, the difference was significant for both PM_2 ($p=0.045$) and PM_4 ($p<0.01$). The type of anchorage influenced the total RR ratio by controlling the amount of tooth movement. The amount of RR for the different surfaces (mesial, distal and apical) within each group was significant for the Nance and miniscrew groups ($p<0.01$). This might be as a result of the larger amount of PM_2 movement in the Nance and miniscrew groups. When the different surfaces between the different anchorage methods were compared, the control group had significantly more RR in the apical surface ($p<0.01$). This might suggest that the control group incurred more tipping movement than the Nance and miniscrew groups.

In conclusion, both anchorage reinforcement methods (Nance appliance and miniscrew) did not provide absolute anchorage but provided significantly more anchorage than conventional molar anchorage. Time is a significant factor for both anchorage reinforcement methods as the majority of anchorage loss occurred after 10 weeks with the Nance appliance and 5 weeks with miniscrews; it may be prudent to delay force application accordingly. The type of anchorage reinforcement and tooth type influenced OIIRR. Overall, the risk of root resorption should be considered when planning orthodontic space closure using different anchorage methods.

Acknowledgments

I would like to express my profound gratitude to my supervisors Professor Brian O'Connell and Professor Noel Claffey whose advice and encouragement has decisively guided this endeavour. They have been generous with their time and expertise. It has been a pleasure carrying out this research under such supervision.

Appreciation is due to Dr. Therese Garvey for her continued help and support during the entire project.

My sincere appreciation is due to Jan Walker for her invaluable help with the preparation of the histological specimens, Peter Nolan for his support with the experimental procedure and Peter O Reilly for his generous help and for facilitating the use of the Bioengineering department's lab. I would also like to thank Alan Kelly for his valuable statistical advice.

Over the years Dr Mohammed Al Haj generously advised me on the different aspects of my project. I would like to thank him sincerely for his invaluable help and assistance.

Thanks are also due to the Orthodontic Society of Ireland for their generous donation to the project. I would also like to thank Absoanchor® for generously contributing the miniscrews used in this study.

Finally, I would like to express to my utmost gratitude to my family for their unwavering support and patience on the many late nights. I also give special thanks to my wife Nora for her love, patience and support.

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List of Abbreviations

AL	**Anchorage loss**
AMs	**Active miniscrews**
ANOVA	**Analysis of variance**
AEFC	**Acellular extrinsic fibre cementum**
CBCT	**Cone-beam computerized tomography**
CIFC	**Cellular intrinsic fibre cementum**
CMSC	**Cellular mixed stratified cementum**
C-P titanium	**Commercially pure titanium**
CRot	**Centre of rotation**
CRes	**Centre of resistance**
DM	**Desired tooth movement**
DRTAD	**Diameter reduced temporary anchorage devices**
HA	**Hydroxyapatite**
H&E	**Haematoxylin and eosin**
IL-1β	**Interleukin-1 beta**
LRTAD	**Length reduced temporary anchorage devices**
NA	**Nance appliance**
NiTi	**Nickel titanium**
OC	**Osteoclast**
OI	**Osseointegration index**
OPG	**Orthopantomogram**
OIIRR	**Orthodontically induced inflammatory root resorption**
OLp	**Occlusal line perpendicular**
PDL	**Periodontal ligament**
PGE_2	**Prostaglandin E2**

PM_1	**First premolar**
PM_2	**Second premolar**
PM_3	**Third premolar**
PM_4	**Fourth premolar**
Ptv	**Pterygoid vertical**
RER	**Rough endoplasmic reticulum**
RMs	**Reference miniscrew**
RR	**Root resorption**
RTV	**Removal torque value**
SEM	**Scanning electron microscope**
SS	**Stainless steel**
TAD	**Temporary anchorage device**
TGF-β1	**Transforming growth factor- β1**
TEM	**transmission electron microscope**
Ti 6Al-4V	**titanium–6 aluminium–4 vanadium**
TPA	**Transpalatal arch**
TRAP	**Tartrate-resistance acid phosphatase**

1 Introduction and Review of the literature

1.1 Introduction

The aim of orthodontics is to move teeth to a more aesthetically satisfying and functionally efficient position. Increasingly, modern orthodontists are realizing that in order to perform a successful treatment, they must consider not only the effect of the forces they directly apply but the concomitant resulting reactions to these forces that inevitably occur. This introduces the issue of anchorage. Anchorage is one of the most important aspects of orthodontics. It is defined as the resistance to unwanted tooth movement (Proffit *et al.*, 2007). Newton's third law of motion in physics states that for every action there is an equal and opposite reaction. Its application within the context of orthodontics means that when a force is applied to a tooth, an equal and opposite force is distributed to the teeth opposing that force in the arch. This then leads to unwanted movement of other teeth along the arch. This undesired effect has constituted a perennial challenge to orthodontists. Thus, in any treatment plan, anchorage has to be carefully assessed to avoid any inadvertent tooth movement which may compromise the final results.

In regarding the problem of anchorage it must initially be recognized that it is not purely mechanical, but a combination of biological and mechanical factors. Thus considerations should be given to the biological surroundings of the dentition as they tend to react to the forces applied (Wright, 1939; Rohde, 1948; Baker *et al.*, 1972). Rohde (1948) emphasised that physical laws manifest themselves differently on living tissues, which may further complicate the situation. This point was later confirmed when several studies failed to provide a simple mathematical equation for the loss of anchorage (Pilon *et al.*, 1996; Geron *et al.*, 2003) and concluded that it is essentially a multifactorial problem. This indicates that biological factors play a critical role in determining the extent of

anchorage and thus, any equation which omits them essentially fails to accurately predict anchorage loss. As such, orthodontic research has been concerned with finding a process that moves the teeth into the desired position with minimal anchorage loss. Such investigations have lead to the development of several auxiliary methods to overcome anchorage loss. These auxiliaries include the use of extra-oral devices such as headgear and facemasks or intra-oral devices such as the Nance appliance and bone screws. Despite the fact that these appliances constitute the backbone of orthodontics and the pathway to optimal orthodontic results, the amount of research conducted to date to validate their efficiency is minimal. To evaluate these appliances a complete understanding of tooth movement, anchorage and the auxiliary appliances is essential.

1.2 Tooth movement

In orthodontics, it is important to understand tooth movement to fully appreciate anchorage, since both concepts overlap. The understanding of tooth movement carries important clinical implications both for planning anchorage and the achievement of treatment objectives. Roberts *et al.* (1996) defined orthodontic anchorage as differential rates of tooth movement. In other words, tooth movement can be controlled by controlling orthodontic anchorage. Tooth movement occurs through a cellular response which is mediated by local stress and strain generated in the tissue by orthodontic forces (Quinn & Yoshikawa, 1985). Therefore, studies have been looking for an ideal force, or a range of forces, that can produce the optimum rate of tooth movement. Several factors must be considered when assessing the ideal force for tooth movement: 1) the stages of tooth movement 2) force and rate of movement 3) individual heterogeneity and 4) type of tooth movement, as these affect the rate of tooth movement.

1.2.1 *Stages of tooth movement*

A force that produces rapid tooth movement without damaging the teeth or the periodontium is defined as an ideal force (Rock & Wilson, 1988). During tooth movement the clinician is trying to achieve ideal forces by varying the amount of activation of the traction springs or elastics. The magnitude of the force determines the rate of tooth movement, the adverse effects on the tooth and periodontium, patient comfort and anchorage loss (Yee *et al.,* 2009). Thus, theoretically, the rate of tooth movement can be controlled if the ideal force for different teeth is identified.

The process of tooth movement following the placement of a force involves several histological changes. To evaluate the requirements for ideal forces, a thorough understanding of the physiology of tooth movement and the effect the forces have upon the teeth and periodontium is required. Reitan (1964) examined bone reaction towards orthodontic forces.

When a tooth is exposed to a light force, the blood vessels within the periodontal ligaments (PDL) become partially compressed. Osteoclasts which are large multinucleate cells derived from hematopoietic cells then attach to the adjacent lamina dura resulting in bone resorption, and tooth movement begins soon after (Dolce *et al.,* 2002). If a heavier force is applied to the tooth, the blood vessels will be occluded and the blood supply will be reduced or stopped to an area within the PDL; this will result in sterile necrosis. This process is referred to as *hyalinization,* and represents an area of ischemia. Reitan (1960) explained that after a delay of several days, osteoclasts appear within the adjacent bone marrow spaces and begin an attack on the bone immediately adjacent to the hyalinized area (undermining resorption). Resorption of this type does not occur at the interface between the PDL and the bone because oxygen and nutritional supply to the PDL cells are cut.

Instead osteoclasts remove the bone around the cell free area. After a lag period, during which necrotic tissue is removed, the tooth moves rapidly into the spaces created. Heavy forces, and even light forces (to a lesser degree), tend to produce hyalinized areas (Fortin, 1971; Reitan, 1957). For light forces, this could be due to the unavoidable tipping during tooth movement causing increased forces in some areas (Reitan, 1957; Pilon *et al.*, 1996).

Tooth movement occurs in 4 stages following force application (Pilon *et al.,* 1996; van Leeuwen *et al.,* 1999). During the first stage (initial phase) the tooth moves rapidly through the PDL space and probably causes some deformation of the surrounding hard tissue. In dogs, this phase lasted from 24 hours to 2 days. The second stage (lag phase) is a period within which the tooth does not move or has a relatively low rate of movement. This phase is associated with hyalinization or recruitment of osteoclasts in the periodontal ligaments (Pilon *et al.*, 1996). Reitan (1957) found that the lag phase lasts for approximately 21 days, whilst Pilon *et al.* (1996) found this phase lasted from 20 to 30 days in dogs. Fortin (1971) showed that this period is increased with heavy forces in dogs. This observation was confirmed by Iwasaki *et al.* (2000) when they found the lag phase was reduced when low force magnitudes were used in a human study. Fortin (1971) suggested that hyalinization is not the only reason for the lag in tooth movement. He suggested that a very slow osteoclastic proliferation and dense bone, which is harder to resorb, could also be decisive factors. It may also represent a period of rest for the osteoclasts in the PDL. The third phase (post lag phase) is characterized by a rapid or gradual increase in tooth movement. von Böhl *et al.* (2004a) found the third phase was reached after 40 days in beagle dogs. Fortin (1971) found that when light forces were used, a greater rate of tooth movement occurred and the post lag period started earlier. This may reflect the fewer areas of hyalinization observed in the pressure side of the teeth with light force. The last phase (linear phase) is where the rate of tooth movement is constant without any further increase in the rate. von

Böhl *et al.* (2004a) found this stage started after 80 days of tooth movement in beagle dogs. At this stage increasing the force will not influence the rate of tooth movement (Pilon *et al.*, 1996).

Thus, an ideal orthodontic force is the force that reduces the lag phase and promotes an earlier post lag period. Ren *et al.* (2003a) found most studies were relatively short to evaluate tooth movement during the four phases and thus, the ideal force has not yet been determined. Although initially it was thought that hyalinization only occurred during the lag phase, von Böhl *et al.* (2004a; 2004b) found small areas of focal hyalinization throughout the experiment when dogs' teeth were assessed over an 80 day period, irrespective of the force used. They concluded that hyalinization was not force dependent and this small focal hyalinization may account for the individual variation in the rate of tooth movement. Hence, individual variations, such inherent metabolic turnover (Pilon *et al.*, 1996) and cell biology (Iwasaki *et al.*, 2000), may have a bigger effect than force on the rate of tooth movement, as will be described later.

1.2.2 *Force and rate of tooth movement*

Rapid tooth movement without any adverse effects on the periodontium and teeth is one of the main objectives of orthodontic treatment. Several investigators (Storey & Smith, 1952; Lee, 1965; Hixon *et al.*, 1969; Hixon *et al.*, 1970; Fortin, 1971; Boester & Johnston, 1974; Owman-Moll *et al.*, 1996a; 1996b; Pilon *et al.*, 1996; van Leeuwen *et al.*, 1999; Iwasaki *et al.*, 2000; von Böhl *et al.*, 2004a; Yee *et al.*, 2009) studied the effect of the force magnitude on tooth movement and reported on the ideal force to produce tooth movement (Table 1-1). An analysis of these studies suggests there are different proposed relationships between force and rate of movement. Quinn & Yoshikawa (1985) suggested four different hypotheses: 1) constant relationship, 2) linear relationship, 3) linear relationship to a point and then rate decreases, 4) linear to a point and then plateau (Figure 1-1).

Table 1-1. The list of studies which investigated the relationship between the force magnitude and the rate of tooth movement (adapted from von Böhl et al. 2004a)

Authors	Year	Pressure (Kpa)	Force F (cN ≈g)	Force type	Object	Duration of Force (days)	Appliance	Subjects
Storey & Smith	1952	10-17	150-250	Tipping	Canine max	21	Closing springs	Human
Lee	1965	10-17	150-260	Tipping / bodily	Canine max	7	Torsion springs	Human
Hixon *et al.*	1969	20-66	300 -1000	Tipping	Canine max	56	Closing springs	Human
Hixon *et al.*	1970	20-93	300-1400	Tipping/ bodily	Canine max/mand	56	Elastics	Human
Fortin	1971	30-90	150-450	Bodily	Premolar man	90	Closing spring	Dogs
Boester & Johnston	1972	4-21	55-310	Tipping	Canine max /mand	70	Closing springs	Human
Owman-Moll *et al.*	1996a	5-10	50-100	Tipping	Premolar max	49	Sectional springs	Human
Owman-Moll *et al.*	1996b	5-20	50-200	Tipping	Premolar max	49	Sectional springs	Human
Pilon *et al.*	1996	10-40	50-200	Bodily	Premolar mand	120	Elastics	Dogs
van Leeuwen *et al.*	1999	2-5	10-25	Bodily	Premolar mand	120	Coil spring	Dogs
Iwasaki *et al.*	2000	4-13	18-60	Bodily	Canine max	84	Coil spring	Humans
Von Böhl *et al.*	2004	5-60	25-300	Bodily	Premolar mand	80	Coil springs	Dogs
Yee *et al.*	2009	3-20	50-300	Tipping /rotation	Canine max	84	Coil springs	human

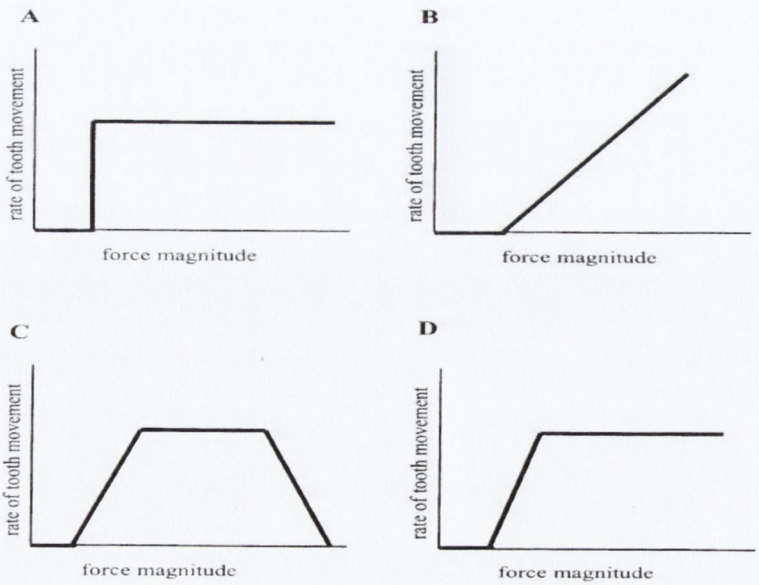

Figure 1-1. The 4 models for the relationship between force magnitude and the rate of tooth movement, as proposed by Quinn &Yoshikawa (1985).

The first model suggested an on/off switch for tooth movement. Tooth movement is switched on when a certain force level is reached and the rate of tooth movement does not increase as the force level is increased (Figure 1-1, A). The clinical impact would be that only one size of elastics or force is needed. Regarding anchorage, incorporating more teeth in the anchorage unit or different extraction patterns would have little influence on the ratio of tooth movement. Pilon and colleagues' 1996 study on Beagle dogs showed that the rate of tooth movement and the amount of anchorage loss were not significantly different for forces ranging between 50 to 200 g. Some dogs had teeth that moved slowly while others moved quickly, regardless of the force applied. Pilon *et al.* (1996) suggested that inherent metabolic factors might be more important than force level in determining the rate of tooth movement. These results seriously questioned the differential force theory. The teeth in the anchorage unit in this study, however, moved less than the individual premolar teeth. This suggests that the root surface area does influence the rate of tooth movement, but the extent of this influence is yet to be known. van Leeuwen *et al.* (1999) investigated the effect of two different force levels (10 cN and 25 cN) on 24 beagle dogs and found the force magnitude did not influence the rate of tooth movement. von Böhl *et al.* (2004a) compared the effect of heavy (300 cN) and light forces (25 cN) on retracting the second premolars in 15 beagle dogs and found no difference on the rate of tooth movement. Owman-Moll *et al.*, (1996a) applied buccal tipping forces to the first premolars in 32 patients and observed the rate of tooth movement over 7 weeks when the force magnitude was doubled (50 g and 100 g). They found no significant difference between both forces. Iwasaki *et al.* (2000), in a clinical study found that heavier forces (60 g) produced a higher rate of tooth movement than lighter forces (18 g) in the first 3 days ($p<0.01$) only. The average velocity for both forces over the 84 days had minor differences (0.4 mm/month) and the difference was not significant ($p<0.05$). Inter-individual velocities, however, varied as much as 3-fold for equivalent mechanical conditions. They concluded that cell biology must account for the

variability in tooth velocities measured in these subjects. In conclusion, it appears that light forces and heavy forces produce similar results, but light forces produce less adverse effects such as hyalinized areas, root resorption, pain, mobility, and pulp pathology. The adverse effects imposed on the supporting tissues are more relevant than the rate of tooth movement in relation to the amount of force applied in orthodontics. Other studies listed below did not support this theory and found a different relationship between force and tooth movement.

In the second model (Figure 1-1, B), a force threshold exists and a linear dose–response relationship above the threshold force. Clinically, increasing the amount of force would reduce the treatment time, as the rate of tooth movement is increased. With regard to anchorage considerations, increasing the number of teeth in the anchorage unit would increase the surface root area over which the force would be distributed, and as a result less movement would occur. Hixon *et al.* (1969) examined retracted canines and found that their data supported the second model. In their study a sectional archwire technique with a loop in a 0.0215 x 0.025" stainless steel (SS) wire was used to retract thirty-two canines. These heavy wires were used to minimise tipping movement. The authors applied variable magnitudes of force to the canines and used study casts and radiographs to measure the amount of movement. They found higher forces produced greater tooth displacement. The forces (Table 1-1), however, were high and resulted in tipping movement, which the authors could not eliminate, as the wire was not rigid enough when the applied forces exceeded 100 g. Later, Hixon *et al.* (1970) tried to modify the technique by using a 0.045" SS wire to retract the canines in the four quadrants in six patients. Although they found higher forces yielded greater tooth movement, they were still unable to eliminate tipping of all teeth. Limitations with this study were the small sample size (6 patients) and the short observation period (8 weeks), therefore the study was limited to the first two phases of tooth movement (initial phase and lag phase). Owman-Moll *et al.* (1996b) had a follow up

clinical study where they increased the force magnitude four-fold (50 g and 200 g). They applied buccal tipping forces to the first premolars in 10 patients for 7 weeks and observed the rate of tooth movement. They used crown tip in pre and post movement study casts to assess the amount of tooth movement. The magnitude of the mean horizontal crown movement increased by 50% when a force of 200 g was applied compared to the 50 g. However avoiding tipping movement is important, as it introduces several variables, which mask the relationship between force and the rate of tooth movement. Uneven distribution of force occurs during tipping movement which results in the crown and root moving at different rates (Ren *et al.,* 2003a). As a result, it is impossible to reproduce comparable tipping movements. In addition, overestimation of the measurements may occur during tooth movement, as these measurements are done from the crown. Therefore, Ren *et al.* (2003a) found studies with tipping movement difficult to compare and their results difficult to interpret. Interestingly, the authors suggested that the large differences between patients with regard to root area, time of beginning tooth movement and metabolic variation are more important than force magnitude.

In the third model (Figure 1-1, C), a threshold force is necessary to induce tooth movement and a dose-response relationship exists in a lower force range. Then a plateau is reached and any further increase in the force leads to a decrease in the rate of tooth movement. Clinicians would therefore use light forces to achieve desired tooth movement and prevent anchorage loss, whilst heavy forces would be beneficial when anchorage loss is desired. Storey & Smith (1952) correlated force magnitude and rate of tooth movement. They defined the optimum orthodontic force as that which produces maximum desirable biologic response with minimum tissue damage, resulting in rapid tooth movement with little discomfort. These authors compared the tipping movement of a cuspid to the bodily movement of a molar and premolar. They suggested the optimal force theory and proposed that there is an ideal force magnitude, which will elicit a maximum biological response and

result in the maximum rate of tooth movement. Storey & Smith (1952) used different designs of springs to apply different force levels. They suggested that a force of 150 to 200 g would cause the maximum amount of cuspid movement, while a heavier force of 300 to 500 g would elicit the maximum amount of movement in the molar and premolar. Storey & Smith (1952) proposed that tooth movement would decrease once the force was increased beyond the optimum force and eventually cease. One of the main limitations of this study was that despite applying equal forces to both the cuspids and the molars, the type of movement was different. This would result in a different force distribution on the periodontal membrane and alveolar bone. Force distribution is important when assessing tooth movement because the biological system which allows the tooth to move is activated by the force delivered to the system (Quinn & Yoshikawa, 1985). As a result this different type of movement could have exaggerated the difference in movement between the canine and molar. Furthermore, Iwasaki *et al* .(2000) suggested that Storey & Smith's 1952 clinical study was not long enough to observe delayed tooth movement that would occur following the first phase of undermining resorption. Therefore, Storey & Smith's (1952) conclusion is questionable, as the reduction in tooth movement could well have been due to hyalinization or a period of rest, as described by Fortin (1971). In addition, Nikolai (1975) suggested that if the optimum force theory is to be credible, it must take into account the influence of tooth surface area and shape, the type of tooth movement desired, and individual biology.

Lee (1965) followed the work of Storey & Smith (1952) and evaluated the optimum force during cuspid retraction using a similar experimental apparatus to Storey & Smith (1952). He measured the surface of the root being exposed to movement and called it the "enface" surface of the root. He proposed 200 g per cm^2 of enface root surface as optimum pressure to be applied in efficient tooth movement. Since force per unit area is defined as

pressure, then the applied force would vary depending upon the size of the root surface involved and the direction of movement being planned. Fortin in 1971 found lighter forces (150 g) produced more tooth movement and less anchorage loss than heavy forces (450 g) in dogs. They agreed with Storey & Smith (1952) and recommended lighter forces to avoid anchorage loss and hyalinization of periodontal membrane. Recently, Yee *et al.* (2009) compared light (50 g) and heavy forces (300 g) in 14 patients who required maxillary canine retraction. Their results supported the optimal force theory proposed by Storey & Smith (1952). Using a split-mouth design and using study casts to measure canine movement, initial tooth movement was similar for both forces. However they found heavy forces increased the rate of tooth movement at a later stage but lost their advantage as they had higher anchorage loss as well. Thus they recommended lighter forces in high anchorage cases. They went on to propose three different strategies depending on the anchorage need. In moderate anchorage cases, heavier forces would allow for equal space closure from both the anterior and posterior units. In maximum anchorage, they recommended light forces to avoid anchorage loss. With absolute anchorage devices they recommend heavy forces to increase the rate of tooth movement. The authors identified several limitations associated with their study. The authors used round 0.020 SS wire which resulted in tipping movement, as a result, overestimating tooth movements. In addition, rotation of the canines occurred in the heavy force group, which also overestimated the amount of tooth movement. Therefore the results of this study should be analysed carefully.

The last model (Figure 1-1, D) resembles the third model though it lacks the decreasing part. In this model, anchorage could be enhanced by adding more teeth to the anchorage unit and by increasing the surface root area. Several studies found no increase in the rate of tooth movement beyond a certain force level. Boester & Johnston (1974) supported this model. Study casts and radiographs were used to measure canine retraction in ten subjects.

In each subject, a different amount of force (55, 140, 225 and 310 g) was applied to each quadrant. The authors used Ricketts 0.016 x 0.016" SS sectional retraction springs, and a tension gauge was used to measure the force level. More tooth movement occurred in the higher forces (140, 225 and 310 g) compared to the lower force (55 g). However there were no significant differences in the space closure or anchorage loss between the higher forces (140, 335 and 310 g). Quinn & Yoshikawa (1985) highlighted two important limitations associated with this study. First, the amount of tooth movement (6-7 mm) achieved over 10 weeks seemed too large to be achieved by bodily movement only and therefore suggested tipping movement occurred. The second was that upper and lower canines were used, which reduced the sensitivity of the study. They suggested that upper and lower canines could move at different rates, hence the results would not be a true representation of the force magnitude.

Assessing the available data Quinn & Yoshikawa (1985) refuted the first model and concluded that there is more compelling evidence for the fourth theory. Although most studies found an increase of force would result in increased tooth movement, the critical question is whether the linear relationship is continuous, decreases or plateaus once a certain force level is reached. This is important from an anchorage point of view, as a linear relationship means that anchorage can be enhanced by including more teeth in the area where movement is not required. The theory suggests a slower movement of the teeth grouped together (anchor teeth), as the force per tooth would be less. Therefore, light forces will still allow for optimal movement of teeth, but the anchor unit will not have reached its plateau rate of movement. Quinn & Yoshikawa (1985) thought there was a limit to which the rate of tooth movement could not go beyond (fourth theory). They found this concept was biologically more appealing and they based it on the limits of the individual metabolic rate and cells turnover. Ren *et al.* (2004) suggested that Quinn & Yoshikawa reasoning for the fourth model was hampered by the lack of available experimental data on the use of

high forces. Based on the data collected from their review on animal studies, Ren *et al.* (2004) found that a dose-response range exists at very low force range. They found there is a tendency for tooth movement to slow down when the forces were increased, but the slope of the curve could not be predicated. Moreover, all Quinn & Yoshikawa (1985) models assumed that the force used should exceed a certain threshold before the system is switched on. This was not the case, as tooth movement can be initiated with minute forces (Ren *et al.,* 2004). A clinical consequence of this would be that it is virtually impossible to control anchorage. Ren *et al.* (2003a) outlined four reasons for the inability to determine the optimum force; 1) inability to precisely calculate the stress and strains produced at the periodontal ligaments, 2) failure to control the type of tooth movement (bodily and tipping) in previous studies, 3) the length of the previous studies might be too short to accurately evaluate the effect of the force, and 4) large interindividual variation with regard to metabolic rate, cell biology, root surface area and bone morphology. Furthermore, Melsen (2007) found most human studies had a small sample size and great variations in the forces applied. When the pressure on the teeth was calculated (Pressure = Force x 10^{-1}/ effective area = half the surface area), using the forces and the estimated root surface area, there was a huge variation which made comparisons between studies difficult. In addition, different force application methods, tooth types and observation periods were used. Different force applications induce another variation as elastics tend to lose force more rapidly than coil springs. Sectional springs avoid friction and the mechanism of the force application is different so comparisons could not be accurate. Melsen (2007) concluded that, based on these studies, a universally accepted optimal force value does not seem to exist. In conclusion it seems there is a relation between force and tooth movement, but the difference in tooth movement is more related to individual variations rather than force levels. Both Melsen (2007) and Ren *et al.* (2003a) found the answer to the question of optimal force is still far away and suggested that well controlled clinical trials and animal

experiments are needed to provide better insight into the relationship between orthodontic forces and the rate of subsequent tooth movement.

1.2.3 *Individual heterogeneity*

Inter-individual and intra-individual variations in tooth movement rates have been reported in animal (Pilon *et al.*, 1996; van Leeuwen *et al.*, 1999; von Böhl *et al.*, 2004a) and human studies (Owman-Moll *et al.*, 1996b). When equal forces were applied to the retracted teeth, the rate of tooth movement varied among and within individuals (Pilon *et al.*, 1996; von Böhl *et al.*, 2004a). Furthermore, when forces were varied within or between individuals, the rate of tooth movement was nearly the same (Owman-Moll *et al.*, 1996a; 1996b; van Leeuwen *et al.*, 1999). Therefore, Pilon *et al.* (1996) suggested that some individuals will be considered as typical slow movers whist others are fast. The authors suggested that these differences in tooth movement are as result of variations in the anatomical structures, bone density, systemic metabolism, cytokines and growth factors. Several studies have demonstrated the effect of bone metabolism on tooth movement. Verna *et al.* (2000) found tooth movement in rats was significantly influenced by high and low induced bone metabolism. Tooth movement was faster in rats with increased bone metabolism. Earlier studies on beagle dogs (Midgett *et al.*, 1981) found tooth movement was affected by a reduced calcium diet. Other studies found medication (Giunta *et al.*, 1995), such as indomethacin, influenced bone metabolism and consequently the rate of tooth movement in pigs. Verna & Melsen (2003) found tooth movement was slower in hypothyroidism induced rats. Pregnant women may also have faster tooth movement (Hellsing & Hammarstrom, 1991). The effect of age on the rate of tooth movement has also been investigated. It has been suggested that in adults there is reduced proliferation activities of the PDL and consequently reduced tooth movement. The reports on the effect on age have been conducted on rodents with two different outcomes. Some reports

suggested increased tooth movement in younger rats (Bridges *et al.*, 1988; Kyomen & Tanne, 1997) whilst others showed no difference between adults and younger rats (Kabasawa *et al.*, 1996). A subsequent study found that tooth movement was slower in adults during the initial and lag phase but was the same during the linear phase (Ren *et al.*, 2003b). The authors suggested that reduced bone activity and organic matrix production in PDL, as well as the reduced mitotic activity of cells, were responsible for the initial delay. Other factors which may vary between individuals and could also influence tooth movement are the levels of cytokines and growth factors such as PGE_2, IL-1β and TGF-β1. These factors are involved in the remodelling process during tooth movement and studies have shown significant difference between individuals during tooth movement (Wise & King, 2008).

1.2.4 *Type of tooth movement*

There are two types of tooth movement which have been described when assessing the rate of tooth movement; tipping and bodily tooth movement. In bodily tooth movement, the crown and the root of the tooth move simultaneously in the desired direction, whilst in tipping movement the crown of the tooth moves while the tip of the root stays stationary (Proffit *et al.*, 2007). It is important to control the type of tooth movement whenever the rate of movement is assessed, as the stress distributions within the periodontal ligaments are different. Hixon *et al.* (1970) found when the same force was applied tipping movement occurred at a faster rate than bodily movement. However Ren *et al.* (2003a) found that most studies failed to prevent tipping movement from occurring while trying to achieve bodily movement and thus Ren *et al.* (2003a) found it very difficult to interpret or compare studies.

Isaacson *et al.* (1993) re-evaluated the relationship between tooth movement and orthodontic mechanotherapy. They suggested that the current concepts of clinical

orthodontic tooth movement are misleading and found bodily tooth movement occurs as a result of a combination of the two types of tooth movement. Traditionally, whether tipping or bodily tooth movement occurs, depends on the relation of the applied force to the centre of resistance and the location of the centre of rotation of the tooth. Centre of resistance (CRes) is defined as that point on the tooth where, if a single force passed through, pure translation would result. This varies with root length. Burstone & Pryputniewicz (1980) determined that for a single rooted tooth the CRes is one third of the root length apical to the alveolar crest along the long axis of the root. Smith & Burstone (1984) defined the centre of rotation (CRot) as the point about which a body appears to have rotated, as determined from its initial and final positions. CRot does not need to be along the long axis of a tooth. During intrusion, for example, CRot falls on a line, which is perpendicular to the long axis of the tooth.

In orthodontics it is assumed that if the direction of an applied force passes through the CRes of a tooth, the tooth will respond with a pure bodily movement in the direction of the applied force. In reality, however, forces are typically applied to attachments on the buccal surfaces of the teeth (coronal and peripheral to the CRes) (Iwasaki *et al.,* 2000). Therefore, the applied force does not pass through the CRes, and will produce some rotation. Therefore, Smith & Burstone (1984) described two possible ways force can be applied to a tooth. First, is by a single force acting away from the centre of resistance (CRes), which is called the 'moment of the force' (Figure 1-2). A single force, therefore, results in the displacement of the CRes in the direction of the line of the force resulting in a tipping movement. The magnitude of the moment is equal to the product of the force magnitude and the moment arm length, which is the shortest perpendicular distance from the force line to the axis of the CRot (Nikolai, 1975). This application of force results in a moment of

force clockwise or counter clockwise around the CRot causing the tooth to tip (Isaacson *et al.*, 1993).

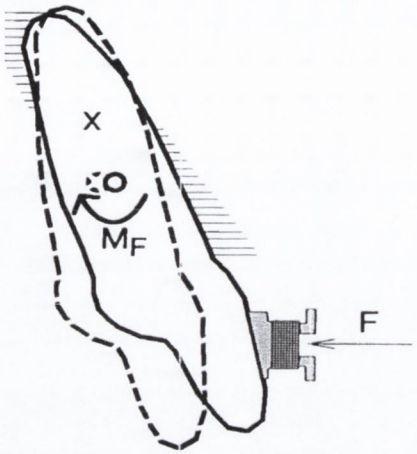

Figure 1-2. A schematic representation of the moment of force (MF). A typical orthodontic force applied away from the centre of resistance (O). This application of a force will cause (O) of the tooth to move parallel and in the same direction as the force. The centre of rotation (X) will be located apical to the centre of resistance (Isaacson *et al.*, 1993).

The second method by which force can be applied to a tooth is by a pair of equal forces which are parallel and of opposite directions, this is termed a couple (Figure 1-3). This creates a tendency for rotation (the moment of the couple), whose magnitude is equal to one of the forces of the couple multiplied by the distance between them. In this case, the CRot is coincident with the CRes of the tooth irrespective of its point of application (Isaacson *et al.*, 1993).

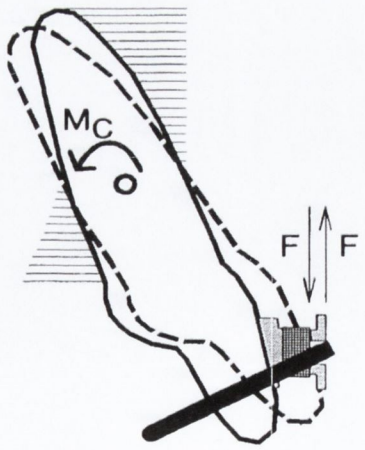

Figure 1-3. A schematic representation of the moment of the couple (MC). A pair of equal but opposite parallel noncolinear forces. The centre of rotation (X) and centre of resistance (O) will be coincident. (Isaacson *et al.*, 1993).

As orthodontic brackets do not allow a force to act directly at the CRes, net bodily movement can be only be effected by applying a force at the attachment in the direction of the desired movement along with a counter moment to prevent tipping in the direction of the force (Iwasaki *et al.*, 2000). Under these conditions the relative amount of crown tipping (moment of the force) and root tipping (moment of the couple) expressed at any given moment in time determines the location of the CRot. When these two opposite directed moments are equal in magnitude, the CRot is at infinity and tooth translation occurs (Figure 1-4). However, Isaacson *et al.* (1993) challenged the idea of bodily tooth movement and suggested that it is unrealistic to expect tooth displacement to occur in any manner other than crown movement exceeding root movement (i.e. moment of force exceeding the moment of couple). They explained that because the rates of decay of the moment of the force and the moment of the couple are not equal, the ratio between them is constantly changing. Thus, bodily movement exists instantaneously and cannot be sustained, and tooth movement occurs by tipping and then uprighting, therefore a well defined and reproducible type of tooth movement is almost impossible to achieve (Ren *et al.*, 2003a). This explains the ambiguity about the effect of force on the rate of tooth movement and led Melsen (1999) to suggest that there is no relationship between the rate and the type of tooth movement.

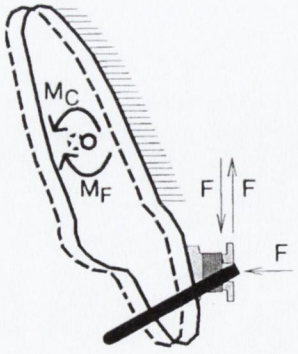

Figure 1-4. A Schematic illustration of the concept of bodily movement. The rotational tendencies of the moments of the force and couple, being opposite nullify each other (Isaacson *et al.*, 1993).

1.3 Anchorage classifications

A successful orthodontic treatment depends on a carefully formulated treatment plan. Orthodontists are often perplexed by the failure of their treatment plan to correspond with actual results. This is often due to an inadequate consideration of anchorage whilst forming the plan. Therefore, it is paramount to understand anchorage and the biomechanical basics prior to installing anchorage reinforcements. Historically, Wright (1939) divided anchorage into simple and stationary. With the advent of implants and modern mechanics, Mitchell (1996) divided anchorage into four types: simple, compound, reciprocal and absolute. On the other hand, Proffit *et al.* (2007) divided anchorage into reinforced, stationary, reciprocal, and absolute. The main difference between Mitchell and Proffit's classifications is that Mitchell uses the term compound anchorage to describe what Proffit suggests is stationary. In this document Mitchell's classification will be used and the difference between the two will be discussed further below.

1.3.1 *Simple Anchorage*

Simple anchorage is the process whereby unwanted tooth movements are prevented by using a tooth or group of teeth with a larger root surface area as an anchor, versus a tooth with a smaller root surface area (Wright, 1939; Mitchell, 1996; Proffit *et al.*, 2007). In theory, the greater the root surface area the greater the resistance to tooth movement (Roberts *et al.*, 1996). Thus, the total root surface area of the anchor teeth should be larger than the tooth with the desired movement. This would result in the force being distributed over a larger surface area and as a result less force per unit area would be applied to the anchor teeth, where movement is not desirable. The root surface area could be increased by a variety of methods: including the second molars while retracting the anterior segment, retracting teeth individually, or different extraction patterns to increase the root surface area in the posterior anchor unit.

When pressure is applied to a tooth the force is distributed along the root surface. Once the force reaches a particular level (threshold pressure) a string of biomechanical events occur and eventually the tooth starts to move (Reitan, 1960). Increasing the total root surface area in the anchor units would increase the threshold pressure for tooth movement in the anchor unit and prevent the force levels from reaching the required threshold pressure. Theoretically this should prevent undesired tooth movement.

It is very difficult to identify the threshold pressure for individual teeth, as it could vary among and within individuals (Pilon *et al.,* 1996; van Leeuwen *et al.*, 1999). This is due to the interaction of many factors such as genetic predisposition (Pilon *et al.*, 1996), inherent metabolic turn over (Reitan, 1957; Hixon *et al.,* 1969; Hixon *et al.*, 1970; Pilon *et al.*, 1996), variation in root surface area and shape (Nikolai, 1975), type of movement (Nikolai, 1975), cell biology (Iwasaki *et al.*, 2000), periodontal status (Mitchell *et al.,* 1973) and bone quality (Reitan, 1964; Fortin, 1971; Mitchell *et al.*, 1973). Consequently there has been no scientific consensus regarding the optimum force or a threshold of force level that would start tooth movement (Melsen, 2007).

A systematic review by Ren *et al.* (2003a) concluded that the threshold pressure is still unidentified despite experimental endeavours to quantify it. A study by Kyoichi (1977) found that forces as low as 3g resulted in tooth movement where as a force of 1 g for 21 days had no impact on the lower first molars. This is in agreement with Weinstein (1967) who found 4 g were sufficient to produce tooth movement. Such studies have proved that the idea of including more teeth in the anchor unit to reduce the forces below the threshold level was not valid, as there is no universally accepted value for the threshold of tooth movement. Furthermore, Melsen (2007) concluded that a threshold for tooth movement does not exist. Nevertheless, the simple anchorage principal is still being applied in orthodontics in spite of the lack of supporting scientific evidence.

1.3.2 *Compound Anchorage*

Compound anchorage relies on the different types of movement of the anchor teeth in controlling unwanted tooth movement. Mitchell (1996) used this term to describe this type of anchorage whereas Proffit *et al.* (2007) used the term *stationary anchorage* for the same concept. Although Proffit *et al.* (2007) is historically more accurate, since the term stationary anchorage was used by Wright (1939) to describe this type of anchorage, it could be misleading as the anchorage units are not stationary. In addition, Wright's classification was prior to the introduction of implants. Thus, stationary anchorage applies more accurately to implants, which will be discussed later on. The orthodontic force required for bodily tooth movements is different than that required for tipping tooth movements (Reitan, 1960). It follows the same basic principle of the amount of root surface area exposed to pressure. In bodily tooth movement, the force is evenly distributed along the whole root surface whereas in tipping tooth movement it is concentrated in the apex and crest of the tooth (Reitan, 1957). These concentrated forces produced cell-free areas *(hyalinization)* which subsequently reduce the rate of tooth movement. Reitan (1960) found less force is required for tipping movement to occur than bodily movement. Ricketts *et al.* (1979) adopts this idea in his utility arch design where he incorporates tip back bend into the archwire to tip the molar teeth distally and prevent their movement, while the other teeth can slide along the arch. This prevents any mesial movement as the anchor teeth will need to be moved first upright and then move forward bodily. This combination of movements will require more force due to the involvement of more root surface. Adding torque to the molar teeth also enhances the anchorage. In Ricketts utility arch design (Ricketts *et al.*, 1979) the first molar roots are buccally torqued to prevent their mesial movement. This results in the buccal surface of the roots being moved into the buccal bone. Ricketts *et al.* (1979) proposed that tooth movement becomes more difficult as the latter is more dense

and has less marrow spaces than trabecular bone. This will mean that more force is required to move the anchor teeth.

1.3.3 *Reciprocal Anchorage*

Reciprocal anchorage is a situation where there is no unwanted tooth movement. This is because the reciprocal force of one set of teeth is utilized to move the other set and therefore the unwanted tooth movement is also desired tooth movement. This can occur when an equal amount of movement is required, such as closing a diastema between the two central incisors or an unequal amount of movement such as space closure following an extraction of the second premolar. In this case both mesial movements of the posterior teeth, and to a lesser degree distal movements of the anterior teeth, are required. The latter is not truly reciprocal though, as the movements are not equal. However the same principals of reciprocal anchorage still apply as both movements are desirable.

1.3.4 *Skeletal (Absolute-Stationary) Anchorage*

Absolute (stationary) anchorage is when no undesired tooth movement or anchorage loss occurs. Wright (1939) and Strang (1941) stated that true stationary anchorage is not feasible intra-orally since it is impossible to prevent the movement of the anchor teeth. As a result, structures besides teeth, such as the basal bone, were utilized to reinforce anchorage and achieve dental and skeletal changes without the unwanted tooth movements. Headgear was one of the main devices that was available which utilized aspects other than dentition to reinforce anchorage. Due to the complications associated with headgear such as patient compliance (Egolf *et al.,* 1990), risk of injuries (Booth-Mason & Birnie, 1988) and force control (part time wear) headgear has never achieved universal popularity with either patients or clinicians.

Using implants as absolute anchorage is a relatively new development, although the idea has been documented as early as 1945 by Gainsforth & Higley. Gainsforth & Higley (1945) have suggested that patient compliance is the most difficult problem faced by orthodontists. In order to develop appliances that do not depend on patient compliance Gainsforth & Higley (1945) attempted to distalize the maxillary teeth in dogs using vitallium screws. An endosseous implant utilized the bone to provide resistance to unwanted reciprocal forces and avoid the dissipation of the forces along the periodontal tissues to the adjacent dentition. Following Brånemark's (Brånemark *et al.,* 1969) encouraging results in the successful osseointegration of titanium implants, Roberts *et al.* (1984) attempted to utilize titanium implants for orthodontic anchorage. They found that osseointegrated implants remained stationary and resisted any applied orthodontic force and suggested the use of implants as a form of absolute anchorage reinforcement. Implants have since been successfully used as a form of absolute anchorage reinforcement for dental and orthopaedic reasons in specific cases (Ismail & Johal, 2002). The complexity of the surgical procedure, cost, waiting period (4-6 months), lack of adequate bone, anatomic limitations (sinuses, nerves, unerupted teeth and developing bone in children) and discomfort have limited their usage (Lee *et al.,* 2007).

There are various alternatives to conventional implants such as Onplants (Block & Hoffman, 1995), Orthosystem® (Wehrbein *et al.,* 1996a), which are reduced length implants, or miniscrews (Creekmore & Eklund, 1983) and mini-implants (Kanomi, 1997), which are reduced width implants. These have been developed lately to circumvent the limitations mentioned above. These devices have been classified as temporary anchorage devices (TADs) since they are removed and discarded at the end of the orthodontic treatment. In contrast to the other TADs, miniscrews and mini-implants are not fully osseointegrated but osseo-aided (Costa *et al.,* 1998; Cope, 2005; Wang & Liou, 2008).

Miniscrews can simply be removed, as opposed to the conventional implants which require a surgical procedure and possibly cause bony defects (Lee *et al.,* 2007). Miniscrews are used for a variety of purposes: distalization, intrusion, extrusion, space closure, en masse retraction, centre line correction, vertical control and correction of canted occlusal plane (Carano *et al.,* 2005b; Melsen, 2005). The glossary of orthodontics (Daskalogiannakis, 2000) classifies these devices (conventional implants, Onplants, Orthosystem®, miniscrews) as *infinite anchorage* devices. Infinite anchorage devices are defined as objects which show no movement as a consequence of reaction forces.

1.4 Sources of Anchorage

Anchorage can be enhanced by extra-oral and intra-oral devices. Depending on the skeletal relation, dental relation, treatment objectives, type of movement required and dentition status, different methods can be used. Each has its advantages and limitations as will be discussed below.

1.4.1 *Extra-oral*

Extra-oral anchorage devices in the form of headgear have been used as early as the nineteenth century. The calvarium or the cervical spine offered resistance to the unwanted movement via a headgear or neck strap. It was mainly used for modifying growth to correct the dentoskeletal discrepancies. It could also provide a counterforce to the anchorage units, thus preventing unwanted movement.

Headgear usage was discouraged by Angle and his followers in the early 1920s when intermaxillary elastics were used. Headgear was originally used for its orthopaedic effects on the faciomaxillary complex. These included the differential enhancement of mandibular or maxillary growth. Angle believed that intermaxillary elastics have the same effect on the mandible and maxilla respectively in addition to the dental movements. This will negate the

need for headgear with all of its associated problems such as safety hazards and unsightly appearance. Oppenheim (1936) produced a challenge when he suggested the use of headgear as adjunctive and he demonstrated the ineffectiveness of the elastics in comparison to headgear in treating skeletal discrepancies. This was validated with the development of cephalometric radiographs by Broadbent (1931). The absence of skeletal changes in cephalometric radiographs which were claimed to occur with elastics was noted by Kloehn (1947). He presented several cases with skeletal discrepancies that were successfully treated with headgear. His success encouraged orthodontists to readopt the headgear and it became a crucial part of orthodontic treatment.

Headgear devices can be used to enhance molar anchorage during space closure. Despite its use there is very little in the literature about the effectiveness of headgear devices as anchorage reinforcements for molars during space closure. A randomised clinical trial by Benson *et al.* (2007) used cephalometric analysis to compare the effectiveness of headgear with midpalatal implants. Fifty one patients with class II division 1 malocclusion were randomly allocated to either group. They found that anchorage loss was twice as much in the headgear group. One of the main limitations of this study was the use of intermaxillary elastics. As these are a form of anchorage reinforcement they would have affected the results which are clearly demonstrated by the difference in the lower incisor proclination between the two groups. The headgear group had more proclination in the lower incisors which could suggest higher use of class II elastics. The authors acknowledged that the usage of class II elastics might affect the results but failed to account for and quantify its usage. Therefore the results of this study must be interpreted with caution. The effectiveness of headgear for distalization of molars was assessed by Bondemark & Karlsson (2005) and found to be as effective as an intra-oral distalizing device. The intra-oral device in this study involved bands on the molars and a Nance appliance attached to

the second premolars with springs pushing the molars distally. In a randomised clinical trial comparing headgear with intra-oral devices, 40 patients were randomly allocated to either group. The intra-oral device had a similar design to the Jones jig (Jones & White, 1992). Both devices were used to correct a minimum of half a unit class II molar relation. They found headgear to be slightly less effective in distalizing the molars but with no anchorage loss. Intra-oral devices were three times more efficient in distalizing the molars but at the expense of an increased overjet which is another form of anchorage loss. This study is more informative with regard to the effects of headgear since fewer variables were involved than in the previous study by Benson *et al.* (2007).

Although headgears are a simple and cost effective method to reinforce anchorage, their unsightly appearance makes them unpopular with patients (Egolf *et al.,* 1990). The recommendation for headgear wear is seven days a week and about 10-12 hours per day (Kloehn, 1953). Patient compliance is important in orthodontics but Kloehn (1953) stressed that it is particularly important with this type of appliance. A study by Wheeler *et al.* (2002) found that compliance was directly related to the success level of the treatment. Several timing devices have been introduced into the headgear to increase the compliance level (Northcutt, 1974; Northcutt, 1975; Cureton *et al.,* 1991). An earlier study by Banks & Read (1987) found that the accuracy of the earlier versions of the timing devices to be only 30%. The newer versions (Affirm) are inexpensive and have contributed to an increase in patient compliance from 56% to 62.7% (Brandao *et al.,* 2006). Cureton *et al.* (1993) assessed the compliance of 28 patients of different age groups and found younger patients are more compliant. However the overall compliance rate was 59% which suggests that the headgear was not generally accepted by patients and thus its limitations.

Another drawback was the injuries that have been reported with headgear usage (Booth-Mason & Birnie, 1988). These included devastating ocular injuries, leading to sight loss. Safety mechanisms such as safety straps and snap release mechanisms have reduced the risks associated with headgear devices and have made them safer if used according to the instructions provided.

Currently headgear is still a very compliance-dependent appliance, which is not very acceptable to older age groups and thus is reserved for younger, more compliant patients.

1.4.2 *Intra-oral*

Anchorage can be achieved intra-orally through different mechanisms. The classic method would be to incorporate multiple teeth at the anchorage segment to increase the root surface area of the group and thus forming a larger counterbalancing unit. Other methods include using an anatomical area, an appliance, or an opposing dental arch to enhance anchorage. Baker *et al.* (1972) have divided the intraoral sources of anchorage into:

a) Teeth: which counterforce the movement by the size and position of the root.

b) Alveolar bone: resist tooth movement by the arrangement of the trabecular bone.

c) The dental arches: offer resistance as a unit when the teeth are joined together and then used against the opposing arch.

d) Palatal or mandibular bone: resist movement when forces are applied to them.

e) Lip and musculature: can be utilized to resist or exert forces.

1.4.2.1 Teeth (Root surface area)

In orthodontic practice it is generally accepted that increasing the root surface area increases anchorage (Wright 1939; Baker *et al.,* 1972; Ong & Woods 2001; Geron *et al.,* 2003). Clinically, this can be achieved by utilizing larger teeth on the anchorage side,

consolidating a group of teeth to form a larger anchor unit or by using a different extraction pattern to shift the balance of root surface area towards the anchor side (Geron *et al.,* 2003). A classic orthodontic example would be banding the second molars to reinforce the anchorage posteriorly. A radiographic study by Jepsen (1963) measured the root surface area of the dentition. In this study Jepsen (1963) found that by banding the second molars the root surface area was doubled. In theory this should double the anchorage enforcement and half the anchorage loss. However in practice, this idea of increasing the root surface area has not been fully validated or quantified due to the numerous large variables involved in tooth movement. Initially, this idea was supported by the differential force theory which suggests that there is an optimal force for each tooth that produces maximum tooth movement with minimal damage. Storey & Smith (1952) have suggested that this force was proportional to the root surface area. Several attempts have been made to support and quantify the surface area theory using clinical (Williams & Hosila, 1976; Creekmore, 1997; Ong & Woods, 2001) and animal studies (Pilon *et al.,* 1996).

One of the methods used to measure anchorage loss and the influence of the root surface area was to compare the mesial movement of the molars where the first or second premolars were extracted. The former would have an anchorage unit with a larger root surface area, thus molar movement should, theoretically, be less.

Williams & Hosila (1976) assessed incisor retraction versus molar mesial movement with different extraction patterns. They assessed the pre- and post-treatment lateral cephalometric radiographs of 260 cases treated with the Begg appliance. One hundred and one cases were treated by extraction of the four first premolars, 24 were treated by the extraction of the maxillary first premolars and mandibular second premolars and 79 cases were treated by the extraction of first molars. Radiographic superimposition using the Bjork

method (Bjork, 1969) for the mandible and a Downs method for the maxilla was used to assess the anterior retraction of the incisors. The mean forward movement of the maxillary and mandibular molars (anchorage loss) was 33.5% and 43.7% of the extraction space when four first premolars and upper first and lower second premolars were extracted respectively. By contrast the anchorage loss was 50.4% when the first molars were extracted. Interestingly, these percentages of anchorage loss did not coincide with the calculations made based on the root surface area ratio. The anchorage loss was less than expected in the first premolar group and more than expected in the first molar group. Although there was some apparent relation between the anchorage loss and root surface area, it was not a direct one.

Creekmore (1997) presented five cases treated with two different appliances (0.018"x0.025" Uni-Twin appliance* and Mobile-Lock# self ligating appliance) and different extraction patterns. His rule of thumb was that when first premolars are extracted the posterior teeth move forward approximately one third of the space whereas when the second premolar is extracted, they moved forward half the extraction space. There is no scientific evidence to validate his rule. Furthermore his use of two different types of appliances in the presented cases might have affected his anchorage loss since different appliances might influence the anchorage loss in varying ways (Rajcich & Sadowsky, 1997).

Similarly Ong & Woods (2001) examined the changes in the maxillary molars and incisors positions following the extraction of maxillary first or second premolars. Seventy six patients treated with premolar extractions by the same orthodontist using a pre-adjusted

* Uni-Twin, Nitinol: 3M Unitek, 2724 S. Peck Road, Monrovia, CA 91016.

Mobil-Lok: Forestadent USA, 12040 Bach Blvd., St. Louis, MO 63132

Edgewise appliance were randomly selected. Forty five had maxillary first premolars extracted and 26 had maxillary second premolars extracted. Study casts and cephalometric measurements were made to calculate the maxillary molar versus incisor movement. The maxillary molars moved forward by 3.7 mm when the first premolars where extracted in contrast to 4.5 mm when the second premolars were extracted. This was expected as the extraction site was closer to the molars in the second group. On the other hand when the maxillary first premolars were extracted in conjunction with mandibular second premolars the maxillary molars moved forward by 4.7 mm. This interesting finding may be due to occlusion factors as the molars are not occluding with lower premolars and are thus free to move forward. Further, this could be due to mechanical factors as lower molars in these cases move forward and thus the upper molars would then follow. This is in agreement with the incisor retraction which was higher in the first premolar extraction group (4.2 mm) compared to the first and second premolar (3.7 mm) combination group. This finding is to be expected if the incisor retraction (2.3 mm) when the four second premolars were extracted is taken into consideration. The lower incisors would retract less when the second premolars are extracted and consequently prevent the maxillary incisors from retracting therefore indirectly resulting in more forward movement of the maxillary molars. This is a classic example of how occlusion and the inter-arch relationship influence anchorage loss. As a result all the changes the study was intending to measure may have been masked because the patient sample was randomly selected and different mechanics were used by the clinician to close the residual spaces. This is one of the limitations associated with previous retrospective studies.

Saelens & De Smit (1998) looked at the changes in the molars positions associated with extractions of the first and second premolar. Pre- and post-treatment lateral cephalograms were used to measure the changes in the molar positions. The cases were

treated using Begg appliances without any extra-oral auxiliaries but with the use of inter-arch elastics. The extraction decision was made based on the level of crowding. The molars moved forward more with the second premolar extractions (5.5 mm versus 4.4 mm) when compared to first premolar extractions. However this is not an indication of the different anchorage potential of the various extractions. These extractions were based on the associated crowding and therefore the movement in the molars was guided primarily by crowding and to a lesser extent by anchorage. This was confirmed later on by Geron *et al.* (2003) where they found that crowding can influence anchorage loss. Another issue affecting the accuracy of the results is that there was no consistency with regard to space closure mechanics. These varying mechanics influence the incisor and molar position.

A retrospective study by Geron *et al.* (2003) and the only study considered adequate by Feldmann & Bondemark's (2006) systematic review looked at five different factors that might affect anchorage loss. Cephalograms and study casts were used to measure the anchorage loss. Geron *et al.* (2003) found anchorage loss to be a multifactorial response to 4 aspects: the extraction site, appliance type, patient age and crowding. Anchorage loss however was only 0.5 mm greater with second premolars and it was considered insignificant. In contrast anchorage loss was found to be significantly greater in labial appliances and inversely correlated to crowding. There are several interesting aspects to consider in this study. Firstly the study does not provide the reader with the amount of active movement, thus the ratio of anchorage loss cannot be determined. Secondly there are a lot of variables which as Geron *et al.* (2003) clearly state affect the anchorage loss thus drawing a conclusion would be difficult as they all overlap. Nevertheless this study illustrates the difficulty of comparing anchorage loss in studies performed on humans with all the uncontrolled biological and mechanical factors. The insignificant difference between various extraction patterns on anchorage loss that has frequently been noted by studies may

be a result of the overwhelming multiple factors masking any changes that might be associated with or caused by a single factor. A solution to this problem may be reached by producing an experimental environment where the tightest possible control over condition and variable may be achieved.

Such a situation is feasible only in animals where the malocclusion and mechanical variables are controlled. Beagle dogs are generally accepted as appropriate models for comparison with human beings (Pilon *et al*, 1996) despite their generally more dense alveolar bone (Reitan & Kvam, 1971). Harris *et al* (1991) and Geron *et al* (2003) found orthodontic mechanics during treatment to be more important than bone density. Ren *et al.* (2004) developed a mathematic model based on the data from past animal studies and compared it to data from clinical research. They found both the maximum rate of tooth movement and the maximum force in dogs were similar to humans. Most of the animal studies which reported on anchorage loss were designed to assess tooth movement and not specifically anchorage. Fortin (1971) assessed tooth movement in dogs. In his study, he found the anchor unit protracted (fourth premolar) by 50% when the second premolar was retracted in 6 beagle dogs. Pilon *et al.* (1996) assessed the influence of different force levels on the rate of tooth movement in 25 beagle dogs. Using three different force levels (50, 100 and 200 g), Pilon *et al.* (1996) found that varying force levels did not significantly influence anchorage loss. However they noted that the anchorage units moved 30% less than the control (second premolars) despite the root surface being ten times larger in the anchorage units. This suggested that there was a relation between the tooth surface and anchorage loss however the biological factors such as metabolic factors, bone quality and root shape played a bigger role. This was demonstrated by the intra-individual correlation and large inter-individual differences in his study. One of the clear advantages of this study was that all the mechanical factors were standardised and the samples were matched. Thus

the individual biological factors in addition to the different forces applied were the only difference between the two groups.

In spite of the numerous studies, orthodontists are still not any closer to an accurate method of evaluating anchorage loss associated with different extractions and anchorage reinforcing methods. One of the primary fundamentals within orthodontic practice is the informed ability to decide which teeth to extract and to determine how much anchorage loss is expected. Yet today we are no closer to answering this question than we were 90 years ago. The problem resides in several inaccurate assumptions about root surface area as an index for anchorage value. Roberts *et al.* (1996) emphasised the fact that using the root surface area as an index for anchorage values assumes that 1) the resorptive mechanism of the bone ahead of the moving tooth is similar to all the teeth, 2) following the lag phase (undermining resorption and hyalinization of the periodontal ligament) tooth movement is linear for all the teeth, 3) anchorage values are directly related to stress at the PDL bone interface. These assumptions however are not consistent with the literature. The osseous morphology was found to be different within the dental arch (Atkinson 1965; 1967). The increased density of the bone posteriorly could increase the anchorage potential distally (Roberts *et al.,* 1990; Roberts, 1994). In addition this bone variance may change the rate of tooth movement (Reitan, 1964; Roberts *et al.,* 1990). Recent studies by von Böhl *et al.* (2004a) and von Böhl *et al.* (2004b) have found that hyalinization was always found and that it was not directly related to force levels. Individual variations were due to local irregularities in the bone and the PDL, which affected the rate of tooth movement.

Other complications include the multifactorial response, the purpose of the studies and the methodology of the studies. None of the previous studies have controlled all of these aspects while assessing an individual factor. The subjects should have been matched for occlusion, crowding, age, appliance and above all equal mechanics. Secondly, most of

these studies were retrospective meaning there was no control over the mechanics used to close the spaces. Thirdly, the orthodontists were modifying their mechanics as treatment progressed to achieve the best results for the patients and as a result influencing the anchorage loss. For example, in a case where there was residual space left the orthodontist would allow the molars to move forward. On the other hand if anchorage loss was too excessive the orthodontist would balance it by reinforcing the anchorage posteriorly. It would have in fact been better to assess the anchorage loss in these studies post alignment prior to the orthodontist interference. Even so, biological factors such as bone density, metabolic rate, and root surface area variations may mask any difference. Also the aim of most of these studies was not to assess anchorage loss in particular, and thus there was no control sample. The aim instead was to assess the changes associated with these extractions. Lastly some of these papers are case reports (Creekmore 1997) so the scientific value is weak.

1.4.2.2 Occlusal Interlocking

In addition to the notion of using root surface area as an index for anchorage value, several other factors which would influence the anchorage balance have been accepted in orthodontics, in spite of the lack of well documented evidence to support them. These include patients' facial proportions, occlusal interlocking and bone quality. It has been accepted in orthodontics that a patient with reduced facial proportions or a low maxillary-mandible plane angle would have less anchorage loss and, therefore, more difficult space closure. This has been attributed to the increased masticatory muscle forces inhibiting eruption and mesial drift. Earlier studies by Alexander *et al.* (1983) found that disocclusion of the posterior teeth resulted in more anchorage loss. This is not supported by Geron *et al.* (2003) who found less anchorage loss in lingual appliances. Lingual appliances disocclude the occlusion posteriorly by virtue of the maxillary lingual brackets which act like a bite

plane. They suggested that other factors may contribute to the difference, such as the reduced interbracket distance, but concluded that more studies should investigate this more closely.

1.4.2.3 Bone Quality

The physiological differences between the different age groups, such as adolescents and adults, may influence tooth movement and anchorage loss (Dyer *et al.,* 1991). Bone density is one of the major differences between such groups. After skeletal maturity is reached at approximately 20 years of age, the amount of cortical bone in many different bones tends to reduce. Epker *et al.* (1965) have documented progressive thinning of the cortical bone after adulthood is reached. In contrast, Liu *et al.* (1977) found the cortical bone was increased, as a significant decrease in trabecular bone was observed in alveolar bone samples taken from adults following third molar extraction. Earlier Reitan (1954) found that there was a delay in bone remodelling in adults compared to adolescents, which in return resulted in initial delay of tooth movement. The overall rate of tooth movement was not slower once proliferation of the connective tissue cells and vascularity was started (Bond, 1972). Thus, the average treatment time was the same (Dyer *et al.,* 1991). This initial delay before tooth movement might indirectly influence anchorage loss. Harris *et al.* (1991) compared tooth movement in adults and adolescents using Johnston's analysis. They found less anchorage loss in adults (0.2 mm) compared to adolescents (2.52 mm). They attributed this difference to the greater amount of time that class II elastics were worn in adolescents rather than bone density. Geron *et al.* (2003) found greater anchorage loss in adults (0.7 mm) when class II elastics were worn for a similar time in both groups. Both Harris *et al.* (1991) and Geron *et al.* (2003) suggested that the mechanics used were more influential than the bone density. As a result of their entirely opposite findings, Geron *et al.* (2003) concluded that more studies must be undertaken to reach a more definitive finding.

1.4.2.4 Appliances

Different appliances may also influence anchorage loss. The current developments in the bracket systems have been aimed at providing a bracket system which will limit or eliminate unwanted tooth movement. Lotzof *et al.* (1996) have conducted a prospective split-mouth study that compared anchorage loss in two different pre-adjusted bracket (Tip-Edge[1] and A-Company Straight Wire[2]) systems in 12 patients. The Tip-Edge appliance produced tipping movement whilst the A-Company appliance produced bodily movement. Since the biological response associated with these two types of movements are different (Reitan, 1957), it would be expected that anchorage loss would vary. This was not the case statistically as they found an insignificant difference between the two appliances. They did however; find 1.7 mm anchorage loss with A-Company as opposed to 2.3 mm with Tip Edge, which is clinically significant. They attributed this lack of statistically significant differences to the small sample size, and thus small power. A prospective split-mouth study by Shpack *et al.* (2008) followed up on the work of Lotzof *et al.* (1996) and compared anchorage loss in 14 patients. Using study casts, Shpack *et al.* (2008) found anchorage loss to be the same, irrespective of the type of appliance used. A retrospective study by Baker *et al.* (1972) also failed to find any significant difference between appliances. They compared anchorage loss in 100 patients using lateral cephalograms. Fifty patients were treated by the Edgewise technique using an auxiliary holding arch and 50 patients were treated by the Begg technique. Despite a higher anchorage loss within the Edgewise group, the total ratio of active movement to anchorage loss was minimally different between the two groups. The ratio of active movement to anchorage loss is more important because it is more informative about the total anchorage loss. As well as all the limitations mentioned earlier

[1] Tip-Edge, TP Orthodontics, LaPorte, Ind

[2] A-Company straight wire, Johnson and Johnson, San Diego, Calif.

about human studies measuring anchorage loss, this study did not mention the age, sex and malocclusion of the patients. Based on the available evidence, the role of a variety of appliances in anchorage loss has not yet been sufficiently established.

1.4.2.5 Mechanics

Hart *et al.* (1992), Dincer & Iscan (1994) and Rajcich & Sadowsky (1997) found anchorage loss was reduced when different mechanics were applied. The concept of differential moments proposes that maximum anchorage can be achieved without the need for auxiliaries. A utility arch is used in this bio-progressive technique to control molar tipping in extraction cases, while simultaneously intruding the incisors (Ricketts *et al.*, 1979; Hilgers, 1987). This included placing a tip in the auxiliary wire to tip the molar crown distally. Hart *et al.* (1992) used pre- and post-treatment lateral cephalograms to assess anchorage loss (mesial movement of the first molars) in 30 patients. The patients were divided into groups according to the severity of the crowding and malocclusion. Hart *et al.* (1992) used differential moments without any auxiliary reinforcement to retract the canines. They demonstrated good anchorage control; 0.60 mm and 0.28 mm anchorage loss in class I and class II malocclusions respectively. Rajcich & Sadowsky (1997) used study casts and lateral cephalograms to assess anchorage loss (mesial movement of the first molars) in 24 patients who required the extraction of the upper first premolars with maximum anchorage. The malocclusion was not standardised, as class I and class II div 1 and div 2 were included, and there was no control group. Rajcich & Sadowsky (1997) used differential moments to achieve maximum anchorage. Anchorage loss was 0.7 mm radiographically and 0.5 mm on the casts. This was comparable to the Hart *et al.* (1992) study where similar mechanics were used. The authors concluded that it is possible to control anchorage loss using differential moments and suggested that this type of

mechanics negates the need for adjunctive anchorage reinforcements, such as headgear, lingual arch and Nance.

It is very difficult to reach such a conclusion from these studies since they did not have a control group to compare anchorage loss. Moreover, a systematic review of the literature by Feldmann & Bondemark (2006) to assess orthodontic anchorage during space closure found that every study had unique questions and aims with different methods to assess the anchorage loss. They concluded that any comparison made between studies to reach a conclusion is invalid. Furthermore, Feldmann & Bondemark (2006) concluded that the scientific evidence to evaluate anchorage loss with different systems during space closure was too weak, and further studies were needed to evaluate anchorage accurately.

1.4.2.6 Bony Cortex

Cortical anchorage is based on the idea that tooth movement is more difficult in cortical bone (Reitan, 1964). Reitan (1964) found that tooth movement was slower in dense compact cortical bone compared to medullary bone. Medullary bone has more clefts and marrow spaces thus making it more vascular and consequently more amenable to remodelling (Melsen, 2007). Reitan (1964) examined the alveolar bone and found the labial bone plate to consist of dense compact bone. On the other hand the inner bone spaces were less dense and contained large marrow spaces and clefts. There are appliances such as lingual arch, transpalatal arch and to a certain level the Nance which utilize the compact bone to enhance anchorage. These appliances maintain the inter-molar width and prevent the molars from translating into the narrower arch anteriorly, thus pitting the molar against the outer dense bone. These appliances utilize the cortical bone to enhance the anchorage. Rebellato *et al.* (1997) and Ellen *et al.* (1998) both found that the Lingual arch did not enhance the anchorage posteriorly when used passively and actively (respectively). Recently, Shpack *et al.* (2008) found that the Nance appliance does not influence anchorage

loss. Together, it seems the idea that cortical bone enhances anchorage is theoretically attractive, but has yet to be validated and quantified.

1.5 Anchorage reinforcement methods

Intra-oral anchorage reinforcement methods have been used in orthodontics since the beginning of the 20th century in cases with increased anchorage requirements. Such methods include appliances such as lingual arch, Nance appliance and recently TADs. The lingual arch and the Nance appliance are frequently used in orthodontics despite the lack of scientific evidence supporting their efficiency. A recent survey in the United Kingdom by Banks *et al.* (2010) found that up to 25% of orthodontists routinely use such appliances and that they are the most commonly used form anchorage reinforcement. Banks *et al.* suggested that the popularity of TADs might increase as they are becoming more integrated into orthodontic graduate training programs, but at the moment lingual arch and Nance appliances are more popular.

1.5.1 *Lingual arch*

The lingual holding arch consists of 0.9 mm (0.36 inch) wire soldered to the lingual aspect of bands cemented on the lower first molars. The wire is extended forward and rested on the lingual surface of the lower anterior teeth. Dewey (1916) attributed the lingual arch to L.S. Lourie who started using a fixed lingual arch as early as 1904. Mershon (1917) published his work on the use and fabrication of a removable variant of the lingual arch. He used it mainly for expansion purposes rather than anchorage. Subsequently, several authors described different uses for the lingual arch. It can be used passively, as in cases of space maintaining (Nance, 1947; Terwilliger, 1950); or actively (Buchner, 1949; Wein, 1959), as anchorage reinforcement for the posterior teeth

Lingual arches utilize two different anchorage principles to prevent the mesial movement of the molars. The first principle is to incorporate more teeth together, thus creating a larger anchor unit in the arch to prevent the movement of these teeth. The second

principle is the cortical anchorage which is utilized by fixing the inter-molar distance (Ricketts *et al.,* 1979). During mesial movement, the molars have to move into a narrower dental arch. However, as the lingual arch maintains a fixed inter-molar distance, this in theory should prevent the mesial movement of the molars as the roots of the molars are forced against the cortical bone. Although these principals seem logical and are generally accepted in orthodontics, there is no scientific evidence to support the theory.

A passive lingual arch has been commonly used to maintain the Leeway space during the transition of primary to permanent dentition. Northway *et al.* (1984) have shown that the arch perimeter tends to reduce following the early loss of primary dentition. One way of assessing if the cortical bone can prevent tooth movement is to ascertain whether having a lingual arch would prevent the physiological mesial migration of the lower first molars. Nance (1947) found the lingual arch to be useful in maintaining the distance between the molars and the incisors but that was at the expense of the lower incisor proclination as the molars continued to drift mesially.

Two studies have attempted to assess the molar movement when a passive lingual arch was used. Singer (1974) used cephalometric radiographs and study models to assess the effect of the passive lingual arch on the dentition. Singer (1974) compared the changes in the lower arch with and without a lingual arch in two groups. Interestingly, Singer (1974) found that the lower molars moved distally in the lingual arch group. This study combined upper arch treatment with the lingual arch, which would indirectly influence the lower molars. This is confirmed by Funk's (1967) work which showed that the lower teeth positions changed during upper arch treatment only.

A randomized clinical trial (RCT) study by Rebellato *et al.* (1997) used the lingual arch as a space maintainer without any upper arch treatment. They used study casts and

lateral cephalometric radiographs to measure the changes in the molar and incisor positions. This study was very well conducted, as the subjects' malocclusions were matched, there was a control group with no treatment, and finally selection bias was eliminated through the use of randomization. They found a statistically significant difference in the amount of mesial movement of molars. The molars in the lingual arch group moved 1.11 mm less than the control group but this was found to be at the expense of the lower incisor proclination, which is a form of anchorage loss. This means that the lingual arch alone did not prevent the movement of the molars but that the incisors did so via their lingual surface contact with the lingual wire. Thus the anchorage gain reported in this study is the result of the combination of both the incisors movement and the lingual arch. This study confirms that there is some anchorage gained through use of the lingual arch but that further investigation is needed. This is because an accurate indication of additional anchorage gained though solely utilizing the lingual arch is not provided.

Although these studies give conflicting results with regard to the direction of molar movement, it is clearly evident that the lingual arch appliance did not prevent the movement of the molars even when forces were not directly applied to the lingual arch. Furthermore as this appliance depends on the cortical bone, the arch shape which has not been taken into consideration plays a great role. The V shaped arch may provide a higher resistance than a U shaped arch, as in the latter the teeth do not necessarily need to move to a narrower arch. This variation should be taken into account when assessing anchorage loss with appliances based on cortical bone.

In light of the evidence provided by the studies on passive lingual arches it appears that they do not provide much support as active anchorage reinforcements. Despite this, several authors namely Buchner (1949) and Wein (1959) have advocated the use of the lingual arch

as an active anchorage reinforcement to resist class II elastic traction in class II malocclusion treatment.

Two studies have attempted to evaluate the anchorage gain when the lingual arch is used actively. Ellen *et al.* (1998) compared two groups of patients where class II elastics were used during treatment: the lingual arch was only used in one group. Using pre- and post-treatment lateral cephalometric radiographs, Ellen *et al.* (1998) found no difference between the two groups which suggests neither loss nor gain of anchorage when the lingual appliance was used. The study has some limitations when it comes to assessing the efficiency of the lingual arch. A major limitation is that it was a retrospective study. In addition, the operator, treatment mechanics, and force applied differed, thus making comparisons less informative as well as largely inconclusive. Furthermore, the studies could not quantify the advantage associated with the lingual arch.

The transpalatal arch (TPA), a maxillary version of the lingual arch, has been assessed by Zablocki *et al.* (2008) in 30 extraction cases to quantify its anchorage capabilities. The patients' age at the start of treatment, malocclusion, and cervical vertebra maturation in this retrospective study were matched. In addition, patients were excluded if headgear or any other auxiliary adjuncts were used. They again found no anchorage advantage with this device when lateral cephalometric radiographs were used to assess molar movements. This is a well conducted study but it is retrospective. Although the sample size was better matched and restricted compared to Ellen *et al.* (1998), it had several potential sources of bias. The mechanics used during treatment in both studies were guided to achieve the best result for the patient, thus introducing a biased result. In addition the pre-treatment crowding was not mentioned. Both these factors would potentially influence the anchorage as was discussed earlier. These factors can only be controlled when the end result is not a concern to the patient or the orthodontist.

In spite of the assumption that these appliances provide anchorage it is evident from the findings of the current studies that this is not the case. The findings of most of these studies need to be reassessed because they have the same limitations discussed earlier in section 1.4.2.1. A prospective controlled study is needed to accurately quantify the amount of anchorage gain or whether anchorage gain is achieved at all.

1.5.2 *Nance Appliance*

A modified version of the lingual arch, the Nance appliance (NA) (Nance, 1947), incorporating an acrylic button has been used in cases with higher anchorage requirements (Figure 1-5). NA has a 0.9 mm (0.36 inch) wire soldered on to the bands on the upper first molars but instead of the wire resting on the lingual surface of the anterior teeth, it has an acrylic button added to the wire and rests anteriorly on the palatal rugae. This acrylic addition could only be used in the upper arch as it would be too uncomfortable in the lower arch due to the tongue's position.

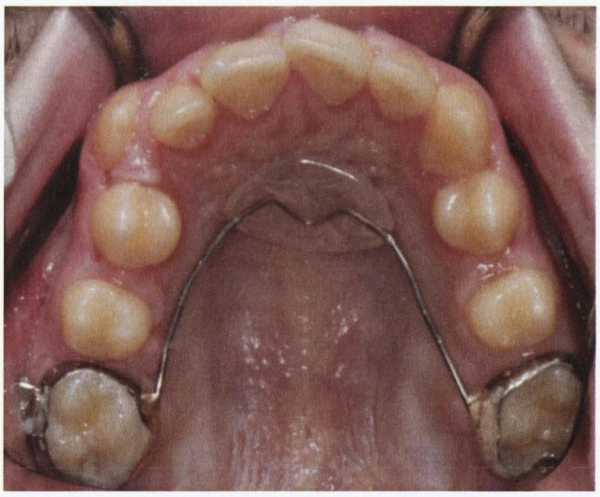

Figure 1-5. Nance appliance

This modification was introduced to overcome the anchorage loss associated with the lingual arch. It is believed that the palatal mucosa and the underlying bone will provide additional anchorage. This has yet to be confirmed by a properly conducted study. At the

moment it has been based purely on clinical judgment, as despite NA usage for the last century, a very limited number of studies have assessed the efficiency of the NA as a method for anchorage reinforcement. A recent study by Shpack *et al.* (2008) compared anchorage loss with bodily and tipping mechanics. A NA was fitted and the maxillary canines were retracted following the extraction of the first premolars. Subsequently, the anchorage loss was measured when the canines were fully retracted and uprighted. Study models pre and post retraction were used in conjunction with a fabricated transferable acrylic reference, which would fit over the palatal rugae to assess anchorage loss. This acrylic had two wires extending laterally to the central fossa of the first molars. The device was therefore placed in the same place and measurements were made prior to and after canine retraction on the study models. Shpack *et al.* (2008) found 17-20% anchorage loss occurred in both systems during canine retraction and they concluded that the NA did not provide absolute anchorage. Unfortunately Shpack *et al.* (2008) did not have a control group where the canines were retracted without the NA appliance, as that would have indicated the amount of anchorage reinforcement the NA provided. The extent to which a NA provides additional anchorage thus remains relatively unknown. One problem resides in the fact that it is very difficult to have a controlled study measuring anchorage loss with and without the NA; this involves an ethical issue since any anchorage loss might compromise the treatment results in the group where NA is not used.

Several studies have looked at the anchorage loss when a Nance acrylic button was incorporated into an appliance to distalize the molars. These appliances were developed to overcome the compliance issues associated with the extra-oral traction appliances. Appliances such as the Distal jig (Carano *et al.,* 1996), Jones jig (Jones & White, 1992), Pendulum appliance (Hilgers, 1992) and Keles slider (Keles & Sayinsu, 2000) all

incorporate a Nance acrylic button into the palate to reinforce the anchorage on the premolars while distalizing the molars.

Anchorage loss was determined by measuring the mesial movement of the premolars when the first molars were distalized. Anchorage loss associated with the distalizing appliances ranged from 20% (Gianelly *et al.,* 1989) to 120% (Ngantung *et al.,* 2001) but most studies found it to be in the range of 80% (Ghosh & Nanda, 1996; Brickman *et al.,* 2000; Keles & Sayinsu, 2000; Bondemark & Thorneus, 2005). Factors which could influence anchorage loss, such as the method of anchorage loss assessment, type of appliance used, force, size of acrylic button, and eruption of second molars were reviewed (Table 1-2).

Table 1-2. Factors which may influence the amount of anchorage in distalizing appliances incorporating an acrylic button

Factors	Studies	Variables Tested	The Effect	Conclusion
Appliance	Gosh & Nanda (1996)	Pendulum appliance	75 % anchorage loss	Anchorage loss was approximately 80 % irrespective of the appliance
	Keles & Sayinsu (2000)	Keles Jig	82 % anchorage loss	
	Brickman et al. (2000)	Jones Jig	80 % anchorage loss	
	Bondemark & Thorneus (2005)	Distal Jig	82 % anchorage loss	
Force	Gosh & Nanda (1996)	Titanium molybdenum alloy (TMA) springs (230 g of force)	75 % anchorage loss	Anchorage loss was the same Irrespective of the force
	Keles & Sayinsu (2000)		82 % anchorage loss	
	Brickman et al. (2000)	Nickel titanium (75 g of force)	82 % anchorage loss	
Size of acrylic	Bondemark & Thorneus (2005)	Palatal acrylic vs Anterior palatal cover	0.1 mm difference in anchorage loss	Clinically and statistically insignificant
Eruption of second molars	Gosh & Nanda (1996)	Erupted second molars	No effect on anchorage loss	Difficult to compare as most studies did not mention the second molars
	Gianelly (1998)		Affected anchorage loss	

Most studies have found anchorage loss to be approximately 80% irrespective of the appliance used. A study by Ghosh & Nanda (1996) found 75% anchorage loss when a pendulum appliance was used. This was similar to Keles jig (Keles & Sayinsu, 2000), Jones jig (Brickman *et al.,* 2000) and Distal jig (Bondemark & Thorneus, 2005) appliances where anchorage loss was found to be 82%, 80% and 82% respectively. It seems that substantial anchorage loss occurred despite using the Nance acrylic button and irrespective of the appliance used.

The amount of force used may also be a factor in the amount of anchorage loss. Although Ghosh & Nanda (1996) and Keles & Sayinsu (2000) used titanium molybdenum alloy (TMA) springs which exert 230 g whereas Brickman *et al.* (2000) used nickel titanium springs which exert 75 g, they all found anchorage loss to be approximately 80%. Even with lower force appliances such as the Jones jig, anchorage loss of a similar magnitude occurred.

The size of the Nance acrylic button covering the palate could be another factor affecting anchorage loss. Bondemark & Thorneus (2005) compared two distal jig appliances, one with the Nance acrylic button limited to the palate while the other had an anterior bite plan with the acrylic covering the entire anterior portion of the palate. The difference in anchorage loss was both clinically (0.1 mm) and statistically insignificant. Based on this study the size of the Nance acrylic button does not influence the amount of anchorage loss.

Gianelly (1998) found that the eruption status of second molars could influence the distalization of the first molars, whereas Ghosh & Nanda (1996) found that its effect was limited. It is interesting to note that despite having the root surface area doubled (Jepsen 1963), once the second molars have erupted, some authors found that anchorage loss and

distalization were not affected. However few authors commented on the status of the second molars in their study, which makes comparisons even more difficult.

These studies indicate that the NA does not provide absolute anchorage. The crucial question of how much more anchorage advantage would be gained by using the NA is still open for debate. An answer can only be provided if a prospective study is conducted comparing anchorage loss in two groups with a NA appliance fitted in one group only and a reliable method of measuring the movements is used. Additionally, the same mechanics must be applied within both groups. Finally, the two groups should be matched in all the aspects involved such as occlusion, crowding, skeletal relationships and age.

1.5.3 *Anchorage loss assessment methods*

Different methods have been used in studies to assess anchorage loss associated with distalizing appliances. It is important to examine the methods used in these studies to ascertain their accuracy, as this would influence the results. Some studies used superimposition on lateral head radiographs (Williams & Hosila, 1976; Saelens & De Smit, 1998; Brickman *et al.,* 2000; Keles & Sayinsu, 2000; Ong & Woods, 2001; Ngantung *et al.,* 2001; Geron *et al.*, 2003; Bondemark & Thorneus, 2005) while others used study models (Gianelly *et al.*, 1989; Ghosh & Nanda, 1996; Ong & Woods, 2001, Geron *et al.*, 2003). Pancherz (1982) (Figure 1-6) and Ricketts'(1975) (Figure 1-7) methods of analysis were most commonly used with the lateral head radiographs. The Pancherz (1982) and Ricketts' (1975) methods utilize pre- and post-treatment radiographs with measurements made from identified points on the molars and premolars to a perpendicular line drawn posteriorly to a stable reference line.

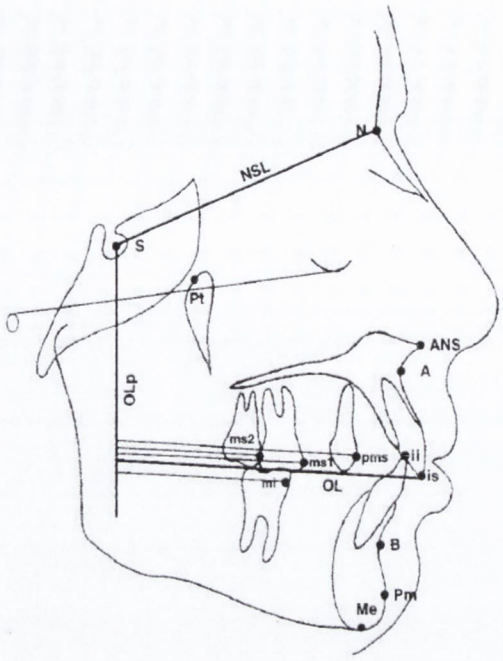

Figure 1-6. Dental linear parameters (Pancherz). The distance of reference points on teeth to the occlusal line perpendicular (OLp) is measured on pre- and post-treatment cephalometric radiograph. The difference (pre and post- treatment) is anchorage loss. (Gulati *et al.*, 1998)

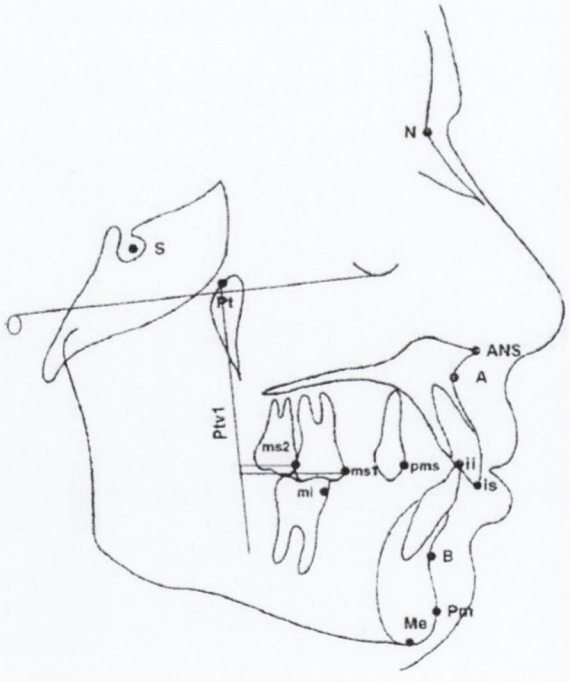

Figure 1-7. Dental linear parameters (Ricketts). The distance of reference points on teeth to the pterygoid vertical (Ptv) is measured on pre- and post-treatment cephalometric radiograph. The difference (pre and post- treatment) is anchorage loss. (Gulati *et al.*, 1998)

Using lateral cephalograms has several limitations namely: error of projection, error of identification, mechanical errors and ethical considerations (Baumrind & Frantz, 1971;

Houston *et al.*, 1986). Houston *et al.* (1986) found perspective errors associated with points not in the midsagittal plane, as lateral cephalometric radiograph is a 2D image of 3D object. The linear measurements are foreshortened whilst the angular measurements become obtuse. Random errors, are also difficult to control as more than 5 degrees rotation may influence the measurements (Ahlqvist *et al.*, 1986). Malkoc *et al.* (2005) found it difficult to reproduce head posture and head rotation, which affected linear measurements. Mannchen (2001) found that the maxilla and the functional occlusal plane rotated during treatment and as a result affected the radiographic measurements. El-Beialy *et al.* (2009) suggested cephalometric radiographs are not accurate for fine movement measurement. Thus, the veracity of superimpositions is questionable due to the difficulty of accurately identifying radiographic landmarks and structures. Projection of bilateral teeth or objects on the midsagittal plane also cause tracing errors. Baumrind & Frantz (1971) found it difficult to identify cusps of posterior teeth. This is because the images are blurred from superimposition of bilateral structures. Therefore Bergersen (1980) found discrepancies between distance measured on film and true distances in the object. Digital landmark identification has been recently been used in cephalometric analysis. Landmarks which are on poorly defined structures are difficult to automatically identify. As long as the landmarks were identified manually, the computer aided analysis did not increase measurement errors (Gravely, 1984). Chen *et al.* (2000) found the reliability of identifying the upper molar cusp was inferior using digital images compared to original radiographs. Cone beam computed tomography (CT) avoids anatomic superimposition and magnification problems and therefore provides better evaluation of craniofacial features with less distortion. Ludlow *et al.* (2009) compared the precision of landmark identification using (CT) with conventional cephalometric views. The CT provided more precise identification but found greater variability of certain landmarks in the mediolateral direction. They attributed this to the inadequate definition of the landmarks in the third

dimension. This, however, does not address the clinical problem of growth during treatment and head rotation, which can influence linear measurements. A more accurate method which utilizes stable reference points, such as implants, is required (Majzoub *et al.,* 1999). El-Beialy *et al.* (2009) developed a method using pre- and post-treatment CT images to assess tooth and miniscrew movement without the need to use reference planes or points. Computer software developed in Cairo University (3D-Biodent) was used to tile up the images and rebuild a 3D volume of the patient's maxilla and mandible. The authors found good reliability of the measurements and suggested it could be a good tool for anchorage loss measurement. This 3D volumetric analysis is a relatively new tool in orthodontics and further studies will be needed to verify its accuracy.

Some studies used study models (Gianelly *et al.*, 1989; Ghosh & Nanda, 1996) to determine the anchorage loss, pre- and post-treatment study models were photocopied and the incisive papilla was marked. Measurements were subsequently made from the molars and premolars to the marked incisive papilla line (Figure 1-8)

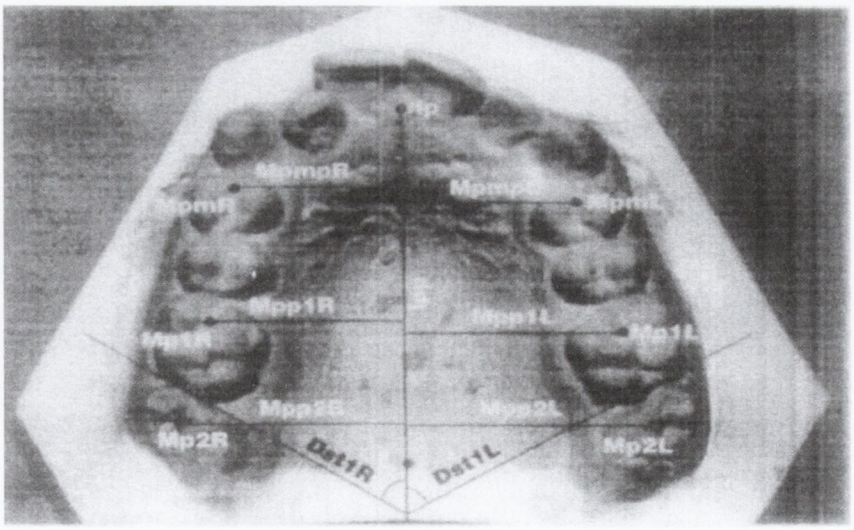

Figure 1-8. Linear and angular parameters on dental cast. (Gulati *et al.*, 1998)

Study model superimposition is another method which has been used to assess anchorage loss. The palatal rugae stability have been investigated with different findings.

Peavy & Kendrick (1967) found the rugae only remained unchanged if the lateral incisor and canine were not moved. Bailey *et al.* (1996) found the rugae landmarks were only stable in non extraction cases. van der Linden (1978) found the first molar moved mesially in relation to the lateral end of the third ruga in untreated cases. Almeida *et al.* (1995) evaluated the stability of the ruga landmarks on the dental casts of 94 patients and found them to be unstable.

A study by Gulati *et al.* (1998) used both methods and found the results to be congruent. This was confirmed by Hoggan & Sadowsky (2001) where they found study models were as accurate as superimposition methods in measuring dental movements. However, Geron *et al.* (2003) found measurements done on study casts and cephalograms were not comparable when he assessed anchorage loss. Geron *et al.* (2003) found study cast measurements unreliable because the reference point used (palatal rugae) by the earlier studies moved during treatment. This movement occurred as a result of remodelling which occurs with incisor movements. Thus any reference point used within the dental arch should be avoided and findings from studies which utilize such a method should be reconsidered. Although Geron *et al.* (2003) claimed radiographic measurements are more accurate, they still have its limitations. Superimposition of structures and reproducibility remain an issue. Thus, a more accurate method which utilizes stable reference points such as implants is required (Majzoub *et al.,* 1999). However, the use of implants as reference points to measure tooth movement would have ethical considerations in human studies.

1.6 Skeletal anchorage

1.6.1 *Classifications of skeletal anchorage*

Skeletal anchorage is derived from devices such as conventional implants, palatal implants, miniscrews and mini implants. These devices are often temporarily used during orthodontic treatment and discarded once the anchorage objectives have been achieved. For this reason these devices were named Temporary Anchorage Devices (TADs). Several different classifications for TADs have been provided recently in the literature. Cope (2005) divided them into BioCompatible and Biological. The BioCompatible category was then subdivided into mechanical and osseointegration, depending on the method by which the device is attached to the bone (Figure 1-9).

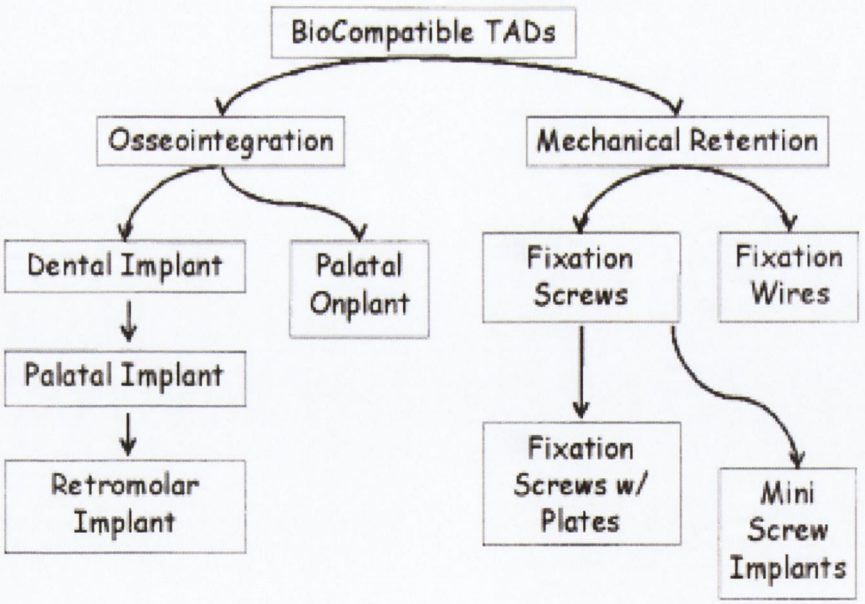

Figure 1-9. Biocompatible temporary anchorage devices classification (Cope, 2005).

Dental implants, palatal implants, palatal onplants, and retromolar implants were classified as being in the osseointegration group, whilst mini-implants, miniscrews, miniplates and fixation wires were categorized as mechanical retention. Wehrbein & Gollner (2009) on the other hand classified TADs into 2 groups according to their size when compared to conventional implants. The two groups are diameter-reduced TADs (DRTADs) and length-reduced TADs (LRTADs). DRTADs included miniscrews and mini-implants whilst LRTADs included palatal implants (Onplant and Orthosystem®).

There are two ways in which TADs can be used to reinforce anchorage. Roberts *et al.* (1990) and Travess *et al.* (2004) suggested that TADs can be used either directly or indirectly. Direct anchorage is when a TAD is placed in the line of the arch and forces are applied directly from the implant to the dentition. This type of anchorage was originally used with dental implants when they were placed for prosthetic reasons but also adopted for orthodontic anchorage (Kokich, 1996; Willems *et al.,* 1999). With the current developments of the TADs, direct anchorage can also be used with miniscrews. Indirect anchorage is when the implants are placed outside the arch and connected to the teeth via an appliance. Indirect anchorage utilizes an implant which is placed solely for orthodontic purposes and is removed at the end of orthodontic treatment. These implants were placed outside the arch to stabilize an appliance, which was then used to counteract the reciprocal forces. Implants placed in the midsagittal area of the palate (Block & Hoffman, 1995; Wehrbein *et al.,* 1996a) to stabilize a transplatalal arch or in the retromolar area (Roberts *et al.,* 1990) with an auxiliary are examples of indirect anchorage.

1.6.2 *Dental Implants*

1.6.2.1 Historical background

The use of implants as a form of absolute anchorage is a relatively new development, although, the idea of using implants in orthodontics has been documented as early as 1945 by Gainsforth & Higley (1945) (Figure 1-10). In this study Vitallium alloy (60% cobalt, 20% chromium, 5% molybdenum) screws (3.4 x 13 mm) were placed in the ascending ramus of 6 dogs. Rubber bands were used to deliver 140 g to 200 g of orthodontic forces to the maxillary teeth. Despite the initial success these screws remained in position for a maximum of 31 days only. The screws failed as result of an infection due to the communication between the screws and the oral cavity. This could have been due to the lack of well developed antibiotics at the time. This study highlighted the idea of implants as source of orthodontic anchorage.

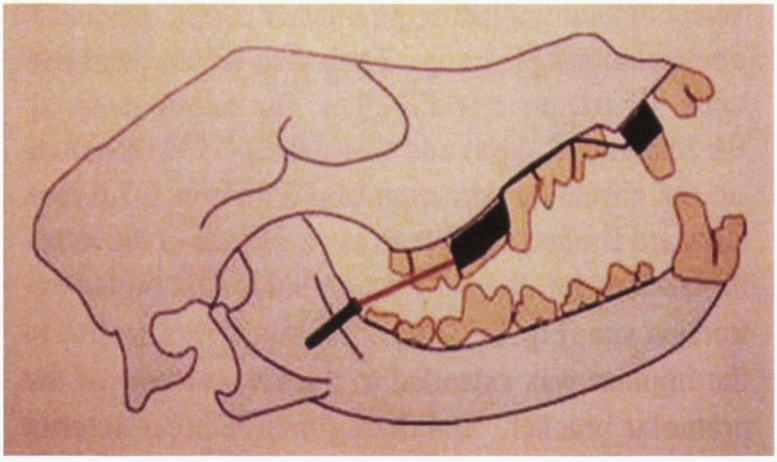

Figure 1-10. Vitallium screw in the ascending ramus of a dog in Gainsforth & Higley (1945) study (taken from Sung *et al.* 2006).

It took another 25 years before another study by Linkow (1969) reassessed the effectiveness of implants as a method of orthodontic anchorage reinforcement. Linkow placed endosseous blade implants in the mandible to apply class II forces to retract the maxillary anterior teeth. Though this was a case study with no long term evaluation, it reinstated the idea of implants as anchorage. Two further studies by Sherman (1978) and Smith (1979) assessed the effectiveness of implants as anchorage reinforcements in dogs and monkeys respectively. The earlier work used vitreous carbon while the latter used bioglass-coated aluminium oxide implants. Both found the implants to be successful in resisting orthodontic forces with no significant movement. Despite having a connective tissue layer intervening in some areas around the implant, Smith (1979) described the interface between the implants and surrounding tissue as fusion.

Even though these studies used materials (bioglass-coated aluminium oxide, vitreous carbon, Vitallium and endosseous blade implants) which were biocompatible with bone, none of them achieved long term attachment to the bone. This changed when Brånemark *et al.* (1969) introduced titanium implants as tooth replacements. Brånemark *et al.* (1969) reported on the successful osseointegration of titanium implants when they were placed into extraction sites in the maxilla and mandibles of dogs. Osseointegration is histologically defined as the direct contact of an implant with bone by the formation of bony tissue around the implant, without the growth of fibrous tissue at the bone-implant interface. These implants remained stationary for 5 years without any signs of rejection or infection. Adell *et al.* (1981) reported excellent retention of titanium endosseous implants 15 years post implantation. At last a suitable material was found in titanium that was biocompatible and achieved long term attachment to the bone.

1.6.2.2 Stability of implants

In 1984 Roberts *et al.* reemphasised the idea of using implants as anchorage reinforcement in orthodontics. Roberts *et al.* (1984) used the femur of a rabbit to assess the stability of 20 titanium implants when exposed to orthodontic forces for 4-8 weeks. A healing period of six weeks (equivalent to 4 months in humans) was observed prior to the application of force.

In 1988, Turley *et al.* reported 100% success when two-stage titanium (6 x 4. 75 mm) implants were placed in the mandibular ridge and palate of dogs. In contrast only 47% of the one stage titanium implants (6 mm x 2.4 mm) achieved and maintained rigid fixation when placed in five different sites (mandible, maxilla, temporal buttress and zygoma). Turley *et al.* (1988) found several factors played a part in the successful implantation. These include: size of the implant, operator technique, surrounding tissue (keratinized gingival) and the site.

Further reports by Roberts *et al.* (1989) and Wehrbein & Diedrich (1993) confirmed the suitability of titanium endosseous implants as anchoring units. In a follow up experiment (Roberts *et al.,* 1989), different types of titanium implants were placed in the mandibles of 4 dogs. Three hundred grams of orthodontic force was applied between two implants for 13 weeks. Roberts *et al.* (1989) found successful integration occurred in 94% of the implants with different surface configuration (custom made with an acid-etched surface, asymmetric threads with acid-etched surface and commercially available implants-Biotes). They concluded that a minimum of 10% direct bone contact was required at the implant interface for orthodontic anchorage to be achieved.

Wehrbein & Diedrich (1993) observed the implants over a longer period (26 weeks) compared to the relatively shorter periods in the previous studies. The aim of this study was to assess the durability of the implants when 200 g of force was applied over a longer

period. This was a significant improvement since most orthodontic treatments are longer than the 13 weeks observed previously. Unfortunately, only two dogs were used in the experiment, which reduced its statistical power. A recent repeat by Saito *et al.* (2000) using 4 beagle dogs, confirmed the earlier result when they found that Branemark implants (3.75 x 7 mm) remained rigid when orthodontic forces (200 g) were applied for an even longer period (32 weeks). These studies have shown that integrated implants do not move in response to orthodontic forces.

1.6.2.3 Uses of dental implants

Implants can be used as anchor units in orthodontics and then later used as abutments for prosthodontic purposes. Implants have been used to close residual edentulous spaces (Roberts *et al.,* 1990; Roberts *et al.,* 1994), upright tilted teeth (Shapiro & Kokich, 1988), and in treating adults with partially edentulous arches (Odman *et al.,* 1994). Furthermore, Southard *et al.* (1995) found implants to be superior for dental intrusion than using other teeth with conventional orthodontic mechanics. Lee *et al.* (2007) have suggested that implants may be used in patients with hypodontia and in patients with periodontal compromised teeth who lack sufficient teeth for conventional implants. Smalley *et al.* (1988) suggested the orthopaedic usage of the osseointegrated implants by demonstrating the separation of the facial sutures in monkeys when 600 g of force was applied. Singer *et al.* (2000) used implants in the zygomatic buttress for facemask attachment and found orthopaedic changes occurred without any dental changes over an 8 month period.

1.6.2.4 Limitations

Kanomi (1997) and Lee *et al.* (2007) suggested that conventional implant uses were limited in orthodontics. Lee *et al.* (2007) found the diameter of a standard implant (3.25 mm to 7 mm) too large for routine use, as it would require an edentulous space to accommodate it. Moreover, anatomic limitations including nerve bundles, sinuses, and

unerupted teeth in children limit their usage to specific patients. The long healing period (4-6 months) for osseointegration prior to orthodontic loading combined with the invasive, expansive and uncomfortable surgical procedures makes implants less than ideal (Kanomi, 1997). As a result orthodontists' search for the ideal type of anchorage reinforcement continues.

1.6.3 *Length reduced temporary anchorage devices (LRTADs)*

Triaca *et al.* in 1992 were the first to suggest the mid palatal area as a suitable site for a length reduced implant (up to 6 mm). The advantage of the midpalatal region was that it did not require an edentulous span within the dental arch to accommodate the implant. Hence clinical practicality was the main reason for choosing the median and paramedian region of the palate (Wehrbein *et al.,* 1996a; Wehrbein *et al.,* 1999a; Bantleon *et al.,* 2002; Crismani *et al.,* 2006). Length-reduced implants LRTADs (Wehrbein & Gollner, 2009) were used in this area to allow for the reduced bone level in this region (Kang *et al.,* 2007). Block & Hoffman (1995) and Wehrbein *et al.* (1996a) developed two different systems which utilized LRTADs in the palate to reinforce anchorage. These systems were the Onplant and Orthosystem, respectively.

1.6.3.1 Onplant

Block & Hoffman (1995) used a two stage hydroxylapatite (HA)-coated titanium subperiosteal disc (Onplant, Noble Biocare, Göteburg, Sweden) to reinforce anchorage. The disc was 10 mm in diameter and 3.5 mm thick. The disc was textured and coated with a 75 μm thick layer of HA on one side whilst the side facing the soft tissue was smooth and had an internal threaded hole for abutment attachment (Figure 1-11).

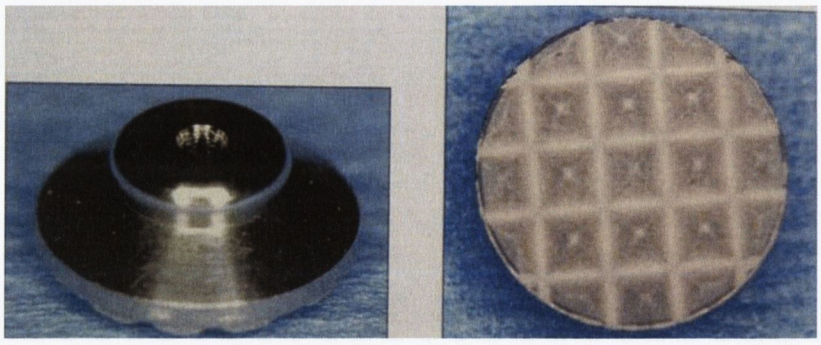

Figure 1-11. Onplant (Taken from http://www.healthmantra.com/ic/mini_implant1.shtml).

Onplant placement requires a full mucoperiosteal surgical procedure followed by disc exposure using the punch surgical technique 10 weeks later. Block & Hoffman (1995) used monkeys and dogs to assess the efficiency of the device. In the dog model the study demonstrated unilateral tooth movement toward the Onplant whereas in the monkeys the study mimicked the en masse retraction of the anterior teeth in humans. Both models were successful in demonstrating the efficiency of the Onplant. The Onplant resisted forces of greater than 300 g which is comparable to forces used in orthodontics. Janssens *et al.* (2002) reported on the use of Onplants to extrude impacted first molars in a 12 -year-old girl with tooth aplasia and cleft palate. Janssens *et al.* (2002) found that the Onplant remained stationary during the 17 weeks of traction while the first molars were extruded. Huang *et al.* (2005) suggested that more studies are required to confirm their efficiency as skeletal anchorage devices and their stability. Huang *et al.* (2005) highlighted several drawbacks associated with Onplant usage: primary stability often could not be achieved by mechanical retention, placement might be limited by anatomical structures, and a cephalometric radiograph was required to confirm osseointegration prior to loading. Thus, Huang *et al.* (2005) concluded that a ten week healing period was essential prior to loading and long term research was required. These devices are not widely used currently because of their limitations and lack of supporting research.

1.6.3.2 Orthosystem®

Wehrbein *et al.* (1996a) presented a one stage endosseous orthodontic implant Orthosystem® (Institute Straumann, Waldenburg, Switzerland) for palatal anchorage (Figure 1-12).

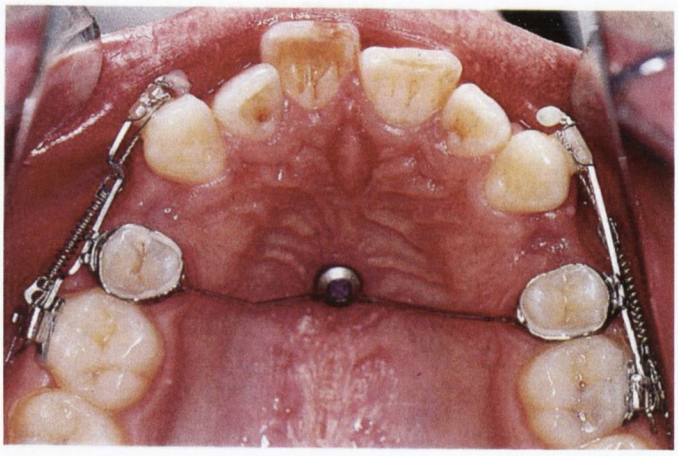

Figure 1-12. Orthosystem® (Wehrbein *et al.*, 1998).

Wehrbein *et al.* (1996b) suggested this could replace compliance dependent extra-oral anchoring aids. A modified conventional implant was used in the midsaggital area of the palate. The implant was 3.3 mm in diameter and 4 or 6 mm in length depending on the bone level. The reduced length was to accommodate the limited available bone height in the area and to avoid perforation of the nasal cavity. Wehrbein *et al.* (1999b) found that the bone height could be evaluated on a pre-treatment lateral cephalogram. To achieve good stability the implants were designed as self tapping. In addition, this reduced the surgical procedure required. These implants were also sandblasted, etched and heated to improve their mechanical retention and osseointegration. The transmucosal neck was smooth and was 4.2 in diameter with a varying height (2.5 – 4.5 mm) to accommodate different levels of mucosal thickness. The transmucosal part of the implant was grooved to hold an orthodontic wire (0.8 mm) with a round clamping cap to hold the wire in situ. Wehrbein *et al.* (1996b) found the device easy to use and successful. However 0.5mm of anchorage loss

was found in the implant supported premolars. Wehrbein *et al.* (1996b) attributed this anchorage loss to the slight deformation of the orthodontic wire attached to the implant. Consequently Wehrbein *et al.* (1999a) suggested increasing the wire thickness to 1.2 mm in an attempt to avoid such movement.

Wehrbein *et al.* (1997) demonstrated the stability of the short palatal implants on dogs over a period of 26 weeks of orthodontic traction. Wehrbein *et al.* (1999a) assessed study casts of nine class II patients. These implants remained stationary during orthodontic traction. Using a study cast and radiographic assessment, Wehrbein *et al.* (1999a) found that although the implants remained stationary there was 0.7-1mm anchorage loss. This was again attributed to the deformation of the transpalatal wire by the orthodontic forces. This was also confirmed by Majzoub *et al.* (1999) who found 15 out of 16 (3.25 mm) implants remained stationary in the calvarial midsagittal region of 10 rabbits. In this study, 150 g of orthodontic force was applied for 8 weeks. This was further confirmed by larger clinical studies (Crismani *et al.,* 2006; Mannchen & Schatzle, 2008; Wehrbein & Gollner, 2009) where the success rate varied from 91% to approximately 96%. Success in the previous repeats was defined as the absence of mobility throughout the entire treatment time and a crystalline sound on percussion.

In addition to immobility, positional stability is crucial if these implants are to provide absolute orthodontic anchorage. Mannchen & Schatzle (2008) suggested osseointegration was essential for positional stability. Histological examination of loaded palatal implants revealed that osseointegration was maintained during orthodontic loading (Wehrbein *et al.,* 1998). They found a mean bone contact of about 70%. Wehrbein & Gollner (2009) on the other hand suggested that an implant could be immobile even if bone to implant contact is small and therefore immobility is not an absolute proof of positional stability. Wehrbein & Gollner (2009) used radiologic positional assessment of the implants on the cephalograms

taken prior to, and at the end of the orthodontic treatment. The angulation and implant position in relation to the maxillary plane was assessed in twenty two patients. They found no significant alterations in both the angulation and position of the implants.

One of the main advantages of palatal implants over conventional implants is that they may be used on adolescents. Wehrbein *et al.* (1996a) and Asscherickx *et al.* (2005a) suggested Orthosystem® could be used in growing patients but has to be inserted into the paramedian region to avoid a possible developmental disturbance of the palatal suture. Using dental CT Bernhart *et al.* (2000) found an area 3-6 mm lateral to midline of the palate which had adequate bone depth to accommodate 6 mm implants. It is important to note that that the bone thickness was less in the paramedian than the median region. Kang *et al.* (2007) found the bone thickness in the midsagittal plane, 9 mm distal to the incisive nerve, to be 5.6 mm compared to 3.5 mm parasagittally.

Wehrbein *et al.* (1999a) suggested the relative ease of placement and removal of palatal implants in comparison to conventional implants makes them a more attractive option to patients. They found patient discomfort was slight and in most cases primary wound healing was achieved following removal of the device. Other advantages included compliance-free, faster treatment time due to en masse retraction and the unnecessary lower arch reinforcement. On the other hand, Wehrbein *et al.* (1999a) emphasised the fact that these advantages must be carefully weighed against the disadvantages.

The complexity of the surgical insertion and removal procedures of the implant, which require proper training, is one of the major disadvantages. These systems have been available in orthodontics for the last decade, yet orthodontists are still reluctant to use them regularly. The disadvantages of palatal implants have been summarized by Wehrbein & Gollner (2009). They include delayed healing (unloaded healing period), the need for auxiliary attachment (indirect anchorage), extensive surgical procedures during placement

and removal, and higher cost. Despite the study by Majzoub *et al.* (1999) which found 2 weeks healing period was sufficient to provide stability to 3.3 mm implants, the current Straumann recommendation is a 12 week latency period prior to loading the Orthosystem. The lack of conclusive evidence on the adequate healing time and the risk of implant loss was their reason for the added healing time prescribed.

1.6.4 *Diameter reduced temporary anchorage devices (DRTADs)*

DRTADs are the most popular form of temporary anchorage due to their ease of insertion, affordability, and the painlessness of the procedure in comparison to the others. Of all the different forms of implants used as anchorage adjuncts by orthodontists in the UK, Banks *et al.* (2010) found miniscrews constituted 65 %.

1.6.4.1 Historical development

Recent developments in anchorage reinforcement have aimed at developing a system which will overcome the limitations and complications associated with conventional implants. These included healing time, complex surgical procedure and limited placement areas (Sung *et al.,* 2006). Whilst LRTADs appear to overcome some of these limitations, the surgical procedure involved and the long healing period remain an issue (Huang *et al.,* 2005). Cope (2005) suggested that an ideal skeletal anchorage device should be biocompatible, simple to place and use, small, cause little discomfort to the patient, immediately loadable and inexpensive. Bone screws seemed to meet these criteria and several studies have highlighted their suitability for medical usage. In 1970 Brons & Boering (1970) demonstrated the stability of 2.7 mm screws in fracture reduction. Later Jeter *et al.* (1984) successfully used 2 mm screws to fix the mandible following an osteotomy. Following their successful introduction and stability in maxillofacial surgery, Creekmore & Eklund (1983) reported on their usage as a form of skeletal anchorage. They

inserted a vitallium screw just below the anterior nasal spine and intruded the maxillary incisors using elastics (Figure 1-13).

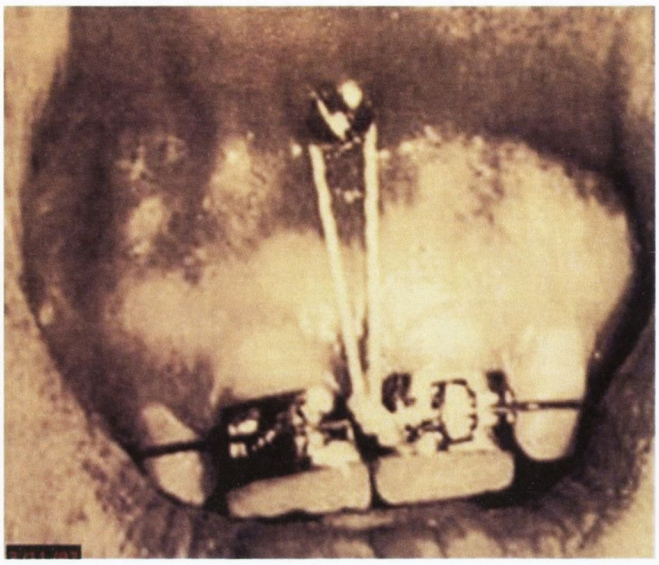

Figure 1-13. Creekmore & Eklund (1983) used vitallium screws to intrude maxillary incisors.

Elastic traction from the screw to the incisors was applied after a healing period of ten days. Creekmore & Eklund (1983) reported no pathology or mobility during the time of treatment. It took another 14 years before this new form of osseo-aided anchorage was reported again by Kanomi (1997). Kanomi (1997) used a titanium (1.2 mm x 6 mm diameter, Leibinger®, Freiburg, Germany) variation of the mini bone screws used to fix bone plates in plastic and reconstructive surgery. Their surgical insertion and removal procedure was much simpler and less invasive than conventional implants and LRTADs. After a healing period of several months, the mandibular incisors were intruded by 6 mm with no pathology or root resorption reported at the end of treatment. Importantly the screws were inserted directly through the mucosa under local anaesthesia without the need for any preparation. Kanomi (1997) also suggested their usage for space closure, molar distalization, and intrusion. Costa *et al.* (1998) described titanium miniscrews which were 2 mm in diameter and 9 mm in length. These miniscrews' heads had two 0.022" x 0.028"

grooves which could be converted into tubes with special caps thus enabling them to be used in conjunction with the orthodontic appliance. These miniscrews were inserted directly into the mucosa without flap preparations and were loaded immediately. Two out of the 16 miniscrews used in the clinical trial became loose and eventually fell out prior to treatment completion. Due to the smaller dimensions of these screws, their use in different parts of the dental arch, as well as the midpalatal region, was suggested, thus providing direct and indirect anchorage. Furthermore these miniscrews could be loaded immediately, as osseointegration was not a pre-requisite for their stability. These miniscrews did not require any laboratory work and had a low cost. Twelve different miniscrews systems specially designed for orthodontics have been available in the market since the reported success of the small titanium bone screws.

1.6.4.2 DRTADs uses

The introduction of the DRTADs has addressed many anchorage problems in orthodontic treatment, which otherwise would have required the extraction of teeth, headgear or orthognathic surgery (Creekmore & Eklund, 1983; Cope, 2005; Melsen, 2005). Due to their small diameter, these implants are very versatile and can be placed in many different sites. There have been many publications of case reports demonstrating the different uses of miniscrews in orthodontics. They can be used for distalization (Young *et al.,* 2007), intrusion (Kanomi 1997) , extrusion (Carano *et al.,* 2005b), and uprighting molars (Carano *et al.,* 2005b). Melsen (2005) also presented cases where DRTADs were used to treat patients with an insufficient number of teeth for anchorage control. Sung *et al.* (2006) and Carano *et al.* (2005b) presented all the different clinical scenarios where DRTADs could be used. They described different clinical cases for DRTADs' usage, namely; to distalize molars, overjet reduction, anterior open bite correction, centreline correction, molar protraction, and space closure. They classified the cases into extraction,

non extraction, anterior open bite cases, lingual orthodontic cases, unilateral anchorage cases, minor tooth movement, and other possible uses such as in conjunction with orthopaedic appliances. It has been clearly demonstrated that DRTADs have the potential for use in many of the challenging malocclusions in orthodontics. They have also reduced need for orthognathic surgery (Melsen 2005) ushering in a new era in adult orthodontics.

1.6.4.3 Materials

Many different materials have been used for implants. Materials should be nontoxic, biocompatible, and have favourable mechanical properties to resist stress and strain. Biomaterials have been divided into three categories: bio-tolerant (stainless steel and chromium cobalt), bio-inert (titanium) and bio-active (ceramic oxidized aluminium) (Favero *et al.,* 2002).

Titanium has been the material of choice in implantology because it is biologically inert and bio-compatible. The mechanical properties of pure titanium (99.5% titanium and 0.5% other elements) are well suited for resisting orthodontic forces (Favero *et al.,* 2002). Two different types of titanium are used in DRTADs manufacturing: commercially pure titanium (C-P titanium) and titanium–6 aluminium–4 vanadium ELI alloys (Ti 6Al-4V). Even though C-P titanium is available in five different grades (1-5) according to their hardness, most manufactures use Ti 6Al-4V since they have higher fatigue strength than C-P titanium (Huang *et al.,* 2005). The higher fatigue strength compensates for the reduced diameter of the DRTADs and therefore reduces the risk of fracture. Lin *et al.* (2007) reported on the different clinical applications associated with the two materials. The former would require pre drilling prior to placement in areas of dense bone to avoid breakage whilst the Ti-6Al-4V would not require any pre drilling, irrespective of the site of placement. Heavy orthodontic loads should be avoided with C-P titanium. Lin *et al.* (2007) suggested better mechanical retention and less chair time with Ti-6Al-4V. On the other

hand, Orthodontic Mini Implant (OMI^{TM}) (Leone America, 501 W. Van Buren, Suite S, Avondale, AZ 85323) uses stainless steel which has an even higher fatigue strength. Whilst stainless steel has a reduced osseointegration capability compared to titanium, DRTADs use the osseous physical engagement for retention (Melsen & Costa, 2000; Deguchi *et al.*, 2003) and thus the reduced osseointegration ability should not compromise its success. Unfortunately a study comparing the different materials used in DRTADs and their effect on the DRTADs' stability has yet to be conducted.

1.6.4.4 Design of DRTADs

DRTADs come in different sizes and with different heads but they all have the same basic components Lee *et al.* (2007): Core, Helix (Thread) and Head (Figure 1-14). Each component plays an important role during the screw function.

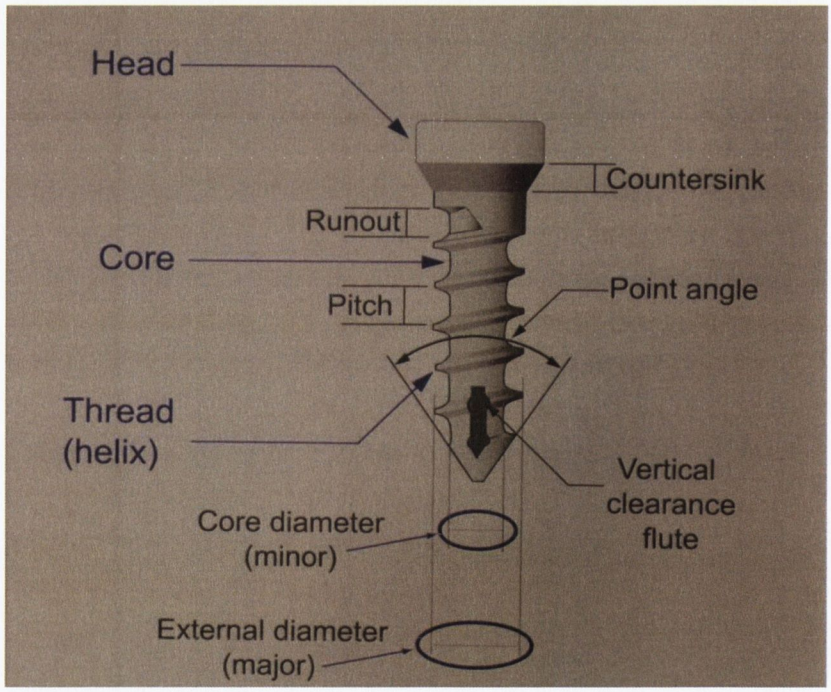

Figure 1-14. Basic components of a screw (Lee et al., 2007).

The head of the screw is used for applying a torquing force to the thread and core during insertion as well as a mean of applying orthodontic forces. Ideally the head should be able to connect with orthodontic auxiliaries and be compatible with the current edgewise bracket system (Mah & Bergstrand 2005). Among the current miniscrew products several variants are available. Initially, several products (Dual Top Anchor System, LOMAS^{TM} and Spider) had the head designed for single point contact with a hole through the neck while others had a hook (LOMAS^{TM}) or button (Dentos^{TM}). Even though these type of heads have a small profile, which would be comfortable to the patient, the disadvantages of these types of heads were: 1) two dimensional control, 2) difficulty of hooking more than one coil spring and 3) if the angulation of the screw is too steep there is a possibility that the coil springs might slip out (Lin *et al.,* 2007). Another drawback of the hole in the neck is that it weakens the neck and could lead to its fracture during removal (Melsen, 2005). A bracket type head on the other hand would provide three dimensional control and allow the screw to be consolidated with a tooth to be used as indirect anchorage (Melsen, 2005). Moreover, several auxiliaries could be attached without slippage (Lin *et al.,* 2007). Currently most manufactures provide their screws with various head options to suit the different clinical applications.

The core, which is attached to the head and wrapped with the thread, provides the support for the screw and the distance between the threads is called the pitch (Perry & Gilula, 1992). The shank is the part of the core which extends from the head to the beginning of the thread.

DRTADs' diameters vary from 1.0 mm to 2.3 mm, depending on the manufacturer. In general smaller diameter DRTADs should be used in a tooth bearing area to avoid the risk of trauma to the adjacent roots (Lin *et al.,* 2007). Increasing the core diameter however

increases the strength and the stability of the DRTADs. Perry & Gilula (1992) found the torsional strength of the DRTADs is proportional to the cube of the diameter. In addition when Carano *et al.* (2005a) compared the mechanical properties of different DRTADs (Dentos, ™ M.A.S. ™ and Leone™) on bone substitutes they found that a minimum diameter of 1.5 mm was needed to resist fracture. Miyawaki *et al.* (2003) also found an association between DRTADs' stability and its diameter. Increasing the diameter increased the mechanical interlocking in the bone and the primary stability of the DRTADs. The drawback of increasing the DRTADs' size, was the higher risk of root contact (Melsen, 2005). Thus reducing the diameter of DRTADs increases the versatility and eases the insertion but compromises strength and stability.

1.6.4.5 Methods of insertion of DRTADs

To overcome the reduced strength associated with the smaller diameter and the reduced strength C-P titanium DRTADs, two methods of insertion have been developed; self tapping and self drilling. Although each company has its own recommendations for the insertion technique, the self tapping technique is usually recommended to overcome the risk of fatigue and fracture of DRTADs. Both methods have been successfully used and tested in cranio-maxillofacial surgery (Heidemann & Gerlach, 1999). Self tapping requires pilot drilling at a low speed prior to inserting the DRTADs. Self tapping DRTADs have a groove in their tip to cut the bone and create a thread pattern during insertion following the pilot drilling (Prabhu & Cousley, 2006). This method is recommended for areas of dense bone (Ellis & Laskin, 1994), small diameter and C-P titanium DRTADs. Self drilling on the other hand does not require any drilling prior to inserting the DRTADs. This is recommended for areas with less dense bone, larger diameter and titanium alloy DRTADs. The latter method avoids complications such as drilling into the dental root, overheating from the drill, over enlargement of the hole and the relatively longer procedure involved in

pilot drilling (Lin *et al.,* 2007). Thus, self drilling DRTADs are more popular with clinicians and most of the current DRTADs are self drilling. It is still crucial to refer to the manufacturers' recommendations and assess the bone quality prior to insertion.

1.6.4.6 Risks

DRTADs have been developed to reduce the costs and risks associated with conventional implants, but there are still risks associated with DRTADs placement and usage. Kravitz & Kusnoto (2007) recommended a thorough understanding of proper placement technique, bone density, peri-implant soft tissue, and regional anatomical structures for optimal patient safety. Melsen & Verna (2005) and Kravitz & Kusnoto (2007) divided the complications associated with DRTADs into three categories: 1) complications during insertion, 2) under loading and 3) during removal.

1.6.4.6.1 Complications during insertion

Trauma to the periodontal ligament or the dental root could occur during interradicular placement. Kravitz & Kusnoto (2007) suggested that complications such loss of vitality, osteosclerosis and ankylosis could occur following root injury. However there are few documented cases of such complications occurring following placement of DRTADs. Earlier reports were based on root contact associated with fixation screws used for skeletal immobilization following orthognathic surgery (Farr & Whear, 2002; Fabbroni *et al.,* 2004). Fabbroni *et al.* (2004) assessed 232 screws placed in 55 patients and found that approximately 37% of the screws contacted the roots. Whilst 9.5% of the screws which contacted the roots were associated with a non vital tooth, only one tooth required root canal treatment as result of the contact. This suggests a low incidence of complications arising as a result of root contact. It is important to consider the larger screws used in maxillofacial fixation compared to smaller dimension DRTADs used in orthodontic

anchorage. The screws in this report were removed after a mean time of 23 days which would allow for healing (Kadioglu *et al.,* 2008) whereas DRTADs in orthodontics are used for much longer. Fabbroni *et al.* questioned the reliability of the electric pulp tests used post trauma especially since some patients suffered from a paraesthesic mandible. Further histological investigations conducted by Asscherickx *et al.* (2005b), Kadioglu *et al.* (2008), Hembree *et al.* (2009) and Rossouw & Buschang (2009) on DRTADs found variable damage following root contact. These damages ranged from slight damage to the periodontal ligaments to irreversible damage to the pulp. Once the DRTADs were removed, Kadioglu *et al.* (2008) and Brisceno *et al.* (2009) reported repair and almost complete healing a few weeks later with no substantial complications. Long term follow up may be required as these studies were limited to 18 weeks post contact and other complications such as progressive root resorption and ankylosis may occur later. Poggio *et al* (2006) used digital volume tomography based on cone beam technique to provide a guide for the placement of DRTADs in the maxilla and mandible. They found that the inter-radicular space between the first molar and second premolar in the maxilla and the mandible was the safest zone.

DRTADs' slippage during insertion is another complication that can occur in sloped bony planes such as the zygomatic buttress, retro-molar pad and buccal cortical shelf (Kravitz & Kusnoto, 2007). Kravitz & Kusnoto (2007) found slippage in the retro-molar pad can lead to the greatest risk of iatrogenic harm.

Nerve damage may also occur during the placement of DRTADs. Kravitz & Kusnoto (2007) highlighted the maxillary palatal slope, mandibular buccal dentoalveolus and the retromolar regions as high risk areas due to their close vicinity to major nerves. They found that extra caution must be observed with adult patients as the nerve canal could be more superficial due to resorption. They recommended that in the retro-molar region, DRTADs

must be no longer than 8 mm. So far there have been no incidents of nerve related complications reported in the literature. Air subcutaneous emphysema is another complication which may occur during routine operative dental treatment but could also occur during DRTADs insertion if a fast hand piece is used to create a pilot hole. Excessive use of air from an air syringe may also lead to emphysema. Kravitz & Kusnoto (2007) presented a case where excessive air from an air syringe created emphysema. Most of these cases require careful observation only (Table 1-3) to rule out infection or further problems. Symptoms usually subside within a 3-10 day period and the application of gentle pressure should suffice (Schuman *et al.,* 2001; Torgay *et al.,* 2006).

Table 1-3. Rice protocol for soft-tissue swelling (Kravitz & Kusnoto, 2007)

Rest	Avoid heavy mastication.
Ice	Apply ice pack to injury for 20 minutes on and 20 minutes off every few hours on first day. Ice relieves pain and swelling.
Compression	Apply compression with ice pack to minimize swelling.
Elevation	Lie down, but keep injured area elevated.

Nasal and sinus perforations occurring during the placing of DRTADs are usually small (<2 mm) and such perforations usually heal without complications (Ardekian *et al.,* 2006). Ardekian *et al.* (2006) found that the stability of immediately loaded dental implants that perforated the sinus was not compromised. Therefore Kravitz & Kusnoto (2007) found no need for repositioning and recommended the continuation of orthodontic therapy with careful monitoring if a DRTAD perforates the sinus.

The bending and fracturing of DRTADs during placement can occur as a result of high torsional stress (Melsen, 2005). Melsen (2005) recommended avoiding excessive pressure, over tightening and to stop turning the screw as soon as the smooth part of the neck had reached the periosteum. Since the material type (Huang *et al.,* 2005) and size (Perry & Gilula, 1992) of the DRTADs influences their strength, it is essential to follow the manufacturer's recommendations during placement to avoid fracturing them. It is also

important to assess the bone quality as dense bone may require predrilling depending on the size of the DRTADs (Lee *et al.,* 2007).

1.6.4.6.2 Complications under orthodontic loading

Failure and migration could occur following the insertion of DRTADs. This can occur as result of bone density, peri-implant health and type of soft tissue, surgical technique, the amount of force application, root proximity, age and mandibular- plane angle (MMPA) (Kuroda *et al.,* 2007; Lee *et al.,* 2010; Miyawaki *et al.,* 2003; Melsen & Verna, 2005; Kravitz & Kusnoto, 2007; Crismani *et al.,* 2010). All these factors will be subsequently discussed under their respective headings.

Soft tissue hypertrophy may occur adjacent to the DRTADs leading to partial or complete coverage of the DRTADs head. This would primarily depend on the patient's oral hygiene. Melsen & Verna (2005) recommended using floss dipped in 0.2% chlorhexidine for maintaining good oral hygiene around the DRTADs. Mucosal irritation and infection may lead to peri-implantitis and eventually increase the DRTAD's failure by 30% (Miyawaki *et al.,* 2003). This was more common when the DRTADs were placed in alveolar mucosa, for this reason Kravitz & Kusnoto (2007) recommended a waiting period of two weeks prior to orthodontic loading in cases where DRTADs were placed in alveolar mucosa.

1.6.4.6.3 Complications during removal

DRTADs can fracture during removal (Melsen & Verna, 2005; Kravitz & Kusnoto, 2007). Melsen & Verna (2005) found this was one of the weaknesses of the earlier DRTAD versions when the head of the DRTADs used to fracture due to the head design where a hole was incorporated into the neck. While this is less likely with the newer versions,

Kravitz & Kusnoto (2007) have recommended a minimum diameter of 1.6 mm for self drilling DRTADs when they are placed in dense cortical bone.

Another complication was the partial osseointegration of the DRTADs which could occur 3 weeks following their placement. Despite anchorage being primarily achieved by mechanical retention of DRTADs, partial osseointegration can occur and, as a result, prevent the removal of DRTADs on the first attempt. Kravitz & Kusnoto (2007) and Melsen & Verna (2005) recommended a second attempt several days later as DRTADs tend to loosen up following the initial attempt.

1.6.4.7 Osseointegration

One of the main benefits of DRTADs was immediate loading. Earlier case reports by Creekmore & Eklund (1983) and Kanomi (1997) reported immediate loading and suggested that stability was achieved by mechanical retention only. This eliminated the long healing time required for osseointegration prior to force application which was necessary with the previous forms of skeletal anchorage such as palatal implants and conventional implants.

Previously Roberts *et al.* (1994) and Wehrbein & Diedrich (1993) found 16 and 12 weeks healing periods were necessary prior to loading conventional implants and LRTADs respectively. On the other hand Melsen & Costa (2000) found DRTADs were stable when they were loaded immediately. This might suggest that DRTADs achieve their retention by mechanical means only, however partial osseointegration was noted by Melsen & Costa (2000) and later confirmed by *in vitro* (Favero *et al.,* 2007) and *in vivo* (Vande Vannet *et al.,* 2007) studies. It is because, in contrast to the previous methods, DRTADs provides anchorage through both phases of its stability that it could be loaded immediately. Primary stability is usually achieved through its mechanical bone interlocking whereas the secondary stability is by osseointegration.

Furthermore, forces on the previous implant systems (conventional implants and LRTADs) hindered osseointegration, hence the 16 and 12 week healing period. This was not the case with DRTADs, as Melsen & Costa (2000) found partial osseointegration occurred despite the immediate loading, and suggested that orthodontic forces were within the 'functional window', which is defined by Frost (1990) as: Healing sufficient for stabilization to occur despite the applied force. Thus, sufficient bone healing would occur around DRTADs despite the orthodontic forces. Park *et al.* (2006) found DRTADs can be maintained with minimal mobility in contrast to conventional implants. They suggested the difference was that orthodontic implants were loaded in one direction only, whereas dental implants were loaded in several directions which does not allow for healing. This was later confirmed by Deguchi *et al.* (2003), Woods *et al.* (2009), Chen *et al.* (2009) and Luzi *et al.* (2009b) who found similar osseointegration in loaded and unloaded DRTADs.

Several studies have assessed the level of osseointegration with DRTADs using different methods. One of these is the Osseointegration index (OI) which measures the percentage of bone-implant contact. Another is the removal torque value (RTV) which measures the torsion force required to remove an implant and its value is related to the bone-implant interface. Whilst the OI is mainly used in animal studies, the RTV can be used in animal (Kim *et al.,* 2009) and human studies (Favero *et al.,* 2007). Clinical parameters such as implant mobility and sound on percussion can also be used to assess whether the implant has been osseointegrated (Wehrbein *et al.,* 1999a; Crismani *et al.,* 2006).

The OI of DRTADs has been assessed by various studies (Melsen & Costa, 2000; Melsen & Lang, 2001; Ohmae *et al.,* 2001; Deguchi *et al.,* 2003; Kim *et al.,* 2005; Woods *et al.,* 2009) and has been found to range from 10% to 58%. Interestingly, Deguchi *et al.* (2003) found that an OI of as little as 5% was sufficient to resist 200-300 cN of orthodontic loading. In addition, Deguchi *et al.* (2003) found that bone quality and overall time positively influenced OI, whereas loading and healing time had no influence. This was

confirmed by later reports which found the loading and healing time and did not have a significant influence on the amount of osseointegration (Woods *et al.,* 2009; Chen *et al.* 2009). On the other hand, Wu *et al.,* (2009) conducted a descriptive histological assessment of 30 miniscrews following a variable healing periods (0, 1, 2, 4 and 8 weeks) and found new woven bone along the bone-implant interface only after 4 weeks. They suggested that the healing process is continuous and week 4 is the critical time point as at 2 weeks the integration of miniscrews and bone was weak. Surface treatment and the insertion method have been assessed by Kim *et al.* (2005) and Heidemann *et al.* (2001) respectively. Both factors have been found to have a slight but insignificant influence on osseointegration.

It seems that osseointegration does occur with DRTADs but to a lesser extent than LRTADs (70% osseointegration) and conventional implants. Although osseointegration is desirable, as it provides absolute anchorage (Roberts *et al,* 1984), the stability of DRTADs has been shown to be independent of osseointegration (Deguchi *et al.,* 2003) at forces less than 200 cN (Miyawaki *et al.,* 2003). Complete osseointegration would be undesirable because it would complicate the removal of the DRTADs at the end of treatment. The simple removal of DRTADs is crucial at the end of treatment as this was one of the main drawbacks of LRTADs and conventional implants.

1.6.4.8 Success of DRTADs

The overall success rate of DRTADs has been investigated in human (Table 1-4) and animal studies over the last decade and it has ranged from 70% - 93%. These studies identify failure as the loss or mobility of DRTADs. Recently, a meta-analysis by Schatzle *et al.* (2009) found the success rate for DRTADs to be 83.6%. The variations seen in the success rate are due to the influence of several factors. Miyawaki *et al.* (2003) were the first to investigate the factors which influenced the success rate of DRTADs. Miyawaki *et al.* (2003) assessed 134 DRTADs and the effect on success rate of patients' age, gender,

diameter, length, maxillary mandibular plane angle (MMPA), immediate loading, peri-implant inflammation, crowding and anteroposterior jaw base relationship. They found the overall success rate to be 83.9-85%, with DRTADs diameter, MMPA and peri-implantitis influencing the success rate while the other factors did not affect the success. Since then these factors were further assessed individually and collectively. These studies assessed the same factors with the addition of healing period before loading, method of DRTAD placement and the location. Luzi *et al.* (2009a) divided these factors into three categories; patient related, operator related and DRTAD related.

Table 1-4. Miniscrew overall success rates (modified from Crismani *et al.*, 2010)

Author	Year	patients (n)	Screws (n)	Overall success rate (%)
Miyawaki *et al.*	2003	44	134	83.9-85
Fitz *et al.*	2004	17	36	70
Cheng *et al.*	2004	44	140	89
Chen et al.	2006	29	59	84.7
Park *et al.*	2006	87	227	91.6
Motoyoshi *et al.*	2006	41	124	85.5
Tseng *et al.*	2006	25	45	91.1
Kuroda *et al.*	2007	58	116	81.1-88.6
Luzi *et al.*	2007	98	140	90.7
Wiechmann *et al.*	2007	49	133	86.8
Motoyoshi *et al.*	2007	57	169	85.2
Chen *et al.*	2007	129	273	76.4-82.6
Luzi *et al.*	2009	137	211	91
Lee *et al.*	2010	141	260	82.4-93.8

Several studies have looked at the effect of gender (Table 1-5) and age (Table 1-6), in particular, on the success rate of DRTADs. These studies found that gender did not influence the success rate, whereas age did. Chen *et al.* (2007) and Lee *et al.* (2010) found that success was much lower in adolescents (20 years). These studies suggested that the bone density and cortical bone thickness were responsible for the higher failure rate since these DRTADs depend mainly on their mechanical retention for stability.

Table 1-5. The effect of gender on the success rate (%) DRTADs (modified from Crismani *et al.*, 2010)

Authors	year	Male (%)	Female (%)	Significant
Miyawaki *et al.*	2003	80	84.7	No
Motoyoshi *et al.*	2006	90	85	No
Park *et al.*	2006	88.8	93.5	No
Kuroda *et al.*	2007	85.7	88.9	No
Chen *et al.*	2007	84.4	85.4	No
Lee *et al.*	2010	89.8	92	No

Table 1-6. The effect of age on the success rate (%) DRTADs (modified from Crismani *et al.*, 2010)

Authors	year	<20	20-30	>30	Significant
Miyawaki *et al.*	2003	80.3	88.2	85	No
Kuroda *et al.*	2007	92.5	82.4	100	No
Chen *et al.*	2007	78.3	84.1	93.6	yes
Lee *et al.*	2010	82.4	93.8	93.8	yes

Bone density and quality play important roles in the stability of DRTADs (Lee *et al.*, 2004; Melsen 2005). Melsen & Verna (2005) suggested failure was usually due to inadequate bone density. Previously Misch (1990) classified bone into four groups (D1, D2, D3 and D4) according to density, where D1 denotes highest and D4 lowest density (Table 1-7). Recently Kravitz & Kusnoto (2007) found D1 and D2 provided greater stability whilst D4 had a higher failure rate. Thus, higher bone density provided greater mechanical retention and higher stability for the DRTADs. The site of placement of the DRTADs is, therefore, a critical factor for success. This is expected since the maxilla and the mandible have different bone densities (Figure 1-15) and the success rate for the DRTADs was not similar. Most studies found higher success in the maxilla (Cheng *et al.*, 2004; Park *et al.*, 2006; Chen *et al.*, 2007; Wiechmann *et al.*, 2007) whilst a smaller number of studies (Motoyoshi *et al.*, 2007; Luzi *et al.*, 2009a) found a slightly higher success in the mandible. Despite having more dense bone, the earlier publication attributed the failure in the mandible to overheating during placement, less attached gingiva and to the higher masticatory forces. Although Luzi *et al.* (2009a) reported higher success in the mandible,

they acknowledged the negative effects of mastication, which could outweigh the potential advantage provided by the higher bone density. Furthermore, Deguchi *et al.* (2003) investigated the effect of the placement site in beagle dogs and found the OI was significantly higher in the mandible compared to the maxilla. This was confirmed when Cornelis *et al.* (2010) found the receptor site anatomy to be more influential than loading. Thus, although the receptor site anatomy plays a primary role in the OI of DRTADs, other factors such as occlusal forces and placement method may influence the stability.

Table 1-7. Bone density classifications (Kravtiz & Kusnoto, 2007)

Bone Density Classification			
Bone Density	**Description**	**Tactile Analog**	**Location**
D1	Dense Cortical	Oak	Anterior Mandible Maxillary Midpalatal
D2	Porous Cortical and Course Trabecular	White Pine or Spruce	Anterior Maxilla Posterior Mandible
D3	Porous Cortical (thin) and Fine Trabecular	Balsa Wood	Posterior Maxilla Posterior Mandible Zygoma
D4	Fine Trabecular	Styrofoam	Posterior Maxilla Tuberosity

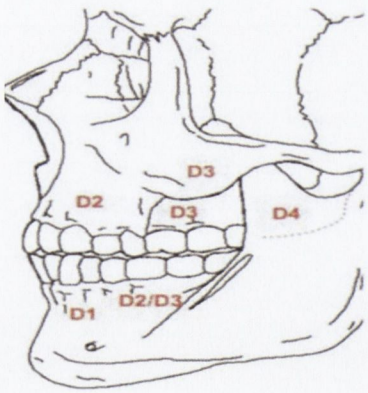

Figure 1-15. Bone density distribution (Kravtiz & Kusnoto, 2007).

Patient related factors such as oral hygiene and attached gingiva have also been analyzed with respect to implant success. Kuroda *et al.* (2007) and Park *et al.* (2006) found higher success rates in patients with good oral hygiene whereas Lee *et al.* (2010) found no

difference. Several studies have found a higher implant failure rate associated with peri-implantitis (Miyawaki *et al.,* 2003; Cheng *et al.,* 2004; Park *et al.,* 2006; Luzi *et al.,* 2009a). Luzi *et al.* (2009a) found that inserting DRTADs within the attached gingival reduced the occurrence of peri-implantitis and recommended implant insertion within the attached gingival margin to enhance the success rate.

The effect of the length and diameter of the DRTADs on the success rate have been extensively investigated in the literature. It has been shown that DRTADs with a diameter less than 1.2 mm failed readily (Miyawaki *et al.,* 2003; Wiechmann *et al.,* 2007) and a systematic review by Crismani *et al.* (2010) found 1.2 mm diameter or greater DRTADs had good success rates (>70%). The length of the DRTADs was another significant factor, as the success rate increased by 22% when 8 mm DRTADs were compared with 6 mm DRTADs (Chen *et al.,* 2006). This was considered significant but studies by Cheng *et al.* (2004), Tseng *et al.* (2006) and Kuroda *et al.* (2007) found no significant differences with different lengths. Crismani *et al.* (2010) consolidated these findings within their review by concluding that DRTADs with at least 1.2 mm in diameter and 8 mm in length were preferable for achieving stability and minimizing accidental root damage.

Other important factors such as latency time, duration and amount of force have been investigated. Although DRTADs achieve their retention initially by mechanical retention, partial osseointegration contributes to DRTAD stability and therefore the effect of latency time on the success of DRTADs was considered. Crismani *et al.* (2010) acknowledged the requirement of a healing period of at least several weeks for osseointegration to occur, but they recommended immediate loading. This was due to the similar success rates reported in the delayed and immediate loading studies. On the other hand, Deguchi *et al.* (2003) recommended a 3 week healing period in dogs, which is equivalent to 4-5 weeks in human studies, to resist orthodontic loading. This was later confirmed by Cornelis' *et al.* (2007)

systematic review which found that immediate loading in animal studies had a higher failure rate. This was based on Melsen & Costa (2000), Buchter *et al.* (2005) and Kim *et al.* (2005) studies which found a higher failure rate when DRTADs where loaded within 2 weeks. However Melsen & Costa (2000) recommended immediate loading and suggested that the orthodontic forces (25 cN) used were within the functional window, in contrast to the forces encountered with other implants such as hip and knee, and thus healing and stabilization would not be affected. Later, Kim *et al.* (2005) found good bone remodelling and osseointegration when DRTADs were loaded with 200-300 cN a week following their insertion. As a result, the current recommendation is for immediate loading with reduced orthodontic forces (Cornelis *et al.,* 2007) or a waiting period of 2 weeks for higher forces (Ohashi *et al.,* 2006). Later studies conducted by Woods *et al.* (2009) and Chen *et al.* (2009) found immediate loading did not inhibit osseointegration and suggested that loading may actually increase the amount of osseointegration. Importantly, the displacement of DRTADs was not recorded in the majority of these studies, as failure was identified as the loss and mobility of DRTADs. Since DRTADs go though different stability stages, primary stability followed by secondary stability weeks later, immediate loading could have affected the primary stability. Once secondary stability was achieved following osseointegration, DRTADs were usually stable without any signs of mobility or loosening. Therefore, it would have been more informative if the displacement was measured at different time intervals to assess whether the primary stability was compromised with the different loading protocols.

The impact of orthodontic forces on the success and stability of DRTADs has been analyzed. Cheng *et al.* (2004) and Kuroda *et al.* (2007) analyzed different force levels ranging from 50 to 200 cN and found no significant difference. Crismani *et al.* (2010) found forces ranging from 50-400 cN were used in different studies without an impact on

the success rate. They recommended up to 200 cN of orthodontic forces, even though it is difficult to establish the upper threshold from the available evidence. Animal studies, on the other hand, have the advantage of histological investigations following force application. Melsen & Costa (2000) found no difference in the bone response on the loaded and unloaded side. In addition Cornelis *et al.* (2010) found orthodontic forces within the range of 150 cN did not influence the bone density or stability around the screws, and excluded loading forces as a risk factor for failure. Buchter *et al.* (2005), on the other hand, found more failures when 300 cN of force was used in minipigs compared to 100 cN. However, Cornelis *et al.* (2007) found it difficult to interpret the findings, since different forces and animal sizes were used, and thus no agreement on the optimum force has been reached. They suggested that more research is required to establish the threshold limit.

Dentist related factors, such as surgical procedure, have also been examined. Conflicting results have been reported when mucoperiosteal flap insertion was compared with transmucosal flapless insertion. Kuroda *et al.* (2007) and Miyawaki *et al.* (2003) found the flapless method more successful whilst Herman *et al.* (2006) found more success in cases with flap surgery. Luzi *et al.* (2009a) suggested no clinical difference but found the flapless method more comfortable for the patient. In conclusion, Crismani *et al.* (2010) systematic review found the studies inconclusive and recommended further investigation to clarify this issue.

Another factor influencing the success of DRTADs is pre drilling as opposed to self drilling procedures during placement of DRTADs. Kim *et al.* (2005) and Chen *et al.* (2008) compared the stability of the DRTADs with the two different methods (pre drilling and self drilling) in beagle dogs and found both methods produced stable DRTADs for anchorage. However, the self drilling DRTADs showed less mobility, more bone to metal contact (Kim *et al.*, 2005) and a higher success rate (93% versus 86%) (Chen *et al.,* 2008). This could be

due to the reduced bone debris and thermal damage associated with self drilling as was suggested by Heidemann *et al.* (2001) earlier. On the other hand, Wang & Liou (2008) found that the method of insertion was not a determining factor for the stability of the DRTADs. Thus, it seems both methods produced stable DRTADs.

1.6.4.9 Anchorage loss associated with DRTADs

Osseointegrated implants have been shown to resist orthodontic loading without any loss in their positional stability (Roberts *et al.,* 1984; Saito *et al.,* 2000). DRTADs are partially osseointegrated and initially resist orthodontic loading by their mechanical retention to bone rather than by biological retention (osseointegration) (Costa *et al.,* 1998; Cope, 2005; Wang & Liou, 2008), so their behaviour under orthodontic loading is unclear. Park *et al.* (2006) suggested that excessive orthodontic loading to partly osseointegrated DRTADs could result in loss of stability and eventually failure. On the other hand, a light force would result in slight mobility but without a complete failure. This transient loss of stability should be investigated for any associated loss of position and anchorage. Liou *et al.* (2004) found DRTADs were displaced following orthodontic loading despite having good clinical stability. Implants can appear immobile following force application due to bone to implant contact even where their positional stability may have been compromised. Thus, it is important to assess the positional stability of DRTADs and any anchorage loss associated with such movement.

A clinical study by Liou *et al.* in 2004 investigated the stability of miniscrews in sixteen adults and whether the miniscrews remained stationary when forces were applied. The stability of the miniscrews was checked clinically and by comparing pre- and post-treatment cephalometric radiographs. They superimposed the two cephalometric radiographs using the point Sella, anterior cranial base and the cranial vault to obtain a best fit. A perpendicular line to Sella-Nasion line through Sella was used as vertical reference

line to measure the miniscrews movement. On average the miniscrews tipped forward by 0.4 mm at the screw head and in 7 patients they were extruded and tipped forward by 1.5 mm. It was concluded that the miniscrews did not remain absolutely stationary and that they should be placed at least 2 mm away from vital structures. The authors suggested that this initial movement occurred during the mechanical stability phase due to the fibrous interface which could be present prior to bone interlocking.

Even though the forces used in Liou *et al.* (2004) were high (400 g), it was the first to highlight the issue of anchorage loss associated with miniscrews. These high forces could be responsible for such an amount of anchorage loss. Furthermore, the use of cephalometric radiographs for measuring anchorage loss is limited as was described earlier (section 1.5.3). In addition, Liou *et al.* (2004) placed the miniscrews in both sides of the maxilla and therefore the miniscrews overlapped (Figure 1-16). Liou *et al.* (2004) averaged the images on the right and left to overcome this error. This would mask small movements associated with the miniscrews, thus rendering this method unreliable. A stable reference point such as another unloaded miniscrew is needed for the measurements to be accurate.

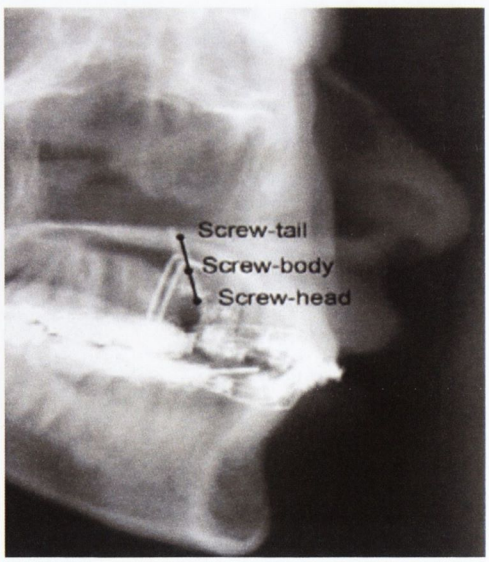

Figure 1-16. A cephalogram showing the miniscrews overlapping on the right and left side of the maxilla (Liou *et al,* 2004).

A recent clinical pilot study by Thiruvenkatachari *et al.* (2006) compared the amount of anchorage loss of molars with and without the use of implant anchorage during canine retraction. Ten patients who required the extraction of all first premolars and had maximum anchorage requirement (75-100% of space used for anterior retraction) were recruited. Class II and Class I patients were included in this study. Following alignment and the levelling phase, implants were placed in one side and no anchorage reinforcement in the contra lateral side. A nickel titanium closed coil was used to retract the canines. Records including lateral cephalometric radiographs, study models, orthopantomograms and photographs were taken pre and post canine retraction. Anchorage loss was determined by assessing the molars' position using superimposed lateral cephalometric tracings pre and post-retraction. Thiruvenkatachari *et al.* (2006) found that there was no anchorage loss on the implant side, but a mean of 1.6 mm anchorage loss in the maxilla and 1.7 mm in the mandible. This was a very good pilot study as it compared how much anchorage loss was expected with and without any reinforcement. The results were noteworthy as they contradict the current orthodontic belief that anchorage loss is greater in the maxilla than in the mandible. Anchorage loss in premolar extraction spaces is suggested to be in the region of 4.5-2.8 mm (Kirschen *et al.,* 2000) whereas in this study it ranged from 1-2 mm. Unfortunately, the study did not explain these findings. Even though the study raised the question of anchorage loss comparison, it has some limitations. The main reservation was the method which was used to assess anchorage loss. Since the right and left molars would have overlapped in the radiographs, it would have been very difficult to assess the anchorage loss. The investigators tried to overcome this problem by placing an L shaped wire on the right band. In addition, the criteria for the quadrant allocation was not explained. The amount (in mm) that the canine was retracted was not mentioned, thus we were not able to determine how much anchorage was lost for each 1 mm of canine retraction achieved. As Class I and II patients were included in this study, this added

another variable which may influence the result. In Class I cases, the upper and lower spaces are closed simultaneously and the occlusion is usually locked in the right place, which aids anchorage. The patient maxillary mandibular plane angle, not mentioned in the study, is also crucial. High angle patients would have higher anchorage loss than low angle patients as the teeth would be disoccluded (Alexander *et al.,* 1983). A study with more sensitive measuring methods and less variables is needed to clarify the question of how much anchorage is lost. If the anchorage advantage is only 1.7 mm, then the risk associated with such miniscrews may need to be re-evaluated. A follow up study by Thiruvenkatachari *et al.* (2008), measured and compared canine retraction (desired tooth movement) with and without miniscrew anchorage reinforcement. They used superimposed pre- and post-treatment lateral cephalograms to assess canine movements. The amount of canine retraction was measured from the pterygoid vertical (Figure 1-7) in the maxilla and SN perpendicular in the mandible. The canines were retracted 0.35 mm – 0.6 mm more in the miniscrew group. The rate of canine movement was also 0.07 mm – 0.12 mm faster per month in the miniscrew group. They concluded the canines were retracted more and moved faster with miniscrew anchorage reinforcement.

A clinical study by Wang & Liou (2008) compared self and pre drilling DRTADs in 32 patients and found neither type provided absolute anchorage. The DRTADs in both groups were displaced under orthodontic loading despite being stable and without any signs of mobility or loosening. Wang & Liou (2008) employed the same method used by Liou *et al.* (2004) to assess anchorage loss, which had the same limitations discussed earlier.

Garfinkle *et al.* (2008) assessed the stability of 82 miniscrews (1.6 mm x 6 mm) inserted in 13 adolescent patients. In each quadrant two miniscrew were placed. One of the miniscrews was used for force application whilst the other was used as a control to measure the loaded (experimental) miniscrew movement. A force of 150 g was applied directly from

the miniscrew to the tooth being retracted until the tooth was fully retracted. Pre- and post-treatment study models were then used to measure the distance between the control and experimental miniscrew. Although they recommended leaving at least 1 mm between the miniscrew and vital structures as miniscrews moved over time, they did not report on the amount of miniscrew movement which occurred.

El-Beialy *et al.* (2009) assessed the stability of 40 miniscrews (1.2 mm x 8 mm) in 12 patients for 6 months. After a healing period of 2 weeks, a force of 150 – 250 g was applied to retract the canines. The displacement of the miniscrews was measured using high-speed dental CT scans of the skull and mandible. Computer software developed in Cairo University (3D-Biodent) was used to tile up the images and rebuild a 3D volume of the patient's maxilla and mandible. The maxilla and the mandible were each superimposed before and after treatment. The coordinates of points on the miniscrews were recorded before and after loading. By subtracting the same defined points of the miniscrews before and after treatment, the measurements of the miniscrews displacement were made directly without the need to use reference points and plans. The mean displacement of the miniscrews was 1.08 mm. This 3D volumetric analysis is a relatively new tool in orthodontics and further studies will be needed to verify its accuracy. This study (El-Beialy *et al.,* 2009) however did not mention the age of the patients enrolled. This is important as the maxilla and mandible relationship may change in a growing patient.

A more recent randomised clinical trial study by Sharma *et al.* (2012) investigated the amount of anchorage loss associated with the transpalatal arch and compared it with miniscrews (1.2 mm x 8 mm). The authors measured the amount of mesial movement of maxillary molars (anchorage loss) during maxillary canine retraction in 30 patients using the same radiographic method used by Thiruvenkatachari *et al.* (2008). A force of 150 g was applied to both groups (TPA and miniscrew) after alignment and levelling to retract the

canines. They found there was 2.5 mm anchorage loss in the TPA group compared with no movement in the miniscrew group. The authors suggested that the miniscrews provided absolute anchorage even though they did not measure the amount of miniscrew movement which occurred as result of the force application.

Although the previous studies highlighted the anchorage loss associated with miniscrews, they did not provide any information about the time frame at which such anchorage loss occurs or an accurate measurement of the amount of anchorage loss. These studies assessed the miniscrews prior to loading and several months later. Thus anchorage loss could occur during the initial phase of the miniscrew stability or throughout the time of treatment. Indentifying the time of anchorage loss, whether it is constant or varies over time, will give the orthodontists a better insight into miniscrew behaviour over the treatment time span. This behaviour over time, in addition to the amount of anchorage loss, may change the method by which miniscrews are utilized for anchorage reinforcement.

1.7 Root resorption

Several terminologies have been used to describe root resorption which occurs as a result of orthodontic treatment. The two most commonly used are orthodontically induced inflammatory root resorption (OIIRR) and external apical root resorption (EARR). It is important to differentiate classifications of root resorption according to the present understanding of the resorptive process in teeth. Tronstad (1988) divided root resorption into inflammatory and replacement. Inflammatory root resorption occurs when the pre-dentine or precementum is damaged. This can affect the outer surface (external) or the inner surface (internal) of the root. Replacement resorption occurs when cells involved in bone remodelling are not able to distinguish between dental tissues and bone.

Inflammatory and replacement root resorption may be transient or progressive, depending on the stimulus. Transient resorption occurs when the phagocytic cells involved in the resorption process are not exposed to an additional continuous stimulus. The initial stimulus of the damaged root surface will sustain the resorption process for a period of 2-3 weeks, after which repair with the formation of cementum-like tissue will take over (Tronstad, 1988). This type of resorption has been referred to as surface resorption and is usually undetectable clinically or radiographically and thus bears little clinical significance (Tronstad, 1988).

Progressive inflammatory root resorption is initiated by the same process as transient inflammatory root resorption, but is sustained by either mechanical irritation, pressure in the tissue, infection, or systemic disease (Tronstad, 1988). Mechanical irritation is seen mainly in root fractures when resorption continues to round the sharp edges of the fractured root (Tronstad, 1988). Pressure stimulation is seen physiologically, in the transition from primary to permanent dentition. Sustained pressure stimulation occurs from slow growing tumours or more frequently as a result of orthodontic treatment. Infection from endodontic or periodontal disease can also sustain the resorption process. Depending on the aetiology

of the infection, resorption may be external (periodontal) or internal (endodontic). Systemic diseases with dentoalveolar manifestations, such as Paget's disease, may also stimulate root resorption.

Progressive external inflammatory resorption is the resorption type seen in orthodontic treatment. It mostly affects the apical third (Tronstad, 1988) of the root and rarely the cervical region (Cwyk, 1984). Brezniak & Wasserstein (2002a) suggested the term orthodontically induced inflammatory root resorption (OIIRR) and divided the resorption into three levels according to severity: surface resorption involving the cementum only and is fully remodelled, dentinal resorption involving the cementum and the outer layers of dentine with cemental repair, and circumferential apical root resorption where root shortening is evident as a result of the full resorption of the root hard tissues.

This chapter will discuss orthodontically induced inflammatory root resorption (OIIRR), its pathogenesis, aetiology, and diagnosis.

1.7.1 *Cementum.*

Cementum is a nonuniform thin avascular connective tissue derived from the investing layer of the dental follicle covering the dentine of the roots (Bosshardt & Selvig, 1997). The main function of cementum is providing attachment to collagen fibres of the periodontal ligament, thus facilitating anchorage of the tooth to alveolar bone. Since cementum is slowly formed throughout life, it allows the continual reattachment of periodontal ligaments and hence for adaption of the teeth movement. It has chemical and physical properties similar to bone but is avascular and lacks the lamellar appearance and marrow spaces. Most importantly, cementum is more resistant to resorption than bone, allowing for orthodontic tooth movement.

Cementum is pale yellow and softer, with a more permeable texture, than dentine having variable thickness along the root. It is thickest at the apex and interradicular area (50 – 200 μm) and thinnest at the cervical area (10 – 15 μm) of teeth (Berkovitz *et al.*, 2009).

Different varieties of cementum exist along human teeth with different levels of mineralization (Soni *et al.*, 1962). Certain authors have suggested that more mineralized cementum is more resistant to resorption (Reitan & Rygh, 1985). Therefore, it is essential to understand the different types of cementum and their locations, as that might influence the pattern and amount of root resorption.

1.7.2 *Cementum Classification*

Cementum is classified according to the presence or absence of cells, origin of the organic matrix or a combination of both.

1.7.2.1 Cells

Cellular cementum contains cementocytes and its processes which extend into channels called canaliculi. It has a faster rate of matrix formation than acellular cementum and therefore the formative cells (cementoblasts) become embedded in the tissue as cementocytes. In addition, a layer of uncalcified matrix, precementum (3-5 μm) (Selvig, 1965), and widely spaced incremental lines are present, reflecting the faster formation. Cellular cementum is usually found at the apical and interradicular area of the root and overlaying acellular cementum (Figure 1-17). It is also referred to as secondary cementum because it is formed subsequent to acellular cementum. Although the cellular cementum overlies the acellular cementum, the reverse may occur. This may be due to the variations in the rate of deposition (Berkovitz *et al.*, 2009).

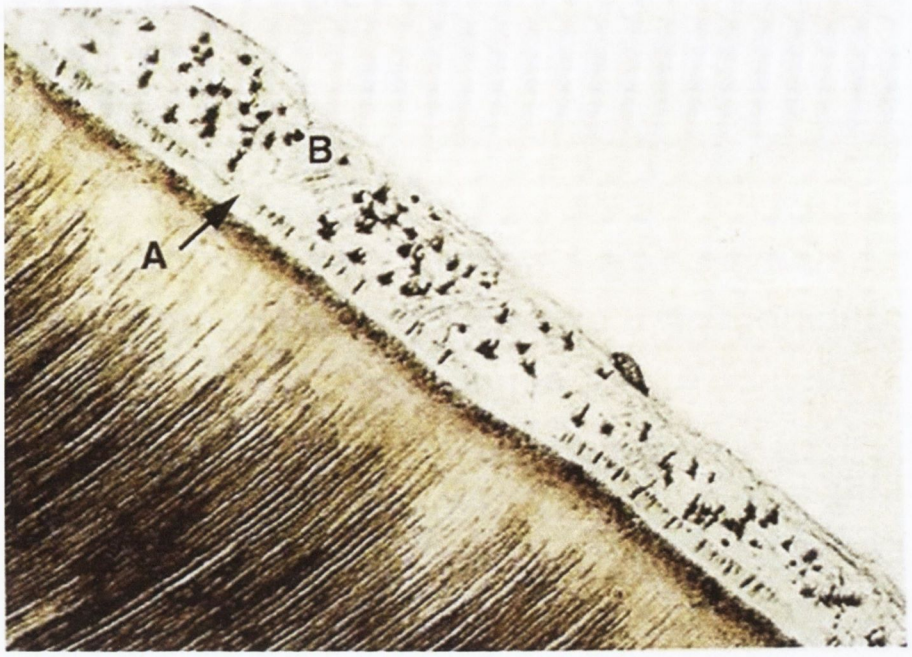

Figure 1-17. Cellular cementum (B) overlying acellular cementum (A). Taken from *Berkovitz et al. (2009). Oral anatomy, histology and embryology: Cementum. (Fourth edition). MOSBY ELSEVIER.*

As its nomenclature suggests, acellular cementum does not contain any cells and has a slower rate of formation. Furthermore, precementum is absent and the incremental lines are closer together. Being formed first it is also called primary cementum. Acellular cementum covers the dentine of the root and extends from the cervical margin to the apical third. Henry & Weinmann (1951) found acellular cementum to be more mineralized and more resistant to resorption than cellular cementum. This was subsequently confirmed by Alatli *et al.* (1996) whose findings showed rat roots to be more susceptible to resorption since they lacked acellular cementum.

1.7.2.2 Origin and nature of organic matrix (Table 1-8)

Table 1-8. Type, distribution and function of cementum.
Nanci, A. (2008). Ten Cate's Oral Histology: development, structure, and function. (Seventh edition) St. Louis, Missouri 63146. MOSBY ELSEVIER.

Type	Origin of Fibres	Location	Function
Acellular (primary)	Extrinsic	From cervical margin to apical third	Anchorage
Cellular	Intrinsic	Middle to apical third and furcations	Adaption and repair
Mixed (alternating layers of acellular / cellular	Intrinsic / extrinsic	Apical portion and furcations	Adaption
Acellular afibrillar		Cervical enamel and along the enamel cementoenamel junction	Unknown

Cementum organic matrix may be either derived from the inserting Sharpey fibres, which are terminal ends of the periodontal fibres (extrinsic), or from the cementoblasts within the cementum (intrinsic). The extrinsic fibres run perpendicular to the surface of the root in the same direction of the periodontal fibres, whereas the intrinsic fibres run parallel to the root surface.

1.7.2.3 Combination

This classification takes into account both the presence of cells and the origin of the matrix. There are two main types: Acellular extrinsic fibre cementum (AEFC) and cellular intrinsic fibre cementum (CIFC).

AEFC is considered primary cementum and covers the cervical two thirds of the root except for the premolars, where it constitutes the majority of the cementum. It is formed slowly and is approximately 15-20 μm thick. AEFC has a smooth surface and its fibres are well mineralized (Berkovitz *et al.*, 2009).

Cellular intrinsic fibre cementum (CIFC) is secondary cementum and covers the apical and interradicular areas (Figure 1-18). CIFC does not play a role in tooth attachment since its intrinsic fibres run parallel to the root surface without Sharpey fibres' extensions from the adjacent periodontal ligament. However, in certain cases the CIFC may be only a temporary phase before extrinsic fibres start to penetrate it. It generally has a rapid formation rate and in contrast to AEFC, has a cementoid layer covering its outer surface. The cementoid layer is similar to osteoid in bone and has an important role to play in the prevention of root resorption. Furthermore, CIFC participates mainly in the repair of previously resorbed roots (Bosshardt & Selvig, 1997).

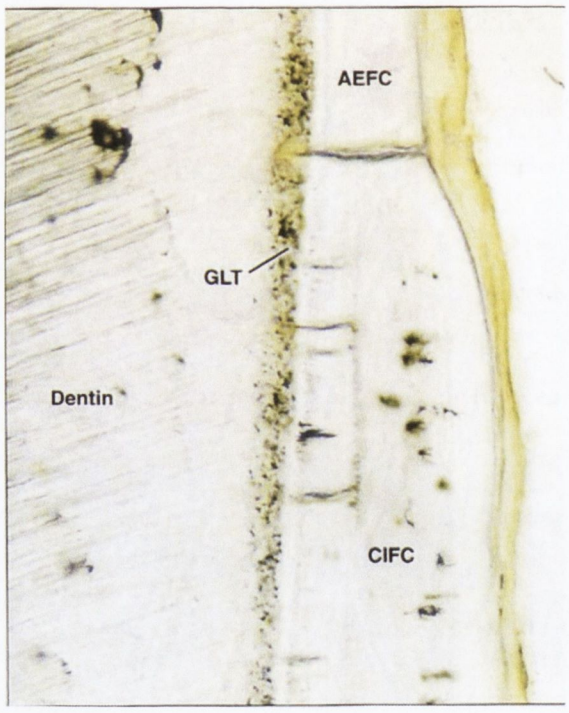

Figure 1-18. Ground sections of human teeth examined by transmitted light illustrating the transition between the acellular extrinsic fiber cementum (AEFC) and cellular intrinsic fiber cementum (CIFC). Cementocytes (dark, rounded structures) are present in the CIFC.
Taken from Nanci, A. (2008). Ten Cate's Oral Histology: development, structure, and function. (seventh edition) St. Louis, Missouri 63146. MOSBY ELSEVIER.

It is therefore important to note that despite the different types of cementum occupying different regions along the root surface, in multi-rooted teeth both acellular extrinsic fibre cementum and cellular intrinsic fibre cementum can be present in alternating layers. This results in a cellular mixed stratified cementum (CMSC). This is confined to apical root portions and furcations (Berkovitz *et al.*, 2009).

Another variant is the mixed fibre cementum where the fibres are derived from both extrinsic and intrinsic sources. The fibres within the matrix can be differentiated based on the orientation and size of the fibres. The mixed fibre cementum is named acellular mixed-fibre cementum if the formation rate is slow and it is generally well mineralized. On the other hand, if the formation rate is fast and less mineralized it is termed cellular mixed-fibre cementum.

Finally, afibrillar cementum; a thin acellular layer covering cervical enamel at the site where reduced enamel epithelium is lost, is a sparse cementum variant which lacks any fibres. These different types of cementum may have different susceptibility levels to root resorption due to the mineralization levels (Henry & Weinmann, 1951; Graber & Swain, 1985; Alatli *et al.*, 1996). For instance, cellular mixed stratified and cellular intrinsic fibre cementum are less mineralized than acellular cementum (Soni *et al.*, 1962; Bosshardt & Selvig, 1997).

1.7.3 *Cementum physical properties*

The mineral content of cementum has been investigated as it was suggested that it might influence the resistance to resorption (Henry & Weinmann, 1951; Bjorvatn & Massler, 1971; Coccia, 1980). The more mineralized the cementum, the harder it is, and therefore the greater its resistance to resorption.

The inorganic material in cementum constitutes 65% of cementum weight and 45% of its volume. Cementum is usually less mineralized than root dentine (Cohen *et al.*, 1992). Hydroxyapatite [Ca_{10} $(PO_4)_6$ $(OH)_2$] is the principle mineral component of cementum,

which is similar to other calcified tissues. As in other hard tissues in the body, hydroxyapatite is not pure and contains other elements that have been taken up from tissue fluid during mineralization. These elements include fluoride, magnesium and sulphur, in addition to trace elements such as copper, zinc and sodium.

Looking at the concentration levels of calcium (Ca), phosphorus (P) and fluoride (F) in different types of cementum and at different regions along the root surface, Rex *et al.* (2005) found that even though there were considerable individual variations, several trends were found in relation to their concentration. For example, although there was no significant difference in the concentration of Ca, P and F between buccal and lingual surfaces, the cervical region of the buccal surface had a higher F concentration. Furthermore, Ca, P and F concentration reduced from the cervical to the apical third. Also, F concentration gradient decreased from the outer to the inner third of cementum, in contrast to Ca and P which had the opposite concentration gradient. A follow up study by Rex *et al.* (2006) investigated the influence of different force levels on the mineral content and found that varying the force levels influenced the concentration. Light forces had no impact, whereas heavy forces reduced the Ca concentration in the tension areas and increased P concentration in the pressure area.

1.7.4 *Cementum resistance to root resorption*

Cementum has a similar structure to bone yet it has higher resistance to resorption (Rygh, 1977). Although both tend to resorb under orthodontic forces it seems bones are more readily resorbed. This could be due to the fact that bone is involved in the metabolic process of calcium homeostasis and is well vascularised, which is critical in its response to metabolic needs. Cementum, on the other hand, does not release calcium under normal conditions and is not vascularised, with scarce anastomosis with the periodontal ligaments. Other features which are said to reduce the resorption of cementum are cementoid, cells lining the cementum surface, and mineralization levels specifically fluoride content.

Cementum is protected from root resorption by an uncalcified layer of 3 μm to 5 μm cementum (precementum/cementoid) and the cementoblasts lining the root surface (Brudvik & Rygh, 1995a). Once these are damaged the underlying calcified cementum lies unprotected against the resorbing cells. Cementoid and its cells have a higher resistance to resorption, and in particular to the organic component. Lindskog & Hammarstrom (1980) found they contain anti-invasive factors and suggested that the periodontal ligament and cementum contain a potent collagenase inhibitor which protects them from root resorption. Once these structures have been damaged, the root loses its protective mechanism against the collagenase activity.

As was discussed earlier, the mineralization levels of cementum enhance the resistance to resorption. Fluoride had been specifically investigated for its influence on root resorption. The significance of fluoride concentration in cementum was thought to parallel the higher resistance to resorption found in bone tissues that have increased fluoride concentration. Cementum has the highest fluoride content of all calcified tissues in the body. In fact, it was found by Nakagaki *et al.* (1985) to contain 5 times and 3 times more fluoride than enamel and bone respectively (Rex *et al.*, 2005). For this reason it had been suggested that fluoride could be one of the reasons for the higher resistance to resorption by cementum compared to bone, during tooth movement. Fluoride supplements have been found to reduce osteoporosis and it is postulated that it might have the same effect on cementum. Although the mechanism by which fluoride increases the resistance of cementum to root resorption is relatively unknown, fluoride enhances the bone resistance to osteoporosis by acting on four different levels. Fluoride has been found to increase bone resistance to osteoporosis by promoting osteoblastic activity and inhibiting osteoclastic activity. Fluoride also degrades bone collagen, therefore protecting it from osteoclasts. Lastly, fluoride increases the crystalline size and transforms the surface hydroxyapatite to fluorapatite, which renders the bone more resistant to osteoporosis.

Fluoride concentration in cementum is variable and tends to increase with age, higher fluoride concentration in water and oral environment (Nakagaki *et al.*, 1985). As a result, to establish the effect of fluoride concentration on cementum, it is important to quantify fluoride concentrations along the root surface, assess the effect of different forces on fluoride concentration, and lastly the effect of increasing fluoride concentration on the resistance to root resorption. Rex *et al.* (2005) found fluoride concentrations varied along the root surface with a decreasing gradient from the cervical to the apical third. This might explain the higher susceptibility to resorption by the apical third which is less mineralized. A subsequent study by Rex *et al.* (2006) found high orthodontic forces tend to alter the concentration of fluoride whereas light forces had little effect. When the effect of increasing fluoride concentrations on root resorption was investigated, by Foo *et al.* (2007) on rats, it was found that it had a variable effect. Although the resorption craters were on average 50% less in the group which received fluoride supplements, the variability and the range of the size of resorption craters make the effect statistically insignificant. Foo *et al.* (2007) suggested that the beneficial effect of fluoride on reducing cementum resorption could have been counteracted by the effect of fluoride on bone. At the moment the effect and influence of fluoride on cementum resistance has yet to be clarified.

1.7.5 *The histology of root resorption.*

Orthodontic induced inflammatory root resorption (OIIRR) is an unavoidable pathological consequence of orthodontic tooth movement (Brezniak & Wasserstein, 2002b). Rygh (1977) found that root resorption occurs as a side effect of the cellular activity associated with the elimination of the hyalinized zone along the root surface. Brudvik & Rygh (1993a) confirmed that OIIRR is associated with the elimination of the hyalinization within the periodontal membrane. It is important to examine the cellular process involved in the elimination of the hyaline zone during orthodontic tooth movement.

When teeth are moved orthodontically, the periodontal ligament (PDL) is exposed to compression and tension forces. In the direction of tooth movement, the PDL is compressed, and in cases of heavy forces the PDL is injured, forming sterile coagulation necrosis (hyalinized zone). Brudvik & Rygh (1993a) found the process of root resorption was closely linked to the remodelling of the periodontal ligament as a result of its injury and necrosis.

In a series of studies conducted on rats and mice, Brudvik & Rygh (1993a; 1993b; 1994a; 1994b; 1995a; 1995b) divided the process of root resorption into different phases according to the areas and the cells. The initial phase of root resorption occurs at the periphery of the hyalinized area (Figure 1-19). It involves the tartrate-resistance acid phosphatase (TRAP) negative mononucleated macrophage like cells (Brudvik & Rygh, 1993b). This phase started 2-3 and 4-6 days in rats and mice respectively, after the formation of the hyalinized zone. It is believed that root resorption occurs at the periphery of the hyalinized zone due to the presence of viable cells and adequate vascularity still present adjacent to the hyalinized zone. These studies have also found that fibroblast-like cells and cementoblasts participated in the removal of precementum by phagocytosis of cellular elements as well as adjacent fibrous components.

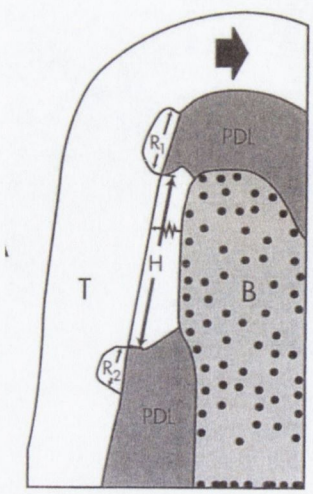

Figure 1-19. Principal pattern of root resorption related to a hyalinized zone. Tooth (T); Hyalinized zone (H); Root resorption (R), Bone (B) and Periodontal ligament (PDL). Root resorptions occur first in the periphery of the hyalinized zone, and later occur in the central parts (Brudvik & Rygh, 1993a).

In the second stage, the centralized hyalinized tissue adjacent to the root surface is removed by multinucleated cells, as well as mono nucleated macrophage cells. This started 3-4 days later than in the periphery (Brudvik & Rygh, 1993a). The multinucleated TRAP positive giant cells without a ruffled border, appeared in the PDL some distance from the root surface. These cells may be osteoclasts or odontoclasts that did not come to full expression (Brudvik & Rygh, 1994a). These cells develop ruffled borders once in contact with cementum in a matter of hours (Brudvik & Rygh, 1994a).

During the later phase, resorption occurs beneath the main hyalinized zone (Brudvik & Rygh, 1994b). It is hypothesized that multinucleated TRAP positive cells, mostly with ruffled borders, are involved. Once they reached the subjacent contaminated and damaged root surface, after having removed hyalinized tissue, the ruffled multinucleated cells continued to remove the cementum surface. It is possible that the orthodontic forces directly damage the outer cementum surface beneath the hyalinized zone as well as causing the hyalinization zone. Therefore, it requires removal of the damaged cementum.

1.7.6 *Cells involved in root resorption*

Brudvik & Rygh (1993a; 1993b; 1994a; 1994b; 1995a; 1995b) conducted several studies on mice and rats to assess the pathological process of root resorption and the cells involved. They found that different types of cells were involved at different stages. These cells were mononucleate macrophages, fibroblast like cells, multinucleated giant cells without ruffled borders and osteoclasts (OC) with ruffled borders.

Osteoclast-like cells (OC) have historically been considered to be primarily responsible for root resorption (Brudvik & Rygh, 1991). In their series of animal studies, Brudvik & Rygh used haematoxylin eosin (H&E) stain and Tartrate-resistant acid phosphatase (TRAP) to identify the cells involved (Brudvik & Rygh, 1993a; 1994b). The H&E was used because it permits differentiation between cells (mono/multi-nucleated cells) in periodontal tissue and alveolar bone in addition to demonstrating the necrotic tissue. TRAP was used to

identify osteoclasts cells since active osteoclasts show a high content of tartrate resistant acid phosphatase (Lilja *et al.*, 1983). This specific isoenzyme in the cytoplasm of multinucleate OC can be distinguished from other cells by its resistance to being inhibited by tartaric acid. Therefore TRAP staining has been used to identify cells involved in orthodontic tooth movement and root resorption (Lilja *et al.*, 1983). This was later combined with the transmission electron microscope (TEM) to investigate the cells in more detail (Brudvik & Rygh, 1993b; 1994a).

Brudvik & Rygh (1993a) found that cells initially penetrated the precementum at the circumference of the necrotic hyalinized zone. These cells were TRAP negative indicating that they are not clast or clast precursors. H&E stains revealed that these were mononucleate cells. Brudvik and Rygh suggested that at least some of these are macrophages, which function as part of the general defence mechanism by removing necrotic tissues and damaged PDL (Rygh, 1977). TRAP positive cells were first observed in the bone marrow spaces. These cells were later involved in the removal of the main central hyalinized zone and root resorption (Brudvik & Rygh, 1994b). When TRAP positive cells reached subjacent contaminated and damaged root surface, after removing the hyalinized zone, they continued to remove cementum surface. H&E stain revealed that these cells were mono and multinucleated cells while the majority of the cells were multinucleated (Brudvik & Rygh, 1994b).

The TEM investigations that followed by Brudvik & Rygh (1993b) revealed the role of mononucleated non-clast cells in the periphery of hyalinized tissue. They found precementum and the mineralized acellular cementum in the periphery of the centralized hyalinized zone were removed by two different processes. Root resorption at the periphery of the centralized hyalinized zone occurred by phagocytosis and extracellular enzymatic

activity. It started by phagocytosis of the cellular and connective tissue remnants in the periodontal ligaments and in the precementum by macrophages and fibroblast-like cells. This is followed by extracellular enzymatic activity such as collagenase which removed the unmineralized connective tissue of the precementum. Furthermore, Brudvik & Rygh (1993b) found that mononucleated cells were responsible for resorbing mineralized acellular cementum. They suggested that these mononucleated cells could be mononucleated osteoclasts of a special type (Collins & Sinclair, 1988). Both light and electron transmission microscopy observations from the first stage confirmed that the cells that started the first stage of root resorption were not multinucleated-like cells as expected, but were mononucleated cells that stained negatively to TRAP and resembled fibroblasts and macrophages.

Transmission electron microscopy (TEM), performed on rats by Brudvik & Rygh (1994a), to investigate in more detail the cells responsible for the removal of the main centralized hyalinized tissue and the tissues underneath. This study revealed that different cells were involved in the process, namely, mononucleated macrophages and multinucleated giant cells. Initially multinucleated giant cells without a ruffled border, and mononucleated macrophage cells were responsible for the removal of the necrotic tissue in the PDL and also for the resorption of the surface parts of the cementum. However, macrophage involvement at this centralized zone was less dominant than the periphery. Although the multinucleated giant cells without the ruffled border had similar morphological traits to the odontoclasts and osteoclasts, Brudvik & Rygh (1994a) believed that they are of mononucleated phagocytic system origin. Multinucleated giant cells with ruffled borders only appeared in contact with the cementum in resorption lacunae. Therefore, it appears that resorption of the cementum is a dynamic process with different types of cells corresponding to the different stages and types of surfaces they are resorbing.

1.7.7 *Repair of cementum resorption*

Root resorption that occurs during orthodontic tooth movement has been attributed to the removal of the defence barrier of cementum by the traumatic aspect of orthodontic tooth movement and the elimination of the hyalinized zone by different cells (Rygh, 1977). Once the force has been reduced or tooth movement has been stopped, a process of repair is initiated by deposition of new cementum (Rygh, 1977). This repair has been recorded as early as the first week of retention (Owman-Moll *et al.*, 1995b) and even occurs in the presence of light forces (Brudvik & Rygh, 1995a; Winter *et al.*, 2009). Several aspects of the repair process have been investigated using animal (Rygh, 1977; Lindskog *et al.*, 1987; Brudvik & Rygh, 1995a) and human models (Langford & Sims, 1982; Owman-Moll *et al.*, 1995b; Owman-Moll & Kurol, 1998; Winter *et al.*, 2009). The spatial repair pattern, cells involved, type of cementum and the type of repair have been observed in different studies.

The repair patterns of orthodontic root resorption have been investigated to identify the initial site where the repair process starts. Animal studies by Brudvik & Rygh (1995a) and Lindskog *et al.* (1987) both found that the process starts at the periphery of the resorption lacuna, whereas Langford & Sims (1982) and Owman-Moll *et al.* (1995b) found it to occur in the bottom of the resorption lacuna. Two observations might explain this variation; firstly since Owman-Moll *et al.* (1995b) is a human study and Brudvik & Rygh (1995a) is an animal study the cells' reaction might be different. Another explanation is that the Owman-Moll *et al.* (1995b) study observed the process after 7 weeks, whereas Brudvik & Rygh (1995a) started their observation after only 10 days. As a result Owman-Moll and colleagues might have missed the initial process. Brudvik & Rygh (1995a) suggested that the periphery is the initial site for repair due to the presence of the vital tissue, root damage being superficial, and the presenting necrotic tissue being thinner than the centre zone. This claim still requires further investigation.

Brudvik & Rygh (1995a) observed the cells involved in the repair process for periods between 2 and 21 days. They found fibroblast-like cells, rich in rough endoplasmic reticulum (RER) and dense bodies, suggesting synthesis of collagen fibril material. These were employed at the circumference of the resorption lacunae after 10 days of active tooth movement, while multinucleate odontoclast cells are still actively resorbing the cementum at the centre of the lacuna. After 21 days cementoblast-like cells, similar to those involved in cementogenesis, were observed in the repair process and new cementum was formed.

The type of cementum involved in the repair process is important, as different types of cementum have different degrees of mineralization which might affect the subsequent resistance to resorption. A study by Mirabella & Artun (1995a) found that patients exposed to a second phase of orthodontic treatment during their adulthood were more resistant to root resorption. One explanation could be that remodelled cementum contributes an additional protective effect in the outer layers. Cellular and acellular cementum have both been identified in repaired lesions with different studies. Brudvik & Rygh (1995a) and Langford and Sims (1982) found that resorption was repaired entirely by cellular cementum. It was hypothesized that the cells were inclusions of rapidly growing tissue. In contrast, Owman-Moll *et al.* (1995b) and Owman-Moll & Kurol (1998), found repair was commenced by a thin layer of acellular cementum followed by a covering layer of cellular cementum, with the majority of the repair being of the cellular type. Acellular repair was mainly at the cervical third of the tooth whereas cellular repair was mostly at the apical third. Recently, Winter *et al.* (2009) found repair by cellular and acellular cementum occurred to the same extent over the whole root, irrespective of the location of the lesion. Therefore this area is still unclear and further investigations are necessary.

1.7.8 *Initiation of cementum repair*

The initiation of the repair process following orthodontic tooth movement has been observed by several studies (Brudvik & Rygh, 1995b; Owman-Moll & Kurol, 1998; Winter

et al., 2009). The repair process started during active force application in both animal (Brudvik & Rygh, 1995b) and human studies (Owman-Moll & Kurol, 1998; Winter *et al.*, 2009). Once the application of force was terminated and tooth movement halted, the percentage of repair increased in all the studies. The percentage of repair was approximately 28% after 1 week and increased to 75% after 8 weeks. This was later confirmed by Owman-Moll & Kurol (1998) and Winter *et al.* (2009) who found the percentage of repair increased to 82% and 90% after 8 and 10 weeks respectively. Whilst both animal and human studies found the repair process started during active treatment, Winter *et al.* (2009) suggested that in humans the process probably started earlier. They both found that the longer the rest period, the higher the percentage of repair and this has a significant clinical implication. This would suggest that active treatment should be ceased once resorption is noted radiographically and the longer the rest period, the greater the repair. In addition it might also suggest that discontinuous force application is less destructive than continuous force application. The effect of the different force regimes (continuous and discontinuous) on root resorption will be discussed later in the chapter.

1.7.9 *Categorization of root resorption*

Root resorption is an undesirable but frequently occurring side effect of orthodontic treatment (Janson *et al.*, 2000). Several ordinal scales have been devised to categorize root resorption according to the amount of resorption. Goldson & Henrikson (1975) and Philips (1955) indices were one of the first to be developed. Malmgren *et al.* (1982) (Figure 1-20) and Sharpe *et al.* (1987) (Table 1-9) modified the previous scales to simplify them and they are currently the most commonly used.

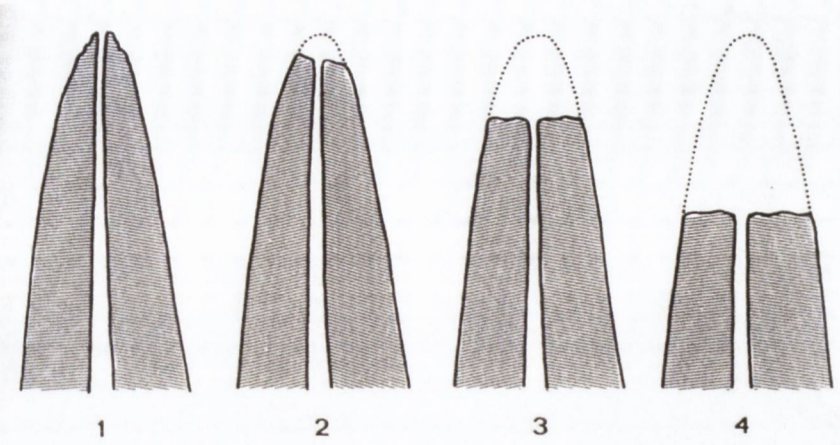

Figure 1-20. Malmgren *et al.* (1982) root resorption index for quantitative assessment of root resorption: 1) irregular root contour, 2) root resorption apically (<2 mm), 3) root resorption apically (< third of the root length) and 4) root resorption apically (> third of the root length).

Table 1-9. Sharpe *et al.* (1987) root resorption index for root resorption assessment

Grade	Amount of root resorption
0	No apical root resorption
1	Slight blunting of the root apex
2	Moderate blunting of the root apex up to one fourth of the root length
3	Excessive blunting of the root apex beyond one fourth of the root length

1.7.10 *Assessment of root resorption*

Root resorption due to orthodontic treatment has been assessed by different methods since it was first described by Ketcham (1927; 1929) as a side effect of orthodontic treatment. Histological studies reported high incidences while clinical studies have revealed a more varied incidence (Brezniak & Wasserstein, 2002a). Methods which have been described in the literature to detect root resorption include radiographs, light microscope, scanning electron microscope and cone beam tomography. However it is important to note there is currently no gold standard for the detection of orthodontically induced root resorption (Dudic *et al.*, 2009).

Several studies used radiographs to assess root resorption. While they are clinically useful for detecting root resorption during treatment, the quantitative value of radiographs remains questionable (Chan & Darendeliler, 2004). The first limitation of radiographs is that they provide a 2 dimensional image so surface resorptions can only be detected if they are mesiodistally positioned. Radiographs can only detect root resorption when it has progressed to a severe or advanced stage (Chan & Darendeliler, 2004). Three different types of radiographs have been commonly used in these studies; orthopantomogram, periapical radiographs and lateral cephalograms.

The orthopantomogram (OPG) is a sectional radiograph and only structures that are within the section (focal trough) are captured. The quality of the image depends on accurate positioning of the patient and the closeness of the desired structures to the focal trough (Sameshima & Asgarifar, 2001). A study by Rumberg *et al.* (1996) found that approximately 30% of panoramic films had projectional and processing errors when compared to biopsy specimens. Furthermore, relative positioning may lead to foreshortening or magnification. This magnification varies but it ranges from 20-35%. Sameshima & Asgarifar (2001) found OPGs overestimated root resorption by 20% when compared to periapical radiographs. Chan & Darendeliler (2004) suggested that this is due to the narrow focal trough, particularly in the anterior portion of the maxilla where there are malaligned teeth. Taylor & Jones (1995) found 40% of panoramic films lacked the clarity to visualize the premaxilla and they required supplemental radiographs. The mandibular incisors are also problematic, they were found to be foreshortened as the teeth were proclined during treatment. Therefore the apices appeared shorter post-treatment. The lack of reproducibility was suggested by Dudic *et al.* (2009) as a limiting factor. Sameshima & Asgarifar (2001) questioned external validity beyond the machine used in their study, as variability among OPG machines has been reported (Lund & Manson-Hing, 1975).

However, this study has also shown that positioning was a greater cause of error than inter-machine variance.

Periapical radiography has been frequently used by the majority of the studies to assess root resorption. Its magnification factor is 5%, which is less than that of an OPG. Sameshima & Asgarifar (2001) found periapical radiographs superior to panoramic images for fine details. Gher & Richardson (1995) used implant length to assess the accuracy of OPG and periapical radiographs and found them to be within 0.4 -1.7 mm and 0.3 mm respectively. This made periapical radiographs more attractive but they too had some limitations. Chan & Darendeliler (2004) suggested that for accurate quantitative measurements to be recorded the film and tooth should be in contact or as close as possible, the long axis of the tooth and the film should be parallel, the beam should meet the tooth at a right angle both vertically and horizontally and the positioning should be reproducible. There are two methods by which periapical radiographs can be used to assess root shortening: bisecting angle and parallel technique. Both techniques have been found to be geometrically inaccurate (Remington *et al.*, 1989; Leach *et al.*, 2001). For the bisected angle technique it is difficult to standardize the position. Foreshortening and elongation are common, which makes quantitative measurements and comparisons more difficult. In addition, it may not always be feasible to obtain an absolute straight view, as was noted as early as 1955 by Phillips in his study. He found the maxillary and mandibular incisors may be obscured beyond evaluation by other structures or by the bone density surrounding them. Periapical radiographs have been shown to underestimate root resorption (Dudic *et al.*, 2008). Laux *et al.* (2000) found resorption was detected in 19% of radiographs compared with 81% of teeth by histological examination. Digital radiography has been used in an attempt to increase accuracy. Dudic *et al.* (2008) found that less than half of the cases diagnosed with root resorption with CT were identified by digital periapical radiographs and concluded that periapical radiographs had limited accuracy in detecting resorption.

Borg *et al.* (1998) found digital radiography has similar sensitivity to film based radiography in detecting resorption, but with lower radiation doses. Digital radiography is as technique sensitive as conventional radiography with regard to geometric distortion. It therefore possesses similar limitations to conventional radiographs.

Lateral cephalograms may also be used as an adjunct to assess the length of upper incisors. However, there is 5-12% magnification and the left and right overlaps make the images unclear. The literature seems to show that radiographs were good for diagnostic purposes but poor with regard to the quantitative measurement of root resorption (Sameshima & Asgarifar, 2001; Chan & Darendeliler, 2004; Dudic *et al.*, 2008). Phillips (1955) found it difficult to differentiate slight and moderate root resorption, which subsequent studies utilizing ordinal scale found to be the case (Malmgren *et al.*, 1982; Sharpe *et al.*, 1987; Blake *et al.*, 1995). He also found that dense bone and surrounding structures obscured the roots beyond accurate evaluation. Maltha *et al.* (2004) suggested that severe resorption can be detected by radiographs but not mild resorption. In conclusion, radiographs are not ideal for the quantitative assessment of root resorption and the results of studies utilizing radiographs should be interpreted with caution. However, radiographs may be clinically useful to detect root resorption during treatment.

Cone-beam computerized tomography (CBCT) is a relatively new radiographic method which has been utilized in different aspects in orthodontics. The main advantage of CBCT is that it provides a 3 dimensional (3D) image of dental structures and provides clear images of highly contrasted structures, such as bone (Sukovic, 2003). In addition, CBCT has minimized the radiation dose, image artefacts, scan time and increased image accuracy compared to conventional computed tomography. In orthodontics, CBCT has been used to assess impacted teeth, cleft patients, temporomandibular joint, bone prior to tooth movement and resorption associated with impacted teeth. The assessment of apical root resorption due to orthodontic tooth movement has not been sufficiently studied (Dudic *et*

al., 2009). Dudic *et al.* (2009) compared OPGs with CBCT in evaluating orthodontically induced root resorption in 145 teeth. Using a Malmgren *et al.* (1982) scale they found a statistically significant difference between both methods. OPGs underestimated apical root resorption and they recommend that CBCT could be used as a complementary diagnostic tool in moderate resorption cases where modification in treatment may be required due to resorption. da Silveira *et al.* (2007) evaluated the diagnostic ability of CBCT in detecting simulated external root resorption and found it to be highly sensitive with excellent specificity. Nonetheless, CBCT use for the quantitative measurement of root resorption has yet to be evaluated.

Histological investigations for root resorption have been shown to be more sensitive for detecting root resorption than radiographic examinations (Kurol *et al.,* 1996; Maltha *et al.*, 2004). Kurol *et al.* (1996) suggested that radiographs are not an adequate tool to accurately detect resorption, especially in early stages. A higher incidence of root resorption has been reported with histological investigation (90%) compared with radiographic investigations (73%). Most of the histological studies are qualitative though several histological methods have been developed to quantify orthodontically induced inflammatory root resorption (OIIRR). Kurol *et al.* (1996) developed a histological method to quantify resorption craters to assess the effect of force magnitudes and types of force on root resorption, as well as the repair pattern, in a series of 8 publications between 1995 and 2000. They used a routine histological preparation before embedding in paraffin and serial sectioning. With the microtome set at 4 μm, the teeth were serially sectioned parallel to the long axis of the tooth in the buccal-palatal direction. For the histological examination 3 Haematoxylin and eosin (H&E) stained sections were selected from 3 levels in the buccal-palatal direction 0.3 mm apart, thus one section was chosen randomly from each level. The first level was chosen when the full root length was reached. A light microscope with a micrometer fitted on the eyepiece was used to measure the resorption craters. Using arbitrary units set into

the eye piece the resorption was measured to the nearest arbitrary unit (13.3 μm). As no uniform definition was found in the literature, they defined resorption in their study as resorption in the cementum or extending to dentine. Resorptions with 5 or more arbitrary units were registered. Smaller resorptions close together were registered as one. Five different definitions were then used according to the number of arbitrary units; small surface extension of root resorption (<10), medium surface extension of root resorption (10-100), large surface extension of root resorption (>100), small depth of root resorption (≤20) and large depth of root resorption (<20). The resorbed root contour (%) and resorbed root area (%) for each tooth was determined using the mean surface extensions of root resorption and mean depth of root resorptions in relation to the mean root contour and root area respectively. The resorbed root contour (%) was calculated by dividing the mean sum of surface extensions by the mean root contour. The resorbed root area (%) was calculated by dividing the sum of resorbed root area (extensions x depth) of root resorptions by the mean root area.

Lu *et al.* (1999) developed another method to quantify root resorption in rats. This method involved embedding and serial sectioning as well, but with the use of a grid rather than arbitrary units. Eight 4.5 μm H&E stained sections, parallel to the long axis of the tooth, were magnified (x120) and photographed. A transparent sheet with 10 x 10 mm grids was superimposed over the photographs. Root resorption was evaluated by counting the number of grids (squares) with or without resorption lacunae. Resorption scores were determined by dividing the number of squares with resorption lacunae by the total number of squares along the root surface. This method was also used by Al-Qawasmi *et al.* (2006) and Abass *et al.* (2008) to quantify root resorption associated with different orthodontic forces in inbred mice and found the method to be reliable and reproducible.

Maltha *et al.* (2004) used embedding and sectioning to quantify root resorption in beagle dogs. Serial mesial-distal sections of 7 μm were cut containing tooth and

surrounding alveolar bone and every 25th section was H&E stained. Of each tooth 5 undamaged sections showing the largest root surface were selected for evaluation. Root resorption was quantified by estimating the original contour of the root and the root length. The largest length and depth were then measured. The relative resorption length (%) was calculated by dividing the largest resorption length by the estimated root length and multiplied by one hundred. The surface resorption area was calculated using the largest depth and length. The authors were only able to easily identify resorption when it extended to dentine. This could have been as a result of the authors using lower magnification to enable them to assess the whole root. Furthermore, the authors found it difficult to estimate the original outline of the dentine-cementum border for larger resorption areas. Although they found their results quite reproducible, they suggested that their study can only give an indication of the extent of resorptions and hence, underestimated the real extent of the resorption. Chan & Darendeliler (2004) suggested that although the histological methods described above are more sensitive than radiographic evaluation, it is important to understand the limitations of such methods. Resorption craters could be partially or totally missed due to the irregular shape and size variation of resorption craters. Achieving absolute longitudinal cut along the long axis would have been more difficult due to the variation in root anatomy and morphology. This could lead to apical or even some mid-root craters being missed. On the other hand these methods have been shown to be simple and reproducible.

Scanning electron microscope (SEM) provides an enhanced visual of root surfaces due to its higher resolution and detail than histological models reconstructed by serial sections (Reitan, 1974; Chan & Darendeliler, 2004). Although resorption craters were measured using SEM by earlier studies, the diversity and curvature of the root shape made it difficult to obtain an absolute straight view and hence induced error in measurements. Furthermore, the technique for physically piecing the images together was not simple and resorption

craters may have been missed if they were located at the edge of the images. Chan & Darendeliler (2004) suggested that images obtained by the earlier studies only provided a straight 2D view of root surfaces and had limited quantitative value. Chan & Darendeliler (2004) developed a new digital 3D method to overcome these earlier limitations. Using SEM as a capturing device and specially written software (AnalySIS Pro 3.1 (Soft Image System, SIS, Münster, Germany) they were able to conduct volumetric measurements of the resorption craters. They calibrated the obtained volumetric measurements of the resorption craters with known volumes of metallic rod and found good accuracy and reproducibility. Interestingly, the same authors found that the 3D volumetric measurements were also correlated to 2D surface area measurements obtained from the same sample. The authors then concluded that 2D measurements of root resorption craters could be as reliable as 3D measurements if they were conducted adequately. A series of 10 publications on root resorption were published by the authors over the next years using this method to assess the effect of force, type of tooth movement, type of appliance and mineral content of cementum on root resorption (see below).

1.7.11 *Risk factors for root resorption*

The incidence of orthodontically induced inflammatory root resorption (OIIRR) varies with the different methods of assessment. Histological studies (Stenvik & Mjor, 1970; Harry & Sims, 1982) have found OIIRR to be as high as 90%. However in most of these cases the loss was minimal and clinically insignificant. Radiographic techniques found the incidence was lower, (Lupi *et al.*, 1996) rising from 15% before treatment to 73% after treatment. With most root resorption lesions being less than 2.5 mm (Linge & Linge, 1983; Linge & Linge, 1991; Lupi *et al.*, 1996; Killiany, 1999; Janson *et al.*, 2000; McNab *et al.*, 2000) and severe resorption lesions, identified as more than 4 mm or one third of the original tooth, affecting 1-5% of orthodontic patients only. Even though root resorption

tends to cease once active treatment is stopped, the long term prognosis of teeth with short roots may be compromised in patients susceptible to periodontal disease. Furthermore, these teeth may not be suitable as abutments for restorative treatment. Consequently, identifying risk factors that can result in severe root resorption is of crucial clinical significance. These risk factors can be divided into patient related factors and treatment related factors.

1.7.11.1 Patient related risk factors

Several Patient related risk factors have been associated with an increased risk of root resorption. These risk factors include race, gender, age, genetic influences, bone density, severity and type of malocclusion, root morphology, root length and roots with developmental abnormalities, systemic factors, drugs, hormone deficiency, hypothyroidism, hypopituitarism, chronic alcoholism, allergy and previous trauma. They have all been investigated for the role they play in the susceptibility of individuals to root resorption.

Sameshima & Sinclair (2001a) found Caucasians and Hispanic patients were at a higher risk of root resorption than Asians. Recently, Tomoyasu *et al.* (2009) found that the Japanese population lacked the gene responsible for root resorption in the Caucasian population. This might explain the ethnic difference, though, further genetic studies are required. Both gender (Kjaer, 1995; Baumrind *et al.*, 1996; Sameshima & Sinclair, 2001a) and age (Harris & Baker, 1990; Mirabella & Artun, 1995b; Owman-Moll *et al.*, 1995b; Taithongchai *et al.*, 1996; Sameshima & Sinclair, 2001a) have been investigated, but most studies found no consistent relationship between them and root resorption (Brezniak & Wasserstein, 2002b).

Bone density has been implicated for its influence on root resorption. Reitan (1974) suggested that bone thickness affects root resorption by controlling the amount of tooth movement and the number of cells arriving at the area. Kaley & Phillips (1991) used

panoramic radiographs to assess the effect of bone density on root resorption. The authors considered contact with cortical bone to be a risk factor (x20) for higher incidence of root resorption. Yet, both the proximity of the roots to the cortical bone and the width of the bone have been investigated with no conclusive evidence (Wainwright, 1973; McFadden *et al.*, 1989; Taithongchai *et al.*, 1996).

Another aspect which has been highly debated and investigated is the variety of morphological characteristics of the root and its relationship to the severity of root resorption. Sameshima & Sinclair (2001a) suggested that although no proof exists as to why the abnormal root shape would resorb more easily, the process which is responsible for the abnormal root could also be contributing to the increased risk. Individual features such as root width, length, blunt-shaped, pipette-shaped roots and the initial root resorption have been assessed. The root width has been found to be inversely related to root resorption (Mirabella & Artun, 1995b; Taithongchai *et al.*, 1996; Sameshima & Sinclair, 2001a; Artun *et al.*, 2009). Hence, narrow triangular roots (pipette shaped) are at a higher risk of root resorption (Marques *et al.*, 2010).

The length of the root is a feature that has been widely investigated (Levander & Malmgren, 1988; Mirabella & Artun, 1995b; Sameshima & Sinclair, 2001a; Artun *et al.*, 2009). Initially there was a suggestion that shorter roots were at higher risk of resorption, especially blunt ended roots. In fact, studies have found that the longer the root length, the higher the risk of root resorption (Goldson & Henrikson, 1975; McFadden *et al.*, 1989). Current research (Levander & Malmgren, 1988; Mirabella & Artun, 1995b; Sameshima & Sinclair, 2001a; Chan & Darendeliler, 2005; Artun *et al.*, 2009) suggests that shorter roots have a lower risk of root resorption, which is contrary to the common perception. However, the effect of resorption on short rooted teeth would have more serious effects on the prognosis of the tooth than that of long rooted teeth. A finite element study by Shaw *et al.*

(2004) found that the longer the root, the more stress it incurred at the apex which may explain the higher resorption associated with longer roots.

Overall the most determining factor seems to be the amount of root resorption prior to orthodontic treatment or the amount of root resorption that occurred during the initial 6 months of treatment. Studies (Levander & Malmgren, 1988; Artun *et al.*, 2009) have found that patients' previous history of root resorption and the amount of resorption during the initial stages of treatment to be highly correlated with the amount of total root resorption during the course of orthodontic treatment. Therefore, it is essential to assess the amount of resorption present prior to initiating orthodontic treatment and during the first six months of treatment to predict the risk level for resorption. Levander & Malmgren (1988) divided the risk levels for root resorption according to different patient features; into mild, slight, moderate and severe. They found that a previous history of root resorption is a severe risk. Furthermore, abnormalities in the root such as invaginations and taurodontism have been found to have a strong connection with root resorption during orthodontic treatment (Kjaer, 1995). Finally, a history of tooth trauma and endodontic root treatment have both been assessed for their influence on the incidence of root resorption (Malmgren *et al.*, 1982; Linge & Linge, 1983; Brin *et al.*, 1991). Some studies have found traumatized incisors are associated with a higher risk (Linge & Linge, 1983; Brin *et al.*, 1991) whilst other found them to be without additional risk provided no signs of root resorption are already evident and treatment was started 4-5 months post trauma (Malmgren *et al.*, 1982). This inconsistency appears to rise from earlier studies that used animal models and were mainly observational. Clinical trials found the risk is similar with and without trauma, but there is a lack of controlled studies of traumatized teeth with previous root resorption. At present more studies are needed to resolve this issue. Endodontic treatment seems to be a protective factor rather than a risk (Mirabella & Artun, 1995b).

1.7.11.2 Treatment related factors

Treatment related factors play an important role in the occurrence of root resorption during orthodontic treatment. Such factors are particularly relevant because they may be controlled clinically. Once risk factors have been identified, clinicians can alter or modify their treatment to reduce the risk of root resorption. Treatment factors have been investigated individually to assess and limit the risk they impose on the roots during treatment. These variables influence the amount of root resorption by the type of tooth movement, amount of tooth movement, type as well as amount of force applied, duration of treatment, extraction and the type of appliance used.

Although root resorption during orthodontic treatment is a common occurrence, little light has been shed on the specific risks associated with the type of tooth movement, or the relationship with compression and tension sites. The type of movement was investigated to see if any particular movement predisposed the roots to more resorption. With different movements the forces are distributed differently along the root surface with particular areas exposed to pressure whilst others to tension. A finite element model study by Shaw *et al.* (2004) was used to determine the location and magnitude of stress generated when orthodontic forces were applied to the tooth. They found forces were concentrated at the apex when intrusion forces were applied and at the alveolar crest when tipping forces were applied. Rotational forces produced the least stress concentrations as the forces were distributed along the root. Reitan (1974) found resorption craters in areas of pressure and tension which was expected, since Baumrind (1969) found the metabolic changes in the compression side similar to those in the tension side. This was later confirmed by Williams (1984) who found resorption in areas of tension in rats. Subsequently, Chan & Darendeliler, (2006) attempted to quantify resorption in both compression and tension areas when tipping forces were applied. They found areas under compression had more resorption than areas

under tension, with similar amounts of resorption per unit area in the cervical and apical regions. They could not explain why there was more resorption in the compression areas.

The type and direction of movement has been suggested as one of the factors which could play a role in root resorption. Therefore, each type of movement was assessed exclusively to distinguish the extent of damage they impose. Tipping movement is the most common type of movement in orthodontics. It involves moving the tooth with the centre of rotation apical to the apex of the tooth. As a result, there will be an area of compression on the cervical end on one side and in the apical end on the opposite side (Figure 1-21).

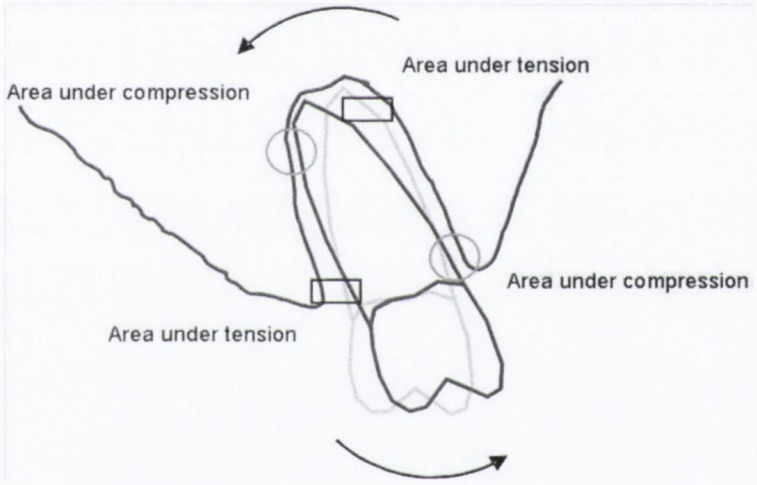

Figure 1-21. Areas of compression and tension during tipping movement (Chan & Darendeliler, 2006).

Most of the studies which looked at the effect of force application on root resorption inadvertently involved tipping movement (King & Fischlschweiger, 1982; Barbagallo *et al.*, 2008; Gonzales *et al.*, 2008). As heavier forces were applied, greater root resorption occurred in these studies. Barbagallo *et al.* (2008), in a split-mouth study, compared tipping tooth movement with a contralateral tooth which was not moved. They found more resorption occurred on the tipping side. Chan & Darendeliler (2006) found significantly more resorption occurred on the buccal-cervical and lingual-apical than other areas when tipping forces were applied. This suggested that the area of compression is more

susceptible to resorption than tension areas. Even though resorption was also observed in the tension areas, when both areas were compared by Chan & Darendeliler (2006) and King *et al.* (2011), they found resorption in tension areas was significantly less. Therefore, increasing the amount of tip (King *et al.*, 2011) and force (Chan & Darendeliler, 2005) increased the amount of resorption.

Bodily movement is another type of movement which has been investigated and compared to tipping movement. In bodily movement, forces are distributed along a larger surface area, in contrast to tipping where forces are concentrated at the apex and cervical region. There are few studies that compare the effect of both on root resorption. Removable appliances produce tipping movement only, whereas fixed appliances can produce bodily movement. Therefore removable and fixed appliances were used to compare tipping and bodily movement, respectively. Linge & Linge (1983) used radiographs to compare the effect of removable appliances with springs and fixed appliances and found the fixed appliance group had more resorption. A subsequent study (Linge & Linge, 1991) found that removable appliances with elastics had low correlation with root resorption. A more recent study by Barbagallo *et al.* (2008) compared removable thermoplastic appliances, fixed appliances with a light force (25 g), fixed appliances with a heavy force (225 g) with a control (teeth without any force application). They found that light force fixed appliances and removable appliances had 5 times and 6 times respectively more resorption than the control. Heavy force had 9 times more root resorption than the control. They concluded that removable appliances have a similar effect to light force fixed appliances.

Torque is a type of movement which is referred to as a third order movement in orthodontics and is used at the later part of the course of treatment. During this type of movement the centre of rotation is at the middle of the root resulting in buccolingual rotation of the tooth. It is essential for aesthetics, stability and occlusal relationships. Several studies have found torque to be a risk factor for root resorption. Kaley & Phillips

(1991) found severe resorption is 4.5 times more likely with subjects exposed to torque and 20 times more if torqued against the lingual cortical plate. They suggested that contacting the cortical bone is a risk factor and that the combination of both increased the risk. Casa *et al.* (2001) found resorption in the apical and bucco-cervical regions with the severity of root resorption positively correlated to force levels and the duration of treatment. A Recent study by Bartley *et al.* (2011) quantified the distribution and the effect of increasing the torque levels. Although the overall amount of root resorption was similar in both 2.5° and 15°, the resorption in the apical region was significantly higher in the higher torque group. The authors explained this increased resorption in the apical region, by the higher susceptibility of the apical region, because of its softer and less mineralized cementum, and the higher pressure at the apical region during torque movement. At the other areas where the force was less concentrated, the authors suggested that the data were insufficient to demonstrate any difference. It seems that torque does increase the risk of root resorption but a larger sample size is needed to accurately assess the overall effect. Furthermore, the effect of torque on root resorption, where the different torque levels have equal force, will need to be determined. The force levels in the Bartley *et al.* (2011) study were different (47.5 g and 285 g) for each torque group, therefore the resorption could have been as a result of the different force levels rather than the different torque levels. Moreover, the torque level of 2.5° is minimal considering the 4.5° slop present in the brackets.

Intrusive movement in orthodontics has been suggested to be the most damaging to the roots as the forces applied would be concentrated on a small surface area. A finite element study (Shaw *et al.*, 2004) has shown that intrusive movement creates greater relative stress at the root apex than the other types of movement. Force magnitude has been shown to be positively correlated to resorption and, it is therefore predicated that intrusive movement has the highest susceptibility to root resorption. Harry & Sims (1982) found that intrusion

resulted in resorption at the apex of the root which was directly related to the concentration of stress. Assessing intrusive and extrusive forces, Han *et al.* (2005) found that extrusive forces did not increase the amount of root resorption, whereas intrusive forces significantly increased the amount of root resorption. However, a recent study by Jimenez Montenegro *et al.* (2012) found that heavy extrusive forces produce more resorption on the distal aspect of the root only. They suggested that this could be due to root morphology and initial angulation. Harris *et al.* (2006) also found that the amount of resorption produced with intrusion forces was directly related to the amount of force applied. Sameshima & Sinclair (2001b) found no significant difference in the amount of resorption recorded when intrusive or extrusive forces were applied. The latter study used radiographs (OPG), whereas the earlier studies used histological and 3D assessment (CT scan) which could account for the different results achieved. The earlier studies (Kaley & Phillips, 1991; Beck & Harris, 1994; Parker & Harris, 1998) agree with the recent literature which indicates that the greatest damage occurs with intrusive tooth movement since, it concentrates the pressure at the apex.

Rotational movement is the least investigated with regard to root resorption. Most of the studies were focused on the histological rearrangement of the fibril component of the periodontal ligaments and its influence on stability (Edwards, 1968). Rotational movement has been recognized as the most unstable tooth movement, however, its influence on root resorption has, until recently, been obscure. It has been postulated that rotational movement produces the least force concentration and its potential risk for root resorption is low (Shaw *et al.*, 2004). Jimenez-Pellegrin & Arana-Chavez (2004) and recently Wu *et al.* (2011) found resorption was localized mainly within the middle third of the root surface. Wu *et al.* (2011) found the resorption craters specifically at the compression site on the buccal-distal and lingual-mesial surfaces. The resorption craters increased when the magnitude of the

applied force was increased. In conclusion, heavy rotational forces did cause more resorption, specifically at the pressure areas along the root surface.

The different types of tooth movement have been assessed individually for their effects on root resorption with the conclusion that increasing the force and the amount of movement resulted in a greater amount of resorption. Unfortunately few studies compared and quantified the amount of resorption with different types of tooth movements (Table 1-10).

Table 1-10. The list of studies assessing the relationship between the different types of tooth movement and orthodontically induced inflammatory root resorption

Name	Assessment methods	Type of tooth movement	Conclusion
Phillips (1955)	**Radiographs**	**Bodily Tipping Torque**	**No relationship**
DeShields (1969)	**Radiographs**	**Tipping Bodily Intrusion**	**Bodily**
Mirabella & Artun (1995b)	**Radiographs**	**Bodily Intrusion Extrusion**	**Bodily**
Kaley & Philips (1991)	**Radiographs**	**Bodily Tipping Torque intrusion**	**Torque**
Baumrind *et al.* (1996)	**Radiographs**	**Bodily Intrusion extrusion**	**Bodily**
Parker & Harris (1998)	**Radiographs**	**Bodily Torque Tipping Intrusion**	**Torque Intrusion**
Sameshima & Sinclair (2001b)	**Radiographs**	**Bodily Extrusion Intrusion**	**Bodily**

Phillips (1955) compared the amount of root resorption associated with tipping, bodily movement and torque using radiographs in sixty nine patients treated in two different centres. He concluded that there was no association between the amount of root resorption and type of movement. DeShields (1969) on the other hand, using radiographs of fifty two treated patients, found bodily movement to be more destructive than both intrusion and

tipping movement. DeShields (1969) suggested that their different conclusion to Phillips (1955) is due to the absence of a control sample in Philips' study. Mirabella & Artun (1995b) tried to quantify root resorption with different types of movement using non-growing patients. They found anterior posterior movement was significantly associated with root resorption, whereas intrusion and extrusion movements were not. Kaley & Phillips (1991) used a case-control design to assess the different types of movements and found torque to be the most destructive. Mirabella & Artun (1995b) suggested that their findings should be interpreted with caution since the vertical movement was limited to one millimetre only. Baumrind *et al.* (1996) used periapicals to assess resorption in 81 adult patients who were treated by three different orthodontic specialists. Using lateral cephalograms, they assessed four different types of tooth displacement and found bodily retraction had a significant influence on the amount of root resorption whereas intrusion, extrusion and advancement did not. The lack of significant associations between intrusion and resorption goes against the conventional assumption of clinical orthodontics. These conventional assumptions appear to be groundless according to the findings of earlier studies. It was noted by Baumrind *et al.* (1996) that the mean amount of retraction was much more than the mean amount of intrusion, 0.83 mm and 0.19 mm respectively. This might explain the lack of evidence for the higher prevalence of root resorption in intruded teeth, compared to the other types of tooth movement, since the movement was much less in the intrusion group. A recent study by Parker & Harris (1998) used a larger sample size of 110 patients but with different appliance types to quantify root resorption associated with torque, bodily movement, tipping and intrusion. They found torque and intrusion were the strongest predictors of root resorption. Sameshima & Sinclair (2001b) assessed the records of 868 patients and found horizontal movements were the only type of movement associated with root resorption. Based on the current literature that compared root resorption within different types of movement it appears that torque and bodily movement

were the most destructive but, as Mirabella & Artun (1995b) suggested, caution should be taken during the interpretation of these results. As Mirabella & Artun (1995b) clearly identified, most of the intrusion movements were minimal and since they were all retrospective studies they had no control over the amount of movement. There was however a greater amount of tooth movement in the bodily and torque since this type of movement is more frequently utilized during orthodontic treatment. Taking into account studies by DeShields (1969), Kaley & Phillips (1991) and Bartley *et al.* (2011) which found more resorption with more movement, it is not surprising that bodily and torque movements were found to have a higher correlation with resorption. A prospective study with an equal amount of movement within the different movement types would be more informative and give a more quantitative comparison.

Force has been considered by many researchers to be the main causative factor of root resorption during orthodontic treatment. Root resorption occurs when the local areas along the root surface are damaged as a result of force application. Early studies have suggested that increased force resulted in larger areas of hyalinization and more root resorption (Brudvik & Rygh, 1993a). As a result, they recommended application of light force which they assumed would be closer to the physiological forces (Reitan, 1974; Chan & Darendeliler, 2005). Several studies have tried to prove this by comparing heavy and light forces. While the majority of studies found higher forces produced more resorption (King & Fischlschweiger, 1982; Chan & Darendeliler, 2005; 2006; Harris *et al.*, 2006; Barbagallo *et al.*, 2008; Gonzales *et al.*, 2008; Bartley *et al.*, 2011; King *et al.*, 2011; Wu *et al.*, 2011; Jimenez Montenegro *et al.*, 2012), several studies found that increasing the forces did not influence the amount of root resorption (Owman-Moll *et al.*, 1996a; 1996b; Maltha *et al.*, 2004; Winter *et al.*, 2009). The lack of consensus about root resorption and force magnitude in the literature has been put down to several factors. Winter *et al.* (2009)

attributed the different findings between studies to the individual variations in humans. Owman-Moll *et al.* (1996a; 1996b) agreed with Winter *et al.* (2009) and attributed their unexpected results to individual variations and, despite finding no increase in root resorption with higher forces, cautioned clinicians against using high forces. Chan & Darendeliler (2005) also suggested that the studies done by Owman-Moll *et al.* (1996a; 1996b) utilized springs in the continuous groups which were not strictly continuous because force decay was clearly evident. Furthermore, Weltman *et al.* (2010) suggested that the studies which did not find any difference in the amount of root resorption did not have strict criteria for their tooth selection. In addition, they did not take into consideration external predisposing factors which may have influenced the amount of root resorption. Another factor explaining the lack of consensus about root resorption and force magnitude, according to Harris *et al.* (2006), could be the different methodological designs used within various studies. For example, the studies by Owman–Moll *et al.* (1996a; 1996b) and Maltha *et al.* (2004) were histological studies and did not quantify resorption in three dimensions, whereas the others studies used a three-dimensional assessment (Chan & Darendeliler, 2005; 2006; Harris *et al.*, 2006; Barbagallo *et al.*, 2008; Gonzales *et al.*, 2008; Bartley *et al.*, 2011; King *et al.*, 2011; Wu *et al.*, 2011; Jimenez Montenegro *et al.*, 2012).

The type of force applied was also assessed with regard to its influence on root resorption. There are two types of force which can be applied during orthodontic treatment: Continuous and intermittent. It has been suggested that applying continuous force might hinder the repair process of the resorbed cementum whilst intermittent forces allow some repair during the intervals between force applications. Levander *et al.* (1994) found significantly less resorption in patients when a pause period was applied during active treatment. This suggested that intermittent forces may also have a similar effect. Several studies (Acar *et al.*, 1999; Weiland, 2003; Maltha *et al.*, 2004; Ballard *et al.*, 2009) detected

less resorption with the application of intermittent forces as opposed to continuous. In contrast, Owman-Moll and colleagues' 1995a split-mouth study, found no difference between both continuous and intermittent force application. Weltman *et al.* (2010) suggested that this should be interpreted carefully since force decay was evident in the springs used in the continuous force group.

Another component of treatment which has been assessed to determine its effect on the amount of root resorption is the overall duration of treatment. Most studies found that length of treatment was directly related to the amount of root resorption, while fewer studies found it to be irrelevant (Mirabella & Artun, 1995b; Baumrind *et al.*, 1996). Kurol *et al.* (1996) applied 50 cN to 56 premolars and found that increasing the duration of treatment increased the amount of root resorption by 20 times. Mohandesan *et al.* (2007) used radiographs to assess root lengths during treatment and found the amount of root length reduction was twice as much 12 months compared to 6 months post active treatment. Maltha *et al.* (2004) using an animal model, found the amount of root resorption affecting the root surface increased with time. Sameshima and Sinclair (2001b) examined the records of 868 patients treated in 6 different private practices and found that the duration of treatment was significantly associated with root resorption. Paetyangkul *et al.* (2011) used 3D assessment of 54 maxillary premolars following force application over a period of 4, 8 and 12 weeks. They found root resorption was related to both the amount of force and duration of treatment. Light force (25 g) did not have a significant impact on the amount of root resorption after 8 weeks, whereas the heavy force (225 g) did increase the amount of root resorption after 8 weeks. On the other hand both light and heavy forces increased the amount of resorption from 8 to 12 weeks though the difference between both forces was not statistically significant. This highlighted the fact that there might be a threshold time, as Harris & Baker (1990) suggested, where the dynamic process is overwhelmed. According

to Paetyangkul *et al.* (2011), it could also be due to increased osteoclastic activity after 8 weeks of force application. Furthermore, increased root resorption may be related to treatment factors employed with longer treatment durations. For example, longer treatments are more likely to be in cases with impacted canines, deep overbite, increased overjet and severe crowding. The treatment in such cases, may require additional intrusion mechanics, torque and tooth movement. At the moment, it seems that the length of treatment has a role to play, but more studies will be needed to establish if there is a threshold time for root resorption or if it is due to treatment factors employed.

Tooth extraction during treatment has also been assessed with regard to its influence on root resorption. Earlier studies by Kaley & Phillips (1991) and Baumrind *et al.* (1996) found no relationship between root resorption and patients treated with or without extraction. Later, studies by McNab *et al.* (2000), Sameshima & Sinclair (2001b) and Marques *et al.* (2010) found that patients who had extractions during their orthodontic treatment had a higher incidence of root resorption. McNab *et al.* (2000) suggested that extracting teeth during treatment exposed patients to a higher risk of root resorption by the increased tooth movement. Sameshima & Sinclair (2004) suggested that extracting teeth in cases of severe crowding may not have an impact on the amount of root resorption. This is because in severe crowding cases there was there was not much tooth movement expected. This may explain why earlier studies have not found a significant difference between extraction and non-extraction cases. Other factors, such as class II elastics, have also been evaluated with no real significance as most of these studies were retrospective and not well controlled.

Different appliances in orthodontics have been investigated to assess their influence on root resorption (Table 1-11). It is believed that the type of appliance used may influence the amount of root resorption via the force magnitude and type of tooth movement produced.

Table 1-11. The list of studies comparing the effect of different types of orthodontic appliances on orthodontically induced inflammatory root resorption

Appliance	Name	Type of study	Effect
Removable Vs. fixed appliance	Linge & Linge (1983)	Retrospective	Removable less resorption
	Barbagallo *et al.* (2008)	Prospective randomised controlled	Removable appliance and fixed appliance with light forces (25 g) had similar root resorption Removable had less resorption than fixed appliance with heavy forces (225 g)
Begg appliance Vs. Edgewise appliance	Goldson & Henrikson (1975)	Retrospective	Begg appliance more resorption
	Malmgren *et al.* (1982)	Retrospective	No effect
	Parker & Harris (1998)	Retrospective	No effect
	Beck & Harris (1994)	Retrospective	No effect
	McNab *et al.* (2000)	Retrospective	Begg appliance more resorption
Self ligating Vs. conventional brackets	Blake *et al.* (1995)	Case control	No effect
	Pandis *et al.* (2008)	Prospective	No effect
	Scott *et al.* (2008)	Multi -centre randomized controlled	No effect
Continuous Vs. segmental arch wire	Alexander (1996)	Prospective randomized	No effect
Miniscrew Vs. control	Liou & Chang (2010)	Retrospective controlled	More resorption with miniscrew group

It has been suggested that removable appliances are less destructive to the root compared to fixed appliances due to their discontinuous force application. Linge & Linge in 1983 looked at the records of 719 patients and used periapical radiographs to assess the amount of root resorption that occurred following orthodontic treatment. Twenty five percent of the patients were treated using removable appliances and they had significantly less root resorption than the fixed appliance group. A recent randomised controlled study by Barbagallo *et al.* (2008) compared root resorption with removable thermoplastic and fixed appliances in 27 patients. They used x-ray microtomograph to measure root resorption and found heavy forces (225 g) with fixed appliances produced more root resorption than removable thermoplastic appliances, whereas light forces (25 g) with fixed appliances

produced a similar amount of root resorption to removable thermoplastic appliances. The influencing factor is therefore the amount of force applied rather than the type of appliance being utilized.

Different types of fixed appliances have been assessed to evaluate their association with root resorption. A retrospective study by Malmgren *et al.* (1982) investigated the amount of root resorption produced with edgewise and Begg appliances and found no difference. A retrospective study by Parker & Harris (1998) also found no difference when they assessed the records of 110 patients treated with Begg, Tweed and edgewise. This was in agreement with another retrospective study (Beck & Harris, 1994), which examined the records of 83 patients, and found no difference in the amount of root resorption between Tweed and Begg appliances. In addition, Alexander's (1996) prospective randomised study, investigated the amount of root resorption produced with segmental and continuous arch wire in 56 patients, and found no difference in the amount of root resorption. Previous studies used radiographs prior to and after the completion of treatment. On the other hand, Goldson & Henrikson (1975) and McNab *et al.* (2000) found Begg appliances had more root resorption. McNab *et al.* (2000) suggested that the increased incidence of root resorption with the Begg technique compared with the edgewise technique was due to the increased tip-back bends placed in the archwire. They assumed that the tip back bends may have introduced additional stress on the teeth and as a result the teeth exhibited more root resorption. McNab *et al.* (2000) suggested that the earlier studies did not take into account confounding factors such as age, overjet, overbite and extractions. However, excluding extractions (see below) the rest have been found to be insignificant (Sameshima & Sinclair, 2001b). Another interesting concept is the Bioefficient Therapy which takes into account the advancement of orthodontic materials to produce less force on the dentition. Janson *et al.* (2000) found Bioefficient Therapy produced less root resorption which agrees with the previous studies that found force magnitude was positively correlated with root resorption.

Blake *et al.* (1995) (case control study), Pandis *et al.* (2008) (prospective study) and Scott *et al.* (2008) (multi-centre randomized controlled study) found no difference in the amount of root resorption when they compared self-ligating brackets to standard brackets. It was believed that the magnitude and type of force produced by the self-ligating brackets would influence the amount of root resorption produced but that was not the case. Liou & Chang (2010) investigated the amount of apical root resorption of maxillary incisors in 30 patients treated previously by using miniscrews. The maxillary incisors were retruded and intruded during treatment. Liou & Chang (2010) used pre and post-treatment periapical radiographs to assess the amount of root resorption, and compared the findings of the miniscrew patients to 20 patients (control) treated without miniscrews. More resorption was found in the maxillary incisors treated with miniscrews. They attributed the higher amount of root resorption in the maxillary incisors to the greater amount of retraction of the incisors and longer treatment time in the miniscrew patients compared to the control. However, the two groups in the study were not matched, as the miniscrew group had more severe malocclusion and hence required a larger amount of tooth movement. The majority of previous studies (Table 1-11) assessing the effect of different appliances on root resorption overlooked some aspects which would influence their results. Most of the studies were retrospective with little control over the subjects' mechanics or active tooth movement during the course of treatment, thus the samples were not standardised. Even with the prospective studies, the mechanics used during the course of treatment may have also varied according to each case need. The subjects had different crowding, different root angulations and tooth positions. Importantly the amount of tooth movement and duration of active orthodontic space closure associated with each appliance were not recorded. The amount of tooth movement and treatment duration has been shown to affect root resorption. Therefore, a study recording both variables might provide more conclusive results.

Treatment factors may play a role in the amount of root resorption as the type of movement, amount of movement, magnitude of force and duration of treatment have been positively correlated with root resorption. In order to determine the significance of the type of appliance, extractions and elastics in relation to root resorption more studies with randomised controlled groups are required.

1.8 Summary

Following a comprehensive review of the literature it became apparent that the amount of anchorage reinforcement provided by both the Nance appliance and miniscrew and the effect they have on orthodontically induced root resorption has not been fully determined. There has only been one study reporting on the amount of anchorage the Nance appliance (Shpack *et al.,* 2008) provides. Unfortunately the value of the data provided by this study was perhaps compromised, as the study was not specifically designed to measure the amount of anchorage the Nance appliance provided. In addition, the study lacked a control sample with which to investigate the amount of anchorage loss without the Nance appliance. The method used by Shpack *et al.* (2008) to measure the anchorage loss was not sensitive, as it depended on unstable points transferred onto study casts (section 1.5.3). Furthermore, the sample used in the study was not matched for age, crowding, and malocclusion and the duration of active retraction was not controlled. As tooth movement occurs in stages (initial, lag, post lag and linear), anchorage loss may have varied at the different stages of tooth movement during treatment. Currently the anchorage potential of the Nance appliance is unknown and the stages at which anchorage loss occurs is yet to be determined. Thus, a controlled study with an especially formulated methodology to measure anchorage loss associated with the Nance appliance at the different stages of tooth movement was required.

Recent studies (Liou *et al.,* 2004; Wang & Liou, 2008; Garfinkle *et al.* 2008; El-Beialy *et al.* 2009) demonstrated that miniscrews do not provide absolute anchorage. Miniscrews were found to move 1-2 mm in response to orthodontic forces despite their osseointegration. Although these studies have highlighted miniscrew movement during orthodontic treatment, it is not clear if the movement occurred at a certain time after miniscrew placement or whether it is a continuous process. In the previous studies (Liou *et al.,* 2004; Wang & Liou, 2008; Garfinkle *et al.* 2008; El-Beialy *et al.* 2009), the amount of

miniscrew movement was measured at the end of treatment. Thus, it was speculated that miniscrew movement may have occurred at the early stages where miniscrews provided retention by mechanical interlocking prior to osseointegration. Moreover, osseointegration has been found to occur over time and thus the amount of miniscrew movement may vary during periods over the observation interval. Furthermore, tooth movement occurs over stages (initial, lag, post lag and linear) and therefore the amount of miniscrew movement might have also varied over time. In addition, the methods used to measure the amount of miniscrew movement (radiographs) had several drawbacks as was highlighted in section 1.5.3. A more sensitive measurement method which measures anchorage loss over different time points is therefore necessary to clarify the amount and nature of anchorage loss associated with miniscrews.

The effect of the different anchorage reinforcement methods on root resorption has not been investigated until recently. A recent clinical study (Liou & Chang, 2010) attempted to measure the amount of root resorption associated with miniscrews and compare it to a group without miniscrews. Although they found more root resorption associated with patients with miniscrew anchorage reinforcement, this study had several limitations. The amount and duration of movement were not standardised. These factors have been found to influence the amount of root resorption (Sameshima & Sinclair, 2001b). Furthermore, the severity of the malocclusion, which can influence the previous factors (amount of tooth movement and duration of movement) was not matched between the two groups in the Liou & Chang (2010) study. This was highlighted by the authors who attributed the increased amount of root resorption within the miniscrew group to the greater amount of tooth movement in patients with severe malocclusions. Moreover, the method used (periapical radiographs) to measure root resorption by Liou & Chang (2010) has been found to be insensitive (section 1.7.10). The effect of the Nance appliance on root resorption, on the other hand, has yet to be evaluated. A well conducted study, with a

matched duration of active movement, force, malocclusion and a more sensitive method of quantifying root resorption is thus necessary to identify the risks associated with such intra-oral anchorage reinforcement methods to the dentition.

1.9 Aims & Objectives

After undergoing a comprehensive review of the available literature, it emerges that several aspects regarding anchorage reinforcement methods remain unknown. The amount of anchorage loss associated with the two types of anchorage reinforcement methods (Nance appliance and miniscrew) over different time points during orthodontic treatment is undetermined. The lack of controlled studies and accurate assessment methods for tooth movement has also been one of the main drawbacks of the previous reports. Furthermore, the detrimental effects these anchorage reinforcement methods have on the roots of the dentition remain relatively unexplored. The aim of this thesis was to investigate both clinically and histologically the Nance appliance and miniscrew methods of anchorage reinforcement in a dog model, as they are vital to formulating successful orthodontic treatment.

The objectives were as follows:

1. To assess the amount of anchorage loss and desired tooth movement associated with the Nance appliance at 3 time points (5, 10 and 15 weeks) and compare it with a control group with a conventional molar anchorage reinforcement method in a dog model.

2. To assess the amount of anchorage loss and desired tooth movement associated with miniscrews at 3 time points (5, 10 and 15 weeks) and compare it with a control group with a conventional molar anchorage reinforcement in a dog model.

3. To assess the effect each of the following: the Nance appliance, miniscrew and conventional molar anchorage has on orthodontically induced inflammatory root resorption (OIIRR).

1.10 Sample size

R software version 2.11.1 (Vienna, Austria. ISBN 3-900051-07-0, URL **http://www.R-project.org**) was used to calculate the sample-size. The means and standard deviations from a previous study by Saito *et al.* (2000), where anchorage loss was compared in beagle dogs, were used. Two dogs in each group were required for the *t-test* to have a 90% chance of detecting a difference in the means of anchorage loss at the 5% level of significance. Three dogs were used in the control and miniscrew groups instead of 2 as any accidental loss of a dog would compromise half of the sample size. This power analysis was also used to calculate the sample size for the Nance appliance group in the current study. This was due to the absence of a study comparing the anchorage loss with and without the Nance appliance. However, four dogs were allocated to the Nance group compared to 3 in the control group, as any failure for the Nance group would compromise both sides of the jaw whereas in the control any anchorage loss may have been unilateral.

2 The efficacy of the Nance appliance as an anchorage reinforcement method

2.1 Introduction

The term anchorage in orthodontics is used to describe the resistance to unwanted tooth movement. Several extra-oral and intra-oral methods have been developed to resist unwanted tooth movement during treatment. One of the limitations of extra-oral methods is patient compliance, and for this reason intra-oral appliances which do not require patient compliance, such as the lingual arch and the Nance appliance, have been developed.

The Nance appliance was designed to provide anchorage by utilizing the cortical bone of the palate and the outer cortical bone layer surrounding the teeth. Reitan (1964) found that tooth movement was slower in dense cortical bone compared to medullary bone. Melsen (2007) suggested that medullary bone is more amenable to remodelling. This would suggest that tooth movement was more difficult in dense cortical bone. Few studies have assessed the effectiveness of the Nance appliance in providing anchorage. Much of the perceived advantage is based on clinical judgment. A recent study by Shpack *et al.* (2008), assessed anchorage loss associated with the Nance appliance, using study models taken prior to and post-treatment. The study compared bodily and tipping movements in patients who were fitted with a Nance appliance. Shpack *et al.* (2008) found 17-20% anchorage loss in both the tipping and bodily movement groups. One of the major limitations of Shpack and colleagues' 2008 study was the absence of a control group. Providing a control group without anchorage reinforcement and observing anchorage loss in a clinical study is difficult. This involves an ethical issue, as anchorage loss might compromise the overall treatment. Using study models to assess anchorage loss was found to be limited, as the reference points moved during treatment (Geron *et al.*, 2003). Lastly, Shpack and colleagues' 2008 study was not designed specifically to assess anchorage loss

with a Nance appliance. The aim of the current study was to assess the amount of anchorage loss and desired tooth movement associated with the Nance appliance at 3 time points (5, 10 and 15 weeks) and compare it with a control group with a conventional molar anchorage reinforcement method in a dog model.

2.2 *Material and Method:*

2.2.1 *Study outline*

Under Irish Government License No. B100/3896 issued by the Department of Health and Children in Ireland, 7 adult male beagle dogs were used in the study with a mean age of 16.5 (± 3) months and mean weight of 12.8 (± 1.9) kg. Ethical approval was sought and granted by the Trinity College Bio Resources Ethics Committee (Ref. 161106B). The study protocol was in accordance with the Department of Health policies and regulations on animal care. The animals were fed a soft diet throughout the duration of the experiment and instructions were given to carers to avoid hard chewy foods, treats or toys.

2.2.2 *Anaesthetic procedure*

Food was withheld for 12 hours prior to each procedure. The animals were premedicated 30 minutes pre-operatively with 0.1 ml/kg of acetyl promazine by subcutaneous injection. Anaesthetic induction was achieved with phenobarbitone 25 mg/kg intravenously, and an endotracheal tube was inserted to maintain the airway. Anaesthesia was maintained with halothane and oxygen. Local infiltration with 2% lignocaine and 1/100,000 epinephrine was used to aid in haemostasis.

2.2.3 *Extractions*

The mandibular first premolars (PM_1) and third premolars (PM_3) were extracted on both sides of the mandible to facilitate orthodontic space closure and the insertion of miniscrews (Figure 2-1). The surgical sites were sutured using horizontal mattress sutures with 3.0 black silk and the animals were allowed to recover from the anaesthetic. After the surgical procedures, 150 mg of clindamycin was administrated to the animals twice daily and maintained for a period of five days while they were reinstalled in kennels. The sutures were removed after 10 days following which the animals were left for a healing period of 3 months. This period was to allow for bone remodelling prior to the placement of miniscrews

and to facilitate tooth movement into an area with uniform bone structure at the extraction site. This simulated the human clinical situation in as much as teeth are not moved immediately following extractions; rather tooth movement is initiated following teeth alignment.

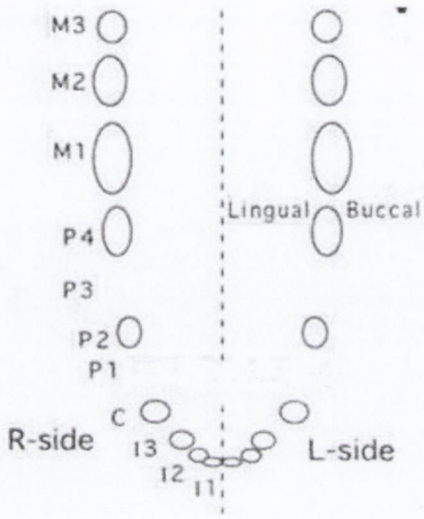

Figure 2-1. Outline of the dog's mandible with extractions sites (PM_1 and PM_3).

2.2.4 *Group allocation*

The animals were divided into 2 groups: a control group (tooth anchorage) and a Nance group (Nance anchorage) (Table 2-1). Three dogs were randomly allocated to the control group and 4 to the Nance group. Four dogs were allocated to the Nance group compared to 3 in control as any failure in the Nance group would compromise both sides whereas in the control group it would not. Each group required a different impression material and method to facilitate the fabrication of the orthodontic and anchorage appliance. This will be described in the sections below.

Table 2-1. The outline of the study (efficacy of Nance appliance as an anchorage reinforcement method)

	Number of animals	Tooth retracted	Anchorage	grams (g)
Control group	3	Second premolar	Fourth premolar	150
Nance group	4	Second premolar	Nance	150

2.2.5 *Impressions*

In both groups plaque and calculus (Figure 2-2) were removed from the PM_2 and PM_4 using hand scalers and a slow handpiece, after which they were cleaned with pumice and water (Figure 2-3).

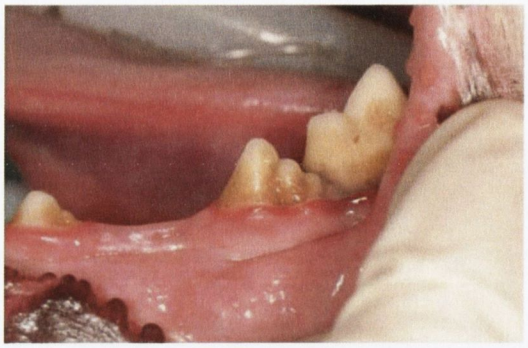

Figure 2-2. Plaque and calculus on the dogs' teeth.

Figure 2-3. Cleaning the dogs' teeth with a slow hand piece and pumice.

Impressions were taken for the purpose of fabricating 2 appliances; the band and Nance appliances. For the control group, impressions were required to fabricate bands only whereas the Nance group required impressions for bands, acrylic button and connecting lingual wire.

2.2.5.1 Impressions for the control group

For the bands a combination of a putty and light body polyvinylsiloxane impression (PRESIDENT, Coltène/Whaledent AG, Feldwiesenstrasse 20, 9450 Altstatten/Switzerland), putty-wash impression, was used to take the impression. This combination allowed for a better impression of the teeth margins to ensure accurate

fabrication of the bands. Disposable aluminium sectional trays (Kwik-Tray, KerrHawe SA., Via Strecce, 4, CH- 6934 Bioggio, Switzerland) (Figure 2-4) were used to make impressions of each side. A total of 14 impressions (2 per animal) of this type were made. The impressions were washed under water first and then disinfected with CIDEX®OPA (ASP, 33 Technology Drive, Irvine, CA 92618 USA) for 5 minutes. The impressions were then rinsed with water for 1 minute, as recommended by the manufacturers, before being placed in plastic sealed bags and labelled. The impressions were poured within an hour in type IV (high strength and low expansion) dental stone (Jade Stone, Whip Mix Corporation, 361 Farmington Avenue, Louisville, KY 40217, USA) which was used for the construction of the bands and the band component of the Nance appliance.

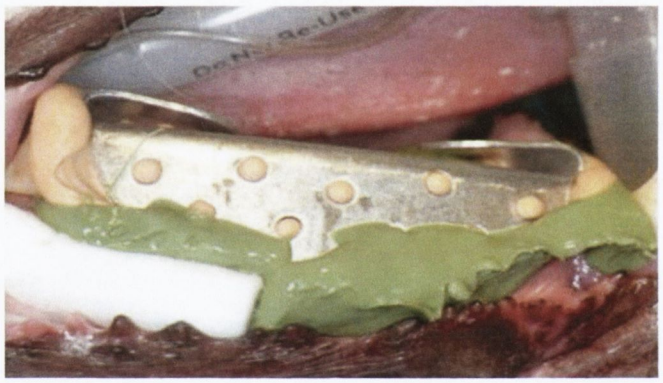

Figure 2-4. A sectional impression, using disposable aluminium tray (Kwik-Tray, KerrHawe SA., Via Strecce, 4, CH- 6934 Bioggio, Switzerland), for the fabrication of PM_2 and PM_4 bands using a combination of a putty and light body polyvinylsiloxane impression (PRESIDENT, Coltène/Whaledent AG, Feldwiesenstrasse 20, 9450 Altstatten/Switzerland).

2.2.5.2 Impressions for the Nance group

For the Nance group 3 different impressions were required. Initially putty wash impressions were taken using disposable aluminium sectional trays to fabricate the band component as described above. Secondly, alginate impressions (Hydrogum, Zhermack®, Via Bovazecchino, 45021 Badia Polesine (RO), Italy) using full arch disposable trays (O-Tray impression tray, DENTAURUM GmbH & Co. KG, Turnstraße 31, 75228 Ispringen, Germany) were made. This impression was disinfected,

sealed, labelled and then poured in type IV dental stone as described earlier for the band impressions. Using these casts, four custom made impression trays were fabricated using Triad ® Visible Light Curing (VLC) (Dentsply De Trey GmbH, Postfach 101074, D-63264, Germany). Finally, the 4 custom made impression trays were used to make secondary impressions with putty (PRESIDENT, Coltène/Whaledent AG, Feldwiesenstrasse 20, 9450 Altstatten/Switzerland) of the entire mandibular dental arch (Figure 2-5). The secondary impressions using the custom made tray resulted in suitable impressions of the floor of the mouth, necessary for the fabrication of the acrylic button and the wire work of the Nance appliance. These impressions were then disinfected, sealed, labelled and poured in type IV stone as described earlier.

Figure 2-5. Putty impression of the floor of the mouth.

2.2.6 *Band fabrication*

Using the sectional dental casts poured earlier custom made bands were cast using Vitallium® 2 Alloy (DENTSPLY, Elephant Dental B.V., Verlengde Lageweg 10, 1628 PM Hoom, The Netherlands) to fit the PM_2 and PM_4. The bands had tubes on the buccal aspect which allowed for the sliding of a 1 mm wire (SS). To ensure that the wires were passive immediately after band cementation, a wire was passed through the PM_4 and PM_2 buccal tubes during the wax up stage of the bands (Figure 2-6). Each band was fitted with hooks on the buccal aspect for the application of orthodontic force (Figure 2-7). The hooks

were soldered gingivally to limit tipping movement and encourage bodily movement as they would be closer to the centre of resistance (CRes) of the tooth. Finally, a reference point for recording movements was placed at the top of each band (Figure 2-8).

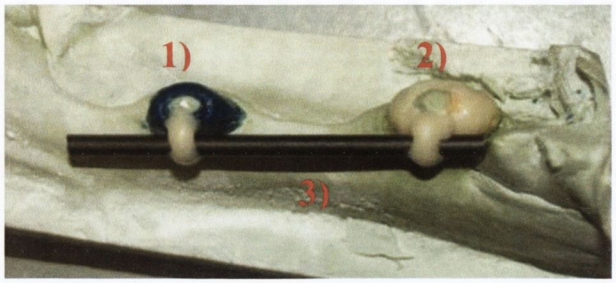

Figure 2-6. PM_2 (1) and PM_4 (2) bands wax up with a wire (3) passed through the buccal tubes.

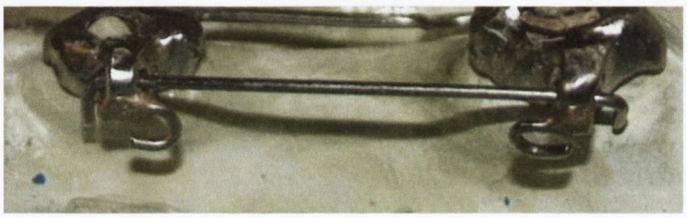

Figure 2-7. Buccal hooks for force application.

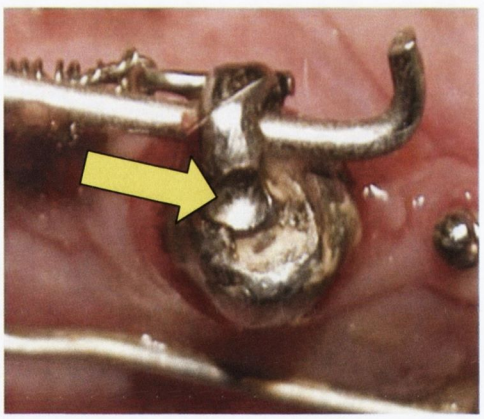

Figure 2-8. Reference point on the bands with arrow indicating reference point.

2.2.7 *Nance fabrication*

The Nance appliance had three components; bands on PM_4, connecting wire and acrylic button. It was fabricated in two stages; the first stage was the fabrication of the band components which was described above. The band component of each side of the Nance was constructed independently (Figure 2-9). The band design and construction were

described earlier and included the use of passive wire between PM_4 and PM_2 to ensure the appliance was passive once cemented.

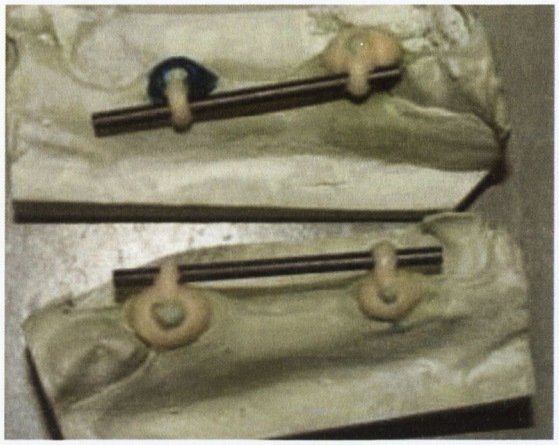

Figure 2-9. The wax up of the bands components of each side of the Nance appliance.

The second stage involved the construction of the acrylic button and the connecting wire work (Figure 2-10). The custom bands were fitted over the PM_4 of the dental casts constructed using the custom made trays.

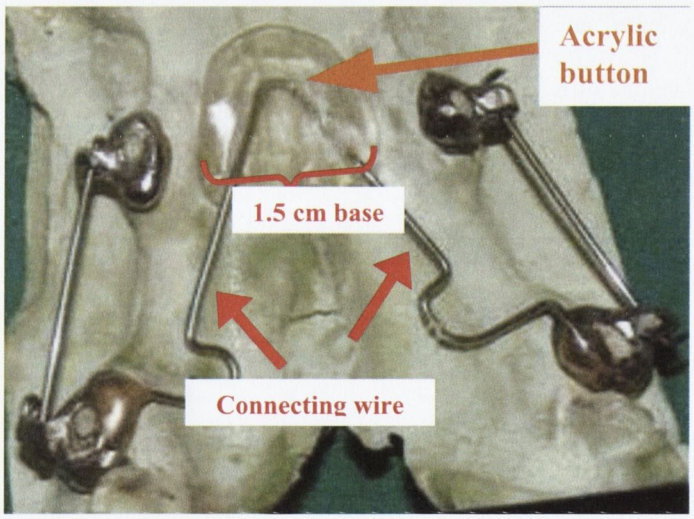

Figure 2-10. The fabrication of the connecting wire and the acrylic button.

The Nance appliance had an acrylic button seated against the lingual fossa of the mandible. The size of the acrylic button was triangular in shape with a 1.5 cm base. The buttons were fabricated by the same dental technician and standardized in size and design. The acrylic button had a 1 mm diameter stainless steel wire extending distally to the previously cast bands on PM_4.

2.2.8 *Cementation*

PANAVIA™ F 2.0 (Kuraray Europe GmbH, Medical Products Division, Hoechst Industrial Park/F 821 65926 Frankfurt, Germany), a universal dual curing resin cement with high bond strength to tooth structures and metals, was used to cement the bands under anaesthesia. The animals' teeth were cleaned and etched prior to cementation according to the manufacturer's instructions. In addition the inner surface of the bands and the Nance bands were sandblasted to increase the bonding strength prior to cementation. Once cemented, the animals remained under anaesthesia for a further fifteen minutes to ensure the setting of the cement.

2.2.9 *Miniscrews*

Miniscrews were used as reference points to measure tooth movements in this study. A total of 28 Ti-6Al- 4V ELI (Titanium – 6 Aluminium- 4 Vanadium ELI alloy) self drilling (1.3 mm width x 7 mm length) tapered miniscrews (Absoanchor®, Dentos, UK) were used in the study (Figure 2-11). Two miniscrews were placed in the PM_1 regions for the control (Figure 2-12) and Nance (Figure 2-13) groups. One of the two miniscrews was a reference miniscrew (RMs) for all measurements carried out; the other miniscrew was placed to monitor positional stability of the reference miniscrew. These miniscrews remained stationary as no forces were applied to them. This was confirmed by measuring the distance between them at 5 week intervals. Accurate measurement of the movement occurring for PM_2 and PM_4 were recorded as described in section 2.2.12.

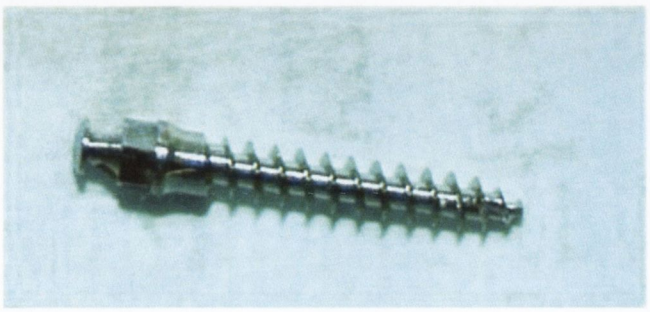

Figure 2-11. Miniscrew 1312 7 mm Absoanchor.

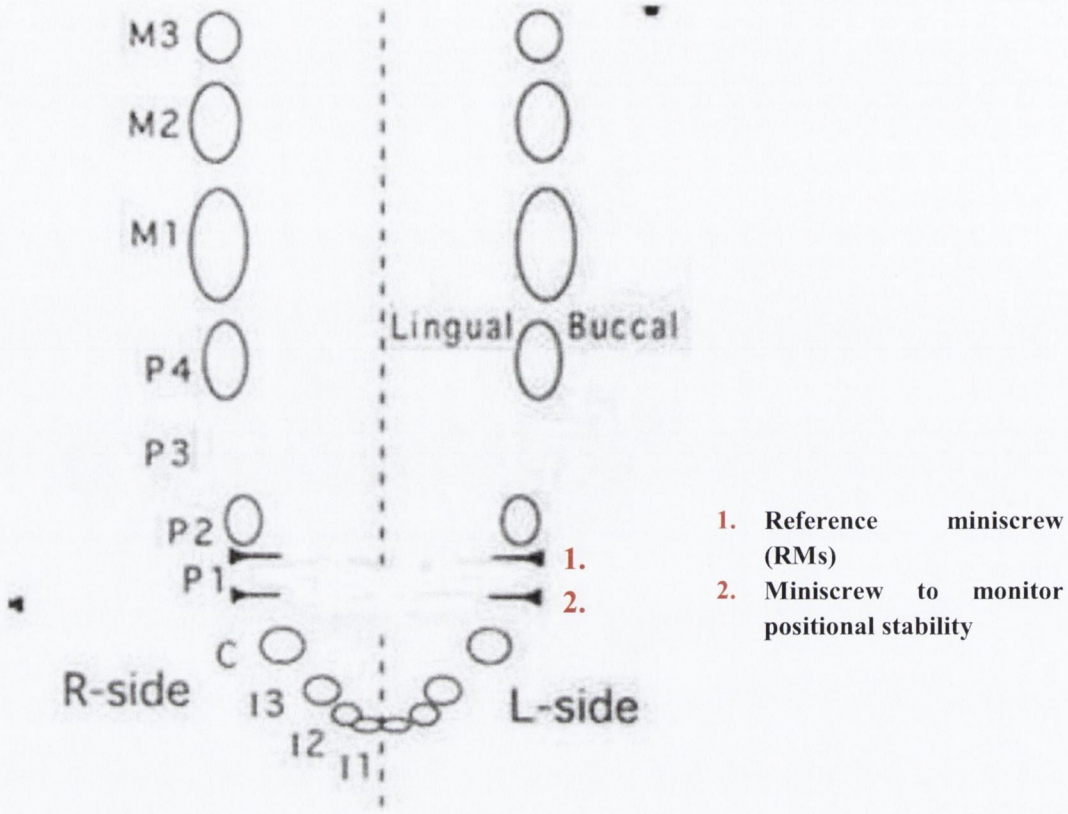

Figure 2-12. Experiment outline in the control group (modified from Ohmae et al. 2001)

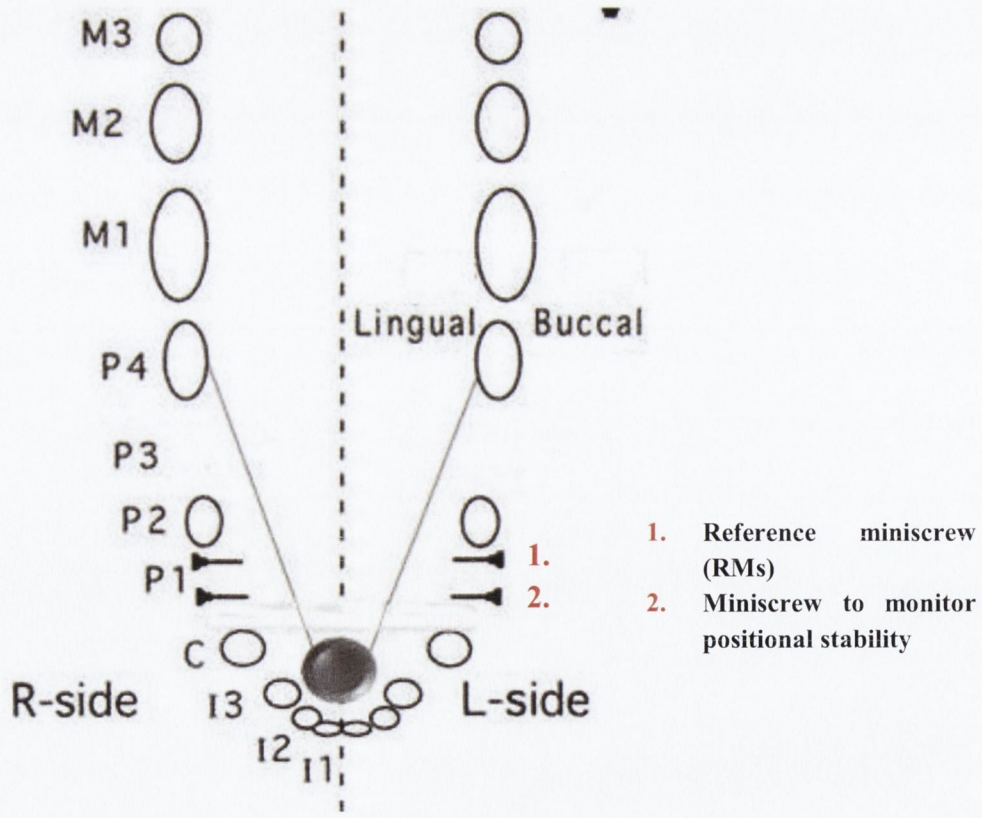

Figure 2-13. Experiment outline in Nance group (modified from Ohmae et al. 2001)

2.2.10 *Miniscrew placement*

Miniscrews were placed with anaesthesia and local infiltration as described earlier. A 1 mm pilot hole was drilled through the soft tissue and into the cortical bone using a 0.9 mm round bur with water cooling. A tunnel was made in the alveolus using a pilot drill (0.3 mm smaller than the diameter of the miniscrew) at a 30°- 60° angle to the long axis of the teeth with the tip aiming apically and using normal saline solution irrigation. The implants were self tapped into their site using a screwdriver supplied by the manufacturer. The animals were allowed to recover for 2 weeks during which antibiotics were administrated as described in section 2.2.3. The animals' weight, gingival healing and miniscrew stability were monitored for a two week period. This was done by examining for signs of inflammation and for miniscrew mobility. From there on the inflammatory status around the miniscrews was monitored and the miniscrew mobility checked every week throughout the 15 week period of study.

2.2.11 *Force application and space closure*

The animals in both groups had a segmental 1 mm SS arch wire placed between the PM_2 and PM_4. The ends of the wire were bent in to prevent the wire from sliding out of the appliance (Figure 2-14). Tooth movement was initiated two weeks following miniscrew placement using 3 mm nickel titanium (NiTi) coil springs (Sentalloy®; medium, GAC International Inc, Bohemia, NY). A 0.01-inch SS wire ligature was used to tie the NiTi springs to the hooks on the PM_2 and PM_4 bands in both groups (Figure 2-15) and (Figure 2-16). The force was calibrated to 150 g using CORREX tension gauge (HAAG-STREIT AG, Gartenstadtstrasse 10 CH-3098, Koeniz/Switzerland). The CORREX tension gauge had a range of 50 to 500 g and a resolution of 20 g.

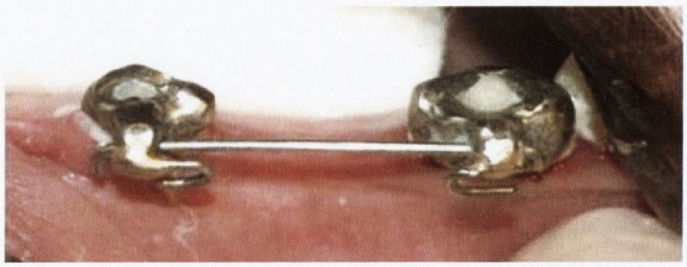

Figure 2-14. 1mm SS sectional wire with the ends turned in.

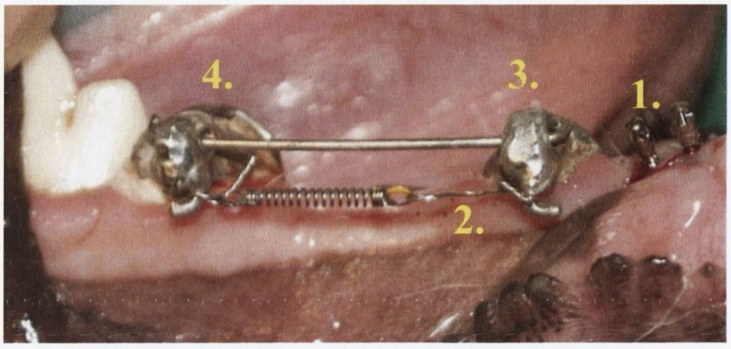

Figure 2-15. A buccal view of the reference miniscrew (1) and the NiTi coil spring (Sentalloy®; GAC International Inc, Bohemia, NY) (2) attached to hooks on the PM_2 (3) and PM_4 (4) bands, using 0.01-inch SS wire ligatures, in the control group.

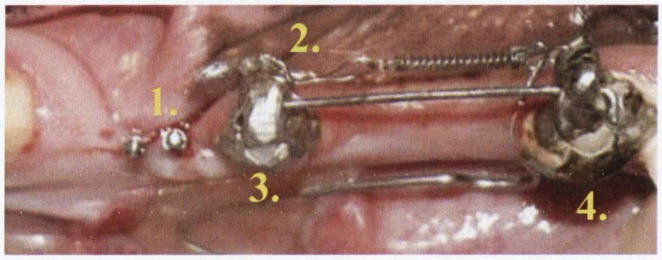

Figure 2-16. An occlusal view of the reference miniscrew (1) and the NiTi coil spring (Sentalloy®; GAC International Inc, Bohemia, NY) (2) attached to hooks on the PM_2 (3) and PM_4 (4) bands, using 0.01-inch SS wire ligatures, in the Nance group.

Once activated, the springs were checked weekly to ensure that they were active. The springs were reactivated every 5 weeks simulating the clinical situation during orthodontic space closure. The orthodontic appliance, teeth, and gingiva were thoroughly cleaned twice a week with a toothbrush and gauzes soaked with 0.2% chlorhexidine.

2.2.12 *Measuring tooth displacement*

A digital caliper ABSOLUTE (Moore & Wright LTD, Bowers Metrology Ltd, Bradford, West Yorkshire, BD3 8HU, UK) was used to measure the movements. The caliper had a resolution of 0.01 mm.

The distances between the reference miniscrews (RMs) and the reference points on PM_2 and PM_4 bands were measured prior to force application ($PM_{2\ (T0)}$ and $PM_{4\ (T0)}$) (Figure 2-17). Each measurement was then repeated 3 times and averaged. This process was then repeated following 5 weeks ($PM_{2\ (T1)}$ and $PM_{4\ (T1)}$), 10 weeks ($PM_{2\ (T2)}$ and $PM_{4\ (T2)}$) and 15 weeks ($PM_{2\ (T3)}$ and $PM_{4\ (T3)}$) (Table 2-2).

Table 2-2. Second premolar (PM2) and fourth premolar (PM4) measurements outline

Measurement parameters		
Desired tooth movement	**$PM2_{(T0)}$**	Distance from the second premolar to the reference miniscrew pre-operatively
	$PM2_{(Tx)}$	Distance from the second premolar to the reference miniscrew at T1, T2 and T3
Anchorage loss	**$PM_{4(T0)}$**	Distance from the fourth premolar to the reference miniscrew pre-operatively
	$PM_{4\ (Tx)}$	Distance from the fourth premolar to the reference miniscrew at T1, T2 and T3

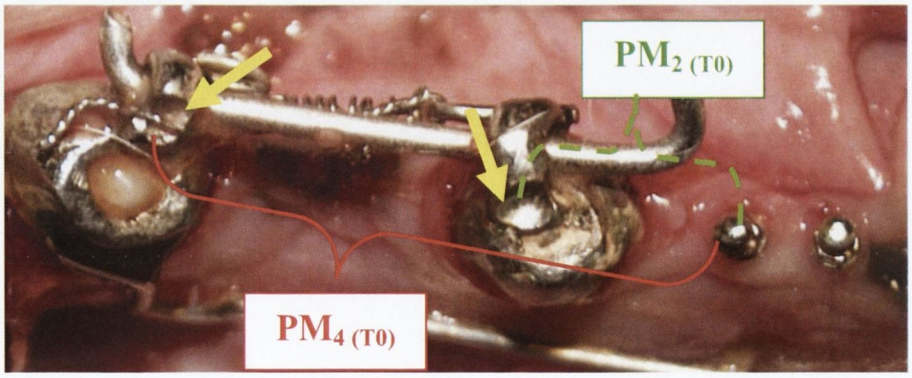

Figure 2-17. The distance from reference miniscrew (RMs) to the second premolar ($PM_{2(T0)}$) and fourth premolar ($PM_{4(T0)}$) pre-operatively. Yellow arrows indicating the engraved reference points on PM_2 and PM_4.

2.2.13 *Data management*

Using the PM_2 and PM_4 measurements, the amount and percentage of desired tooth movement to anchorage loss during space closure was determined. The amount of desired tooth movement was calculated by comparing the measurements made at 5, 10 and 15 weeks (T1, T2 and T3) to those made at baseline for $PM_{2\ (TO)}$. The anchorage loss was calculated in the same manner by comparing measurements made at 5, 10 and 15 weeks (T1, T2 and T3) to those made at baseline for $PM_{4\ (TO)}$. The desired tooth movement and anchorage loss were also both expressed as a percentage of the total space closure for 5, 10 and 15 weeks (T1, T2 and T3).

The following formulae were used:

- Amount of desired tooth movement:
  - $(DM) = PM_{2\ (T0)} - PM_{2\ (Tx)} = mm$
- Amount of Anchorage loss:
  - $(AL) = PM_{4\ (T0)} - PM_{4\ (Tx)} = mm$
- Percentage of desired tooth movement in comparison to the total space closure:
  - $$(DM\ \%) = \frac{DM_{(Tx)}}{DM_{(Tx)} + AL_{(Tx)}} \times 100\%$$
- Percentage of Anchorage loss in comparison to the total space closure:
  - $$(AL\ \%) = \frac{AL_{(Tx)}}{DM_{(Tx)} + AL_{(Tx)}} \times 100\%$$

(T_x = Time 1, 2 or 3) (T_O = baseline position)

2.2.14 *Error of the Method*

The error of the measurement method was calculated according to Dahlberg's equation: $e = \sqrt{\frac{\sum di^2}{2n}}$ in which di is the difference between duplicate measurements and n is the number of repeated measurements. Thirty duplicate pairs of duplicate measurements for the control and Nance were randomly chosen. The error of the method was found to be 0.068 mm for the desired tooth movement and 0.075 mm for the anchorage loss in the control group. The error of the method was found to be 0.069 mm for the desired tooth movement and 0.029 mm for anchorage loss in the Nance group. The random error for both groups is clinically insignificant.

In a small sample size and where no bias exists, it is been found to be advantageous to use the Dahlberg formula. This is because it has less degree for freedom (2n) in the denominator than the other methods such as the method of moments. Houston (1983) suggested a minimum of 25 cases should be replicated. This was supported by Springate (2012) who found increasing the repeated measurements (n) to 30 narrowed the distribution. However it is important to realize the limitations of the Dahlberg formula. It assumes the sample has a normal distribution and there is no bias (systematic error). The method is sensitive to bias as any mean deviations between the two measurements are incorporated. Furthermore, it does not distinguish between systematic error and random error which could make interpretation of the results difficult. Overestimation of the error is also another disadvantage. This is as a result of the differences between measurements are squared and as consequence the magnitude of error increasing.

2.2.15 *Statistical analysis*

The data were found to be normal in distribution. A series of *t-tests* were conducted to assess difference in the means between the variables. A Paired *t-test* was used to compare

anchorage loss and desired tooth movement within each anchorage group at the different time points. As the dependent variables for each group were independent (mean anchorage loss and desired tooth movement), an unpaired *t-test* was used for the comparisons between the two groups. Data were further analysed with Tukey's HSD multiple comparison, as there were multiple comparisons involved, to determine the true level of significance associated with the different anchorage methods over different periods intervals (T1, T2 and T3) for each variable.

The following comparisons were investigated:

- Comparisons within each anchorage method
    - Amount of desired tooth movement (DM)
    - Amount of anchorage loss (AL)
    - Percentage of desired tooth movement (DM %)
    - Percentage of anchorage loss (AL %)
- Comparisons between the two anchorage methods
    - Amount of desired tooth movement (DM)
    - Amount of anchorage loss (AL)
    - Percentage of desired tooth movement (DM %)
    - Percentage of anchorage loss (AL %)

For all cases the significance level was set at $p<0.05$. The data were analysed and graphically depicted using R software version 2.11.1 (Vienna, Austria. ISBN 3-900051-07-0, URL **http://www.R-project.org**).

2.3 Results

The amount of movement for PM_2 and PM_4 was measured at 5, 10, and 15 weeks (T1, T2 and T3). The mean amount of movement was recorded for each time point. The mean of each of the following was then calculated: amount of desired tooth movement (DM), amount of anchorage loss (AL), percentage of desired tooth movement (DM %) and percentage of anchorage loss (AL %) (Table 2-3). These variables were then analysed within and between the two different anchorage methods for each time point (T1, T2 and T3).

Table 2-3. The means and standard deviations of the amount of desired tooth movement (DM), amount of anchorage loss (AL), percentage of anchorage loss (AL%) and percentage of desired tooth movement (DM%) for the control and the Nance appliance groups

		Mean ± Standard deviation (mm)	
Data	Time	Control	Nance
Desired tooth movement (DM)	1	1.10 ± 0.90	1.23 ± 0.97
	2	2.46 ± 2.41	3.96 ± 2.50
	3	5.09 ± 2.45	5.38 ± 2.19
Anchorage loss (AL)	1	0.99 ± 1.36	0.64 ± 0.62
	2	2.26 ± 1.10	1.63 ± 1.13
	3	3.96 ± 1.48	2.03 ± 1.26
Desired movement (DM %)	1	59.98 ± 28.66	66.24 ± 16.82
	2	45.13 ± 23.89	66.90 ± 22.05
	3	54.51 ±13.42	71.15 ± 15.73
Anchorage loss (AL %)	1	40.02 ± 28.66	33.75 ± 16.82
	2	54.85 ± 23.89	33.04 ± 22.05
	3	45.68 ± 13.42	28.75 ± 15.73

2.3.1 *Comparisons within groups (Control & Nance)*

2.3.1.1 Amount of desired tooth movement – (DM)

In the control group, despite the fact that there was a continuous increase in the amount of desired tooth movement over the 3 time points (1.1 mm, 2.46 mm and 5.09 mm) (Figure 2-18), only the second increase (T2-T3) was significant ($p<0.01$) (Table 2-4). The mean amount of desired tooth movement in the Nance group increased over the 3 time points (1.23 mm, 3.96 mm and 5.38 mm) as well (Figure 2-18), but the differences between both time intervals were significant ($p<0.01$ and $p=0.03$ respectively) (Table 2-4).

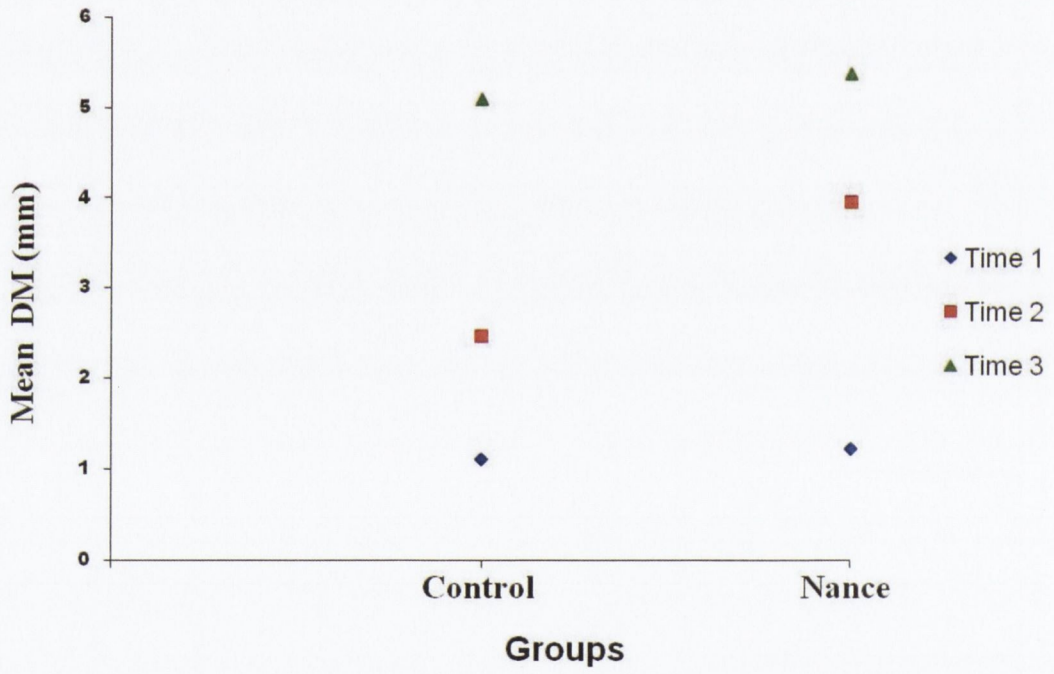

Figure 2-18. The means of the amounts of desired tooth movement (DM) at the different time points (T) within each group (control and Nance).

Table 2-4. The mean difference between the amounts of desired tooth movement (DM) at the different time points (T) within each anchorage group (control and Nance)

Desired tooth movement (DM) (mm)					
	Time	**Mean Difference**	**95% Confidence interval**		**p-value**
Control	**1 vs 2**	-1.36	-2.87	0.16	0.11
	2 vs 3	-2.63	-4.14	-1.11	< 0.01
Nance	**1 vs 2**	-2.73	-4.04	-1.42	< 0.01
	2 vs 3	-1.42	-2.73	-0.10	0.03

2.3.1.2 Amount of anchorage loss – (AL)

The mean amount of anchorage loss (AL) in the control group (0.99 mm, 2.26 mm and 3.96 mm) increased over the 3 time points (Figure 2-19). The increase between the different time points was statistically significant ($p<0.01$) (Table 2-5). Anchorage loss in the Nance group occurred at T1, T2 and T3 with a mean of 0.64 mm, 1.63 mm and 2.03 mm respectively (Figure 2-19). The incremental increase (mean difference) from T1 to T2 was statistically significant ($p<0.01$) whilst the increase from T2 to T3 was not (Table 2-5).

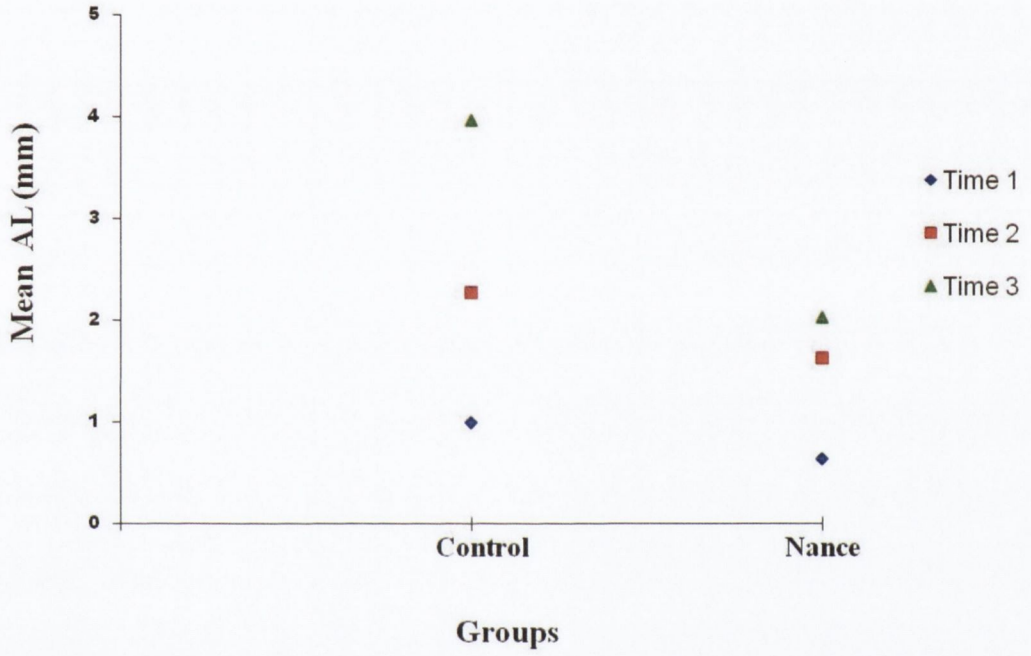

Figure 2-19. The means of the amounts of anchorage loss (AL) at the different time points (T) within each group (control and Nance).

Table 2-5. The mean difference between the amounts of anchorage loss (AL) at the different time points (T) within each anchorage group (control and Nance)

Anchorage loss (AL) (mm)					
	Time	Mean Difference	95% Confidence interval		p-value
Control	1 vs 2	-1.27	-2.17	-0.37	<0.01
	2 vs 3	-1.70	-2.60	-0.80	<0.01
Nance	1 vs 2	-0.99	-1.77	-0.20	<0.01
	2 vs 3	-0.40	-1.18	0.38	0.67

2.3.1.3 Percentage of desired tooth movement – (DM %)

The mean percentage of desired tooth movement of the total space closure in the control group decreased from 60% at T1 to 45.1% at T2 but then increased to 54.5% at T3 (Figure 2-20). On the other hand, the mean percentage of desired tooth movement in the Nance group was 66.2% at T1 and remained relatively constant at T2 (66.9%) and T3 (71.2%) (Figure 2-20). None of the changes was statistically significant (Table 2-6).

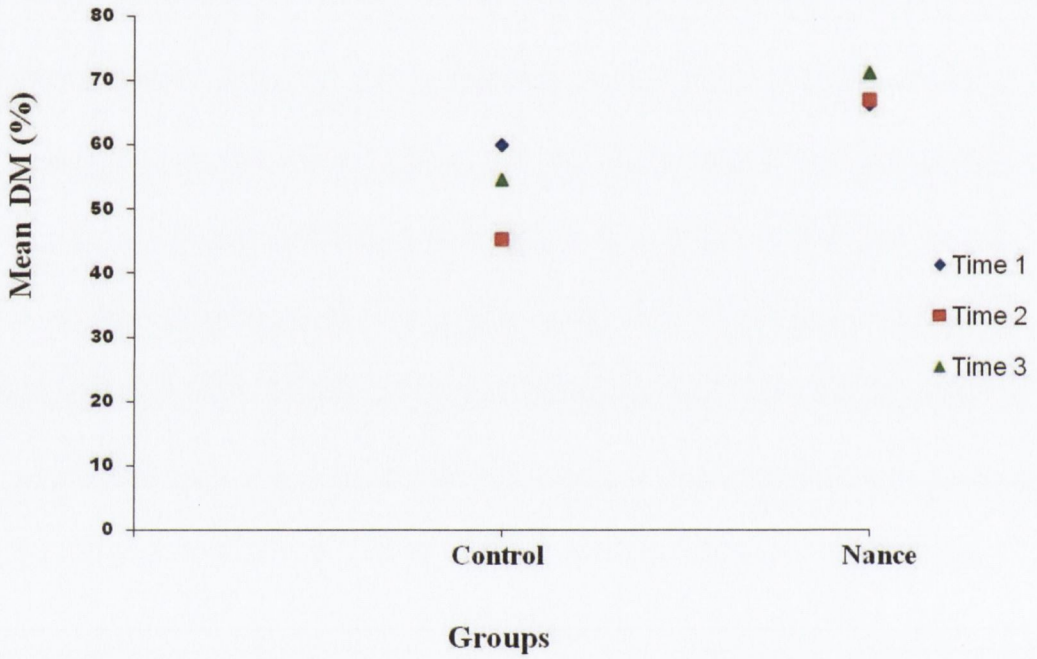

Figure 2-20. The means of the percentages of desired tooth movement (DM %) at the different time points (T) within each group (control and Nance).

Table 2-6. The mean difference between the percentages of desired tooth movement (DM %) at the different time points (T) within each anchorage group (control and Nance)

Desired tooth movement (DM %)					
	Time	**Mean Difference**	**95% Confidence interval**		**p-value**
Control	**1 vs 2**	14.85	-2.27	31.96	0.13
	2 vs 3	-9.38	-26.50	7.73	0.61
Nance	**1 vs 2**	-0.66	-15.48	14.16	1
	2 vs 3	-4.25	-19.10	10.57	0.96

2.3.1.4 Percentage of anchorage loss – (AL %)

The mean percentage of anchorage loss of the total space closure in the control group at T1 was 40% and increased to 54.9% at T2. However the percentage of anchorage loss reduced to 45.7% at T3 (Figure 2-21). On the other hand, the mean percentage of anchorage loss in the Nance group was relatively unchanged at T1 and T2 (33.8% and 33%) and reduced slightly at T3 (28.8%) (Figure 2-21).The differences between T1, T2 and T3 were not significant in either group (Table 2-7).

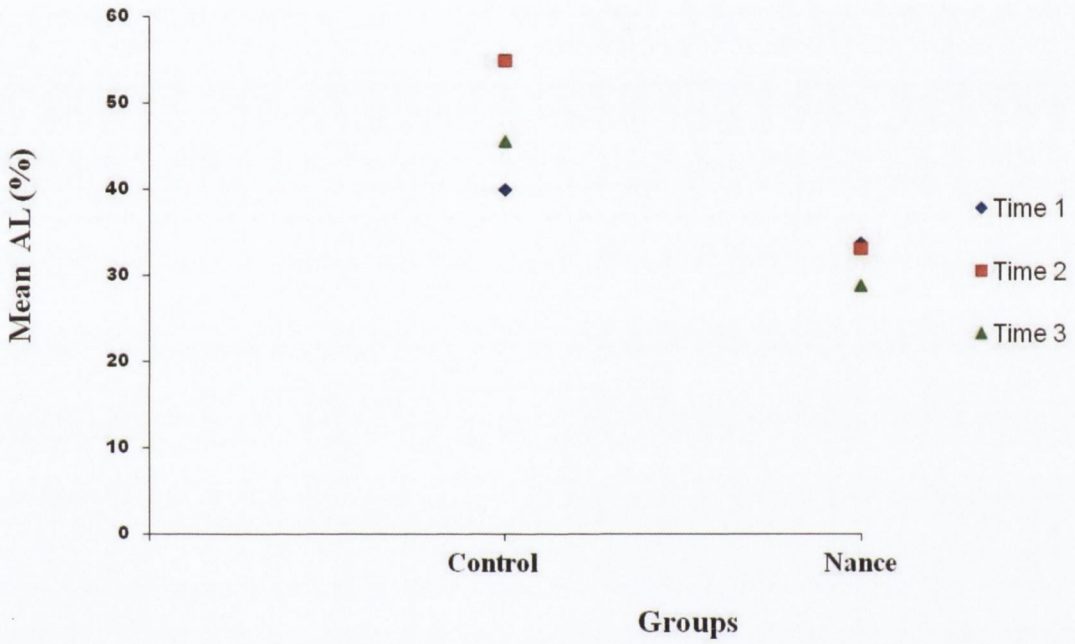

Figure 2-21. The means of the percentages of anchorage loss (AL %) at the different time points (T) within each group (control and Nance).

Table 2-7. The mean differences between the percentages of anchorage loss (AL %) at the different time points (T) within each anchorage group (control and Nance)

Anchorage loss (AL %)					
	Time	Mean Difference	95% Confidence interval		p-value
Control	1 vs 2	-14.83	-31.90	2.23	0.13
	2 vs 3	9.17	-7.90	26.23	0.63
Nance	1 vs 2	0.71	-14.07	15.49	0.99
	2 vs 3	4.29	-10.49	19.08	0.96

2.3.2 *Comparisons between groups (Control Vs Nance)*

2.3.2.1 Amount of desired tooth movement – (DM)

At T1 and T3 the means of the amount of desired tooth movement for both groups were similar (Figure 2-22). At T2, the mean desired tooth movement (3.96 mm) was significantly higher (p=0.03) in the Nance group (Table 2-8).

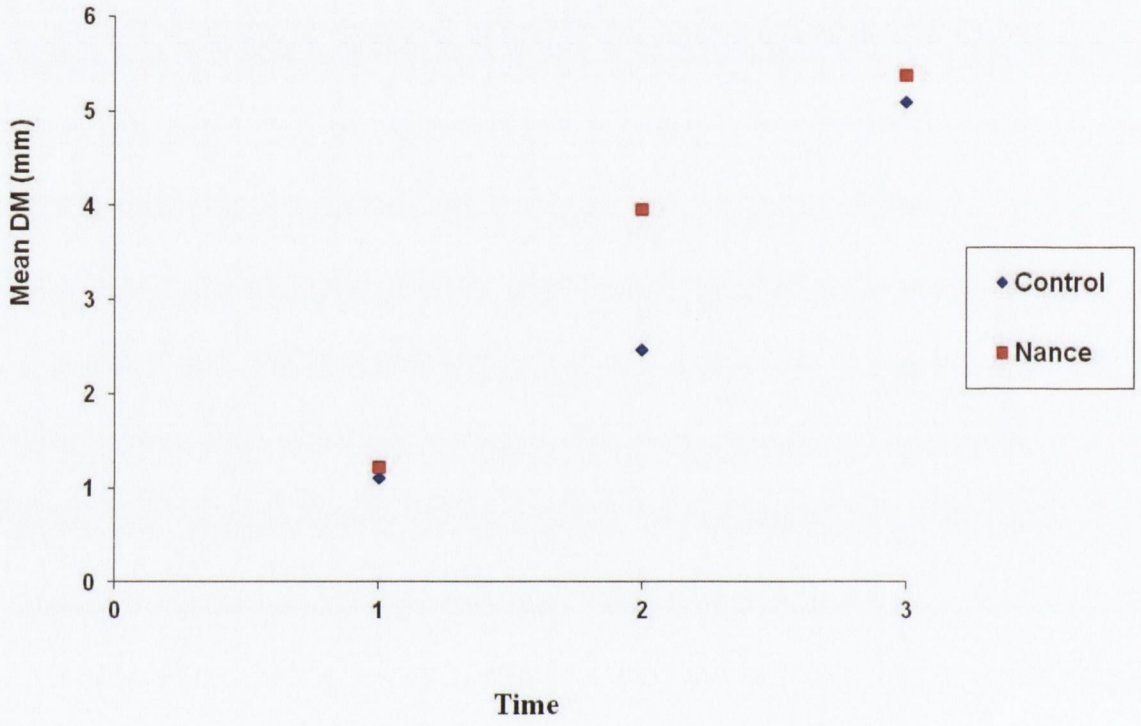

Figure 2-22. The means of the amounts of desired tooth movement (DM) for the control and Nance groups at different time points (T).

Table 2-8. The mean difference between the amounts of desired tooth movement (DM) of both anchorage groups (control and Nance) at different time points (T)

Desired tooth movement (DM) - Control Vs Nance group (mm).				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	-0.12	-1.53	1.30	0.99
2	-1.49	-2.90	-0.08	0.03
3	-0.28	-1.70	1.13	0.99

2.3.2.2 Amount of anchorage loss – (AL)

The difference between the means of the amount of anchorage loss (Figure 2-23) for the control and Nance groups at T3 (3.96 mm and 2.03 mm respectively) was statistically significant ($p<0.01$) (Table 2-9). The differences at the other two time points (T1 and T2) were insignificant (Table 2-9).

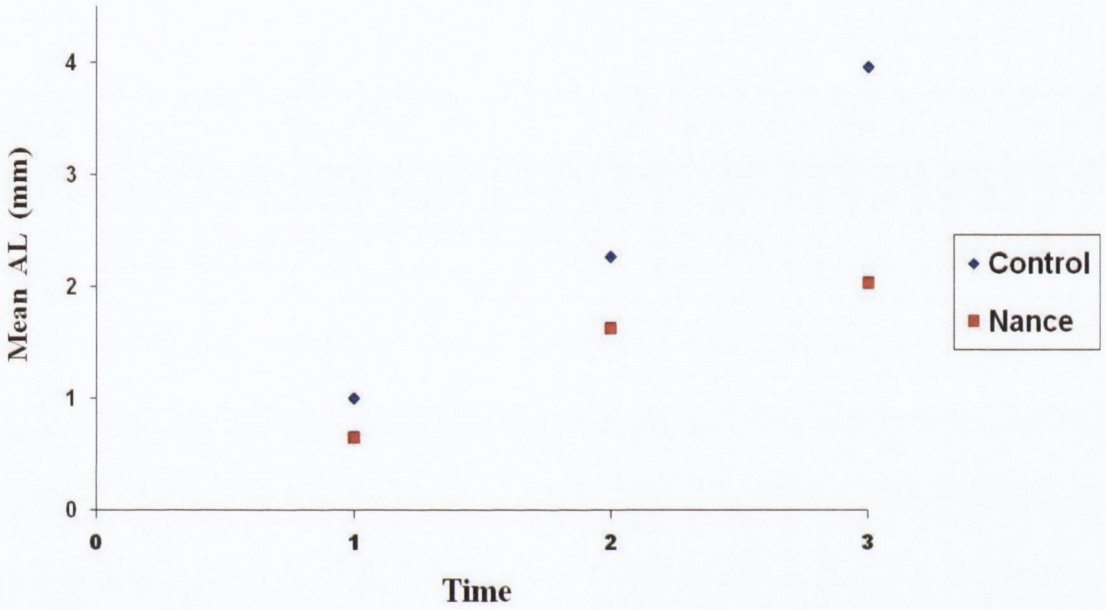

Figure 2-23. The means of the amounts of anchorage loss (AL) for the control and Nance groups at different time points (T).

Table 2-9. The mean differences between the amounts of anchorage loss (AL) of both anchorage groups (control and Nance) at different time points (T)

Anchorage loss (AL) - Control Vs Nance group (mm).				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	0.35	-0.49	1.20	0.83
2	0.64	-0.21	1.48	0.25
3	1.93	1.09	2.78	<0.01

2.3.2.3 Percentage of desired tooth movement – (DM %)

At T1 both groups had a similar percentage of desired tooth movement of the total space closure (Figure 2-24). However, in the Nance group the mean percentages of desired tooth movement at T2 (66.9%) and T3 (71.2%) were significantly higher than the control group ($p<0.01$ and $p=0.04$) (Table 2-10).

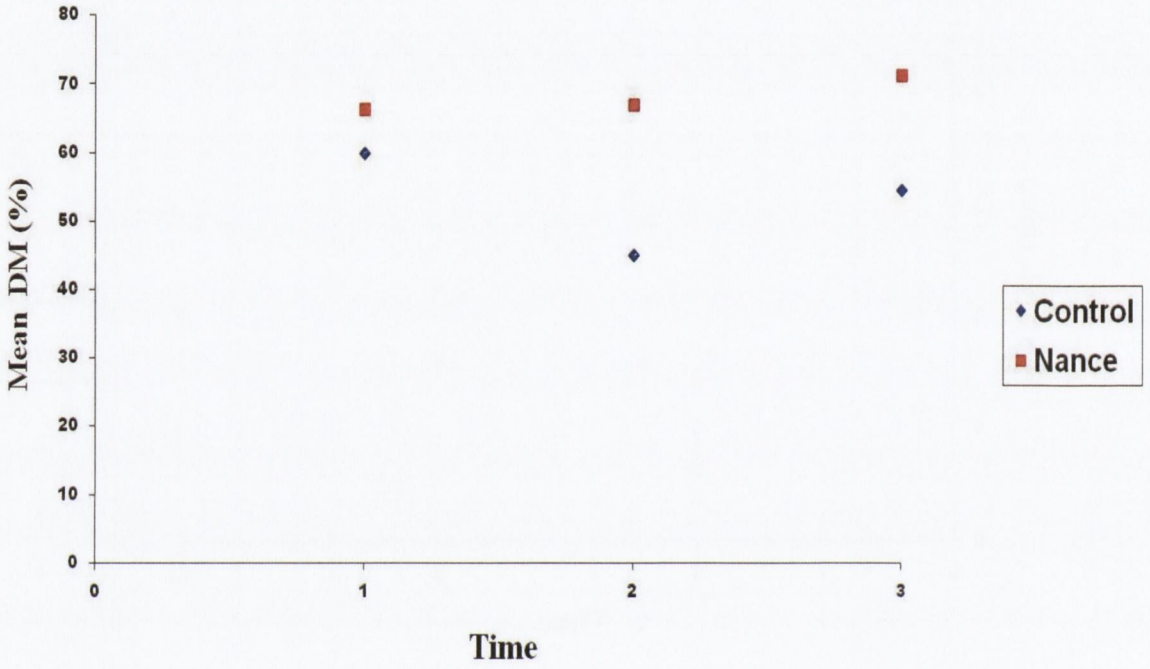

Figure 2-24. The means of the percentages of desired tooth movement (DM %) for the control and Nance groups at different time points (T).

Table 2-10. The mean differences between the percentages of desired tooth movement (DM %) of both anchorage groups (control and miniscrew) at different time points (T)

Desired tooth movement (DM %) –Control Vs Nance group (%)				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	-6.27	-22.28	9.74	0.87
2	-21.78	-37.79	-5.77	<0.01
3	-16.64	-32.65	-0.63	0.04

2.3.2.4 Percentage of anchorage loss – (AL %)

The mean percentage of anchorage loss of the total space closure in the control group and the Nance group was similar (40% and 33.8%) at T1 (Figure 2-25). At T2 and T3 the percentage of anchorage loss was significantly higher in the control group (Table 2-11).

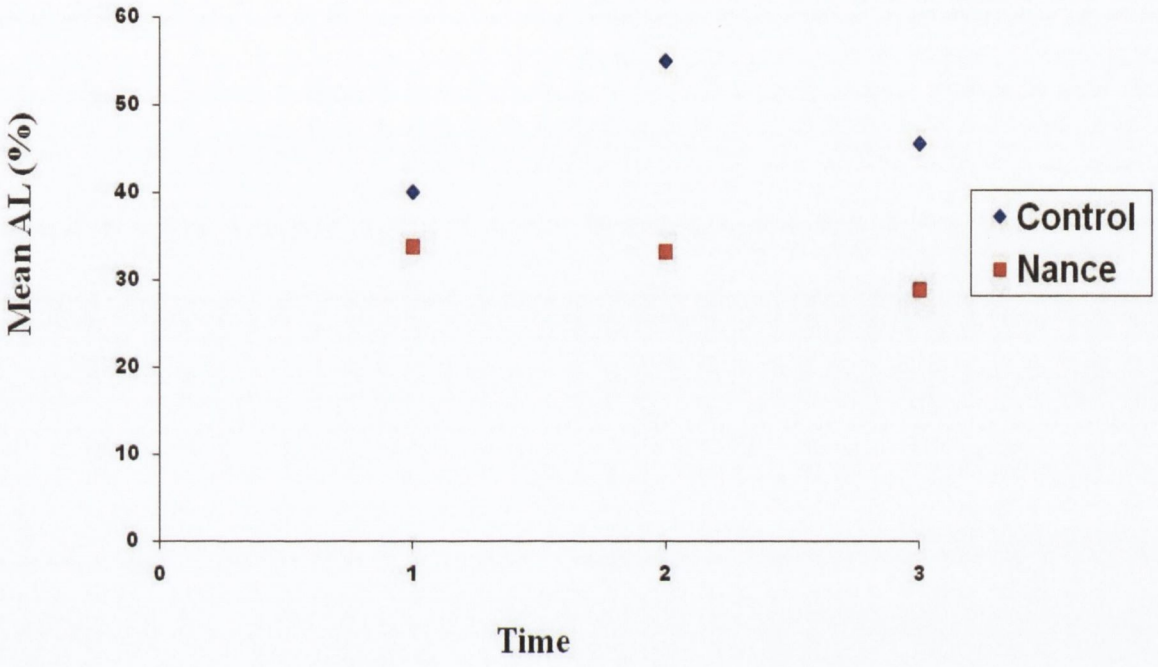

Figure 2-25. The means of the percentages of anchorage loss (AL %) for the control and Nance groups at different time points (T).

Table 2-11. The mean differences between the percentages of anchorage loss (AL %) of both anchorage groups (control and miniscrew) at different time points (T)

Anchorage loss (AL %) – Control Vs Nance group (%)				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	6.21	-9.76	22.18	0.87
2	21.75	5.78	37.72	<0.01
3	16.88	0.91	32.84	0.03

2.4 Discussion

The aim of this study was to assess the efficacy of the Nance appliance as an anchorage reinforcement method in orthodontics and to evaluate the amount of desired tooth movement and anchorage loss over a period of 15 weeks. The mean amount of desired tooth movement was approximately the same in the control (5.09 mm) and Nance (5.38 mm) group after 15 weeks. The mean amount of anchorage loss on the other hand was higher in the control group (3.96 mm) than in the Nance group (2.03 mm) after 15 weeks.

The current study differs from previous studies on anchorage loss (human and dog subjects) in 2 respects. Firstly, previous studies investigated anchorage loss by assessing tooth movement at the end of treatment and then comparing it to that at the start of treatment (Fortin, 1971; Williams & Hosila, 1976; Pilon *et al.,* 1996; Saelens & De Smit, 1998; van Leeuwen *et al.,* 1999; Ong & Woods, 2001; Geron *et al.*, 2003; Shpack *et al.*, 2008). The present study provides data for 3 intervals at 5, 10 and 15 weeks following treatment commencement in beagle dogs. Previous studies have found that the lag phase lasted 20-30 days (Reitan, 1957; Pilon *et al.* 1996) and the linear stage started after 80 days (von Böhl *et al.* 2004a). Thus, the current study provides information about the variation in anchorage loss over the three tooth movement stages (lag, post lag and linear phase) and whether it is greater at any particular tooth movement stage during treatment. In addition, the amount of desired tooth movement associated with the different anchorage protocols over time was recorded. Secondly, anchorage loss in earlier studies was recorded using putative stable points on study models (Ong & Woods, 2001; Geron *et al.*, 2003; Shpack *et al.*, 2008) or serial radiographs (Williams & Hosila, 1976; Saelens & De Smit, 1998; Ong & Woods, 2001; Geron *et al.,* 2003). Such methods have been found to have limitations in accurately assessing anchorage loss (Section 1.5.3). Mannchen (2001) found the maxilla and the functional occlusal plane used in the radiographic methods rotated during treatment

and, as a result, affected the accuracy of the measurement. Geron and co-workers (2003) found the reference points used in the studies utilizing study models moved during treatment and recommended avoiding points located on the dental arch. A more accurate method using stable reference points, such as implants, is required (Majzoub *et al* 1999). For this reason, the current study used miniscrews within the dental arch as a reference to measure tooth movement. It is now accepted that miniscrews osseointegrate and thus are stable over time (Melsen & Costa, 2000; Deguchi *et al.,* 2003).

Perhaps a significant limitation of research conducted on human subjects to assess anchorage loss relates to the myriad of unconsidered factors affecting tooth movement during treatment in the study design (Geron *et al.*, 2003; Feldmann & Bondemark, 2006). This obviously has a great impact on the accuracy of the results. These factors include patient compliance factors, treatment factors, malocclusion factors and patient related factors. Compliance factors such as wearing elastics can influence the result (Harris *et al.*, 1991; Hart *et al.*, 1992; Dincer & Iscan, 1994; Rajcich & Sadowsky, 1997; Geron *et al.*, 2003). Treatment factors include different mechanical approaches (Harris *et al.*, 1991; Geron *et al.*, 2003) and treatment objectives that also influence anchorage loss. Malocclusion is another critical factor (Geron *et al.*, 2003) influencing tooth movement both directly or indirectly; directly in cases where there is occlusal interference (Alexander *et al.*, 1983) impeding or reducing tooth movement. Malocclusion influences tooth movement indirectly in cases where differences in treatment strategies result from underlying variability in patient malocclusions. There are also other patient related confounding factors which may include metabolic turnover (Pilon *et al.*, 1996), cell biology (Iwasaki *et al.*, 2000) and bone quality (Reitan, 1964; Fortin, 1971; Mitchell *et al.*, 1973; Roberts *et al.*, 1990; Roberts, 1994; Geron *et al.*, 2003).

In an attempt to overcome some of the limitations above, animals were used in this study. Beagle dogs are generally accepted as appropriate models for comparison with

human beings (Pilon *et al.*, 1996) despite their generally more dense alveolar bone (Reitan & Kvam, 1971). Using a dog model for orthodontic tooth movement has many advantages (Ren *et al.*, 2004). These advantages are anatomical, physiological and mechanical. There are no major differences in the size and anatomy of the periodontal ligaments and alveolar bone between dogs and humans, which makes them a suitable model for tooth movement (Pilon *et al.,* 1996). von Böhl & Kuijpers-Jagtman (2009) in a systematic review found no major differences in tissue reaction between species during experimental tooth movement. The rate of movement and the optimum force should be considered when assessing tooth movement. Optimum force is the force which can produce maximum tooth movement with minimum damage (Storey & Smith, 1952). Using data from previous studies on animal and humans, Ren and colleagues (2004) found a similar maximum rate of tooth movement in dogs (0.27 mm/week) and humans (0.29 mm/week) despite the dogs having slightly more dense bone than humans (Reitan & Kvam, 1971). They also found that the difference between the maximum force (optimum force) to produce the maximum rate of tooth movement in dogs (248 cN) and humans (272 cN) was statistically insignificant. This was unexpected since the root surface area for the most commonly used tooth (second premolar) in beagle dogs is 1 cm^2 whereas it is 2.9 cm^2 in the most commonly used tooth in human studies (canine). They proposed two explanations for this large variation on the pressure produced per cm. The first was that the rate of bone turnover, which controls the rate of tooth movement, induced by mechanical stress is not species-specific. The second explanation was that most human studies produced tipping movement whereas in the animal studies the type of movement was well controlled to produce bodily movement. This resulted in the force being distributed over a larger surface of the root compared to the tipping movement in humans where the force was concentrated on the cervical and apical portions of the root. Ren and colleagues (2004) found that the data available from the current studies were limited with regard to the range of forces applied and that more

studies with larger force range are required to clarify the issue of the maximum force and maximum tooth movement. Ren and colleagues (2004) and Melsen (2007) did not find a universally accepted optimal force and concluded that the answer for the optimal force remains unresolved.

The duration of the human studies was limited by ethical and treatment considerations. For example, Hixon and co-workers (1969) had to terminate the study earlier as it was affecting the overall treatment time of one of the patients. Ren and colleagues (2003a) suggested that the lengths of the previous human studies were too short to accurately evaluate the effect of force on tooth movement. Human studies, which assessed tooth movement rate, were limited to the post lag phase of tooth movement (Storey & Smith, 1952; Lee *et al.,* 1965; Hixon *et al.,* 1969; 1970; Boester & Johnston, 1972; Owman-Moll *et al.,* 1996a, b; Iwasaki *et al.,* 2000; Yee *et al.,* 2009). These human studies may have failed to assess the relationship between force and tooth movement, since the linear phase of tooth movement starts after 80 – 85 days of initiating tooth movement (Pilon *et al.,* 1996; von Böhl *et al.,* 2004a). In the dog model, the overall treatment was not a consideration, and as a result, the observation period was longer than all the human studies which assessed tooth movement (Table 1-1).

A further advantage of using a dog model was that inbred dogs showed little genetic variation. This may reduce variation in the rate of tooth movement and thus making it easier to assess the effect of the appliance on the rate of tooth movement. Pilon and co-workers (1996) found twin dogs produced similar rates of tooth movement.

Using a dog model offered a mechanical advantage as well. The ability to make standardised and custom made appliances to produce bodily tooth movement was one of the main advantages, as this reduced the variables associated with human studies. Hart *et al.* (1992), Dincer & Iscan (1994) and Rajcich & Sadowsky (1997) found anchorage loss was reduced when different mechanics were applied. It is therefore essential to try to have

standardised mechanics during the study. The archwire sequence, force magnitude and activation period can be well controlled in the dog model, whereas in the human model this creates clinical or ethical problems. Harris and co-workers (1991) and Geron and colleagues (2003) found orthodontic mechanics during treatment to be more important than bone density. The current study had the advantage of having a control group. Tooth movement in the control group was without any anchorage reinforcement, treatment objectives or limitations, unlike many human studies. Another significant advantage was the absence of occlusal interferences associated with human studies, which can influence anchorage (Alexander *et al.,* 1983).

2.4.1 *Desired tooth movement (DM)*

Tooth movement was observed within each group over a total of 15 weeks. During this time tooth movement was measured at three intervals: 5 weeks (T1), 10 weeks (T2), and 15 weeks (T3). The pattern and amount of desired tooth movement was analysed.

The desired tooth movement in both groups (control and Nance) increased continuously over the 15 weeks period, but the pattern of increase was different. In the control group the tooth movement was not statistically significant from T1 to T2 but was significant between the T2 and T3 ($p<0.01$). On the other hand, the Nance group desired tooth movement, was statistically significant between (T1-T2) and (T2-T3). In spite of the different patterns between both groups (control and Nance), the overall amount of tooth movement was similar in both groups (5.09 and 5.38 mm). This was because the rate of desired tooth movement in the Nance group reduced at T3 whereas in the control group it increased. The rate of tooth movement has been found to range from 0.68 mm to 1.55 mm per month (Hixon *et al.*, 1969; Boester & Johnston, 1974; Ren *et al.,* 2004). In the present study the mean rate of tooth movement over the 15 weeks was similar to the previous studies, 1.45

mm per month for the control group and 1.53 mm for the Nance group. The mean rate of tooth movement however changed at the different time periods.

At T1 (5 weeks), both groups (control and Nance) had a similar mean amount of desired tooth movement (1.1 mm and 1.23 mm). At T2 (10 weeks), the control group (2.46 mm) had less amount of desired tooth movement than the Nance group (3.96 mm). Since the force levels were checked every 5 weeks to ensure they were constant at the beginning of each period, the different pattern in the rate of tooth movement (control - 1.36 mm and Nance – 2.73 mm) could be due to the inclusion of the Nance appliance. Thus, it can be speculated that the introduction of the appliance may have affected the force distribution and magnitude, resulting in a slower rate of tooth movement at 10 weeks (T2) in the control group. The force distribution would have changed once the Nance appliance was introduced, as some of the forces would be transmitted to the cortical bone through the acrylic button attached to the fourth premolars (PM_4). Therefore, the force on the PM_2 may have been less in the Nance group and consequently had a shorter lag phase of tooth movement (Fortin, 1971; King & Fischlschweiger, 1982; Iwasaki *et al.*, 2000). Alternatively, the force levels may have been higher on the PM_2 within the Nance group than the control group. This could have been as a result of the PM_4 moving less in the Nance group compared to the control group. The space reduction and consequently the force reduction were less in the Nance group after 10 weeks (T2) time period compared to the control group. This was the result of the anchorage reinforcement provided by the Nance appliance which reduced the PM_4 movement. This is in agreement with the previous studies, which have shown that higher forces produced a higher rate of tooth movement (Storey & Smith, 1952; Hixon *et al.*, 1969; 1970; Boester & Johnston, 1972; Owman-Moll *et al.*, 1996b; Iwasaki *et al.*, 2000; Yee *et al.,* 2009). Thiruvenkatachari and co-workers (2008) found similar differences in the rate of tooth movement, when they compared the rate of canine retraction in a miniscrew enforced anchorage group and a molar enforced

anchorage group. Thiruvenkatachari and colleagues (2008) attributed the faster rate of canine retraction in the miniscrew group, compared to the molar anchorage, to the loss of anchorage (molar movement) in the control as well. The force decay associated with the NiTi coil spring has been suggested by the manufacturers is within the range of 20 g/ 1 mm reduction in its length. Gonzales and colleagues (2008) tested the NiTi coil springs and found a force difference of 10 g with 0.6 mm change in length after 28 days. The problem resides in the fact that all the studies measured the force at the application point rather than at the PDL. The introduction of the Nance appliance may have thus altered the strain on the PDL despite having the same force at the point of application (brackets).

At T3, both the control and Nance groups had a similar mean amount of desired tooth movement (5.09 mm and 5.38 mm respectively). The rate of tooth movement increased for the control group whilst it reduced in the Nance group after 10 weeks (T2). This is demonstrated in figure 2-18 where the incremental increase (mean difference) of desired tooth movement in the Nance group (1.42 mm) reduced, whilst in the control group (2.63 mm) it increased at 15 weeks. This reduction in movement for the Nance group could be due to the higher hyalinization areas with the heavy forces (Reitan, 1957; Fortin, 1971; Pilon *et al.,* 1996; Iwasaki *et al.*, 2000) or due to tooth movement reaching the biological limit (Quinn & Yoshikawa, 1985; Pilon *et al.,* 1996; Ren *et al.,* 2004), and as a result started to reduce. On the other hand, the control group had not reached the biological limit and therefore the rate of movement increased. Roberts and co-workers (1981) suggested that 3 mm per month is the maximum biological limit for tooth movement. This may be a transient phase for the Nance group and once the hyalinization areas were removed, the rate may increase again if the study was conducted over a period longer than 15 weeks.

This different pattern between the control and anchorage reinforcement group was not observed in the previous human studies assessing the rate of tooth movement because the

duration of the studies was less than 70 days, which fell within the first 10 weeks of the observation period in the present study. At the end of the human studies (< 10 weeks) they found a difference in the rate of tooth movement when a higher force group was compared with a lower force group. Most human studies found higher forces produced higher rates of tooth movement, which is similar to the present study after 10 weeks. The Nance group in the present study had more tooth movement than the control group after the 10 week time point. Since the observation periods in most human studies did not extend beyond 10 weeks, they may have failed to observe the changes in the rate of movement (reduced rate of movement in the Nance group and increased rate of movement in the control) observed in this study after the 15 week time point. An exception to the previous human studies on tooth movement was Yee and co-workers (2009) study, which spanned 84 days (12 weeks). Yee and co-workers (2009) showed similar patterns of tooth movement (canine retraction) to that of the current study. After 4 weeks, the difference between the heavy and light force groups was not significant but the difference became significant after 8 and 12 weeks with more tooth movement occurring in the heavier force group. The difference in the rate of tooth movement between the higher and lower forces at the end of the Yee and colleagues (2009) study was larger than the current study though (1 mm). This could have been due to the inability to control the tipping and rotation movements in the heavy force group, which the authors highlighted as a limitation of their study. Consequently, the difference between the two groups in Yee and colleagues' study could have been exaggerated. A rat study by Gonzales and co-workers (2008) observed the amount of tooth movement associated with different forces levels (10 g, 25 g, 50g and 100 g) at three time intervals. They found forces of 25 g and 50 g produced more tooth movement than a force of 100 g after 14 days (second time interval). After 3 days (first time interval) and 28 days (third time interval) the amount of tooth movement was similar for the 3 different force levels. The authors did not explain the reason for such a difference at the second time

interval. Gonzales and co-workers (2008) and the current study had similar patterns of tooth movement. Significant difference in the amount of tooth movement was observed at the second time interval whilst the amount of tooth movement at the first and last time interval was similar. This may suggest that a different force level may affect tooth movement during the transition from the lag to post lag phase (Fortin, 1971; King & Fischlschweiger, 1982; Iwasaki *et al.*, 2000).

In conclusion, there was a significant difference ($p=0.03$) between the control and Nance groups at the 10 week time point (the desired tooth movement was more in the Nance group) but there was no significant difference at the 15 week time point. In clinical terms, both groups had similar efficacy in achieving the desired tooth movement after 15 weeks. However, the percentage of desired tooth movement to the total space closure was significantly different between the two groups at 10 and 15 weeks ($p<0.01$ and $p<0.05$). This was because the percentage of total tooth movement comprised the amount of anchorage loss and the amount of desired tooth movement associated with both groups (control and Nance) (see below).

2.4.2 *Anchorage loss*

2.4.2.1 Comparisons within groups (Control & Nance)

The anchorage loss was observed over 15 weeks and was measured at 5 weeks (T1), 10 weeks (T2) and 15 weeks (T3). Although, anchorage loss occurred in both groups, the patterns were different. Anchorage loss in the control group occurred at the 3 time points (0.99 mm, 2.26 mm, and 3.96 mm respectively) with a statistically significant increase between each period ($p<0.01$). On the other hand, anchorage loss occurred over the 3 time points in the Nance group (0.64 mm, 1.63 mm, and 2.03 mm) but with a statistically significant increase ($p<0.01$) between time points T1 and T2 only. The incremental

increase (mean difference) of anchorage loss in the control group was the highest between time points T2 and T3 (1.7 mm) whereas it was the lowest (0.4 mm) in the Nance group for the same period. Therefore, the majority of anchorage loss in the Nance group occurred during the first 10 weeks. The possible clinical implications of this include the avoidance of any excessive strain on anchorage at this particular period (first 10 weeks). The initial anchorage loss observed may be explained by the acrylic button in the Nance appliance having been initially in contact with compressible soft tissue. Later in the process, the compressed soft tissue may form a stable platform with underlying cortical bone. Another factor which could be responsible for anchorage loss could be the deformation of the wire, as a similar deformation was responsible for anchorage loss in the Orthosystem® (Wehrbein *et al.,* 1996b). It is possible that once the Nance wire reached its elastic limit and the soft tissue became compressed by the acrylic button, the incremental increase in anchorage loss became insignificant between the 10 and 15 weeks time points. The arch shape must also be considered, as it is also possible that the dogs' V-shaped arch may allow the posterior anchor teeth to rotate with the centre of rotation being the acrylic button of the Nance appliance. Once the rotated teeth start to move against the buccal or palatal cortical bone, the anchorage potential of the appliance is restored as the cortical bone provides more resistance to tooth movement (Reitan, 1964; Roberts *et al.,* 1990). In conclusion, the anchorage loss for the Nance appliance occurs mainly during the first 10 weeks and extra precautions may be warranted during this period to avoid unwanted tooth movement and a compromised treatment result.

The percentage of total tooth movement that comprised anchorage loss and the amount of desired tooth movement was inversely related. Thus, if the percentage of anchorage loss reduced, this could have been due to reduced amount of movement in the anchor teeth but also could have been due to increased desired tooth movement. The percentage of desired tooth movement in the control group stayed relatively the same at the three time points 5

weeks, 10 weeks and 15 weeks (60%, 45.1% and 54.5%) with no statistical significance. The mean percentage of anchorage loss in the control group was 40% and increased by approximately 15% before returning to 45.7% over the 3 observation time points (5, 10 and 15 weeks). The increase in the percentage of desired tooth movement and the reduction in the percentage of anchorage loss after 10 weeks were because there was more desired tooth movement (2.63 mm) than anchorage loss (1.7 mm) over the last 5 weeks (T3). The changes over time were statistically insignificant.

The mean percentage of anchorage loss reported in the control group was similar to anchorage loss (50%) reported by Fortin's (1971) dog study. Fortin (1971) found 50% anchorage loss when the second premolars were retracted for approximately 13 weeks following the extraction of the third premolars. Fortin (1971) tied the fourth premolar with the first molar using an orthodontic wire to form an anchor unit. They found the anchor unit moved as much as the second premolars. Although comparisons to human studies are difficult because of the different mechanics used and treatment objectives in human studies, it is interesting to note that anchorage loss in the control group in the current study was similar to the anchorage loss (45-50%) reported in human studies when the first molars or first premolars were extracted (Williams & Hosila, 1976; Ong & Woods, 2001; Geron *et al.,* 2003, Yee *et al.,* 2009). When anchorage loss in the control group in the present study was compared to a previous human study (Geron *et al.,* 2003) study, it was 3.96 mm for a total 9 mm of space closure in the current study and 3.9 mm for a total of 7 mm of space closure in the human study (Geron *et al.,* 2003). The mean percentage of anchorage loss in the control group in the present study was 45.7% whilst it was 55% in Geron and colleagues (2003) study. Perhaps the anchorage loss in the current study was more than expected, since the root surface area ratio for the anchor teeth in the current study is not 50:50. This was also found by Pilon and his co-workers in 1996 when they found 25% anchorage loss in their study. The root surface area of the anchor unit (fourth

premolar and the canine) in the beagle dogs was 10 times more than the second premolar (Pilon *et al.,* 1996). Therefore, it would have been expected that the anchorage loss would be 10 times less in the animal study if the root surface area was the only factor responsible for determining the amount of anchorage loss. This was also found in human studies where the root surface area of the first molar and second premolar in humans is 2.5 times that of the canines (Jepsen, 1963). Thus, the root surface area ratio is 10:1 in beagle dogs and 2.5:1 in humans. It is apparent that other factors such as crowding (Geron *et al.*, 2003), inter-occlusion (Alexander *et al.*, 1983), and mechanics (Harris *et al.,* 1991; Geron *et al.*, 2003) may play a bigger role and as a consequence the percentage anchorage loss in the human study was influenced by these factors. Although the larger anchor teeth in the current study did move less than the smaller retracted teeth, the movement was not proportional to the root surface area ratio. This may suggest what the previous studies have shown; that root surface area was a factor in anchorage loss but there were other contributing factors and the extent of the relationship between root surface area and anchorage is not clear (Pilon *et al.*, 1996).

The mean percentages of anchorage loss (33.8%, 33% and 28.8%) in the Nance group remained relatively the same after 5, 10 and 15 weeks and the differences over time were statistically not significant. The slight reduction in the percentage of anchorage loss from 10 weeks to 15 weeks was due to the combination of both, the reduction of PM_4 rate of movement (anchorage loss = 0.40 mm) and the continuous movement of PM_2 (desired tooth movement = 1.42 mm) At T3. As a result, the mean percentage of anchorage loss was similar after 5 weeks (T1).

The Nance group in the current study had 2.03 mm anchorage loss for a total of 7.41 mm of space closure whilst Shpack and colleagues' 2008 human study found 1.4 mm anchorage loss for a total of 7 mm of space closure. Thus, the mean percentage of anchorage loss in the Nance group in the current study was 28.8% whereas it was 20% in

the Shpack and colleagues study (2008), despite the alveolar bone being more dense in beagle dogs. This may as well as being due to species and morphological differences, may be partly explained by factors such as interocclusal interference (Alexander *et al.,* 1983). In the human study the teeth interoccluded, which may reduce anchorage loss, whereas in the animals they did not. Furthermore, the patients in Shpack's 2008 study required the extraction of the first premolars and consequently the mechanics (Hart *et al.*, 1992; Dincer & Iscan, 1994; Rajcich & Sadowsky, 1997) used may have been designed to reduce the anchorage loss. This may support the findings of earlier studies: orthodontic mechanics during treatment may play a more decisive role than cortical bone in controlling anchorage. This issue may have been resolved if Shpack and co-workers (2008) had evaluated the difference in anchorage loss between a control and a Nance group, as is the case in the current study.

2.4.2.2 Comparisons between groups (Control Vs Nance)

Anchorage loss was significantly different (1.93 mm – $p< 0.01$) between the two groups at the end of the 15 weeks study. There was a mean total of 3.96 mm anchorage loss in the control group compared to 2.02 mm in the Nance group. As there was no study in the literature comparing anchorage loss with and without the Nance appliance, Shpack and colleagues (2008) compared their results (1.4 mm) with those of Geron and co-workers (2003) (3.9 mm). Shpack and colleagues (2008) found a 2.5 mm difference between their results using a Nance appliance and those of Geron and co-workers (2003), where no anchorage enforcement was used. However, there are two important limitations with this method of cross-study result comparison. Firstly, in Shpack and colleagues' 2008 study the anchorage loss was assessed once the canine was retracted, whereas in the Geron and colleagues' 2003 study anchorage was assessed at the end of treatment where the incisors were retracted as well as the canines. Therefore, caution should be exercised in interpreting

studies carried out under different conditions and circumstances. In particular, the validity of the comparison must be questioned as the anchorage loss was assessed at different stages of treatment, which invariably affects overall results. Secondly, the sample in both studies was not matched with regard to malocclusion and crowding, which Geron and co-workers (2003) acknowledged as an influencing factor. The current study may better represent the amount of anchorage loss associated with the Nance appliance, since both groups were matched and controlled for a similar number of teeth, stage of treatment, malocclusion, and mechanics. In conclusion, the Nance appliance provided a significant advantage ($p<0.01$) after 15 weeks and the null hypothesis was rejected.

The percentage of anchorage loss for the control and Nance groups at the 15 week time point was 45.7% and 28.8% respectively. The difference between the percentages of anchorage loss for the control and Nance group were statistically significant at the 10 (21.8%) and 15 (16.9%) week time points ($p<0.01$ and $p=0.03$ respectively). The differences between the percentages of desired tooth movement for both groups (control and Nance) were significant at 10 and 15 weeks ($p<0.01$ and $p=0.04$). Anchorage loss in the Nance group reduced over time whereas in the control group there was an increase over the first 10 weeks but subsequently, as the desired tooth movement increased, the anchorage loss percentage reduced. Even though the percentage of desired tooth movement increased in the control group over the last 5 weeks, the percentage of anchorage loss in the control group was still more than in the Nance group.

2.4.3 *Limitations*

It is important to understand the limitations associated with this study and the application of the findings of the present study to a clinical situation. Inherently, as this study was done on different species the compatibility with humans is immediately

questioned. These limitations include anatomical, physiological, and mechanical factors. Although it was found that the force and the rate of tooth movement were similar in human and dogs, despite the difference in bone density (Reitan & Kvam, 1971), the effect on anchorage is unknown. Reitan (1964) and Roberts and colleagues (1990; 1994) suggested that increased bone density could increase the anchorage potential but this has not been substantiated. This could have an effect on the anchorage; directly on the tooth movement or indirectly on the Nance acrylic button. In both cases, the increased bone density in dogs would resist the movement of the tooth and the Nance appliance, therefore increasing the anchorage potential. Another anatomical limitation was the difference between the root ratio of the retracted teeth and the anchorage unit. In humans, the canine or the premolar root surface area is 3.02 cm^2 and 2.3 cm^2 respectively, whilst the molar is 5.25 cm^2. On the other hand, the dog's second premolar root surface area is 1 cm^2 and the fourth premolar is approximately 2 cm^2. This could influence the amount and percentage of anchorage loss associated. Although, the ratio of anchorage loss was not directly related to the amount of root surface area (Pilon *et al.*, 1996; van Leeuwen *et al.*, 1999; Geron *et al.,* 2003), it could still have an influence and this has to be taken into consideration. As this study had a control with no anchorage auxiliary, the percentage of anchorage advantage provided by the appliance can be determined, and this percentage could be applied to clinical situations rather than the amount.

Mesial migration of the dentition in humans should also be considered. During occlusal function it is believed that a portion of occlusal forces would be directed anteriorly (Southard *et al.,* 1990). This is called anterior component of force (AFC) and is thought to cause tipping of the posterior teeth. Moreover, more tipping would occur if there is no interproximal contact. This is not the case in dogs as the upper and lower premolars do not interdigitate. Saito *et al.* (2000) found unloaded fourth premolars did not move in dogs

over 32 weeks. The AFC in humans could affect the anchorage balance and this should be taken into consideration.

Using the mandible in the dog model as opposed to the maxilla, where the Nance appliance is usually used, could also influence the amount and ratio of anchorage loss. This could be due to the shape of the arch and the rate of tooth movement. The mandible would have a deeper shape anteriorly which could provide more resistance to movement compared to the more flat palatal rugae area. The shape and size of the acrylic button in the Nance appliance may also have been different in the dog model as a result of the different size of the dog mandible. The size of the acrylic was investigated by Bondemark & Thorneus (2005) and found it had no influence on the amount of anchorage loss. Tooth movement in the maxilla and the mandible of humans was compared. Hixon and colleagues (1970) found the maxillary canines moved at faster rate, whilst Boester & Johnston (1974) found no difference. Ren and colleagues (2004) suggested there is no difference in the rate of tooth movement between the maxilla and the mandible, as the difference in the Hixon and colleagues (1970) study was not statistically significant and they pooled the data from both the maxilla and the mandible together. Furthermore, the mandible in dogs is triangular in shape which might offer more anchorage compared to a more rectangular shaped mandible in humans.

Occlusal interlocking was another factor which could have affected the anchorage loss. In the dog model, the premolars do not interlock whereas in the human dentition the teeth do interlock (Figure 2-26). Alexander *et al.* (1983) found disoccluded teeth had more anchorage loss whilst Geron *et al.* (2003) found no difference. However, they both recommended that more studies are required to investigate the effect of occlusal interlocking on anchorage.

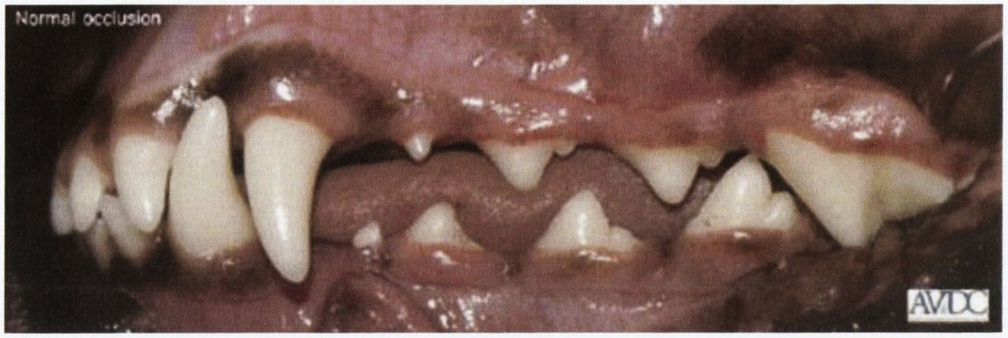

Figure 2-26. The beagle dog's normal occlusion.
(Taken from http://www.colliesonline.com/july2011/dental-1-070911.php)

The appliance used in the study was also different from the clinical situation. The appliance was custom made with 1 mm round wire which will promote bodily tooth movement. This is not the case in a true clinical situation and anchorage loss could be different. The advantage of controlling the type of tooth movement was, to provide more accurate measurements of tooth movements (Ren *et al.,* 2003a). The uneven distribution in force and movement of the crown and root, makes comparisons between studies and interpretation of the findings difficult (Ren *et al.,* 2003a). Therefore it was advantageous to exclude the tipping movements present in clinical situations as much as possible.

The duration of the study should be considered. The changes observed were for 15 weeks only, whilst orthodontic treatment is usually much longer and anchorage loss could change during the course of treatment. Although anchorage loss may occur during any stage of orthodontic treatment, anchorage is mainly required when teeth are retracted into extraction spaces. This would usually take 3-4 months during orthodontic treatment after the levelling and alignment phase of treatment. Therefore, for the purpose of this study, it provided valuable information about the anchorage loss occurring during the tooth retraction phase of orthodontic treatment.

2.4.4 *Conclusion*

The current study has demonstrated the significant advantage of the amount and percentage of anchorage gained with the Nance appliance. This tended to improve over time with the Nance group whereas in the control group, anchorage is compromised further as the treatment proceeds. Thus, the first 10 weeks seems to be critical as the majority of anchorage loss in the Nance group occurred during this interval. In conclusion, both groups (control and Nance) had a similar amount of desired tooth movement (5.09 mm and 5.38 mm) but the Nance appliance provided the clinician with a significant amount (1.93 mm) of anchorage advantage after 15 weeks. In addition, the Nance provided a significant percentage of anchorage (21.8% and 16.9%) and desired tooth movement (21.8% and 16.6%) at 10 and 15 weeks respectively.

3 The efficacy of the miniscrew as an anchorage reinforcement method

3.1 Introduction

Skeletal anchorage is derived from devices such as conventional implants, palatal implants and miniscrews. Conventional implants and palatal implants have been shown to resist orthodontic loading without any loss in their positional stability (Roberts *et al.,* 1984; Wehrbein *et al.,* 1997; Saito *et al.,* 2000). Miniscrews are loaded immediately during orthodontic treatment and initially resist orthodontic loading by their mechanical retention rather than osseointegration (Costa *et al.,* 1998; Cope, 2005; Wang & Liou, 2008). The miniscrews have been shown to osseointegrate but to a lesser extent than palatal implants (Deguchi *et al.,* 2003; Wehrbein *&* Gollner, 2009). Park *et al.* (2006) suggested that excessive loading of partly osseointegrated miniscrew may result in loss of stability, so the behaviour of miniscrews under orthodontic loading is not clear.

Several studies found miniscrews moved 1-2 mm following orthodontic loading, despite being stable at the end of orthodontic treatment (Liou *et al.,* 2004; Wang & Liou, 2008; Garfinkle *et al.* 2008; El-Beialy *et al.* 2009). The previous studies highlighted the anchorage loss associated with miniscrews but they did not provide any information about the time frame which such anchorage loss occurred. Anchorage loss may occur during the initial stages only, or could have occurred gradually. Another aspect which has been mentioned in the literature is the amount of desired tooth movement which may occur with such anchorage reinforcement methods. Thiruvenkatachari *et al.* (2008) was the first to compare the desired tooth movement with and without any anchorage reinforcement. Thiruvenkatachari *et al.* (2008) found more desired tooth movement with miniscrew anchorage reinforcement. The desired tooth movement was measured at the end of the treatment, which varied from one subject to another and was influenced by the amount of

anchorage loss. The aim of the current study was to assess the amount of anchorage loss and desired tooth movement associated with miniscrews at 3 time points (5, 10 and 15 weeks) and compare it with a control group with conventional molar anchorage reinforcement in a dog model.

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3.2 *Materials and methods*

3.2.1 *Study outline*

Under Irish Government License No. B100/3896 issued by the Department of Health and Children in Ireland, the mandibular premolar regions (PM_3) of 6 adult male beagle dogs were used in the study with a mean age of 15 ($\pm$ 2.9) months and mean weight 12.5 ($\pm$ 1.7) kg. Ethical approval was sought and granted by the Trinity College Bio Resources Ethics Committee (Ref. 161106B). The study protocol was in accordance with the Department of Health policies and regulations on animal care. The animals were fed a soft diet throughout the duration of the experiment and instructions were given to carers to avoid hard chewy foods, treats or toys.

3.2.2 *Anaesthetic procedure & extractions.*

The dogs were first anaesthetised and then the mandibular PM_1 and PM_3 were extracted bilaterally to facilitate orthodontic space closure and the insertion of the miniscrews. The protocol used for the pre anaesthesia care, anaesthesia induction and maintenance was similar to the procedure used in the previous study and was outlined in section 2.2.2. In addition, the extraction procedure, the post extraction care and the 3 months waiting period were also similar to the previous study and were outlined in section 2.2.3.

3.2.3 *Group allocation*

The animals were divided into 2 groups; 3 dogs were allocated to the control group and 3 dogs were allocated to the miniscrew group. The three dogs used in the control group in the previous study were utilized in this study to act as the control group whereas the miniscrew group had 3 new dogs. The 2 groups were divided based on the anchorage method used. Anchorage was achieved with miniscrews in the miniscrew group whereas the control group had the PM_4 as an anchor (Table 3-1).

Table 3-1. The outline of the study (efficacy of the miniscrew as an anchorage reinforcement method)

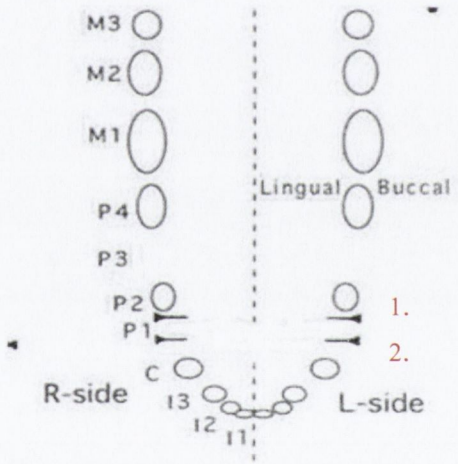
	Number of animals	Tooth retracted	Anchorage	grams (g)
Control group	3	Second premolar	Fourth premolar	150
Miniscrew group	3	Second premolar	Miniscrew	150

3.2.4 *Impressions & band fabrication*

Impressions were taken to fabricate the custom made bands for the orthodontic appliance used to achieve orthodontic tooth movement in both groups. Each tooth was cleaned prior to taking impressions as described in section 2.2.5. Disposable sectional aluminium trays (Kwik-Tray, KerrHawe SA., Via Strecce, 4, CH- 6934 Bioggio, Switzerland) were used to make impressions of each side of the mandible. A combination of putty and light body polyvinylsiloxane impression (PRESIDENT, Coltène/Whaledent AG, Feldwiesenstrasse 20, 9450 Altstatten/Switzerland) was used as outlined in section 2.2.5.1. A total of 12 impressions of this type were made. The impressions were then disinfected, labelled and poured in type IV (high strength and low expansion) dental stone (Jade Stone, Whip Mix Corporation, 361 Farmington Avenue, Louisville, KY 40217, USA) to construct the bands used in the orthodontic appliance (see section 2.2.5.1). Bands were cast using Vitallium® 2 Alloy (DENTSPLY, Elephant Dental B.V., Verlengde Lageweg 10, 1628 PM Hoom, The Netherlands) to fit the PM_2 and PM_4 in both groups. Reference points and hooks were incorporated, as outlined in section 2.2.6, to record tooth movement and to apply traction respectively. The inner aspect of each band was sandblasted prior to cementing them using PANAVIA™ F 2.0 (Kuraray Europe GmbH, Medical Products Division, Hoechst Industrial Park/F 821 65926 Frankfurt, Germany) while the animals were anaesthetized (section 2.2.8).

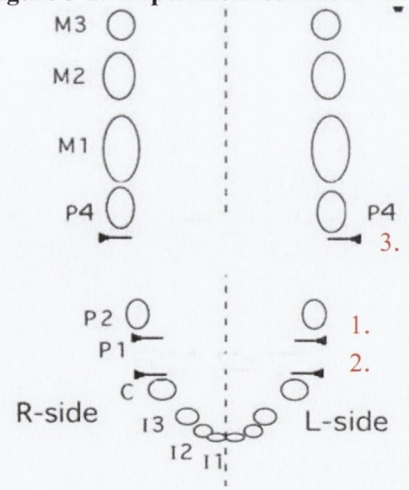
3.2.5 *Miniscrews*

A total of 30 Ti-6Al- 4V ELI (Titanium – 6 Aluminium- 4 Vanadium ELI alloy) self drilling (1.3 mm width x 7 mm length) tapered miniscrews (Absoanchor®, Dentos, UK) were used in the study. Two miniscrews were placed in the PM_1 region in each animal (Figure 3-1). As outlined in section 2.2.9, one of the miniscrews was the reference (RMs) for all distance measurements that were carried out while the other miniscrew was placed to monitor the positional stability of the reference miniscrew. In the miniscrew group, active miniscrews (AMs) were placed just mesial to the PM_4 (Figure 3-2). The AMs were used as anchorage in the application of distal force to the PM_2. The miniscrews were placed with anaesthesia and local infiltration as described earlier (section 2.2.10).



1. **Reference miniscrew (RMs)**
2. **Miniscrew to monitor positional stability**

Figure 3-1. Experiment outline in the control group (modified from Ohmae et al. 2001)



1. **Reference miniscrew (RMs)**
2. **Miniscrew to monitor positional stability**
3. **Active miniscrews (AMs)**

Figure 3-2. Experiment outline in the miniscrew group (modified from Ohmae et al. 2001).

3.2.6 *Force application and space closure*

The animals in both groups had a segmental 1 mm SS arch wire placed between the PM_2 and PM_4. The ends of the wire were bent in to prevent the wire from sliding out of the appliance. Tooth movement was initiated two weeks following miniscrew placement using 3 mm nickel titanium (NiTi) coil springs (Sentalloy ®; medium, GAC International Inc, Bohemia, NY). In the control group a wire ligature was used to tie the NiTi springs to the hooks on the PM_2 and PM_4 bands (Figure 3-3). In the miniscrew group the NiTi springs were tied to the hooks on the PM_2 in one end and to the AMs on the other end (Figure 3-4). The force was calibrated to 150 g using CORREX tension gauge (HAAG-STREIT AG, Gartenstadtstrasse 10 CH-3098, Koeniz/Switzerland). The CORREX tension gauge had a range of 50 to 500 g and a resolution of 20 g.

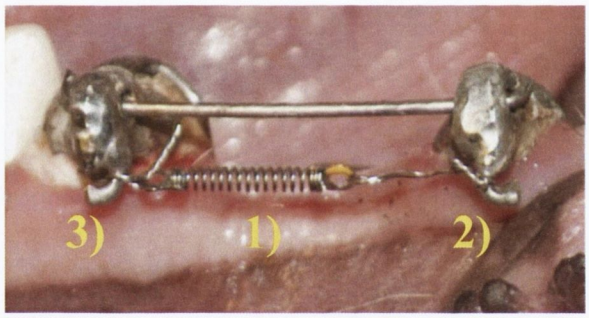


Figure 3-3. A buccal view of a NiTi coil spring (Sentalloy®; GAC International Inc, Bohemia, NY) (1) attached to hooks on the PM_2 (2) and PM_4 (3) bands, using 0.01-inch SS wire ligatures, during space closure in the control group.

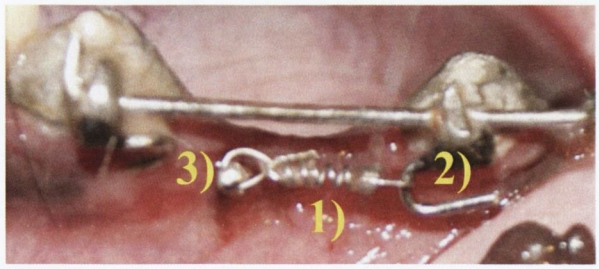


Figure 3-4. A buccal view of a NiTi coil spring (Sentalloy®; GAC International Inc, Bohemia, NY) (1) attached to the hook (2) on the PM_2 band and the active miniscrew (AMs) (3), using 0.01-inch SS wire ligatures, during space closure in the miniscrew group.

Once activated, the springs were checked weekly to ensure that they were active. The springs were reactivated every 5 weeks simulating the clinical situation during orthodontic

space closure. The orthodontic appliance, teeth, and gingiva were thoroughly cleaned twice a week with a toothbrush and gauzes soaked with 0.2% chlorhexidine.

3.2.7 *Measuring the displacement*

A digital caliper ABSOLUTE (Moore & Wright LTD, Bowers Metrology Ltd, Bradford, West Yorkshire, BD3 8HU, UK) was used to measure the movements. The caliper had a resolution of 0.01 mm.

In the control group the distances between the reference miniscrews (RMs) and the reference points on PM_2 and PM_4 bands were measured prior to force application ($PM_{2(T0)}$ and $PM_{4(T0)}$) (Figure 3-5). In the miniscrew group the distance between the RMs and the PM_2 and AMs were measured prior to force application ($PM_{2\ (TO)}$ and $AMs_{\ (TO)}$) (Figure 3-6). Each measurement was then repeated 3 times and averaged. This process was then repeated for both groups following 5 weeks ($PM_{2\ (T1)}$, $PM_{4\ (T1)}$ and $AMs_{\ (T1)}$), 10 weeks ($PM_{2\ (T2)}$, $PM_{4\ (T2)}$ and $AMs_{\ (T2)}$), and 15 weeks ($PM_{2\ (T3)}$, $PM_{4\ (T3)}$ and $AMs_{\ (T3)}$) (Table 3-2).

Table 3-2. Second premolar (PM_2), fourth premolar (PM_4) and miniscrew (AMs) measurements outline

Measurement parameters		
Desired tooth movement	**$PM_{2(To)}$**	Distance from the second premolar to the reference miniscrew pre-operatively
	$PM_{2(Tx)}$	Distance from the second premolar to the reference miniscrew at T1, T2 and T3
Anchorage loss Control	**$PM_{4(To)}$**	Distance from the fourth premolar to the reference miniscrew pre-operatively
	$PM_{4(Tx)}$	Distance from the fourth premolar to the reference miniscrew at T1, T2 and T3
Anchorage loss Miniscrew	**$AMs_{(To)}$**	Distance from the anchorage miniscrew to the reference miniscrew pre-operatively
	$AMs_{(Tx)}$	Distance from the anchorage miniscrew to the reference miniscrew at T1, T2 and T3

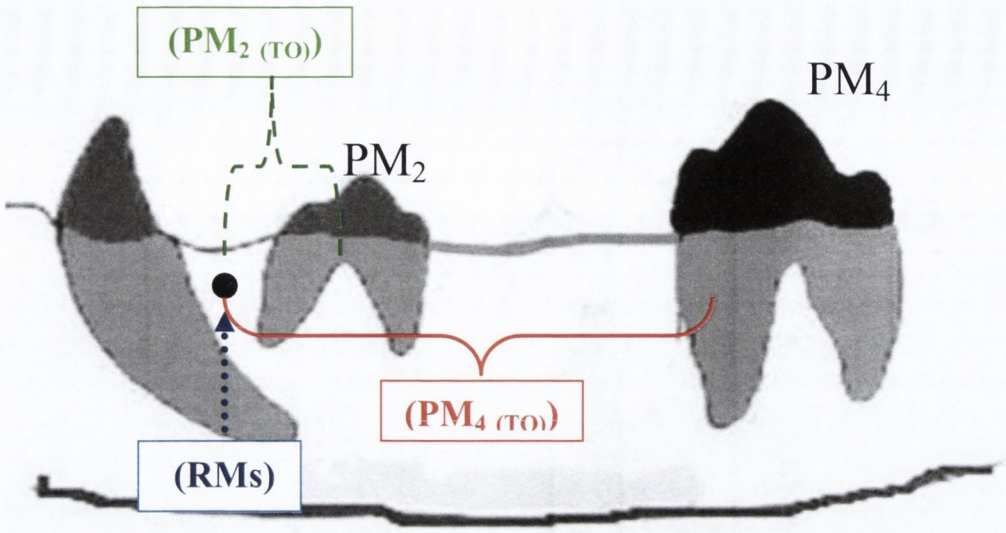


Figure 3-5. Measuring the displacement in the control group.

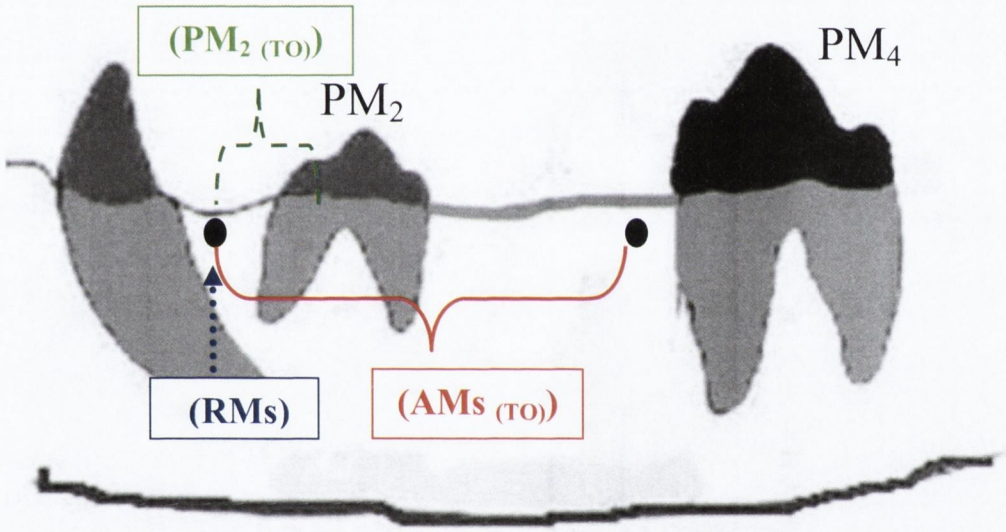


Figure 3-6. Measuring the displacement in the miniscrew group.

3.2.8 *Data management*

Using the PM_2, PM_4 and AMs measurements, the amount and percentage of desired tooth movement to anchorage loss during space closure were determined. The amount of desired tooth movement in both groups (control and miniscrew) was calculated by comparing the measurements made at 5, 10 and 15 weeks (T1, T2 and T3) to those made at base line for $PM_{2\ (T0)}$ (see equations below). The anchorage loss was calculated in same manner by comparing measurements made at 5, 10 and 15 weeks (T1, T2 and T3) to those made at baseline for $PM_{4\ (TO)}$ and $AMs_{\ (T0)}$ for both the control and miniscrew groups

respectively (see equations below). The desired tooth movement and anchorage loss were also both expressed as a percentage of the total movement at 5, 10 and 15 weeks (T1, T2 and T3) (see equations below).

The following formulae were used:

Amount of desired tooth movement (DM) (mm)

In Control group = $DM = PM_{2\,(T0)} - PM_{2\,(Tx)} = mm$

In Miniscrew group = $DM = PM_{2\,(T0)} - PM_{2\,(Tx)} = mm$

(x = Time 1, 2 or 3) (T0=baseline position)

Amount of Anchorage loss (AL) (mm)

In Control group = $AL = PM_{4\,(T0)} - PM_{4\,(Tx)} = mm$

In Miniscrew group = $AL = AMs_{(T0)} - AMs_{(Tx)} = mm$

(Tx = Time 1, 2 or 3) (T0=baseline position)

Percentage of desired tooth movement in comparison to the total space closure

In Control group $= \dfrac{DM_{(Tx)}}{(DM_{(Tx)} + AL_{(Tx)})} \times 100\%$

In Miniscrew group $= \dfrac{DM_{(Tx)}}{(DM_{(Tx)} + AL_{(Tx)})} \times 100\%$

(Tx = Time 1, 2 or 3)

Percentage of Anchorage loss in comparison to the total space closure

In Control group $= \dfrac{AL_{(Tx)}}{(DM_{(Tx)} + AL_{(Tx)})} \times 100\%$

In Miniscrew group $= \dfrac{AL_{(Tx)}}{(DM_{(Tx)} + AL_{(Tx)})} \times 100\%$

(x =Time 1, 2 or 3)

3.2.9 *Statistical analysis*

A series of *t*-tests were conducted to assess difference in the means between the variables. For comparisons within groups a paired *t*-test was used whereas for between groups the test was unpaired. Data were further analysed with Tukey's HSD multiple comparison to determine the level of significance associated with the different anchorage methods at different time points (T1, T2 and T3) for each variable. As there were multiple comparisons, Tukey's HSD correction was used to find the true significance.

The following comparisons were investigated:

- Comparisons within each anchorage method
    - Amount of desired tooth movement (DM)
    - Amount of anchorage loss (AL)
    - Percentage of desired tooth movement (DM %)
    - Percentage of anchorage loss (AL %)

- Comparisons between the two anchorage methods
    - Amount of desired tooth movement (DM)
    - Amount of anchorage loss (AL)
    - Percentage of desired tooth movement (DM %)
    - Percentage of anchorage loss (AL %)

For all cases the significance level was set at $p<0.05$. The data were analysed and graphically depicted using R software version 2.11.1 (Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org).

3.2.10 *Error of the Method*

The error of the method was calculated according to Dahlberg's equation: $e = \sqrt{\frac{\sum di^2}{2n}}$ in which di is the difference between duplicate measurements and n is the number of repeated measurements. Thirty duplicate pairs of duplicate measurements for the control and miniscrew group were randomly chosen. The error of the method was found to be 0.068 mm for the desired tooth movement and 0.075 mm for the anchorage loss in the control group. The error of the method was found to be 0.04 mm for the desired tooth movement and 0.027 mm for anchorage loss in the miniscrew group. The random error for both groups is clinically insignificant.

In a small sample size and where no bias exists, it is been found to be advantageous to use Dahlberg formula. This is because it has less degree for freedom (2n) in the denominator than the other methods such as the method of moments. Houston (1983) suggested a minimum of 25 cases should be replicated. This was supported by Springate (2012) who found increasing the repeated measurements (n) to 30 narrowed the distribution. However it is important to realize the limitations of the Dahlberg formula. It assumes the sample has a normal distribution and there is no bias (systematic error). The method is sensitive to bias as any mean deviations between the two measurements are incorporated. Furthermore, it does not distinguish between systematic error and random error which could make interpretation of the results difficult. Overestimation of the error is also another disadvantage. This is as a result of the differences between measurements are squared and as consequence the magnitude of error increasing.

3.3 Results

The amounts of movement of PM_2 and PM_4 in the control group, and PM_2 and AMs in the miniscrew group were measured at T1, T2 and T3. The mean amount of movement was recorded for each time point for PM_2, PM_4 and AMs. The mean of each of the following was then calculated: amount of desired tooth movement (DM), amount of anchorage loss (AL), percentage of desired tooth movement (DM %) and percentage of anchorage loss (AL %) (Table 3-3). These variables were then analysed within and between the two different anchorage methods for each time point (T1, T2 and T3).

Table 3-3. The means and standard deviations of the amounts of desired tooth movement (DM), amounts of anchorage loss (AL), percentages of desired tooth movement (DM %) and percentages of anchorage loss (AL %) for the control and the miniscrew groups

		Mean ± Standard deviation (mm)	
Data	Time	Control	Miniscrew
Desired tooth movement (DM)	1	1.10 ± 0.90	0.97 ± 0.74
	2	2.46 ± 2.41	4.25 ± 1.45
	3	5.09 ± 2.45	5.11 ± 1.32
Anchorage loss (AL)	1	0.99 ± 1.36	0.64 ± 0.67
	2	2.26 ± 1.10	0.96 ± 0.58
	3	3.96 ± 1.48	0.92 ± 0.65
Desired movement (DM %)	1	59.98 ± 28.66	59.81 ± 36.97
	2	45.13 ± 23.89	79.94 ± 13.68
	3	54.51 ±13.42	84.26 ± 10.05
Anchorage loss (AL %)	1	40.02 ± 28.66	40.18 ± 36.97
	2	54.85 ± 23.89	20.05 ± 13.68
	3	45.68 ± 13.42	15.73 ± 10.05

3.3.1 *Comparisons within groups (Control & Miniscrew)*

3.3.1.1 Amount of desired tooth movement – (DM)

The mean total amount of desired tooth movement for both the control (5.09 mm) and the miniscrew (5.11 mm) groups was similar after 15 weeks. The pattern of increase was however different at the different time points. In the control group there was a continuous increase in the amount of desired tooth movement over 15 weeks (1.1 mm at T1, 2.46 mm at T2 and 5.09 mm at T3) (Figure 3-7) but only the second increase (T2-T3) was significant ($p<0.01$) (Table 3-4). The increase in the mean amount of desired tooth movement in the miniscrew group on the other hand was also continuous (0.97 mm at T1, 4.25 at T2 and 5.11 at T3) (Figure 3-7). However, in contrast to the control group, the difference between the time points was significant between T1 and T2 ($p<0.01$) rather than T2 and T3) (Table 3-4).

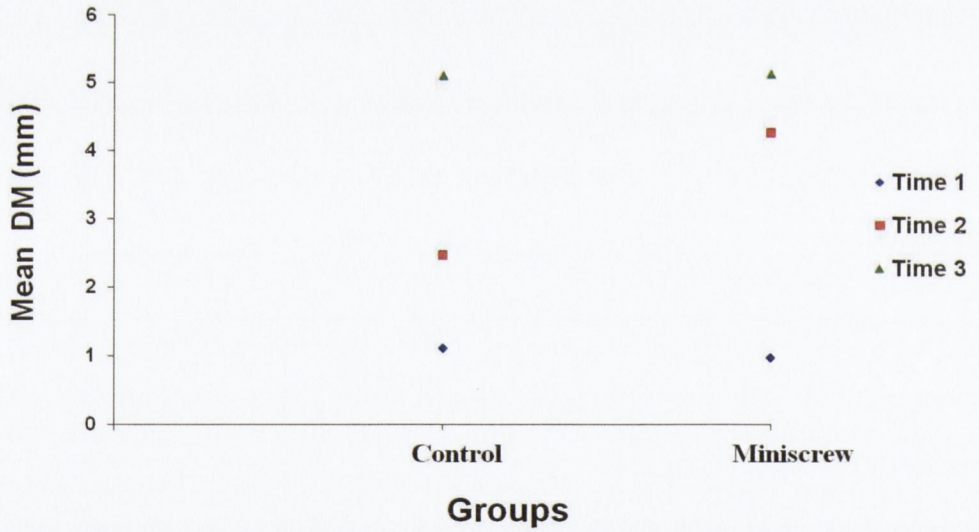


Figure 3-7. The means of the amounts of desired tooth movement (DM) at the different time points (T) within each group (control and miniscrew).

Table 3-4. The mean difference between the amounts of desired tooth movement (DM) at the different time points (T) within each anchorage group (control and miniscrew).

Desired tooth movement (DM) (mm)					
	Time	Mean Difference	95% Confidence interval		p-value
Control	1 vs 2	-1.36	-2.76	0.45	0.06
	2 vs 3	-2.63	-4.03	-1.23	<0.01
Miniscrew	1 vs 2	-3.29	-4.68	-1.88	<0.01
	2 vs 3	-0.86	-2.34	0.61	0.53

3.3.1.2 Amount of anchorage loss – (AL)

The mean amount of anchorage loss (AL) in the control group increased over 15 weeks (0.99 mm at T1, 2.26 mm at T2 and 3.96 mm at T3) (Figure 3-8). The increase between the three different time points was statistically significant ($p<0.01$) (Table 3-5). On the other hand, anchorage loss in the miniscrew group occurred mainly during T1 with a mean of 0.64 mm. The amount of anchorage loss stayed relatively the same at the next two time points (0.96 mm and 0.92 mm) (Figure 3-8). As a result, the incremental increase in the amount of anchorage loss (mean difference) from T1 to T2 and from T2 to T3 was not statistically significant (Table 3-5).

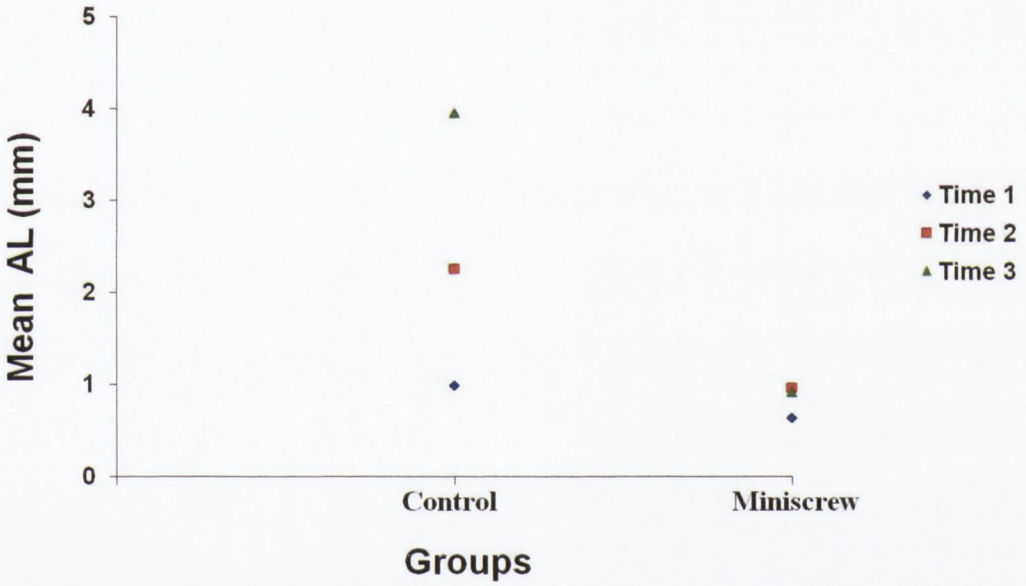


Figure 3-8. The means of the amounts of anchorage loss (AL) at the different time points (T) within each group (control and miniscrew).

Table 3-5. The mean difference between the amounts of anchorage loss (AL) at the different time points (T) within each anchorage group (control and miniscrew)

Anchorage loss (AL) (mm)					
	Time	Mean Difference	95% Confidence interval		p-value
Control	1 vs 2	-1.27	-2.06	-0.48	<0.01
	2 vs 3	-1.70	-2.49	-0.91	<0.01
Miniscrew	1 vs 2	-0.32	-1.11	0.47	0.84
	2 vs 3	0.04	-0.78	0.87	0.99

3.3.1.3 Percentage of desired tooth movement – (DM %)

The mean percentage of the desired tooth movement of the total movement in the control group decreased from 60% at T1 to 45.1% at T2 but then increased to 54.5% at T3 (Figure 3-9). None of the changes over the time points were significant (Table 3-6). In contrast, the mean percentages of desired tooth movement of the total movement in the miniscrew group increased at the three time points (T1-59.8%, T2-79.9% and T3-84.3%) (Figure 3-9). The increase though was only statistically significant from T1 to T2 (p=0.03) (Table 3-6).

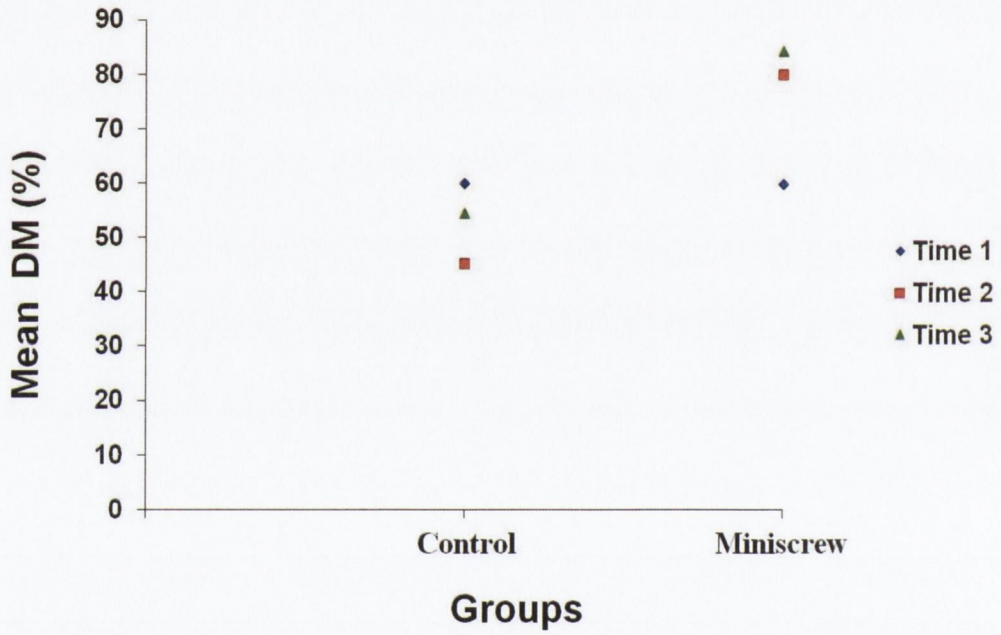


Figure 3-9. The means of the percentages of desired tooth movement (DM %) at the different time points (T) within each group (control and miniscrew).

Table 3-6. The mean difference between the percentages of desired tooth movement (DM %) at different time points (T) within each anchorage group (control and miniscrew)

Desired tooth movement (DM %)					
	Time	Mean Difference	95% Confidence interval		p-value
Control	1 vs 2	14.85	-4.33	34.03	0.22
	2 vs 3	-9.38	-28.56	9.80	0.73
Miniscrews	1 vs 2	-20.13	-39.31	-0.95	0.03
	2 vs 3	-4.32	-24.43	15.80	0.99

3.3.1.4 Percentage of anchorage loss – (AL %)

The mean percentage of the anchorage loss of the total movement in the control group stayed relatively the same over 15 weeks. At T1 it was 40%, and then it increased to 54.9% at T2 before reducing to 45.7% at T3 (Figure 3-10). Therefore the differences between T1, T2 and T3 were not statistically significant (Table 3-7). On the other hand, the mean percentage of anchorage loss in the miniscrew group reduced over the three time points (40.2%, 20% and 15.7% respectively) (Figure 3-10). The percentage of anchorage loss reduction was only significant between T1 and T2 ($p = 0.03$) (Table 3-7).

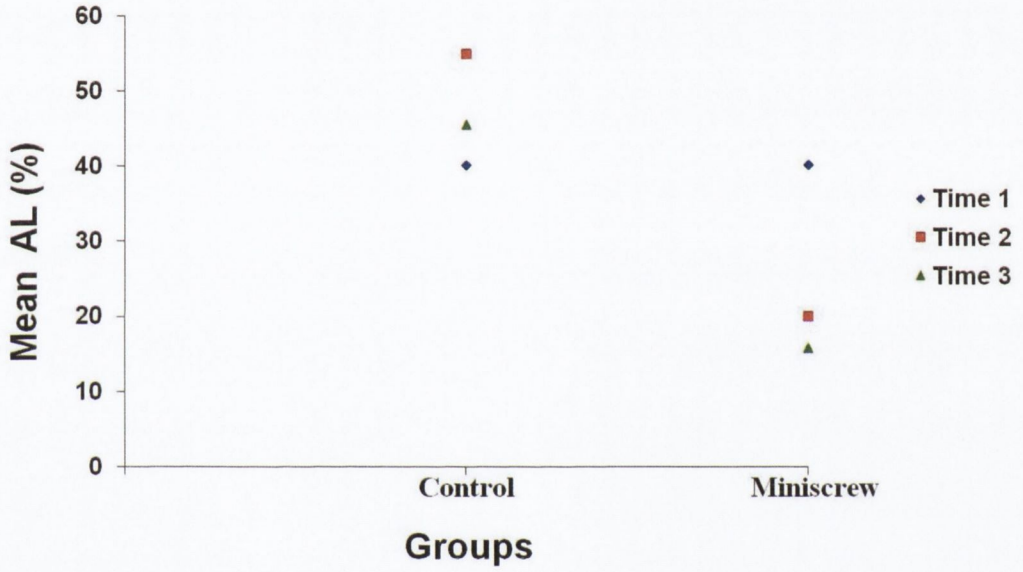


Figure 3-10. The means of the percentages of anchorage loss (AL %) for the different time points (T) within each group (control and miniscrew).

Table 3-7. The mean differences between the percentages of anchorage loss (AL %) at different time points (T) within each anchorage group (control and miniscrew)

Anchorage loss (AL %)					
	Time	**Mean Difference**	**95% Confidence interval**		**p-value**
Control	**1 vs 2**	-14.83	-33.97	4.31	0.22
	2 vs 3	9.17	-9.97	28.30	0.73
Miniscrews	**1 vs 2**	20.22	1.08	39.36	0.03
	2 vs 3	4.33	-15.74	24.41	0.99

3.3.2 *Comparisons between groups (Control Vs Miniscrew)*

3.3.2.1 Amount of desired tooth movement - DM

The means of the amounts of desired tooth movement at T1 (1.1 mm and 0.97 mm) and T3 (5.09 mm and 5.11 mm) were similar for both groups (Figure 3-11). The mean amount of desired tooth movement at T2 in the miniscrew group (4.25 mm) was higher than the control group (2.46 mm) and was statistically significant ($p<0.01$) (Table 3-8).

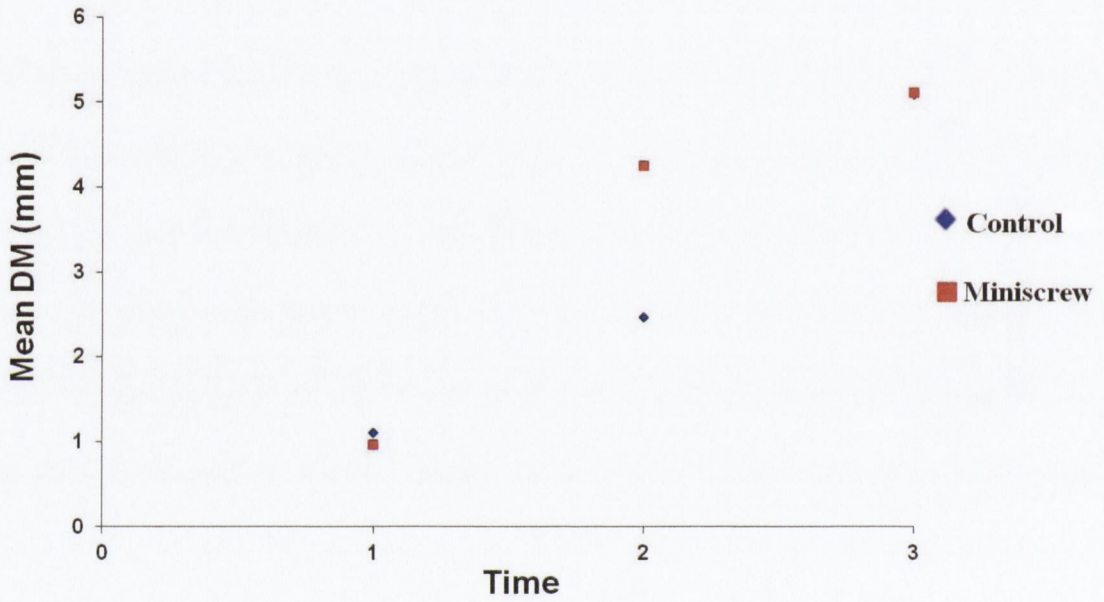


Figure 3-11. The means of the amounts of desired tooth movement (DM) for the control and miniscrew groups at different time points (T).

Table 3-8. The mean difference between the amounts of desired tooth movement (DM) of both anchorage groups (control and miniscrew) at different time points (T)

Desired tooth movement (DM) - Control Vs Miniscrew group (mm).				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	0.14	-1.26	1.54	0.99
2	-1.79	-3.19	-0.39	<0.01
3	-0.02	-1.49	1.45	1

3.3.2.2 Amount of anchorage loss - AL

The difference between the means of the amount of anchorage loss for the control and miniscrew groups was not statistically significant at T1 (Table 3-9). The difference became statistically significant at T2 and T3 ($p<0.01$) (Table 3-9). This was the result of the relatively unchanged amount of anchorage loss in the miniscrew group at T2 (0.96 mm) and T3 (0.92 mm) compared to the continuous increase in the amount of anchorage loss in the control group (T2 - 2.26 mm and T3 - 3.96 mm) (Figure 3-12).

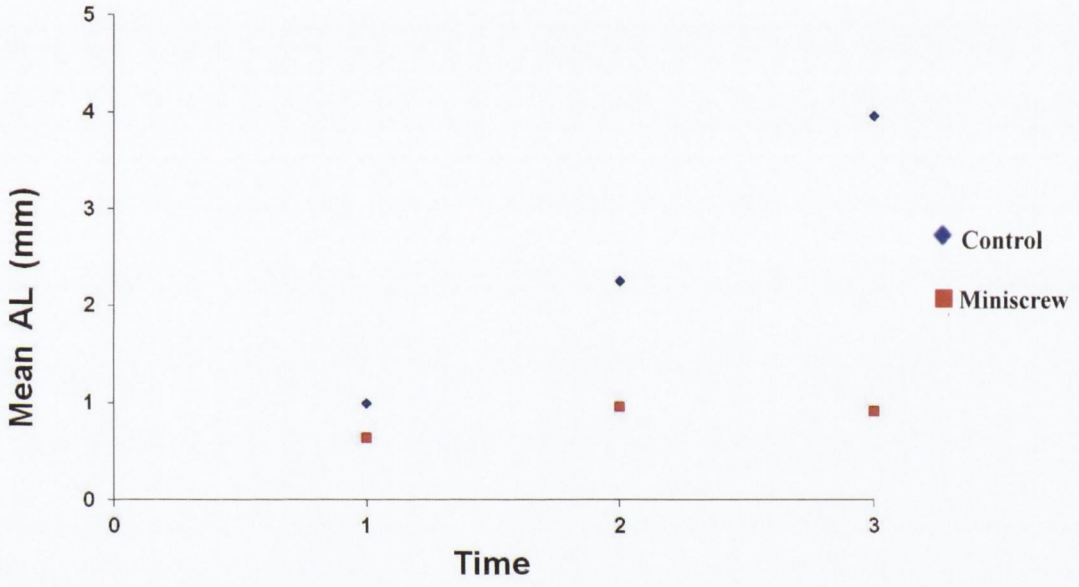


Figure 3-12. The means of the amounts of anchorage loss (AL) for the control and miniscrew groups at different time points (T).

Table 3-9. The mean differences between the amounts of anchorage loss (AL) of both anchorage groups (control and miniscrew) at different time points (T)

Anchorage loss (AL) - Control Vs Miniscrew group (mm).				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	0.35	-0.43	1.14	0.78
2	1.30	0.51	2.08	<0.01
3	3.04	2.21	3.87	<0.01

3.3.2.3 Percentage of desired tooth movement – (DM %)

At T1, both groups had similar mean percentages of desired tooth movement of the total movement (Figure 3-13). However, in the miniscrew group the mean percentages of desired tooth movement at T2 (79.9%) and T3 (84.3%) were higher than the control group (45.1% and 54.5%) and statistically significant ($p<0.01$) (Table 3-10).

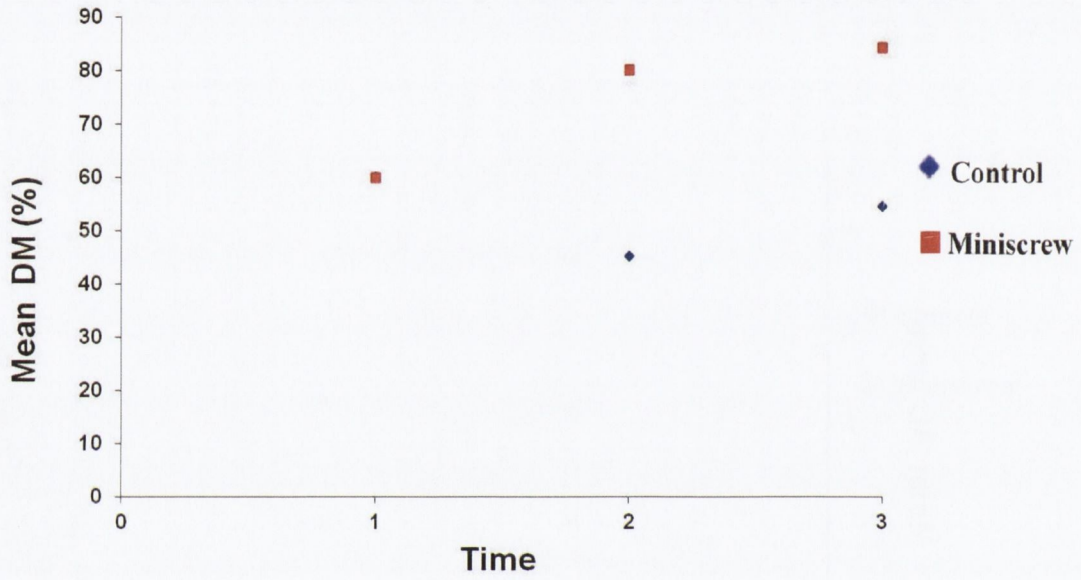


Figure 3-13. The means of the percentages of desired tooth movement (DM %) for the control and miniscrew groups at different time points (T).

Table 3-10. The mean differences between the percentages of desired tooth movement (DM %) of both anchorage groups (control and miniscrew) at different time points (T)

Desired tooth movement (DM %) – Control Vs Miniscrew group (%)				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	0.16	-19.02	19.34	1
2	-34.82	-53.99	-15.63	<0.01
3	-29.75	-49.87	-9.64	<0.01

3.3.2.4 Percentage of Anchorage loss – (AL %)

The mean percentage of anchorage loss (AL %) of the total movement in the control group and the miniscrew group was similar (40% and 40.2%) at T1 (Figure 3-14). At T2 and T3, the percentages of anchorage loss in the control group (54.9% and 45.7%) were higher than the miniscrew group (20% and 15.7%) (Figure 3-14). The differences between the control group and the miniscrew group at T2 and T3 were statistically significant ($p<0.01$) (Table 3-11).

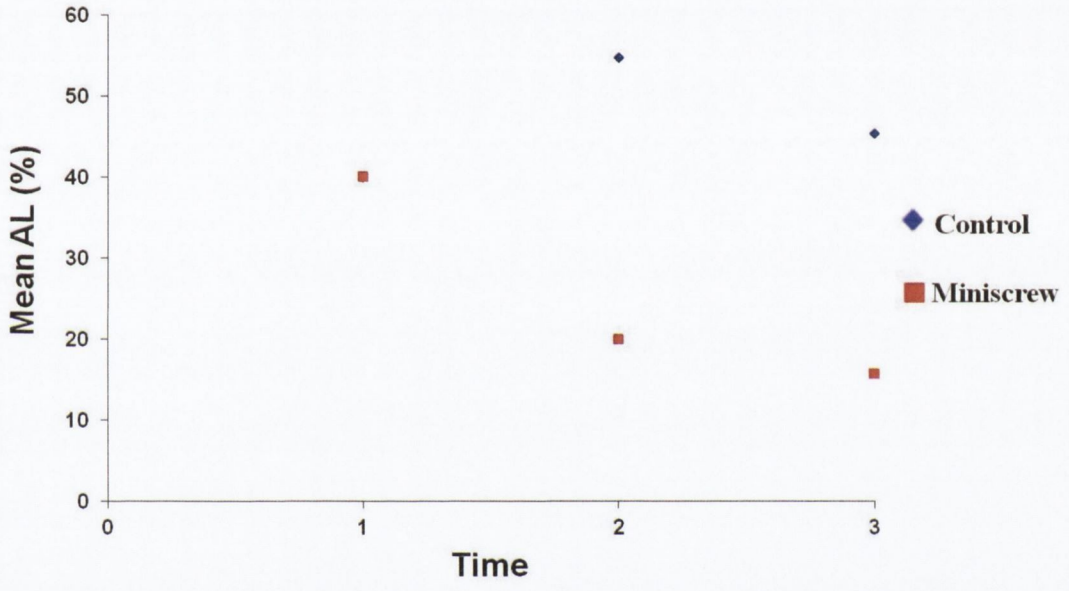


Figure 3-14. The means of the percentages of anchorage loss (AL %) for the control and miniscrew groups at different time points (T).

Table 3-11. The mean differences between the percentages of anchorage loss (AL %) of both anchorage groups (control and miniscrew) at different time points (T)

Anchorage loss (AL %) – Control Vs Miniscrew group (%)				
Time	**Mean Difference**	**95% Confidence interval**		**p-value**
1	-0.22	-19.36	18.92	1
2	34.83	15.69	53.97	<0.01
3	29.99	9.93	50.07	<0.01

3.4 *Discussion*

The aim of this study was to assess the efficacy of the miniscrew as an anchorage reinforcement method in orthodontics, by evaluating the relative amounts of desired tooth movement and anchorage loss over a period of 15 weeks in 2 groups (control and miniscrew). The mean amount of desired tooth movement was approximately the same in the control (5.09 mm) and the miniscrew groups (5.11 mm) after 15 weeks. The mean amount of anchorage loss was significantly higher in the control group (3.96 mm) than the miniscrew group (0.92 mm) after 15 weeks.

3.4.1 *Desired tooth movement (DM)*

The desired tooth movement of the second premolar (PM_2) was observed within each group (control and miniscrew) over a total of 15 weeks. During this time, the tooth movement was recorded at three time points: 5 weeks (T1), 10 weeks (T2) and 15 weeks (T3). The desired tooth movement (PM_2) in both groups increased at each time point (T1, T2 and T3) with a similar overall mean amount of tooth movement (5.09 and 5.11 mm). At T1 (5 weeks), the control and miniscrew group had a similar mean amount of desired tooth movement (1.1 mm and 0.97 mm respectively). At T2 (10 weeks), the mean amount of desired tooth movement in the miniscrew group (4.25 mm) was approximately double the mean amount of movement in the control group (2.46 mm). At T3 (15 weeks), both groups (control and miniscrew) had approximately the same mean amount of total desired tooth movement (5.09 mm and 5.11 mm).

In orthodontics, when tooth movement is assessed, it is important to assess the rate as well as the amount of movement. After 5 weeks, the control and miniscrew group moved at a similar rate (1.1 mm and 0.97 mm). Thereafter, the rate of tooth movement changed between groups (control and miniscrew). The rate of movement of PM_2 in the miniscrew group was faster than the control group from T1 to T2 whilst in the control group the PM_2 movement rate was faster than the miniscrew group from T2 to T3. In the control group,

the movement from T1 to T2 (1.36 mm) was slower than between T2 and T3 (2.63 mm). In contrast, in the miniscrew group, the tooth movement slowed down between T2 and T3 (0.86 mm) compared to T1 and T2 (3.29 mm). As a result, both moved approximately the same distance over the 15 week observation period. This decline in the PM_2 rate of movement in the miniscrew group and the corresponding increase in PM_2 rate of movement in the control group is similar to the pattern observed with PM_2 in our earlier study (Chapter 2), in which the Nance appliance and control were compared. It seems that the anchorage reinforcement methods (miniscrew and Nance appliance) may have introduced another variable which may have affected the PM_2 rate of tooth movement. The difference in the rate of tooth movement between both groups started at T2 (Figure 3-11), which corresponded with a significant difference between the mean amounts of the anchor units' movement within the control and miniscrew groups (Figure 3-12). This might suggest that the resistance to movement by the anchor units had influenced the PM_2 rate of movement. As at T1, when both anchor units in the control and miniscrew groups moved approximately the same distance (0.99 mm and 0.64 mm), the desired tooth movement (PM_2) in both groups moved an equal distance as well. It is only when the anchor units started to move less (from T1 to T2), that the mean amount of desired tooth movement in both groups (control and miniscrew) was significantly different ($p<0.01$). It may be postulated that once the miniscrews contacted the bone, the force started to dissipate to the bone. As the tooth is within a hydrodynamic system (Bien, 1966), the forces might have been maintained within the confined area around the tooth. It could also be speculated that, as the anchorage units in the control group moved more than the miniscrew group, the distance between the two units (anchor unit – PM_2) reduced more in the control group. This space reduction may have been accompanied by force reduction due to the shorter activation distance of the NiTi closing coil. The difference in the rate of desired tooth movement between the control and miniscrew groups may have been as a result of this

difference in force. This is similar to Thiruvenkatachari and colleagues' 2008 study on the rate of canine retraction. In this split-mouth prospective study they compared the rate of canine retraction with miniscrew anchorage and conventional molar anchorage. Once the canines were fully retracted, they found that the canines in the miniscrew group retracted about 0.35 mm more in the mandible and 0.6 mm more in the maxilla than in the conventional molar anchorage side. The mean rates of canine retraction in the miniscrew anchorage were 0.07 mm and 0.12 mm per month faster, in the mandible and maxilla respectively, than the conventional molar anchorage. They suggested that the difference in rates and amounts of tooth movement between the miniscrew and conventional molar was due to the higher anchorage loss in the molar anchorage, and thus the force reduced gradually. This gradual anchorage loss may have exposed the miniscrew group to a higher force and therefore a higher rate of tooth movement (discussed earlier, section 2.4.1). The observation period in Thiruvenkatachari and colleagues' 2008 clinical study varied for each individual, as the length of the observation period for each subject depended on the amount of time it took to retract the canines fully. Moreover, the rate of tooth movement in the Thiruvenkatachari *et al.* study (2008) was determined at the end of the study. They divided the amount of space closure by the amount of time it took to achieve such space closure. Therefore any variation in the rate of tooth movement during the observation period was not recorded. Secondly, the amount of tooth movement was also recorded once the canine was retracted and the space fully closed. This amount of tooth movement would have also depended on how much the molar moved. This means that molar movement (anchorage loss) affected the amount of canine retraction (desired tooth movement).

In the current study, there was a significant difference in the mean amount of desired tooth movement between the control and miniscrew groups ($p<0.01$) after 10 weeks, but no significant difference after 15 weeks. However, the percentage of desired tooth movement

of the total space closure was statistically significant between both groups (control and miniscrew) after 10 and 15 weeks ($p<0.01$) (see below).

3.4.2 *Anchorage loss (AL)*

3.4.2.1 Comparisons within groups (Control Vs Miniscrew)

Anchorage loss was observed over 15 weeks in both the control and miniscrew groups. The amount of anchorage loss was measured at three time points, T1 (5 weeks), T2 (10 weeks) and T3 (15 weeks). Anchorage loss (PM_4) occurred for the control group at three time points (0.99 mm, 2.26 mm and 3.96 mm) with a statistically significant increase between each period ($p<0.01$). Anchorage loss (miniscrew movement) in the miniscrew group occurred mainly over the first 5 weeks (0.64 mm). The mean anchorage loss for the miniscrew group remained stable (0.96 mm and 0.92 mm) at the next two time points (T2 and T3) and these differences between the time points were not statistically significant ($p>0.05$).

The mean amount of anchorage loss (miniscrew movement) recorded after 15 weeks (0.92 mm) in the present study was similar to the anchorage loss reported by previous studies in humans (Liou *et al.,* 2004; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009). These studies found that the miniscrews had moved from their original position at the end of treatment. Liou and colleagues (2004) were the only group to try to explain miniscrew movement during treatment. They hypothesized that the miniscrews moved when initially loaded due to a layer of fibrous tissue interposed between the miniscrew and the surrounding bone. This fibrous tissue allowed the miniscrew to behave similar to a tooth against the periodontal tissue. Once the fibrous tissue was compressed against the bone, the threads of the miniscrew mechanically locked into the surrounding bone. Liou and colleagues (2004) did not substantiate this hypothesis as their study lacked histological investigation and the miniscrew movement was assessed only clinically at the end of the

treatment. The findings of the current study supported Liou and colleagues' 2004 hypothesis, as the miniscrews in the current study moved mainly during the first 5 weeks (0.64 mm) with further but less movement (0.34 mm) in the subsequent time point (10 weeks). The miniscrew movement at the 10 weeks time in the current study, was also within the recommended preloading time for osseointegration to occur in the Orthosystem® (Wehrbein & Diedrich, 1993). Although previous researchers (Melsen & Costa, 2000; Park *et al.,* 2006; Deguchi *et al.,* 2003; Woods *et al.,* 2009; Luzi *et al.,* 2009b) suggested immediate loading, as it was assumed the miniscrews provided mechanical retention, they did not comment on the amount of miniscrew movement that may initially occur, as the miniscrews do not osseointegrate immediately. Some investigators were concerned for the possibility that osseointegration is impeded by the application of orthodontic force immediately after installation (Melsen & Costa, 2000; Park *et al.,* 2006; Deguchi *et al.,* 2003; Woods *et al.,* 2009; Chen *et al.,* 2009). They found that orthodontic forces and loading did not affect the osseointegration potential. It is interesting to note that although the miniscrews did move in previous studies (Liou *et al.,* 2004; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009) as they did in the current study, they appeared integrated at the end of the experiment. Park and colleagues (2006) found that miniscrews remained in place even in the presence of some mobility. It has been also shown that the stability of miniscrews was independent of osseointegration (Deguchi *et al.,* 2003) at forces less than 200 cN (Miyawaki *et al.,* 2003). The stability of miniscrews in the current study at later time points may further indicate that miniscrews do not integrate for some time following placement. This is in agreement with Wu and co-workers' 2009 animal study which found a significantly higher removal torque value (RTV) after a healing time of 4 weeks compared to 0 and 2 weeks healing time. Histologically, Wu and co-workers (2009) found more mature bone and calcified tissue around the miniscrews after a healing time of 8 weeks compared to 0, 2 and 4 week healing times. Zhang and colleagues (2010) reported more

osseointegration when miniscrews were loaded after 4 weeks compared to miniscrews loaded immediately or after 2 weeks. The authors recommended a 4 week healing period to obtain improved stationary anchorage. However, the majority of the studies which did not find any significance between immediate and delayed loading had an observation period of 2-4 weeks only. In addition, the stability of the miniscrews was assessed rather than the amount of displacement. This observation period (2-4 weeks) may have been insufficient, as Wu and colleagues (2009) and Zhang and colleagues (2010) found that woven bone appeared along the peri-implant surface after 4 weeks. Thus, it seems the first 5 weeks in the current study were critical to miniscrew displacement (anchorage loss).

Other factors which may have affected the amount anchorage loss in the current study were also considered. Bone density and quality (D1, D2, D3 and D4) have been found to play a role in the stability of miniscrews (Lee *et al.,* 2004; Melsen, 2005). Dogs have been found to have higher bone density than humans (Reitan & Kvam, 1971). Melsen & Verna (2005) suggested more miniscrew success as bone density increased. Deguchi *et al.* (2003) found higher osseointegration in the mandible of dogs compared to the maxilla, which has less bone density. Other studies (Cheng *et al.,* 2004; Park *et al.,* 2006; Chen *et al.,* 2007; Wiechmann *et al.,* 2007) found the insertion procedure and masticatory force had more effect on success than the bone density. Whilst bone density may influence miniscrew osseointegration the extent to which it does so remains unclear. Other factors which may influence the stability of miniscrews in the current study were considered and the most recent recommendations were applied. The magnitude of applied force used in the current study was within the range of forces used in previous studies assessing anchorage loss associated with miniscrews (Thiruvenkatachari *et al.*, 2006; Thiruvenkatachari *et al.*, 2008; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009; Sharma *et al.,* 2012). The magnitude of the applied force has been investigated with little agreement on the optimum force (Cornelis *et al.*, 2007). Most studies found forces ranging from 50-400 cN did not influence the success

of miniscrews (Crismani *et al.*, 2010). The method used to insert miniscrews (flap and flapless) was another factor which has been investigated with inconclusive findings (Crismani *et al.*, 2010). Pre drilling is another factor which was investigated for its influence on the success on miniscrews. Although Wang & Liou (2008) found that the method of insertion was not a determining factor for the stability, Ellis & Laskin (1994) recommended pre-drilling in cases with dense bone. As a result, pre drilling was used in the current study as dog bones are more dense than human bones. Pre loading time was also investigated for its influence on the stability of miniscrews. In the current study, there was a 2 week waiting period as some studies recommended (Buchter *et al,.* 2005; Kim *et al.*, 2005; Ohashi *et al.,* 2006). In addition, most of the previous clinical studies which assessed anchorage loss associated with miniscrews had a 2 week waiting period (Thiruvenkatachari *et al.*, 2006; 2008; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009; Sharma *et al.,* 2012). The length (7 mm) and diameter (1.3 mm) of the miniscrews used in the current study corresponded with the recommended parameters for successful miniscrews (Crismani *et al.*, 2010). Therefore, the effects of the above factors on the movement of miniscrew movement were minimized as much as possible.

The percentages of total movement that comprised anchorage loss and the percentages of desired tooth movement were inversely related. Thus, the lower the percentages of anchorage loss may have not been solely due to reduced amount of movement in the anchor unit (miniscrew), but also could have resulted from increased desired tooth movement. The mean percentage of anchorage loss of the total movement in the miniscrew group reduced over the three observation intervals (40.2%, 20% and 15.7%). Consequently, the mean percentage of desired tooth movement increased from 59.8% to 79.9% to 84.3% over the same time intervals. The change in the mean percentages of anchorage loss and desired tooth movement was statistically significant ($p=0.03$) between 5 and 10 weeks only. This reduction in the percentage of anchorage loss was the result of a

combination of reduced miniscrew movement (anchorage loss) and continued PM_2 movement (desired tooth movement). The reduced movement of the miniscrews over time may have occurred as result of mechanical interlocking with bone and osseointegration as was described above.

3.4.2.2 Comparisons between groups (Control Vs Miniscrew)

After 5 weeks (T1) there was 0.35 mm more anchorage loss in the control group than the miniscrew group. This was not significant statistically or clinically. At the next two time points T2 and T3 (10 and 15 weeks), the mean amount of anchorage loss was higher by 1.3 mm and 3.04 mm respectively in the control group than for the miniscrew group. These differences were statistically and clinically significant ($p<0.01$). This increase in the differences in the mean amounts of anchorage loss between both groups (control and miniscrew) was as a result of the decreased miniscrew movement after the first 5 weeks, whilst the anchorage loss continued in the control group over the next 10 and 15 weeks (2.26 mm- 3.96 mm). This reduction in miniscrew movement was also reflected in the mean percentage of anchorage loss. When the mean percentage of anchorage loss of the total movement was compared between both groups (control and miniscrew) it was statistically significant at T2 and T3 ($p<0.01$). The control group had approximately 34.8% and 30% more anchorage loss at T2 and T3. Although the difference in mean amount of anchorage loss increased further (1.3 mm to 3.04 mm) between both groups from T2 to T3, the difference in percentage of anchorage loss reduced as a result of the increased mean rate of desired tooth movement in the control group over the last time point (T3).

When the mean percentage of desired tooth movement was compared between both groups, the miniscrew group had approximately 34.8% and 29.8% (10 and 15 weeks) more desired tooth movement and was statistically significant ($p <0.01$). Despite the mean total amount of desired tooth movement being similar in both groups after 15 weeks, the

percentage was different. This was because the amount of anchorage loss was less in the miniscrew group in the last period (0.92 mm compared to 3.96 mm). This would suggest that space closure would occur more readily in the control group since space is being closed from both directions in a reciprocal manner (desired tooth movement and anchorage loss). On the other hand, space closure may take longer in the miniscrew group but it would be more favourable, as it is mainly achieved by desirable tooth movement. However if space closure is the desired aim then tooth anchorage rather than miniscrew anchorage is preferable.

The findings of the current study may have several clinical implications regarding anchorage loss. Although the miniscrews provided 30% more anchorage reinforcement than the control over 15 weeks, anchorage loss occurred mainly during the first 5 weeks of the current study. In high anchorage demand cases, where any anchorage loss is unacceptable, the clinician is advised to wait for 5 weeks prior to applying any force. Using direct anchorage methods, such as applying forces directly to the miniscrews rather than a tooth or an appliance attached to the miniscrew, should result in less anchorage loss. Any anchorage loss that may occur would result in the miniscrew moving rather than a tooth within the arch. The miniscrews moved approximately 0.92 mm during the current study and therefore should be placed at least 1-2 mm away from vital structures, as was suggested by the previous studies (Liou *et al.,* 2004; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009). In relation to desired tooth movement, both the control and miniscrew groups achieved a similar mean amount of desired tooth movement. However, space closure may occur more readily without miniscrews.

3.4.3 *Conclusion*

The current study demonstrated that although the miniscrews did not provide absolute anchorage, miniscrews provided a significant advantage over conventional tooth anchorage

during orthodontic tooth retraction. The first 5 weeks seems to be critical as the majority of anchorage loss (70%) for the miniscrew group occurred during this interval. Moreover, anchorage loss was not marked after the first time point (5 weeks) in the miniscrew group. The percentage of the total movement that was desired tooth movement was also significantly higher in the miniscrew group than in the control group. This is because space closure was achieved by desired tooth movement only with less anchorage loss. In conclusion, when both the desired tooth movement and anchorage loss are taken into consideration, the miniscrews provided approximately 30% more of both desired tooth movement and of anchorage reinforcement.

4 The effect of the different anchorage methods on orthodontically induced inflammatory root resorption

4.1 Introduction

Orthodontically induced inflammatory root resorption (OIIRR) is an unpredictable pathological process associated with orthodontic tooth movement (Brezniak & Wasserstein, 2002a). OIIRR is associated with the biological process that occurs during tooth movement. It has been reported that 1-5 % of orthodontic patients will have severe root resorption (Linge & Linge, 1983). Histological studies have demonstrated that OIIRR following orthodontic treatment affects 90% of teeth (Stenvik & Mjor, 1970; Harry & Sims, 1982) whereas radiographic studies found it to be less (73 %) (Lupi *et al.*, 1996).

The aetiology of OIIRR is multifactorial, with several patient related and treatment related risk factors have been identified. Patient related risk factors that influence root resorption include the length, width and the shape of the root of the teeth (Sameshima & Sinclair, 2001a; Artun *et al.*, 2009; Marques *et al.*, 2010). Treatment related factors that affect root resorption are the type and magnitude of force, type and amount of tooth movement and the duration of treatment (Sameshima & Sinclair, 2001b). Consequently, different types of fixed and removable appliances (Malmgren *et al.*, 1982; Linge & Linge, 1983; Blake *et al.*, 1995; McNab *et al.*, 2000; Barbagallo *et al.*, 2008; Scott *et al.*, 2008), have been investigated for their effect on root resorption.

The influence of some anchorage appliances such as miniscrews on root resorption has only been recently investigated. A recent study in humans looked at OIIRR associated with miniscrews (Liou & Chang, 2010). More resorption was found with the miniscrew group compared to the one using conventional molar anchorage. In any event the study used radiographs to assess OIIRR, a technique which has been shown to underestimate the amount of root resorption. Furthermore, the two treatment groups were not evenly

matched, as the miniscrew group of patients had more severe malocclusions compared to the conventional group. Thus, the miniscrew group's treatment required larger amounts of tooth movement. Therefore a controlled study (matched sample, duration and tooth movement) with more sensitive investigation method may provide more information.

The purpose of this study was to assess the effect of the Nance appliance and the miniscrew on OIIRR compared to conventional molar anchorage (control) using a histological method developed by Lu and colleagues (1999) in a dog model.

4.2 Materials and Method

Under Irish Government License No. B100/3896 issued by the Department of Health in Ireland, two tooth types (mandibular second (PM_2) and fourth (PM_4) premolars) of ten beagle dogs were used. Ethical approval was sought and granted by the Trinity College Bio Resources Ethics Committee (Ref. 161106B). At the end of studies in Chapter 2 and 3, after 15 weeks of tooth movement with orthodontic appliances, ten beagle dogs were sacrificed by intravenous injection of 200 mg/kg of pentobarbitone.

4.2.1 *Histological Preparation*

4.2.1.1 Paraffin wax embedding of scaffold samples

Block sections, including the teeth being examined, were removed and fixed in 10% neutral buffered formalin (Cellpath Ltd, Newtown, UK). Samples were decalcified in 5% formic acid (Sigma-Aldrich, England) for 2 weeks. Prior to the embedding procedure, the block sections were reduced by removing the excess bone, limiting the blocks to the tooth and the adjacent alveolar bone. This was done using a scalpel (blade No. 11) to ensure that the microtome sections were made in the area of interest (the root of the teeth). Furthermore, Gutta-percha was inserted into the blocks adjacent to the mesial root to identify the mesial and distal roots following staining (Figure 4-1). Samples were then locked into plastic cassettes and placed in the histokinette (Type 99 FE 7326; British American Optical Company, England) where they were sequentially dehydrated in 70% alcohol twice, spirit alcohol twice, absolute alcohol twice, xylene twice and finally molten paraffin wax for two hours each. Following this treatment, samples were removed from the cassettes and placed into metal moulds. Heated liquid paraffin wax was poured into each of the moulds in the Tissue Tek II (British American Optical Company, England), and these were allowed to cool on a chilled surface until the wax solidified.

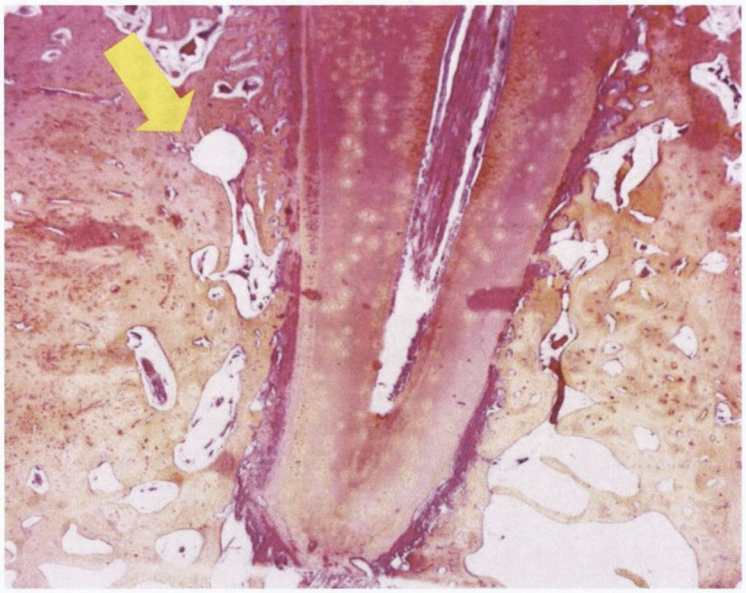


Figure 4-1. Gutta-percha inserted mesial to the root of a beagle dog to identify the mesial surface. The yellow arrow is pointing at the Gutta-percha position.

4.2.1.2 Sectioning of wax embedded sections

Wax embedded samples were placed in the microtome (Ernst Leitz Ltd. Germany). Serial longitudinal mesio-distal 4 μm thick sections containing the tooth and surrounding alveolar bone were cut. Every 14th Section (at 56 μm intervals) were placed onto a glass slide (Western Laboratory Services, Hampshire, UK) and placed in a hotbox oven (60 °C; Sanyo-Gallenkamp Hotbox Oven, Model #OHG050, Loughborough, England) overnight in order to fix the wax sections to the glass slide.

4.2.1.3 Staining with haematoxylin and eosin (H&E)

Wax embedded sections were de-waxed in xylene for 5 min and rehydrated in a series of descending graded alcohols (absolute alcohol, 96%, 70%, 50% and 30%) for 1 minute in each and then washed in running tap water. Sections, including the apex of the root, were then stained with Harris haematoxylin (Sigma-Aldrich, England) for 15 minutes, differentiated in 1% acid alcohol, (blued) in tap water and counter stained in 1% aqueous eosin (Sigma-Aldrich, England) for one minute. Stained sections were dehydrated by an ascending graded alcohol series (70%, 96%, absolute alcohol) for 2 minutes in each solution and then cleared in xylene. Resinous mounting medium (DPX, BDH Laboratory

Supplied, 100 Poole, England) was placed over each section and samples were mounted with a glass cover slip (Sigma-Aldrich, England).

4.2.1.4 Histomorphometric Analysis

From each tooth, 6 H&E stained sections including the apical foramen of the root and the apical 4 mm of the root length were randomly selected for histomorphometric analysis. The rationale for using the apical section was based on evidence from earlier studies suggesting that resorption starts at the apex of the roots and the majority of the resorption craters were located at this apical section (Reitan, 1974; Kurol *et al.,* 1996; Owman-Moll *et al.*, 1996b; Chan & Darendeliler, 2005; King *et al.*, 2011). The sections (n= 240) were examined at x40 magnification using optical microscope (Olympus Optical Co., Ltd, London EC1Y, United Kingdom). Computer-assisted measurements were obtained using image analysis software (Analysis® soft imaging system GmbH, Germany). For each section the mesial and distal root was assessed separately for root resorption. Root resorption was defined as microscopically visible resorption lacunae in the cementum (Kurol *et al.,* 1996; Maltha *et al.*, 2004) (Figure 4-2).

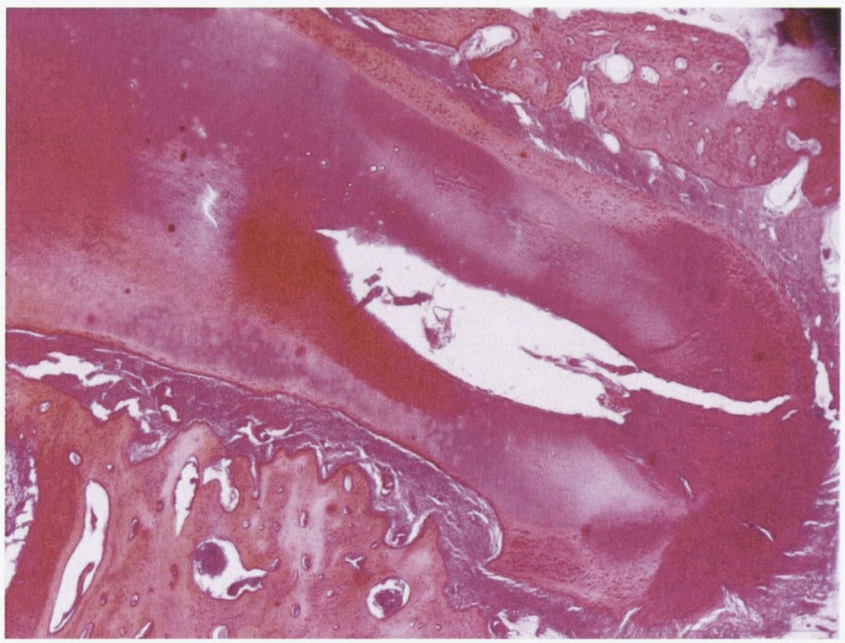


Figure 4-2. A H&E section showing an area of root resorption affecting the mesial surface of the fourth premolar following 15 weeks of tooth movement . The root resorption is extending into the cementum and dentine of a beagle dog's root.

4.2.2 *Evaluation of root resorption*

The quantification of root resorption was performed using a method previously described by Lu *et al.* (1999). The images were first captured and saved on a computer. Analysis software (Analysis® soft imaging system GmbH, Germany) was then used to calibrate and present all the measurements in millimetres. Using the Analysis software, a 0.25 mm x 0.25 mm grid was superimposed over the apical 4 mm. The grid was oriented so that it was parallel to the long axis of the root. The root surface was divided into three surfaces mesial, distal and apical as illustrated in (Figure 4-3). The apical surface was defined as the apical 4 squares (1 mm) on the mesial and distal surface of the root in addition to the apex of the root. The number of squares with and without resorption lacunae was counted along each root surface (Figure 4-4). Four different measurements were recorded, the number of squares with resorption in the mesial surface, distal surface, apical surface and the total ratio of resorption. The total ratio of resorption was determined by dividing the number of squares with resorption with the total number of squares along the entire root surface. This was done for each tooth type (PM_2 and PM_4) and root type (mesial and distal root) of each beagle dog.

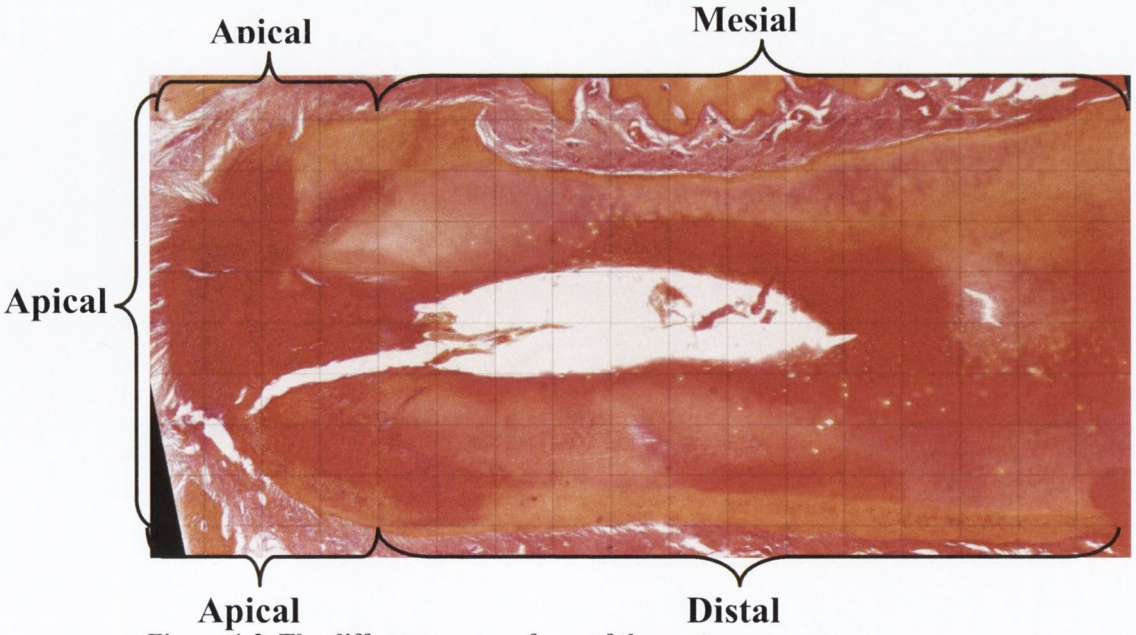


Figure 4-3. The different root surfaces of the root.

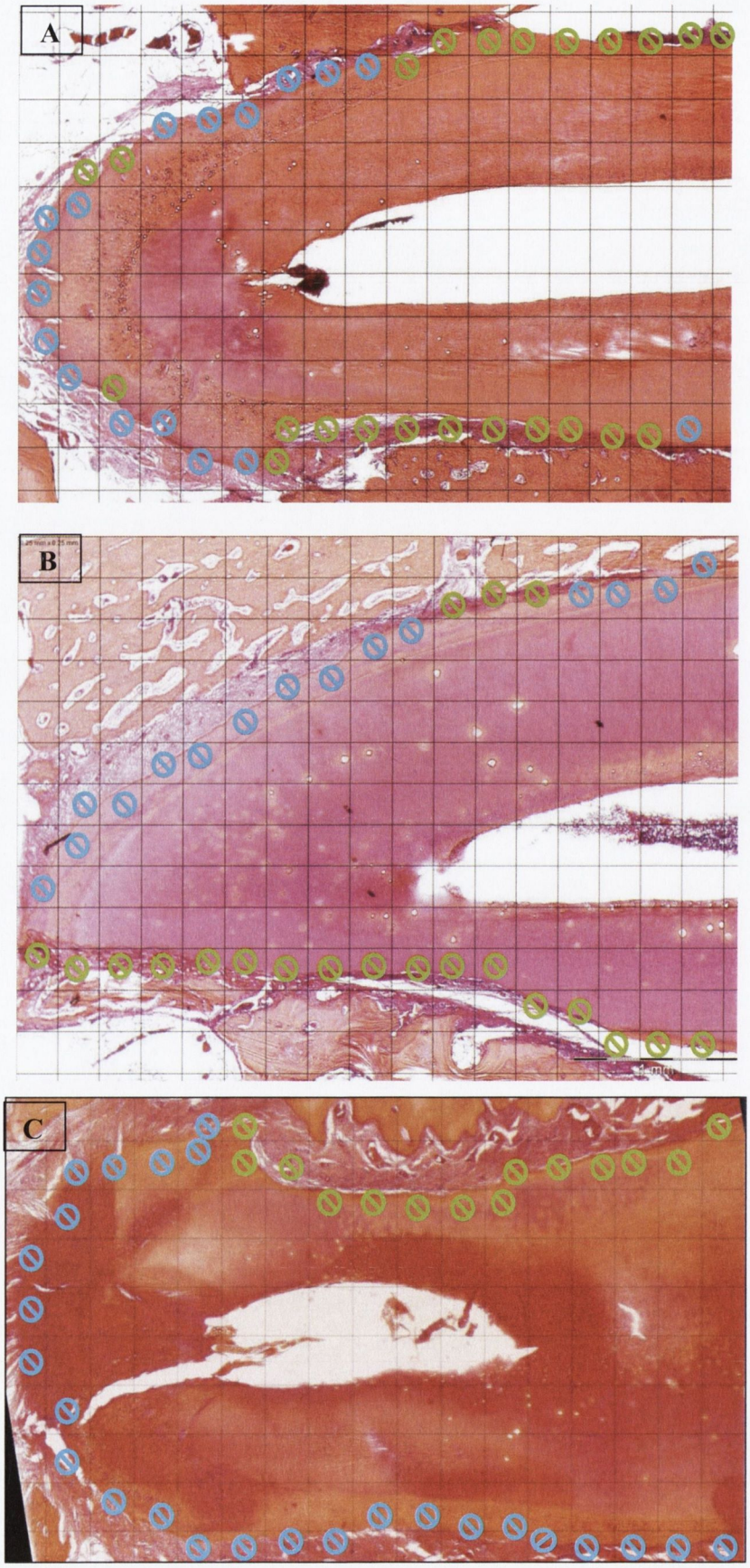


Figure 4-4. Evaluation of root resorption (A-C). Number of squares with resorbed lacunae (green) and squares without resorption lacunae (blue).

4.2.3 *Error of the method*

To evaluate the reliability of the measurement of root resorption, a sample consisting of 12 slides was randomly selected and remeasured by the same examiner and another independent examiner. The second measurements were carried out in a blinded manner and under the same conditions two months after the first measurement. The total ratio of root resorption for each slide was then calculated and the intra-examiner and inter-examiner reliability was evaluated using the paired *t-test* after log-transformation of the total ratios of root resorption. The significance level was set $\alpha = 0.05$. The error of the method was calculated according to Dahlberg's equation: $e = \sqrt{\frac{\sum di^2}{2n}}$ in which di is the difference between duplicate measurements and n is the number of repeated measurements. The validity and limitations of Dahlberg's equation were discussed in section 2.2.14 and 3.2.10. However, it is almost impossible to exclude bias in the small number of measurements in the original study. Therefore, Springate (2012) recommended, when there is a small number of repeated measurements (<25), the conduct of a Student's *t-test* to assess bias and quote the 95% confidence interval.

4.2.4 *Statistical analysis*

There were four response variables: mesial, distal and apical surface and total percentage response. The independent variables included one between groups variable (anchorage methods with three levels - control, Nance and miniscrews) and two within subject variables (type of tooth and type of root with two levels each). The following effects with regard to root resorption were investigated and analyzed:

- The effect of the different anchorage methods and tooth types (second and fourth premolar) on the total ratio of root resorption.
    - Within each anchorage method.

- Between the different anchorage methods.

- The effect of the different anchorage methods on the different tooth surfaces' (mesial, distal and apical) counts of root resorption.
  - Within each anchorage method.
  - Between the anchorage methods.

Two- way ANOVA and one - way ANOVA were used to assess the effect of the different anchorage methods and tooth types on the total ratio of root resorption within and between the different anchorage methods respectively. Kruskal-Wallis rank sum test, a non-parametric test utilizing medians, was used to assess the effect of the different anchorage methods on the different surfaces' counts of root resorption within and between the anchorage methods. This test required the individual measurements to be independent and thus repeated measurements for each root type of each tooth were averaged and the median of the averaged measurements was recorded. Dunn's multiple comparisons were used for the post-hoc multiple group comparisons.

In all cases the significance level was set at $p<0.05$. The data were analysed and graphically depicted using **R software version 2.11.1** (Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org) the choices of statistical tests was based on the variables and the manner of data distribution as detailed in the results section.

4.3 Results:

The effect of different anchorage methods on the total root resorption ratio was assessed. This was further assessed to see the effect on the different tooth types and the different root surfaces. The reliability of the results was first assessed using paired *t-tests* and Dahlberg's equation (1940) as described in section 4.2.3. The results for the different tooth types and different root surfaces were first observed using exploratory graphs to assess the variability of the data and to look for the possible trends. This was followed by a statistical analysis to assess the significance of each. In light of trends and distribution three types of analysis were used, two- way ANOVA, one - way ANOVA and Kruskal-Wallis rank sum test. Kruskal-Wallis rank sum test was used to assess the effects of different anchorage methods on the different root surfaces because the response variables were counts with zeros and as a result they were not normally distributed. A non-parametric test utilizing the medians as measure of location was therefore used. The data were aggregated and averaged over histological sections, root types (mesial and distal) and tooth.

4.3.1 *Error of the results.*

No significant differences were found between the ratios of root resorption for both the intra-examiner and inter-examiner ($p>0.05$) (Table 4-1). Using Dahlberg's equation (1940) the error of the measurements of the total ratio of root resorption for the intra-examiner and inter-examiner were 0.02 and 0.02 respectively. Therefore the reliability of the quantitative assessment of root resorption under the circumstances was high.

Table 4-1. Paired t-test to assess the inter and intra-examiner error

	Mean Difference	95% Confidence Level		p-value
Intra examiner	-0.013	-0.026	0.0002	0.34
Inter examiner	-0.002	-0.03	0.03	0.89

4.3.2 *The effect of the different anchorage methods and tooth types (second and fourth premolar) on the total root resorption ratio.*

The total root resorption ratios for the three different anchorage methods and the different tooth types were assessed. An exploratory graph was first used to assess the variability of the data and look for possible trends, followed by a statistical analysis.

4.3.2.1 Variability of the data and the trends

The data were aggregated-averaged over histological sections and slides. There was a difference in the average total root resorption ratio between the two tooth types (second and fourth premolar) for Nance appliance and miniscrews anchorage methods. There was more resorption with the second premolar. The difference was not as obvious for the control group (Figure 4-5).

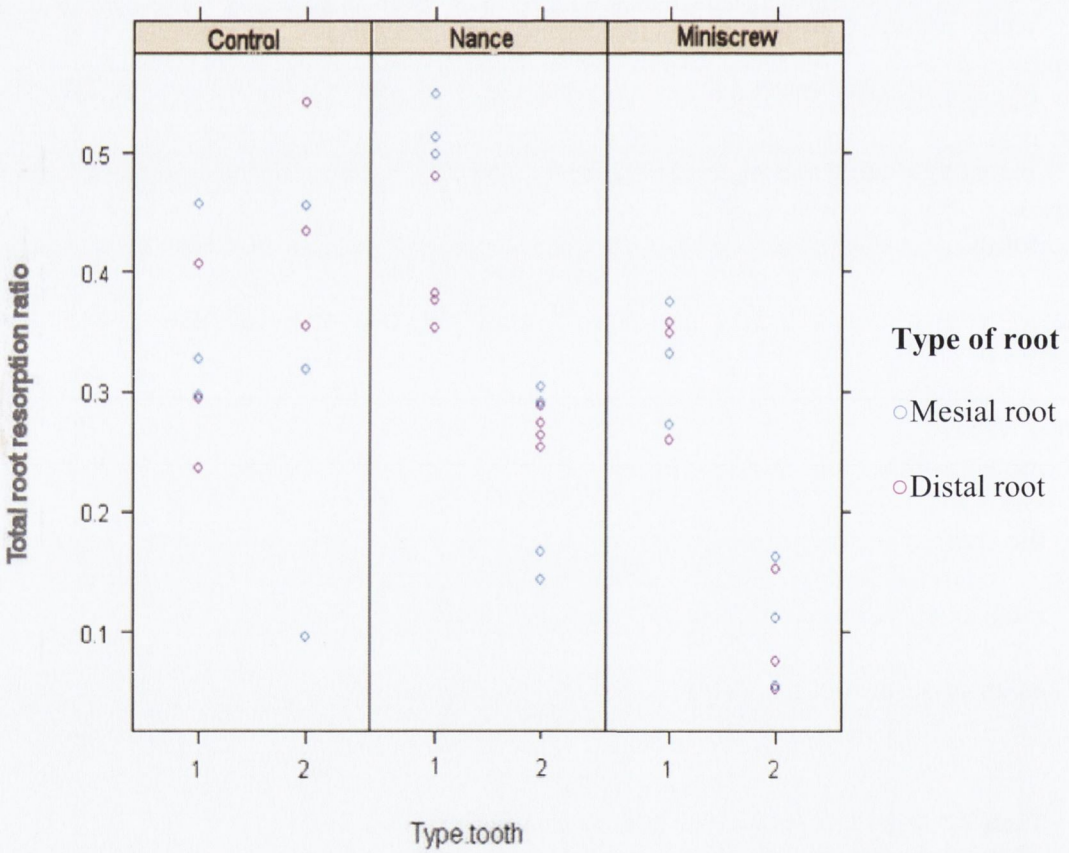


Figure 4-5. The average total root resorption ratios for the different anchorage methods (control, Nance and miniscrew). Each point represents an averaged count for a type of root (mesial and distal root) for each tooth type (second premolar=1 and fourth premolar=2) for every dog. The colours distinguish the two root types.

4.3.2.2 The effect of the different anchorage methods and tooth type on the total root resorption ratio.

The effect of different anchorage methods on the total root resorption ratio for the different tooth types (second and fourth premolar) was assessed. A two-way mixed analysis of variance (ANOVA) was carried out on the total root resorption ratio. The independent variables included one between groups variable, (anchorage with three levels - control, Nance and miniscrews) and one within subject variable, which is the type of tooth with two levels.

The anchorage method had a significant influence on the total root resorption ratio. Assessing the total root resorption ratios for the different anchorage methods (Table 4-2), the mean total root resorption ratio for the control (0.35) and Nance (0.33) groups were significantly higher than the miniscrew (0.21) ($p<0.01$) (Table 4-3).

Table 4-2. The means and standard deviations of the total root resorption ratios for each anchorage method

	Means and Standard deviations of total root resorption ratios	
Anchorage method	Control	0.35 ± 0.16
	Nance	0.33 ± 0.16
	Miniscrew	0.21 ± 0.18

Table 4-3. A two way mixed analysis of variance (ANOVA) for the effect of the different anchorage methods, tooth type and the interaction

	DF	Sum Sq	Mean Sq	F value	Pr (>F)
Anchorage method	2	0.08	0.38	9.6	*< 0.01
Type of Tooth	1	0.09	0.09	66.6	*< 0.01
Anchorage : type.tooth	2	0.06	0.03	21.7	*< 0.01

The mean total root resorption ratio for each tooth type (second and fourth premolar) was significantly different ($p<0.01$) (Table 4-3). When the tooth types were compared within each anchorage method (Table 4-4), the interaction term was significant ($p<0.01$). Therefore the difference due to tooth types is not the same for each anchorage method. In the Nance and miniscrew group the resorption rate was lower in the fourth premolar (PM_4) (0.25 and 0.10) compared to the second premolar (PM_2) (0.44 and 0.32) (Table 4-4). Whereas in the control group the resorption rate was higher in PM_4 (0.36) compared to the PM_2 (0.33) (Figure 4-6).

Table 4-4. The means and standard deviations of the total root resorption ratios for each tooth type (PM_2 and PM_4) within each anchorage method

Anchorage method	Type of tooth	Total root resorption ratio
Control	PM_2	0.33 ± 0.15
	PM_4	0.36 ± 0.17
Nance	PM_2	0.44 ± 0.12
	PM_4	0.25 ± 0.13
Miniscrew	PM_2	0.32 ± 0.17
	PM_4	0.10 ± 0.09

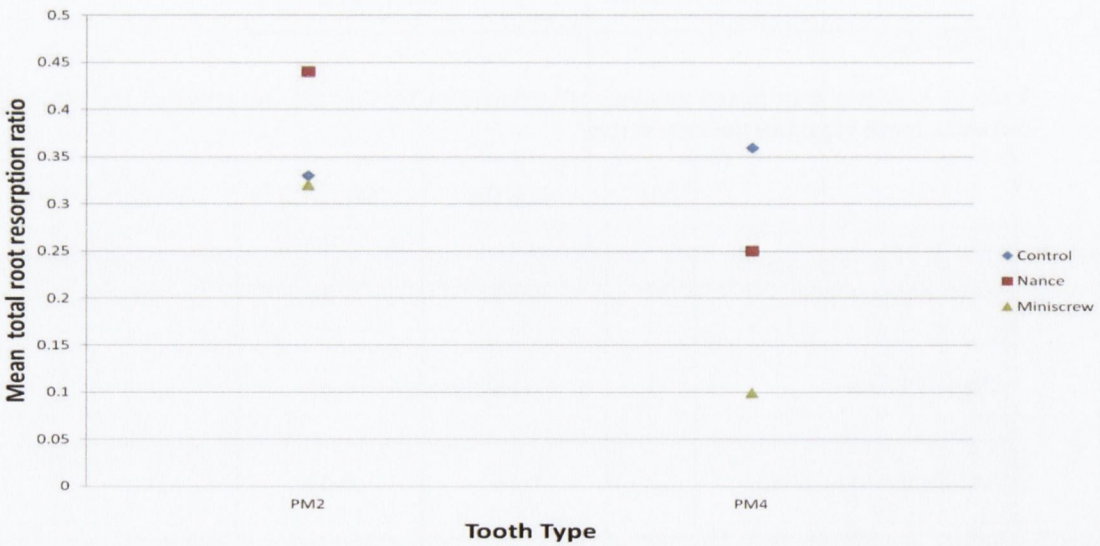


Figure 4-6. The means of the total root resorption ratios for each tooth type (PM_2 and PM_4) within each anchorage method.

4.3.2.3 The effect of the different anchorage methods on the total root resorption ratio of each tooth type individually (between the different anchorage methods).

The mean total root resorption ratio for each tooth type (PM_2 and PM_4) was compared between the different systems individually. The mean total resorption ratio for the PM_2 was highest in the Nance group (0.44) followed by the control group (0.33) and miniscrew group (0.32) respectively (Figure 4-7). On the other hand, the total resorption ratio in the PM_4 was highest in the control group (0.36) followed by the Nance group (0.25) and miniscrew group (0.10), respectively (Figure 4-7). A one-way mixed analysis of variance (ANOVA) was carried out on the total root resorption ratio with one between-subject factor, anchorage with three levels (control, Nance and miniscrews). There was a statistically significant difference between the means of total ratio of root resorption for both second premolar ($p=0.045$) and fourth premolar ($p<0.01$) between the different anchorage methods (Table 4-5).

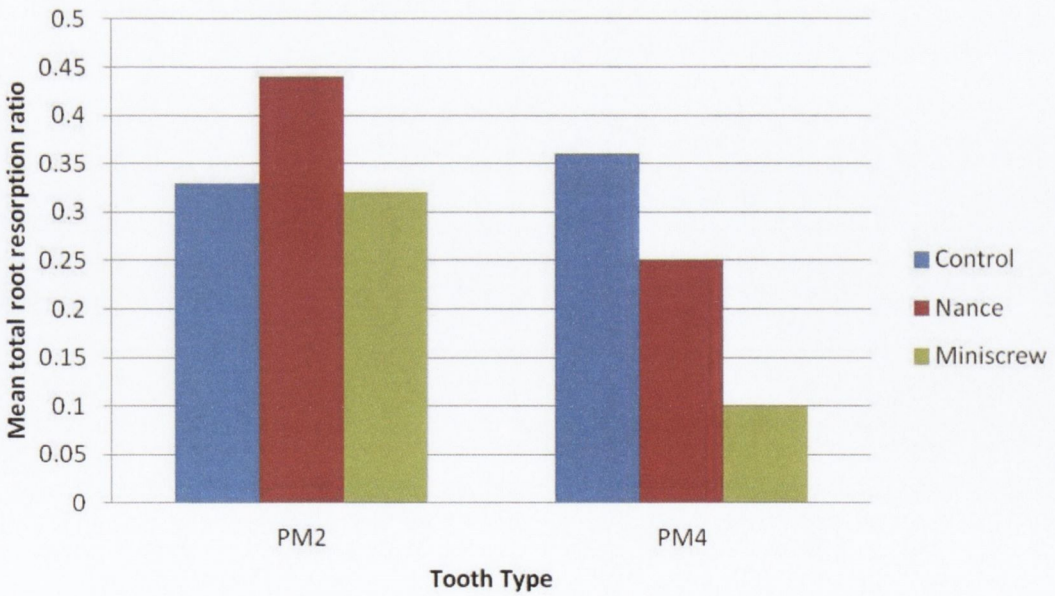


Figure 4-7. The means of the total root resorption ratios of for the second premolar (PM_2) and the fourth premolar (PM_4) for each anchorage method.

Table 4-5. A one-way mixed analysis of variance (ANOVA) for the total root resorption ratio of the second (PM_2) and fourth premolar (PM_4) between the different anchorage methods

Tooth Type	DF	Sum Sq	Mean Sq	F value	Pr (>F)
PM_2	2	0.03	0.15	4.96	*0.045
PM_4	2	0.10	0.53	22.8	*<0.01

4.3.3 *The effect of the different anchorage methods on the number of squares with root resorption on each surface (mesial, distal and apical).*

The number of squares with root resorption for the three surfaces (mesial, distal and apical) was assessed for the different anchorage methods (control, Nance and miniscrew). Exploratory graphs were first used to assess the variability of the data and look for general trends followed by a statistical analysis.

4.3.3.1 Variability of the data and the trend

The data were observed at three levels to assess the trends. Initially each surface was observed with the root and tooth type in addition to the anchorage type. The data were subdivided into root surfaces and the number of squares with resorption was plotted to assess if there was any trend within the mesial surface (Figure 4-8), distal surface (Figure 4-9) and apical surface (Figure 4-10). Although there was a slight trend of more resorption on the distal surface of the second premolar compared to the fourth premolar (Figure 4-9), it was somewhat hard to see the trend for the distal, mesial, and apical surfaces when they were assessed separately.

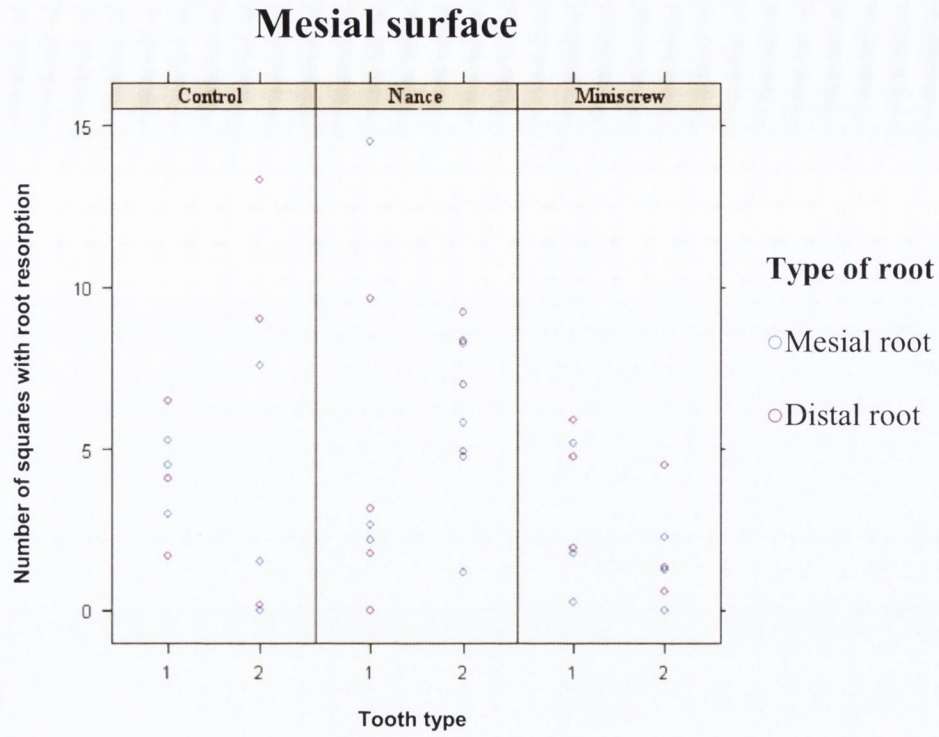


Figure 4-8. The number of squares with root resorption in the mesial surface for the different anchorage methods (control, Nance and miniscrew). Each point represents an averaged count for a root type (mesial and distal root) for each tooth type (PM_2=1 and PM_4=2) for each animal. The colours distinguish the two root types.

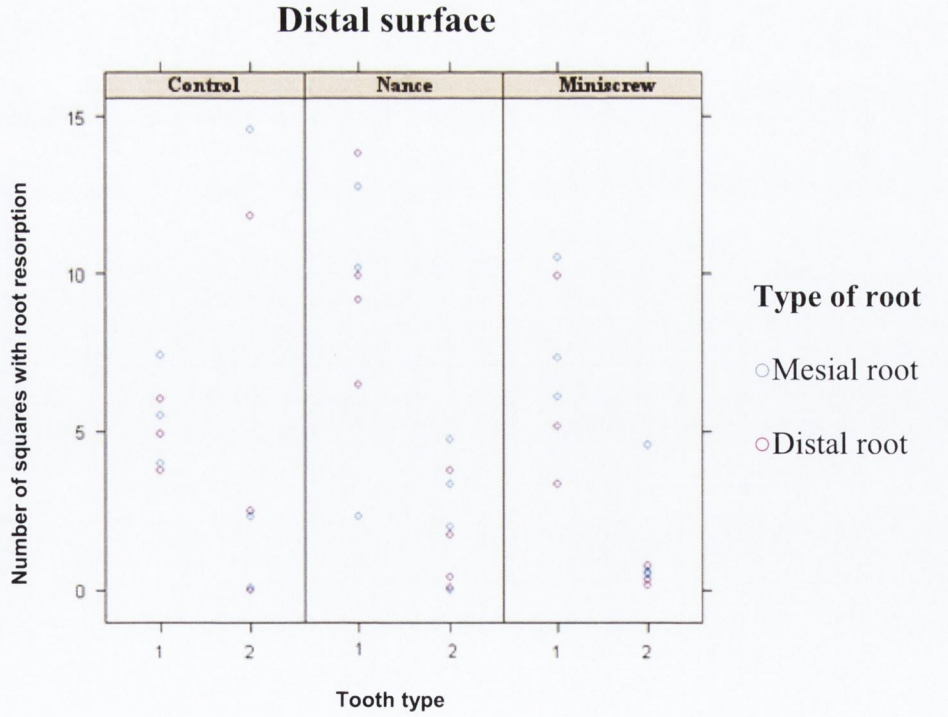


Figure 4-9. The number of squares with root resorption in the distal surface for the different anchorage methods (control, Nance and miniscrew). Each point represents an averaged count for a root type (mesial and distal root) for each tooth type (PM_2=1 and PM_4=2) for each animal. The colours distinguish the two root types.

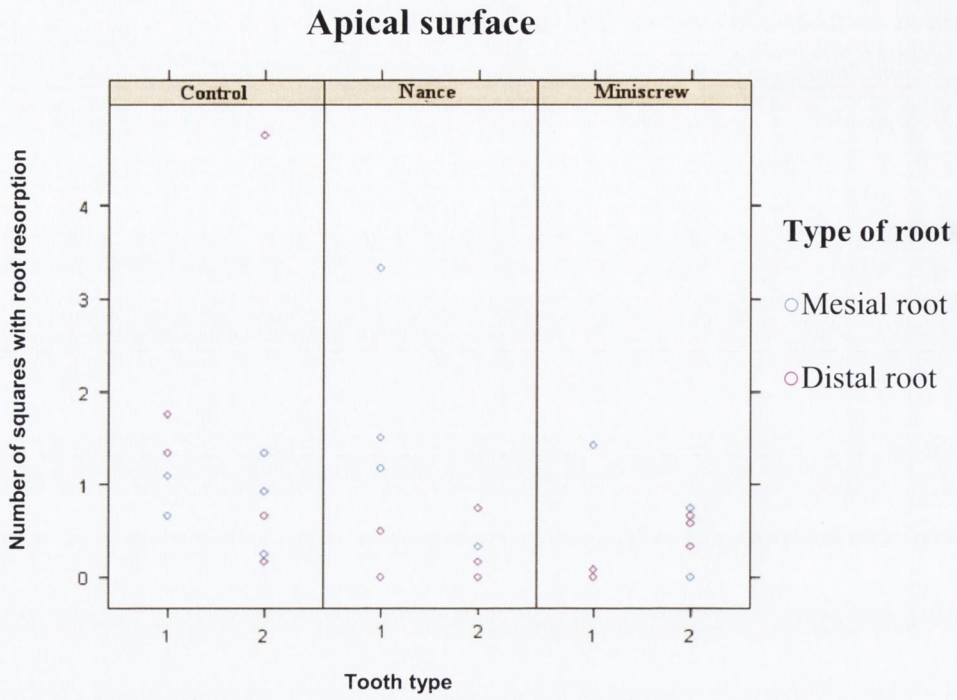


Figure 4-10. The number of squares with root resorption in the apical surface for the different anchorage methods (control, Nance and miniscrew) Each point represents an averaged count for a root type (mesial and distal root) for each tooth type (PM_2=1 and PM_4=2) for each animal. The colours distinguish the two root types.

The number of squares with resorption in the apical, mesial and distal surfaces within the three anchorage methods (control, Nance and miniscrew) were marked without identifying the tooth and root type (Figure 4-11). The counts of resorption for the apical surface were less than in the mesial and distal surfaces within the three anchorage methods.

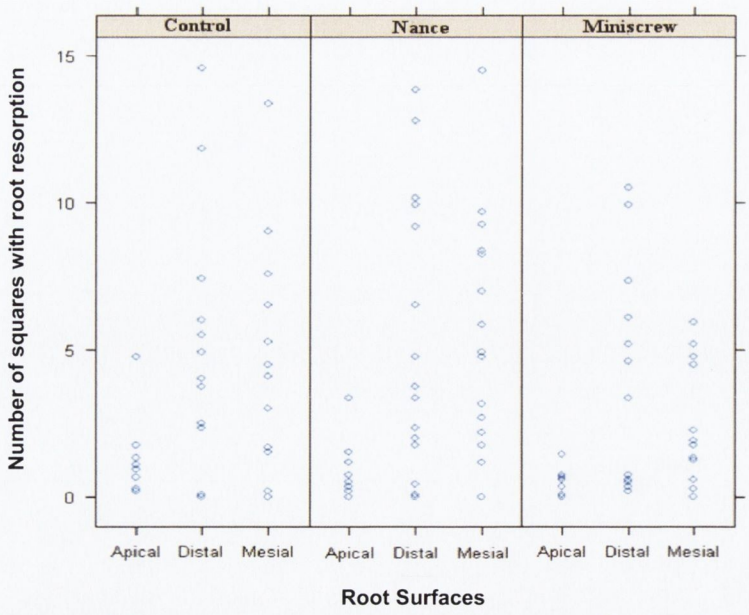


Figure 4-11. The number of squares with root resorption for the each tooth surface (mesial, distal and apical) within each anchorage method (control, Nance and miniscrew). Each point represents a tooth in each dog.

The number of squares with root resorption was also averaged over root types as well as tooth types for each dog to observe the resorption trend of three surfaces (apical, mesial and distal) individually between the different anchorage methods (Figure 4-12). There was no trend noticed with regard to any particular anchorage method.

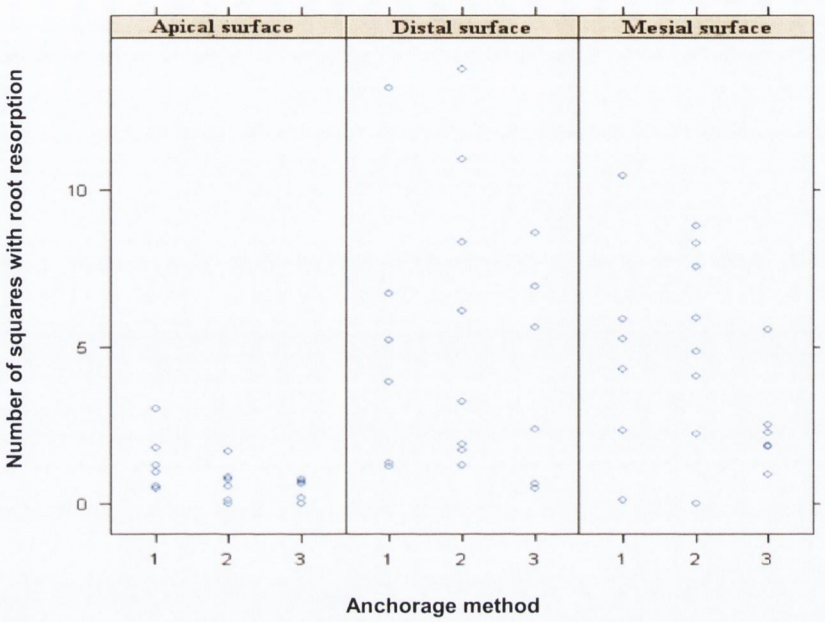


Figure 4-12. The number of squares with root resorption for each tooth surface (mesial, distal and apical) between the different anchorage methods (control=1, Nance=2 and miniscrew=3). Each point represent a tooth type for each dog.

4.3.3.2 The effect of the different anchorage methods on the number of squares with root resorption within each anchorage method.

The number of squares with root resorption for each surface (mesial, distal and apical) was assessed within each anchorage method. The medians of the number of squares with resorption in the mesial and distal surfaces within the Nance group (4.42 and 4.33) were approximately the same (Table 4-6). In the miniscrew group, the median number of squares with resorption was higher in the distal surface (1.92) compared to the mesial surface (1.25). In the control groups the medians of the number of squares with resorption in the distal surface (4.83) was also more than the mesial surface (2.25) (Table 4-6). The medians of the number of squares with resorption in the apical surface was the lowest of all surfaces, (0) in the Nance and miniscrew groups and (0.92) in the control group (Table 4-6).

Table 4-6. The median and the inter-quartile range of the number of squares with root resorption for each tooth surface within each anchorage method

Anchorage method	Type of surface	Median	Inter quartile range	Minimum	Maximum
Control	Mesial	2.25	0.25 – 8.87	0	14.67
	Distal	4.83	0 – 8.41	0	15.33
	Apical	0.92	0 – 1.87	0	5.83
Nance	Mesial	4.42	1.79 – 8.33	0	15.33
	Distal	4.33	0 – 8.91	0	16
	Apical	0	0 – 0.67	0	3.33
Miniscrew	Mesial	1.25	0.25 – 3.08	0	11.33
	Distal	1.92	0.45 – 7.25	0	14.17
	Apical	0	0 – 0.41	0	2.67

Assessing the medians of the number of squares with resorption for each tooth type separately, there were different patterns for PM_2 and PM_4 with regard to the mesial and distal surfaces. In the PM_2, the median number of squares with resorption in the distal surface was higher than the mesial surface in the three anchorage groups; control (7.33 and 2.67), Nance (10.75 and 2.92) and miniscrew (6.42 and 2) (Table 4-7). The median number of squares with root resorption in the apical surface was the lowest of all surfaces in the three groups; control (1.25), Nance (0) and miniscrew (0) (Table 4-7).

Table 4-7. The median and the inter-quartile range of the number of squares with root resorption for each tooth surface of the second premolar (PM_2) within each anchorage method

Anchorage method	Type of surface	Median	Inter quartile range	Minimum	Maximum
Control	Mesial	2.67	0.25 – 7.88	0	13
	Distal	7.33	1.70 - 8	0	9.83
	Apical	1.25	0.38 – 1.75	0	3.5
Nance	Mesial	2.92	0 – 6.42	0	15.33
	Distal	10.75	6.46 – 11.75	0	16
	Apical	0	0 – 1.13	0	3.33
Miniscrew	Mesial	2	0.5 – 4.75	0	11.33
	Distal	6.42	4.5 – 9.75	0.5	14.17
	Apical	0	0 - 0.42	0	2.67

In the PM_4, the medians of the number of squares with root resorption in the mesial surface for the Nance (5.42) and miniscrew group (1.17) were higher than the distal (0.25) and (0.50) respectively (Table 4-8). In the control group, the median number of squares with root resorption in the distal (2.42) was slightly higher than the mesial surface (2.25) (Table 4-8). The median number of squares of root resorption in the apical surface was the lowest of all surfaces for the three anchorage methods.

Table 4-8. The median and the inter-quartile range of the number of squares with root resorption for each tooth surface of the second premolar (PM_4) within each anchorage method

Anchorage method	Type of surface	Median	Inter quartile range	Minimum	Maximum
Control	Mesial	2.25	0.25 - 9.88	0	14.67
	Distal	2.42	0 - 11.67	0	15.33
	Apical	0.42	0 – 2.04	0	5.83
Nance	Mesial	5.42	2.46 - 8.33	0.5	15
	Distal	0.25	0 – 3.63	0	7.17
	Apical	0	0 – 0.33	0	0.83
Miniscrew	Mesial	1.17	0 - 2.04	0	7.17
	Distal	0.50	0 - 0.88	0	9.17
	Apical	0.17	0 – 1.17	0	1.33

Kruskal-Wallis rank sum test was used to assess if there was statistically significant difference between the mesial, distal and apical surfaces within each anchorage method. The difference was significant in the Nance and miniscrew group ($p<0.01$) (Table 4-9). In the control group the difference was not significant (Table 4-9).

Table 4-9. Kruskal-Wallis rank sum test results for thre different surfaces (mesial, distal and apical) within each anchorage method

Anchorage method	DF	p-value
Control	2	>0.05
Nance	2	*<0.01
Miniscrew	2	*<0.01

Using Dunn's multiple comparisons, the difference between the mesial and apical and distal and apical were statistically significant ($p<0.01$) for the Nance and miniscrew groups (Table 4-10). This was because the apical surface had a minimal number of squares with root resorption.

Table 4-10. Dunn's multiple comparisons results for the different surfaces (mesial, distal and apical) within the Nance and miniscrew group

Anchorage method	Surfaces comparisons	Mean Rank Difference	p-value
Nance	Mesial vs Distal	4.62	> 0.05
	Mesial vs Apical	29.66	*< 0.01
	Distal vs Apical	25.04	*< 0.01
Miniscrew	Mesial vs Distal	-4.58	> 0.05
	Mesial vs Apical	17.65	* < 0.01
	Distal vs Apical	22.23	* < 0.01

The median number of squares with root resorption in each surface was then assessed for each tooth type (PM_2 and PM_4) within each anchorage method. In the PM_2, the difference in the number of squares with root resorption between the surfaces was significant within the Nance and miniscrew groups ($p<0.01$) (Table 4-11).

Table 4-11. Kruskal-Wallis rank sum test results for the different surfaces (mesial, distal and apical) of the PM_2 within each anchorage method

Anchorage method	DF	p-value
Control	2	> 0.05
Nance	2	*< 0.01
Miniscrew	2	*< 0.01

Using Dunn's multiple comparisons, the differences in the PM_2 between the mesial and apical and distal and apical surfaces were statistically significant ($p<0.01$) in the miniscrew group (Table 4-12). In the Nance group, the difference was statistically significant between the distal and apical only ($p<0.01$) (Table 4-12).

Table 4-12. Dunn's multiple comparisons results for the different surfaces (mesial, distal and apical) of the PM_2 within the Nance and miniscrew group

Anchorage method	Surfaces comparisons	Mean Rank Difference	p-value
Nance	Mesial vs Distal	-8.79	> 0.05
	Mesial vs Apical	7.79	> 0.05
	Distal vs Apical	16.58	*< 0.01
Miniscrew	Mesial vs Distal	-8.13	> 0.05
	Mesial vs Apical	11.25	* < 0.05
	Distal vs Apical	19.38	* < 0.01

In the PM_4, the difference between the surfaces was only significant in the Nance group ($p<0.01$) (Table 4-13). Using Dunn's multiple comparisons, the difference between the median number of squares with root resorption in the mesial and distal and mesial and apical surfaces was significant ($p<0.01$) (Table 4-14).

Table 4-13. Kruskal-Wallis rank sum test results for the different surfaces (mesial, distal and apical) of the PM_4 within each anchorage method

Anchorage method	DF	p-value
Control	2	> 0.05
Nance	2	*< 0.01
Miniscrew	2	> 0.05

Table 4-14. Dunn's multiple comparisons results for the different surfaces (mesial, distal and apical) of the PM_4 within the Nance group

Anchorage method	Surfaces comparisons	Mean Rank Difference	p-value
Nance	Mesial vs Distal	14.94	*< 0.01
	Mesial vs Apical	23.41	*< 0.01
	Distal vs Apical	8.47	> 0.05

4.3.3.3 The effect of the different anchorage methods on the number of squares with root resorption between the different anchorage methods.

The number of squares with root resorption for each tooth surface (mesial, distal and apical) was assessed individually and compared between the different anchorage methods. Using the medians, Kruskal–Wallis rank sum test was used to assess if there was a significant difference between each surface (mesial, distal and apical) individually between the three anchorage methods (control, Nance and miniscrew). When the number of squares with root resorption for each surface (mesial, distal and apical) was combined for both tooth types (PM_2 and PM_4), there was a statistically significant difference between different anchorage methods for the apical surface ($p<0.01$) only (Table 4-15).

Table 4-15. Kruskal-Wallis rank sum test results for each surface (mesial, distal and apical) individually between the three anchorage methods (control, Nance and miniscrew)

Surface Type	DF	p-value
Mesial	2	0.06
Distal	2	0.88
Apical	2	*< 0.01

Dunn's multiple comparisons for the apical surface revealed a statistically significant difference between the control and both the miniscrew and Nance groups ($p<0.05$) (Table 4-16).

Table 4-16. Dunn's multiple comparisons results for the apical surface between the three different anchorage methods (control, Nance and miniscrew)

Surface	Anchorage method comparisons	Mean Rank Difference	p-value
Apical	Control vs Nance	15.27	*< 0.05
	Control vs Miniscrew	15.44	*< 0.05
	Nance vs Miniscrew	0.17	> 0.05

Each tooth type (PM_2 and PM_4) was then assessed separately across the different anchorage methods. In the PM_2, the medians of the number of squares with root resorption in the mesial and distal surface were the highest in the Nance group (2.92 and 10.75), followed by the control group (2.67 and 7.33) and miniscrew group (2 and 6.42), respectively (Table 4-7). Statistically the differences were not significant ($p>0.05$) for the mesial and distal surfaces (Table 4-17). The median number of squares with root resorption in the apical surface was 1.25 for the control group and 0 for the Nance and miniscrew groups. The difference between the medians of the number of squares with root resorption in the apical surface was statistically significant between the different anchorage methods ($p = 0.03$) (Table 4-17).

Table 4-17. Kruskal–Wallis rank sum test results for each surface (mesial, distal and apical) individually in the PM_2 between the three anchorage methods (control, Nance and miniscrew)

Surface Type	DF	p-value
Mesial	2	0.93
Distal	2	0.10
Apical	2	*0.03

Dunn's multiple comparisons for the apical surface revealed a statistically significant difference between the control and the miniscrew groups ($p<0.05$) only (Table 4-18).

Table 4-18. Dunn's multiple comparisons results for the apical surface in the PM_2 between the three different anchorage methods (control, Nance and miniscrew)

Surface	Anchorage method comparisons	Mean Rank Difference	p-value
Apical	Control vs Nance	6.17	> 0.05
	Control vs Miniscrew	10.46	*< 0.05
	Nance vs Miniscrew	4.292	> 0.05

In the PM_4, the median number of squares with root resorption in the mesial surface was the highest in the Nance (5.42) followed by the control (2.25) and miniscrew (1.17) respectively (Table 4-8). In the distal and apical surface, the median number of squares with root resorption was highest in the control (2.42 and 0.42) followed by the miniscrew (0.5 and 0.17) and Nance group (0.25 and 0) respectively (Table 4-8). The differences between the three anchorage methods was only statistically significant for the mesial surface ($p=0.02$) (Table 4-19). Dunn's multiple comparisons for the mesial surface revealed statistical significance between the Nance and miniscrew groups ($p<0.05$) only (Table 4-20).

Table 4-19. Kruskal–Wallis rank sum test results for each surface (mesial, distal and apical) individually in the PM4 between the three anchorage methods (control, Nance and miniscrew)

Surface Type	DF	p-value
Mesial	2	*0.02
Distal	2	0.55
Apical	2	0.11

Table 4-20. Dunn's multiple comparisons results for the mesial surface in the PM_4 between the three different anchorage methods (control, Nance and miniscrew)

Surface	Anchorage method comparisons	Mean Rank Difference	p- value
Mesial	Control vs Nance	-0.67	>0.05
	Control vs Miniscrew	0.92	>0.05
	Nance vs Miniscrew	1.58	*<0.05

4.4 Discussion

The purpose of this animal study was to quantify the amount of orthodontically induced inflammatory root resorption (OIIRR) associated with different anchorage reinforcement methods (control, Nance appliance and miniscrews). In the control group, no anchorage reinforcement appliance was used; but instead the PM_4 was used as a form of conventional tooth anchorage. A histological method developed by Lu and colleagues (1999) in an animal model was used to assess the total ratio (percentage) of root resorption and the number of squares with resorption along the different surfaces (mesial, distal and apical) of the PM_2 and PM_4 following 15 weeks of orthodontic tooth movement.

Several methods for quantifying resorption craters, using conventional light microscopy, have been described in the literature (section 1.7.10). Kurol and colleagues (1996) described a method using a micrometer mounted on the eye piece and arbitrary units. Maltha and colleagues (2004) used low magnification with the light microscope to enable them to measure the whole root. The authors measured the resorption craters when they extended to dentine only, as they were unable to identify resorption limited to cementum only. In addition, the authors found it difficult to predict the original outline of the root. Therefore, Lu and colleagues' 1999 method was used in the current study, as resorption into cementum as well as dentine can be measured and did not require the prediction of the original root outline. Different groups of researchers (Al-Qawasmi *et al.*, 2006; Abass *et al.*, 2008) used this method later on, and found it reproducible. In the current study, this method had good inter-examiner and intra-examiner reliability (section 4.3.1).

The use of a dog model to study tooth movement had certain advantages most of which were discussed in Chapter 2. An important advantage was the control the investigator had over the direction of tooth movement. The majority of the previous histological, scanning

electron microscopic (SEM) and x-ray microtomography human studies on tooth movement investigated teeth which have been moved buccally or lingually rather than along the dental arch (Chan & Darendeliler, 2005; Srivicharnkul *et al.*, 2005; Chan & Darendeliler, 2006; Rex *et al.*, 2006; Barbagallo *et al.*, 2008; Ballard *et al.*, 2009; Cheng *et al.*, 2009; Deane *et al.*, 2009; Oh *et al.*, 2011; Paetyangkul *et al.*, 2011). This was because space creation along the dental arch for experimental reasons in humans may not be possible for ethical considerations. Buccal or palatal tooth movement may involve contact with dense cortical bone which in turn may influence the root resorption pattern (Reitan, 1974; Kaley & Philips, 1991). Furthermore, the amount of tooth movement possible is limited by the amount of bone to the buccal or lingual. In the current study, the teeth were moved along the dental arch for a distance representative of that in the human clinical situation.

4.4.1 *The effect of the different anchorage methods on the total root resorption ratio*

The difference between mean total root resorption ratio (percentage) for the 3 different groups (control, Nance and miniscrew) was statistically significant ($p<0.01$) irrespective of tooth type (PM_2 and PM_4). Whilst similar percentages of resorption were found for control (35%) and Nance (33%) groups, the miniscrew was found to have the least percentage of resorption (21%). The bulk of the previous human studies comparing the effect of different orthodontic appliances on OIIRR have failed to see a significant difference between appliances (Malmgren *et al.*, 1982; Beck & Harris, 1994; Blake *et al.*, 1995; Alexander *et al.*, 1996; Parker & Harris, 1998; McNabb *et al.*, 2000; Scott *et al.*, 2008; Pandis *et al.*, 2008). However, the duration of tooth movement was not controlled and the amount of tooth movement was not recorded in the studies cited above. This may explain why previous studies failed to detect a difference in the amount of root resorption between the

difference appliances. Furthermore, none of the previous studies relied on histology for those measurements but on radiographs, which cannot capture the same amount of detail. A recent radiographic study on humans (Liou & Chang, 2010) which assessed the effect of miniscrews on resorption, recorded the amount of tooth movement. The authors found that more resorption occurred with the use of miniscrews than conventional tooth anchorage. They attributed this to more extensive tooth movement achieved with miniscrew anchorage (Liou & Chang, 2010).

Both the duration of treatment (Harris & Baker, 1990; Kurol *et al.*, 1996; Sameshima & Sinclair, 2001b; Maltha *et al.*, 2004; Mohandesan *et al.*, 2007; Paetyangkul *et al.*, 2011) and amount of tooth movement (DeShields, 1969; Kaley & Phillips, 1991; Mirabella & Artun, 1995b; Liou & Chang, 2010; Bartley *et al.*, 2011) during treatment have been found to affect root resorption. In the current study, all the animals were treated for an equal duration and the amount of tooth movement was recorded. The amount of movement of the PM_2 (5.11 mm) and PM_4 (3.96 mm) in the control group was greater than in the Nance (5.38 mm and 2.03 mm) and miniscrew (5.11 mm for PM_2 only) groups. Since the duration of treatment was equal across the groups, the findings of the current study that the control and the Nance groups had more resorption than the miniscrew group may have been associated with the greater (PM_2 and PM_4) amount of tooth movement. Furthermore it should be bourne in mind that the PM_4 was not moved in the miniscrew groups.

4.4.2 *The effect of tooth types (PM_2 and PM_4) on the total root resorption ratio*

The effect of the root surface area (PM_2 and PM_4) on root resorption was assessed. The mean percentage (total root resorption ratio) of root resorption for PM_2 (36%) was significantly greater than PM_4 (23%) ($p<0.01$). The difference in resorption found for the PM_2 and PM_4 may have been due to root surface area difference. Root width has been found to be inversely related to root resorption (Mirabella & Artun, 1995b; Taithongchai *et*

al., 1996; Sameshima & Sinclair, 2001a; Artun *et al.*, 2009). Another explanation for the greater percentage of root resorption found for PM_2 may be related to the amount of tooth movement of each tooth type, as in the current study the amount of PM_2 movement was considerably greater than that for the PM_4.

To clarify the relationship between the anchorage reinforcement methods and tooth type (interaction), each tooth type within each group was analysed (Figure 4-6). The interaction was highly significant ($p<0.01$). In the Nance and miniscrew groups, the PM_2 (44% and 32%) had a significantly higher mean percentage of root resorption than the PM_4 (25% and 10%). In contrast, the PM_4 in the control group had a marginally greater percentage of root resorption (36%) than PM_2 (33%). The reduced PM_4 movement in the Nance and miniscrew, may have resulted in a lower mean percentage of root resorption compared to the PM_2. In the control group, although the PM_2 moved more and had less root surface area than the PM_4, the PM_4 had approximately the same percentage of root resorption. It can be assumed that as the difference in the mean amount of tooth movement between PM_2 and PM_4 (1.15 mm) in the control group was less than in the Nance (3.35 mm) and miniscrew (5.11 mm) groups, the difference in the means of percentages of root resorption between PM_2 and PM_4 in the control group was also small. Previous human studies also suggested that shorter roots are not at a higher risk of root resorption (Goldson & Henrikson, 1975; Levander & Malmgren, 1988; McFadden *et al.*, 1989; Mirabella & Artun, 1995b; Sameshima & Sinclair, 2001a; Chan & Darendeliler, 2005; Artun *et al.*, 2009). Therefore, the method of anchorage reinforcement indirectly influenced the percentage of root resorption by controlling the amount of tooth movement in the PM_4. It seems that the amount of tooth movement may have a larger effect on root resorption than root surface area.

4.4.3 *The effect of the different anchorage methods on the total root resorption ratio of each tooth type (between the different anchorage methods).*

From this study we could conclude that the method of anchorage reinforcement influences tooth movement or the force applied to different types of teeth. To clarify the effect of the different methods of anchorage reinforcement on root resorption, each tooth type was assessed between the different groups (control, Nance and miniscrew). Therefore, the effect of the method of anchorage reinforcement was assessed without the influence of root size and, in the case of PM_2, the amount of tooth movement as well. This was because the PM_2 moved an approximately equal distance in the three groups after 15 weeks.

The mean percentage of root resorption of each tooth type (PM_4 and PM_2) was assessed between the different groups (control, Nance and miniscrew). The highest mean percentage of root resorption for PM_4 was in the control group (36%), followed by the PM_4 in the Nance (25%) and miniscrew (10%) groups respectively. The difference was statistically significant ($p<0.01$). The mean percentage of root resorption for PM_4 within the different groups (control, Nance and miniscrew) in the current study was greater with larger PM_4 movement. This may confirm that the amount of root resorption is related to the amount of tooth movement, which corresponds to the findings of previous studies (DeShields, 1969; Kaley & Phillips, 1991; Bartley *et al.*, 2011). Interestingly, the PM_4 in the miniscrew group had resorption without active tooth movement and without orthodontic forces. This is in agreement with previous studies (Kurol *et al.,* 1996; Chan *et al.,* 2004) which found root resorption where there was no active tooth movement and suggested resorption could be a naturally occurring physiological process. When resorption of the PM_2 was compared between the different anchorage reinforcement methods, it was significant ($p=0.045$). The PM_2 in the Nance group had the highest mean percentage of root resorption (44%) followed by the PM_2 in the control (33%) and miniscrew (32%) groups. The PM_2 in the three groups (control, Nance and miniscrew) moved an approximately equal distance (5.09

mm, 5.38 mm and 5.11 mm) over the same period of time. Thus, the amount and duration of tooth movement do not explain the higher percentage of root resorption associated with the PM_2 in the Nance group. This may indicate that the introduction of the Nance appliance may have resulted in a higher percentage of root resorption. The mechanism by which the Nance appliance reinforces anchorage may explain the unexpectedly higher percentage of root resorption in the PM_2. The Nance appliance increases the root surface area ratio of the anchor units by connecting the right and left molars together across the palate or the floor of the mouth, as in the current study. As several studies have found contralateral teeth move at different rates (Pilon *et al.,* 1996; van Leeuwen *et al.*, 1999), which may lead to a rotational movement of the appliance with the acrylic button on the palate being the fulcrum. This movement may have caused the PM_2 to become pressed against the dense cortical bone layer, resulting in higher root resorption. Reitan (1974) and Kaley & Philips (1991) suggested that increased bone density may increase the risk of root resorption although there is no conclusive evidence to support this hypothesis (Wainwright, 1973; McFadden *et al.*, 1989; Taithongchai *et al.*, 1996). Another explanation for the higher percentage of root resorption in the PM_2 with the Nance appliance maybe due to the possible movement of the acrylic button. The acrylic button of the Nance appliance presses against the palatal soft tissue and underlying bone. Although the cortical palatal bone provides anchorage, it was found in the earlier study (Chapter 2) that the anchor units (PM_4) did move. The movement of the anchor units may have occurred as a result of the compression of the soft tissue underlying the acrylic button. This may have resulted in the acrylic button of the appliance being displaced inferiorly. The long arms of the Nance appliance would have acted like a lever as the dog's tongue pressed against the acrylic button. This change of angulation may have influenced the force on the PM_2 resulting in greater resorption. Furthermore, tongue pressure and other activities may have resulted in jiggling forces affecting both the PM_2 and PM_4, leading to a higher percentage of root

resorption for the PM_2. Alternatively, the introduction of the Nance appliance may have affected the type of tooth movement (bodily or tipping) of the PM_2. In the previous studies which compared the different types of movement (Phillips, 1955; DeShields, 1969; Kaley & Phillips, 1991; Mirabella & Artun, 1995b; Baumrind *et al.*, 1996; Parker & Harris, 1998; Sameshima & Sinclair, 2001b) the distance the teeth were moved varied amongst the subjects. The duration of active orthodontic tooth movement, which has been found to influence the amount of root resorption, was not controlled in the previous studies. As a result, most of the studies which assessed the different types of tooth movement concluded that although bodily movement caused more root resorption than other types of movement, it could have been due to the larger amount of tooth movement which accompanied bodily tooth movement. This was not the case with PM_2 in the current study, as the amount of tooth movement was similar between the groups.

The force levels may have also varied as a result of the introduction of the Nance appliance. In the earlier studies (Chapter 2 and Chapter 3) the pattern and amount of desired tooth movement (PM_2) were different in the anchorage reinforcement groups (Nance and miniscrew) compared with the control group at T2. It was suggested that this could have been due to variation in force levels. The reports on the effect of force on root resorption have been conflicting. There have been contradictory reports whose findings suggest that force magnitude does not increase root resorption (Owman-Moll *et al.*, 1996a; 1996b; Maltha *et al.*, 2004; Winter *et al.*, 2009). A number of studies demonstrated that heavier forces produced more root resorption and as a result the majority considered them harmful (King & Fischlschweiger, 1982; Chan & Darendeliler, 2005; 2006; Harris *et al.*, 2006; Barbagallo *et al.*, 2008; Gonzales *et al.*, 2008; Bartley *et al.*, 2011; King *et al.*, 2011; Wu *et al.*, 2011; Jimenez Montenegro *et al.*, 2012). Few studies have investigated the effect of force and amount of tooth movement together on root resorption (Owman-Moll *et*

al. 1996a; 1996b; Maltha *et al.,* 2004; Gonzales *et al.,* 2008). Even though the amount of tooth movement was recorded in these latter studies, the amount of tooth movement was not controlled or matched between groups. These studies found tooth movement to be more influential on the severity of root resorption than the force magnitude. Maltha and co-workers (2004) suggested that it would be interesting to investigate resorption if the same amount of tooth movement created by different force levels is somehow compared. In the current study it was difficult to associate the higher resorption in the Nance group to force levels as higher resorption was not seen in the miniscrew group which had a similar tooth movement pattern. This could be because the majority of studies which found larger resorption when higher forces were applied had an approximately 9 fold increase in the force level. In the current study the difference in force levels between the different groups would have been much less (20-40 g). Thus, the higher resorption in the Nance group may have been related to the reasons explained earlier rather than the force magnitude.

4.4.4 *The effect of the different anchorage methods on the number of squares with root resorption on each surface (mesial, distal and apical).*

4.4.4.1 Comparisons within each anchorage group

The type of tooth movement (bodily, tipping, intrusion, extrusion and torque) has been suggested as one of the factors which could play a role in root resorption. Different types of movement have been shown to produce different force distributions and root resorption along the different root surfaces (Casa *et al.,* 2001; Shaw *et al.,* 2004; Chan & Darendeliler, 2006; Bartley *et al.,* 2011; Wu *et al.*, 2011; Jimenez Montenegro *et al.,* 2012). The number of squares with root resorption in each surface (mesial, distal and apical) was therefore compared for each anchorage method. Based on these previous human studies, more resorption on the distal surface of the PM_2 may have been expected

whilst the PM_4 would have had more resorption on the mesial surface, provided the teeth were moved bodily. In contrast, tipping movements would have produced resorption apically, as well as affecting the mesial and distal surfaces of each tooth (Chan & Darendeliler, 2006). A dog study, (Maltha *et al.,* 2004) found that resorption occurred with bodily movement almost exclusively in the middle zone of the pressure surface (mesial or distal) of the root and not at the apex. For the control group of the current study, the differences between the root surfaces with regard to the median number of squares with root resorption were not significant, even when each tooth type (PM_2 and PM_4) was assessed separately. When both tooth types were combined, resorption was not significantly different between the surfaces because both tooth types moved approximately the same amount (45% of total movement for PM_2 and 55% for PM_4). When each tooth type was assessed separately, the median number of squares with resorption on the distal surface was 7.33 and on the mesial surface was 2.67 for PM_2. The median number of squares with resorption on the mesial surface for PM_4 was 2.42 compared to 2.25 on the distal surface. When the differences between the surfaces for each tooth type were analysed, they were not found to be statistically significant. As both surfaces were affected, tipping movement may have occurred in conjunction with bodily movement (Chan & Darendeliler, 2006; King *et al.*, 2011). Furthermore, there was a higher number of squares with resorption on the apical surface in the control compared with the other groups (Nance and miniscrew). This pattern is perhaps to be expected as tipping movement is easier to envisage with the control anchorage than with the more stable Nance and miniscrew anchorages (see below).

The number of squares with resorption along the different surfaces for the Nance and miniscrew groups was measured. A difference between the mesial and distal would have been expected for the PM_2 and PM_4 in bodily tooth movement (Maltha *et al.,* 2004). For

the PM_2, there was more resorption on the distal surface than the mesial for the Nance and miniscrew groups but the differences were not statistically significant. This may have been due to the small sample size or the limitation of the current histological method, which may miss resorption craters along the surfaces. For the PM_4, there was more resorption for the mesial surface than the distal surface for both groups (Nance and miniscrew). The difference was only statistically significant for the Nance group as no movement was detected for the PM_4 in the miniscrew group. Chan & Darendeliler (2006) found significantly less resorption on the tensile surface than on the compression surface, which may also explain the lesser amount of resorption on the tensile surfaces in the PM_2 and PM_4.

4.4.4.2 Comparisons between the different groups

The number of squares with resorption within each surface (mesial, distal and apical) was also compared between the different groups. When both tooth types (PM_2 and PM_4) were combined, only the median number of resorption squares in the apical surface between the control and the other two groups (Nance and miniscrew) was significant. The control had significantly more median numbers of squares with resorption in the apical surface resorption than the other anchorage reinforced groups (Nance and miniscrew). This suggests that tipping movement was more prevalent with the control group, consistent with the assumption that the miniscrew and the Nance appliance induced more bodily movement. In the miniscrew group, placing the miniscrew gingivally along the buccal mucosa guarded the NiTi closing coil from the masticatory forces and food plunging into the NiTi closing coil, thus reducing the likelihood of tipping movement. This may have not been the case in the control group, in which the plunging effect may have resulted in slight tipping, and possibly intrusive, forces. The design and rigidity of the Nance appliance could have also prevented the PM_4 from tipping thus indirectly influencing the movement of the PM_2. When the PM_2 was assessed individually, there was only a significant

difference between the miniscrew and control group for the apical surface. Although the difference may seem clinically insignificant (1.42), the method used in the current study does not quantify the total resorption area. Thus the difference between the resorption produced by the control and the other groups (Nance and miniscrew) may be much larger. For the mesial and distal surfaces in the PM_2, there was no difference since the PM_2 in the three groups moved an approximately similar distance for the same duration. The amount of PM_4 movement was different in the three groups and this led to a significant difference between the groups, and in particular the mesial surface, since the PM_4 was moved mesially. The Nance group had the highest median number of squares with resorption in the mesial surface for the PM_4 followed by the control and miniscrew groups, respectively. Only the difference between the Nance and the miniscrew was significant. The control group had less resorption than the Nance group on the mesial surface of the PM_4 despite more movement. This might be due to tipping movement in the control group and, as a result, the distal surface in the control group had more resorption than the distal surface of the PM_4 in the Nance group.

4.4.5 *Limitations*

It is important to consider whether the findings in the current dog study are comparable to humans and whether conclusions drawn from this study can be applied to clinical situations. Reitan & Kvam (1971) were the first to address this question. They investigated the different species used in experimental tooth movement and found dogs to be the closest to humans. There were several things they noted to be different in dogs: labial bone and cementoid. They found the labial and lingual bone in dogs to be more dense with relatively less marrow spaces compared to humans and suggested that this may affect the resorptive process. They also found an increase in the cementoid layer in the tension side which also might affect the resorption process (section 1.7.4). The repair pattern of orthodontic root resorption has also been found to differ slightly between animals and humans. In animals,

the repair process starts at the periphery of the resorptive lesion (Lindskog *et al.,* 1987; Brudvik & Rygh, 1995a) whereas in humans it starts at the bottom of the resorptive lesion (Langford & Sims, 1982; Owman-Moll *et al.,* 1995b). The root surface area and root configuration of dogs also differs from that of humans. All these aspect may have affected the amount and pattern of root resorption. However, a systematic review by von Böhl and colleagues (2009) found no major differences in tissue reactions between species during experimental tooth movement.

The orientation of the histological slides may have masked the resorption craters. Although attempts were made to have the cuts parallel to the long axis of the tooth and several sections were taken from each sample, some resorption craters may have still been missed. This was because of the irregular shaped resorption craters, irregular morphology of the roots and technical difficulty. Although the current study was quantitative, root resorption is a three dimensional process and two dimensional assessment can underestimate the extent of root resorption. As a result, two dimensional assessment of root resorption can only give an indication of the extent of resorptions.

The point in time at which the histological evaluation is done may also be a limitation. Several studies have found that the hyalinization process occurs during all phases (initial, lag, post lag and linear) of tooth movement rather than as a single event (von Böhl *et al.,* 2004a; 2004b) which was thought to occur during the lag phase only. Repair of the cementum may also have been occurring during the 15 week period as it occurs from 2 to 21 days following force application (Brudvik & Rygh, 1995a). Moreover, repair would occur even during active force application (Brudvik & Rygh, 1995b; Owman-Moll & Kurol, 1998; Winter *et al.,* 2009) which may mask any resorption craters.

Inter-individual differences such as anatomical structures, bone density and cellular activity may have affected the results in the current study. A larger sample size may have

been needed to overcome such variations. However due to ethical considerations, the sample size was limited.

The appliance used in the current study also differs from those used in a clinical situation. This was discussed earlier in the first study (Chapter 2). The right and left side of the mandible in the current study were not connected except in the case of the Nance appliance. The inclusion of all the teeth might have exposed the teeth to different forces and types of tooth movement.

4.4.6 *Conclusion*

In conclusion, the roots' surface area and the amount of tooth movement had more impact on the amount of root resorption than the type of anchorage method investigated. However, anchorage methods influenced the amount of resorption indirectly by controlling the amount of movement produced in the anchor units. When the teeth had equal amounts of movement and root size, the introduction of the Nance appliance increased the amount of root resorption. The method of anchorage reinforcement affected the distribution of resorption among the different surfaces (mesial, distal and apical) as more apical resorption was noted in the control group. This might indicate that more tipping occurred within the control group. In clinical terms, the anchorage reinforcement methods used in the current study did not cause more resorption; on the contrary, they reduced the amount of resorption by restraining the movement of the anchor units. Nonetheless, orthodontists should be cautious, as space closure with anchorage reinforcement methods is accompanied by more desired tooth movement, thus exposing the retracted teeth to more resorption. Currently, a threshold for the amount of tooth movement responsible for root resorption is not known. In conclusion, orthodontists should evaluate the amount of desired tooth movement prior to utilizing anchorage reinforcement methods with respect to the risk of root resorption, as well as anchorage requirements. In the case of the Nance appliance,

orthodontists should be wary of the effect of joining both sides of the arch together as that might increase the risk of root resorption by introducing a rotational effect.

5 Final discussion

Many orthodontic appliances have evolved over the years with the aim of developing the ideal anchorage appliance; one that would achieve absolute anchorage. Intra-oral anchorage appliances are most convenient because their efficacy does not depend on patients' compliance. When an orthodontic appliance is first introduced, three factors must be assessed: whether it achieves the intended objective, whether it affects the efficiency of treatment and whether it has undesirable side effects on the dentition. In orthodontics these factors translate respectively into assessing the amount of anchorage loss/gain, desired tooth movement and orthodontically induced inflammatory root resorption. The purpose of this research was to investigate these factors clinically and histologically for the Nance appliance, miniscrew and conventional tooth anchorage (control) in a dog model.

5.1 Anchorage loss

The amount of anchorage loss associated with the Nance appliance, miniscrew and control group was assessed after 15 weeks of retracting the mandibular PM_2 in dogs. Neither of the methods for anchorage reinforcement (Nance and miniscrew) provided absolute anchorage. The amount of anchorage loss varied between the different anchorage methods over time. The Nance appliance had a mean anchorage loss of 2.03 mm and provided 1.93 mm more anchorage compared to the control after 15 weeks. Importantly, the percentage of anchorage loss to the total space closure was approximately 28.8% and this was 16.9% less than the control group. Clinically and statistically these differences were significant and although the Nance appliance did not provide absolute anchorage, it provided significantly more anchorage than the control. Thus, the Nance appliance can be used in moderate anchorage demand cases where 28.8% anchorage loss of the total space is acceptable. In comparison, Shpack and colleagues' 2008 human study found 1.4 mm anchorage loss for a total of 7 mm of space closure (20%) using a Nance appliance, despite

the alveolar bone being more dense in beagle dogs. Also, the Shpack and colleagues study (2008) did not have a control group with which to compare their results. The miniscrew group in the present study had a mean anchorage loss of approximately 0.92 mm at the end of the 15 weeks but provided approximately 3 mm more anchorage than the control group. The mean percentage of anchorage loss of the total movement was approximately 15.7% for miniscrews; 30% less than the control. Clinically and statistically this was significant, suggesting that miniscrews can be used in high anchorage demand cases. As a consequence, it can be conjectured that force should be applied directly to the miniscrew rather than through a tooth intermediary to avoid anchorage loss in the dentition. If 1-2 mm of anchorage loss, or 15.7% anchorage loss to the total space, is acceptable then miniscrews can be used indirectly by joining them to the anchor tooth. Previous human studies found 1-2 mm movement of miniscrews during orthodontic treatment (Liou *et al.,* 2004; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009); an amount similar to that seen in the present study. As previous human studies have recommended, miniscrews should also be placed 1-2 mm away from vital structures to avoid damaging them by the movement of the miniscrews (Liou *et al.,* 2004; Garfinkle *et al.,* 2008; El-Beialy *et al.,* 2009).

Approximately 80% of the Nance appliance and 70% of the miniscrew's total anchorage loss occurred after 10 and 5 weeks respectively. Thus, time had a significant influence on the amount of anchorage loss associated with the different anchorage reinforcement methods. For the Nance appliance, the first 10 weeks were critical for anchorage loss whereas for the miniscrews it was the first 5 weeks. The amount of anchorage loss following these time intervals was not significant for either anchorage method. In the case of the Nance appliance, the anchorage loss could have been due to contact with compressible soft tissue, wire deformation (Wehrbein *et al.,* 1996b; Benson *et al.,* 2007) and arch shape. For the miniscrews this may be due to a layer of fibrous tissue interposed between the miniscrew and the surrounding bone prior to mechanical

interlocking and final osseointegration (Liou *et al.,* 2004). This has important clinical implications as anchorage reinforcement methods seem to be less efficient initially. For both anchorage methods, Nance and miniscrew, the clinician should perhaps postpone applying traction forces to the anchorage appliances during the first 10 weeks (Nance appliance) and 5 weeks (miniscrew), in high anchorage demand cases. Two aspects on the significance of time in the current study must be considered. Firstly, the study observation interval was 15 weeks only; active space closure may take longer in some orthodontic patients. Due to possible longer periods of treatment in orthodontic patients, the amount of anchorage loss may vary from that seen in the current study and anchorage loss may accelerate again at later time points. Another important issue relates to the preloading time for both appliances. The Nance appliances and miniscrews were left *in situ* for two weeks prior to applying orthodontic forces and initiating active space closure. For the human clinical situation, the appliance may be left for 6 months prior to starting active space closure, which may influence the amount of anchorage loss. Whether the pattern of anchorage loss seen in the current study would be similar if anchorage reinforcement appliances were left dormant for 6 months is unknown. It may be that most of the anchorage loss associated with such anchorage reinforcement methods occurs during the first 6 months when no active traction is applied. Alternatively, anchorage loss may occur during the first 6 months and again when active orthodontic force is applied.

5.2 Desired tooth movement

Desired tooth movement was measured for both anchorage reinforcement methods (Nance appliance and miniscrew) and compared with that of a control group. The amount of desired tooth movement was similar for all the groups at 5 and 15 weeks. At 10 weeks, the amount of desired tooth movement was higher for both anchorage reinforcement methods (Nance appliance and miniscrew). The introduction of the anchorage

reinforcement methods in the current study may have influenced the force on the tooth being retracted and as a result accelerated the rate of tooth movement during the second 5 week period. Previous studies have found that a dose-response relationship exists between force and tooth movement until a certain force level is reached (Quinn & Yoshikawa, 1985). However, studies assessing the effect of force magnitude on the rate of tooth movement have been inconclusive. This was because the threshold and the optimum force have never been identified due to the difficulties discussed earlier in the literature review (Ren *et al.,* 2003a; Ren *et al.* 2004; Melsen, 2007). Particularly notable was the inability to measure the strain on the periodontal ligaments, as in this current study. Although the force was standardised, the strain on the periodontal ligament may have varied between the appliances. It can be speculated that the introduction of the anchorage reinforcement methods has reduced the force on the retracted teeth because the force was distributed along the anchorage appliances. Alternatively, the force could have been higher on the retracted teeth due to the lack of movement of the anchor units in the anchorage reinforcement methods (Nance appliance and miniscrew). Importantly, the mean amount of movement was similar after 15 weeks which corresponds to the linear phase in tooth movement. Thus, the transition of lag to post-lag phase (5-10 weeks) of tooth movement may have been affected (Fortin, 1971; King & Fischlschweiger, 1982; Iwasaki *et al.*, 2000). This was similar to the pattern observed in the earlier animal (Gonzales *et al.,* 2008) study comparing heavy and light forces. The only significant difference in the amount of tooth movement was observed at the second time interval with a similar total amount of tooth movement at the end of the experimental time. The authors of the previous study did not give an explanation for the observed pattern.

The percentage of desired tooth movement influenced the total space closure during the 15 weeks and, therefore, the overall time for orthodontic space closure. The Nance

appliance and miniscrew groups displayed a significantly higher percentage of desired tooth movement than the control; 16.6% and 29.8% respectively. The overall effect was that less overall space closure occurred after 15 weeks in the anchorage reinforcement groups as less or no space closure occurred due to anchorage loss. Clinically, this implies that in anchorage reinforcement cases space closure may take longer but with more beneficial effects as greater desired tooth movement was achieved.

5.3 Root resorption

The amount of root resorption associated with the different anchorage reinforcement methods was assessed after 15 weeks of active tooth movement. The current study found that anchorage methods influenced the amount of resorption indirectly by influencing the amount of tooth movement. Most of the previous human studies comparing the effect of different orthodontic appliances on OIIRR have failed to see a significant difference between appliances (Malmgren *et al.*, 1982; Beck & Harris, 1994; Blake *et al.,* 1995; Alexander *et al.,* 1996; Parker & Harris, 1998; McNabb *et al.,* 2000; Scott *et al.,* 2008; Pandis *et al.,* 2008). On the other hand, Liou & Chang (2010) found the amount of root resorption was related to the amount of tooth movement when they compared patients treated with and without the use of miniscrews. In the current study, the miniscrew group had the least amount of total tooth movement (PM_2 and PM_4) and perhaps consequently, lesser root resorption. Another factor which was found to influence the amount of root resorption was root size. The PM_2 had a higher total ratio of root resorption than PM_4. However, when both tooth types (PM_2 and PM_4) were moved an equal distance in the control group, they had an approximately similar total ratio of root resorption. On the other hand, when an approximately equal amount of tooth movement and root size were compared, the Nance appliance had the highest total ratio of root resorption among the groups. This might have been due to the type of tooth movement or the rotational

movement associated with the Nance appliance. In conclusion, the current study found that the amount of tooth movement and tooth size influence the amount of root resorption but that the amount of tooth movement possibly had a greater influence.

The distribution among the different root surfaces (mesial, distal and apical) was investigated to determine if any particular surface had a higher predisposition to root resorption. Previous studies found that different types of tooth movement affected different root surfaces (Casa *et al.,* 2001; Shaw *et al.,* 2004; Chan & Darendeliler, 2006; Bartley *et al.,* 2011; Wu *et al.*, 2011; Jimenez Montenegro *et al.,* 2012). A dog study, (Maltha *et al.,* 2004) found resorption occurred almost exclusively in the middle part of the pressure surface (mesial or distal) of the root and not on the apical part when the PM_2 was moved bodily. The different surfaces were compared within and between the different groups to determine the types of movement associated with the different anchorage reinforcement methods. In the control group, there was no significant difference between the surfaces even when each tooth type (PM_2 and PM_4) was investigated independently. When both tooth types were combined, no significant difference between the surfaces was observed. This was because both tooth types moved approximately an equal distance. This indicates that the amount of tooth movement had a larger influence than root size. When each tooth type was investigated independently for the control group, all three surfaces (mesial, distal and apical) were affected by resorption. It is speculated that some form of tipping tooth movement may have been responsible for affecting the three surfaces of the teeth. For the Nance group the distal surface of the PM_2 had more resorption than the other surfaces, whereas in the PM_4 the mesial surface had more resorption than the other surfaces. This pattern suggests bodily tooth movement as there was more resorption at the tooth surfaces in the direction of movement. For the miniscrew group, the distal surface of the PM_2 had more resorption than the other surfaces whilst in the PM_4 there was no difference between the surfaces. This resorption pattern in the PM_2 may confirm its bodily tooth movement in

a distal direction. As root resorption is related to the amount of tooth movement, no significant difference was observed between the different surfaces in the PM_4 in the miniscrew group.

When each root surface was compared between the groups, the control group had significantly more resorption in the apical surface which may imply tipping tooth movement as the cause for the control group. The mesial surface of the PM_4 in the Nance group had significantly more resorption than the same surface in the miniscrew group, which may be a function of tooth movement in the Nance group. There was no significant difference between the mesial and distal surfaces in the PM_2 between the groups. This may have been because the PM_2 moved approximately an equal distance in the three groups. In conclusion, according to the findings of this study, the amount of tooth movement had a larger influence on root resorption than tooth size and anchorage type. Furthermore, the distribution of the resorption on the root surfaces of the control group suggested tipping movement.

In clinical terms the anchorage reinforcement methods did not increase the amount of root resorption. However, in a clinical situation closing an orthodontic space by using anchorage reinforcement may cause higher resorption by increasing the amount of desired tooth movement. Orthodontists should be cautious with space closure using anchorage reinforcement methods, and in particular with miniscrews. Using miniscrews the space will be closed almost entirely by desired tooth movement, which could be double the amount of tooth movement that would have been expected with conventional molar anchorage. Therefore, orthodontists should take into consideration the risk of root resorption, as well as the anchorage requirement, when planning orthodontic space closure.

6 Future work

The results of this thesis have presented new research questions which suggest several research directions to follow as outlined below:

Time seems to be a factor for the amount of anchorage loss and desired tooth movement associated with the Nance appliance and the miniscrew. A study with a longer duration (30 weeks) may provide information about the pattern of both variables (anchorage loss and desired tooth movement). Different loading times (2, 5 and 10 weeks) for the miniscrew and assessing the amount of anchorage loss over 15 weeks following loading might also provide more information about the effect of loading time and anchorage loss. A histological investigation of the miniscrew at different time intervals following loading may provide an explanation about the miniscrew movement and anchorage loss. The effect of the different anchorage methods on OIIRR at different times (5, 10 and 15 weeks) is another prospect. Since cementum repair is a continuous process, histological examination at different times following loading may explain the amount of root resorption and its prevalence amongst the different root surfaces. It may also be helpful to refine the methods of detecting root resorption by the use of scanning electron microscopy.

In summary from the results of these animal studies the following may be concluded:

- The mean desired tooth movement (DM) was the same after 5 and 15 weeks with the different anchorage methods (conventional molar, Nance appliance and miniscrew).
- DM was different at 10 weeks between the control and anchorage reinforcement methods (Nance appliance and miniscrew). This may suggest that both anchorage reinforcement methods influenced tooth movement during the transition from the lag to the post lag phase of tooth movement.

- The mean percentage of DM of the total movement was significantly higher in both anchorage reinforcement methods (Nance appliance and miniscrew) compared to the control at the end of the 15 weeks.

- The majority (80%) of anchorage loss (AL) in the Nance appliance occurred during the first 10 weeks whilst in the control group AL occurred equally over the 3 time intervals.

- The mean AL in the Nance appliance was 28.8% of the total movement whilst in the control it was 45.7%.

- The Nance appliance provided a statistically significant ($p<0.05$) amount (1.93 mm) and percentage (16.9%) of anchorage gain over the control group (conventional molar anchorage) after 15 weeks of tooth retraction.

- In the miniscrew group, the majority (70%) of the total AL (0.92 mm) at the end of the experiment group occurred during the first 5 weeks.

- The mean AL in the miniscrew group was 15.7% of the total movement.

- The miniscrew provided a statistically significant ($p<0.05$) amount (3.04 mm) and percentage (30%) of anchorage gain over the control group (conventional molar anchorage) after 15 weeks of tooth retraction.

- The anchorage method influenced the amount of root resorption by influencing the amount of tooth movement. The Nance appliance and miniscrew reduced the amount of PM_4 movement.

- The miniscrew group had the least amount of total tooth movement and the least amount of root resorption.

- The PM_2 had more root resorption than PM_4 but that was possibly because they had greater amount of movement.

- The amount of tooth movement had more influence on root resorption than the tooth type. In the control group, both tooth types had relatively the same amount of root resorption whilst in the anchorage reinforcement methods (Nance appliance and miniscrew) the PM_4 had less root resorption than the PM_2.

- The PM_2 in the Nance group was associated with more resorption than the PM_2 in the other groups. This may suggest that the mechanism by which the Nance appliance reinforces anchorage influenced the amount of root resorption.

- The amount of root resorption for the PM_4 was related to the amount of tooth movement. Thus, the PM_4 in the miniscrew group had the least amount of resorption and the control group had the most.

- The amount of root resorption for each surface (mesial, distal and apical) was significantly different in the Nance and miniscrew group.

- The distal surfaces of the PM_2, in all groups, had more resorption than the mesial surfaces but were not statistically significant.

- The mesial surfaces of PM_4 in the Nance and miniscrew groups had more resorption than the distal surfaces. However it was only statistically significant in the Nance group.

- The control group was associated with more resorption in the apical surface than the other anchorage methods; perhaps due to more tipping movement. On the other hand, the mesial and distal surfaces were mainly affected in the Nance and miniscrew groups which may suggest more bodily tooth movement.

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