

An in-vitro assessment of the retrievability of fractured dental implant abutment screws

A thesis submitted to the University of Dublin in partial fulfilment of a
Doctorate in Dental Surgery D.Ch.Dent. (Prosthodontics)

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2021

DECLARATION

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May 2021

SUMMARY

Fractured implant abutment screws pose a significant clinical challenge and have the potential to preclude the restoration of osseointegrated dental implants. As a result, a wide range of products and techniques aimed at retrieving fractured abutment screw fragments have been reported. Establishing a standard treatment protocol for retrieving fractured abutment screw fragments is difficult. Currently, there is no consensus regarding the efficacy and risk assessment of the reported techniques and clinical incidents of abutment screw fracture are usually managed tentatively.

The aims of this in-vitro study were to compare the efficacy of a commercially available universal screw retrieval kit with a homemade screw retrieval kit in retrieving fractured abutment screw fragments from dental implants. Additionally, the study aimed to assess the effect of dental implant system type, operator experience, screw fracture morphology, torque value at which the screw fractured and the location of the implant within the mouth, on the ability to retrieve fractured abutment screw fragments.

A total of 64 implants had fractured abutment screws placed. A successful attempt to retrieve a fractured screw fragment was defined as the complete removal of the screw fragment within 15 mins with no damage to the internal threads of the implant. Fifty-seven abutment screw fragments were successfully retrieved, thereby representing a success rate of 89.1%.

The results indicated that fractured abutment screw fragments may be removed safely and in a reasonably short period of clinical time. The combination of standard dental instruments and modified standard dental instruments found in the homemade screw retrieval kit used in the study were as effective in the retrieval of fractured abutment screw fragments as the commercially available universal abutment screw retrieval kit. Operators that are inexperienced in retrieving fractured abutment screw fragments from dental implants may overcome this clinical complication as easily as experienced operators.

ACKNOWLEDGEMENTS

I wish to acknowledge my research supervisor, Dr. Brendan Grufferty, for all his advice and unwavering support during the course of this thesis. I also wish to sincerely thank my research co-supervisor, Dr. Ioannis Polyzois, for all his help, enthusiasm and expertise during the study. Additionally, a big thank you to Dr. Maria Van Harten for helping me understand statistics and to Dr. Suha Aljudaibi for her assistance during the early stages of the project. I feel extremely appreciative and grateful to all of my prosthodontic teachers and mentors. To Dr. Michael O'Sullivan, Dr. Gerry Cleary, Dr. Anne Gunderman, Dr. Colm Sugrue, and again to Dr. Brendan Grufferty, thank you all for helping me achieve things I thought I could never have imagined. Thank you to my good friend Dr. David McReynolds for encouraging me to apply to the Prosthodontics programme and guiding me during my early years. You set me on the right direction. A big thank you to all my friends in the Dublin Dental Hospital who made the whole journey enjoyable, especially my prosthodontic co-residents, Dr. Mohammad Alqhtani, Dr. Gabrielle O'Donoghue, Dr. Tashia Moodley and a very special thank you to Dr. Shkre Agkhre for being a great friend and teammate during our three years together as graduate students and all the long evenings in the lab. Thank you Ilaria for all your love and support during my training and for picking me up when I was down. Lastly, words cannot describe my sincere thanks to my parents, Bala and Sitha, for all the sacrifices they have made so that I can have an education.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

The restoration of missing teeth with implant-supported prostheses is a well-documented and predictable treatment modality, with favourable long-term survival rates reported for both dental implants and their implant-supported prostheses (1). A significant proportion of patients were reported to experience a complication associated with dental implants within five years of treatment (1, 2), with this proportion expected to rise as treatment with dental implants became more widespread (3).

Complications with dental implants and implant-supported prostheses may be categorised as biological or mechanical. Mechanical complications are related to shortcomings with the implant or with the associated prosthetic components (4). Abutment screw loosening was reported as the most common minor mechanical complication (1, 5). Fracture of implant abutment screws is a more challenging complication and was claimed to be preceded by loosening of the abutment screw (6-9).

Fractured abutment screws have the potential to preclude restoration of the dental implant and as a result, a wide range of products and techniques aimed at retrieving fractured screw fragments were reported (10). Establishing a standard treatment protocol for retrieving fractured screw fragments is difficult and few experimental in-vitro trials have been published. Currently, there is no consensus regarding the efficacy and risk assessment of the reported techniques and clinical incidents of abutment screw fracture are usually managed tentatively (11).

1.2 BASIC SCREW MECHANICS

The principle use of screws in restorative implant dentistry is to fasten restorations to implant fixtures and the abutment screw is an integral part of the implant-abutment connection (12). A screw can be considered a simple machine that follows the mechanics of a spiralled inclined plane (13). The purpose of a simple machine is to reduce the effort needed to work, and a screw operates efficiently by converting rotational movement into linear movement, in other words, allowing a relatively small rotational force (torque) to exert a large axial force on a load (14).

When two components are secured by a screw, a unit is created, and termed a screw joint (15). A screw is tightened by applying torque, which develops a force within the screw called preload. As a screw is torqued, preload causes the screw to elongate, placing the screw shank and threads in tension, and elastic recovery of the screw pulls the components of the screw joint together. Preload maintains a secure connection between the screw threads and the screw's mating counterpart by generating an equivalent clamping force between, for example a dental prosthesis and a dental implant (16) (Figure 1). The established preload is proportional to the applied torque, and a screw will only become loose if external forces tending to separate the screw joint (joint-separating forces) exceed the preload and dental implant abutment screws operate on this principle (15). Joint separating forces in excess of the preload cause the abutment screw threads and

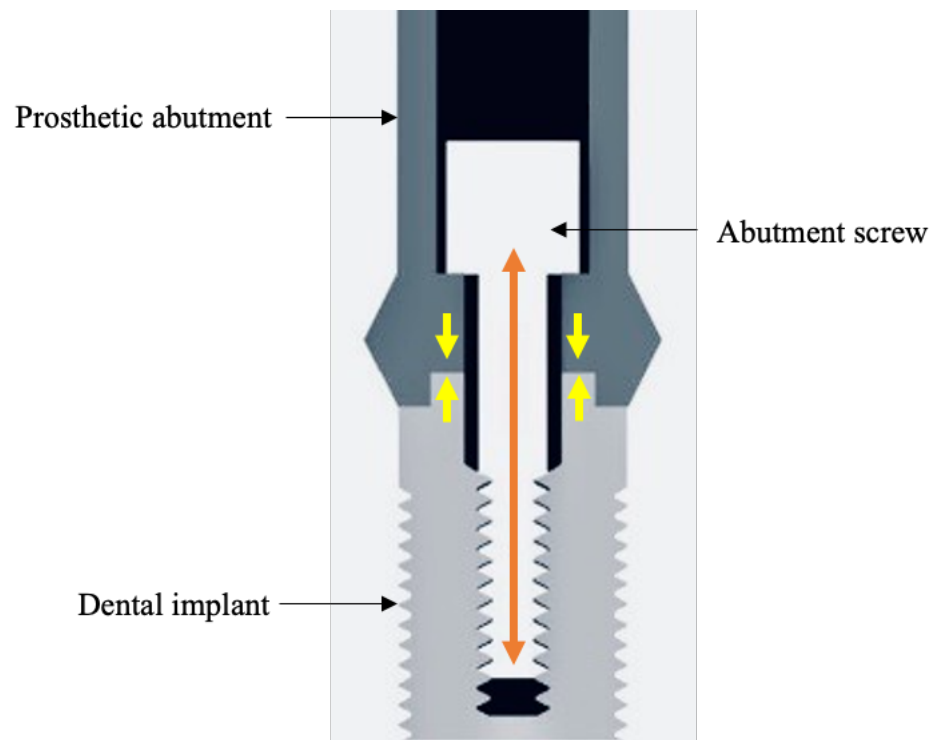


Figure 1: Schematic representation with a cross sectional view of the screw joint created in a dental implant-abutment complex. The abutment screw connects the prosthetic abutment to the dental implant.

the internal threads of the dental implant to slip, thereby resulting in a loss of preload (16). Tightening a dental implant abutment screw is aimed at using the preload stress to maximise the fatigue life of the screw, while providing resistance to loosening or fracture (17).

1.3 DENTAL IMPLANT ABUTMENT SCREW FRACTURE

1.3.1 Incidence of dental implant abutment screw fracture

The survival and complication rates of implant-supported prostheses were the subject of a number of systematic reviews (6, 18-25). Jung et al. (2008, 2013) and Pjetursson et al. (2012, 2007, 2014) analysed prospective cohort studies, prospective case series and retrospective studies from 1994 to 2000 and reported annual rates for abutment screw fracture ranging from 0.16% to 0.44% (2, 6, 19, 22, 24). In addition, it was calculated that these figures corresponded to five-year complication rates ranging from 0.8% to 2.2% (1). It was expected that subsequent to 2000, complication rates would be reduced over the years with improvements in the design of the prosthetic components (4), and this was confirmed by a clinical study which reported an annual rate of abutment screw fractures ranging from 0% to 1.2%. However, the estimated five-year rate ranged from 0% to 5.8% (1), and this apparent increase was explained by increased reporting in more recent publications. Rates of clinical complications with dental implant prostheses were shown to vary considerably between older studies, and may have occurred due to differences in the methods of data collection (1, 5).

1.3.2 Mechanism of abutment screw fracture

Rangert et al. (1989) postulated that in order to obtain satisfactory function in a screw joint, the preload must be preserved so that the screw joint will not open. Opening of the screw joint results in tensile stress application to the abutment screw (9). Furthermore, Rangert et al. (1989) and McGlumphy et al. (1998) postulated that opening or loosening of the screw joint, preceded abutment screw fracture (9, 15). The process of screw loosening was reported to occur in two stages: the initial tensile deformation of the screw established by the preload was reduced as a result of repeated joint-separating forces, and the clamping force in the screw joint was subsequently reduced. In the second stage, micro-motion of the screw joint occurred with the further reduction in the clamping force (26). In implant dentistry, the resultant instability and micro-motion in the implant-abutment connection led to screw loosening (15, 17). The loose restoration, subjected to further external joint-separating forces led to fracture of the abutment screw as a result of stress accumulation and fatigue failure (27).

In some instances, abutment screw fracture was reported to occur without prior loosening (28). The manufacturers recommend that the optimum torque to achieve preload is approximately 75% of the yield strength of the metal alloy (15, 16, 29). The application of excessive torque causes plastic deformation and fatigue of the metal alloy, resulting in abutment screw fracture (17). Excessive torque may be applied upon initial screw tightening (17) or as a result of cold weld formation between the abutment screw threads and the internal threads of the implant (30). The cold weld prevents micromovement within the screw joint when joint-separating forces are applied and stress application to the abutment screw subsequently causes fatigue and fracture of the screw (27).

In-vitro studies using static load fatigue testing with Brånemark Mark III implants demonstrated that abutment screw fractures most commonly occur at the junction of the screw head and the screw shank, or at the junction of the screw shank and first screw thread (7, 8). Similar findings were recently reported in a longitudinal clinical cohort study (31), in addition to anecdotal clinical reports (32-34).

The understanding of the biomechanical behaviour of dental implant screws is based on fundamental engineering mechanical principles, theories and in-vitro testing methodologies which are not validated in a clinical setting. The development of models to understand the clinical behaviour will contribute to a knowledge of abutment screw behaviour in the oral environment.

1.3.3 Risk factors contributing to abutment screw fracture

In a systematic review, five factors associated with an increased rate of dental implant complications were identified (4):

- The absence of a metal framework in overdenture restorations.
- Presence of cantilever extensions in excess of 15 mm for full-arch fixed dental prostheses.
- Bruxism
- Increased length or span of the restoration.
- History of mechanical and technical complications with dental implant restorations.

The results of this systematic review were derived from randomised controlled trials, controlled trials, prospective and retrospective cohort studies over a study period of at least four years and data were analysed using clinical cases with and without exposure to the risk factors. Therefore, a causal relationship between specific risk factors and mechanical complications, such as abutment screw fractures, could not be determined.

1.3.3.1 Implant-abutment connection type as a risk factor for implant abutment screw loosening and fracture.

The implant abutment connection type refers to the morphology of the interface between the dental implant and the abutment and it was suggested that the stability of the implant-abutment connection was related to the type of connection. Furthermore, specific connection types were associated with mechanical complications, for example abutment screw loosening or fracture (35, 36).

The external hexagon was the first connection type used by Brånemark (1977) (37). The external hexagon connection was designed to provide a means of engagement for the surgical placement of a dental implant and also to serve as an anti-rotational feature for single-unit prostheses (17). However, the height of the external hexagon (0.7 mm) was insufficient and limited the efficacy with which it could resist non-axial loading of the implant. Therefore, instability of the implant-abutment connection had the potential to result in micromovement of the abutment, with external forces transmitted directly to the abutment screw and to the platform of the endosseous implant. Stress concentration at the level

of the implant abutment connection could cause fatigue, resulting in screw loosening or fracture (35, 36, 38).

Subsequently, the internal hexagon connection and the conical connection were developed to overcome the limitations of the external hexagon (38). The internal connection is located inferior to the coronal portion (platform) of the implant, and inside the body of the implant (17). The contact area between the abutment and the implant is increased and the stress distribution is altered when loaded. It was postulated that by placing the connection within the implant, the centre of rotation is lowered, which would provide greater abutment stability when resisting lateral loads. In addition, the depth of the connection also provided a broader distribution of stress within the implant when lateral loads were applied. Consequently, the stress would be broadly distributed to the surrounding bone, thereby preventing stress concentration at the osseous crest (35, 36, 38).

Conical connections were designed as a variant of the internal connection and based on a machined taper of the two mating surfaces, termed a Morse taper (17). The Morse taper comprises a press-fit connection between the mating surfaces, such that sufficient friction exists to result in the formation of a cold weld (39). Dental implants employing a conical connection type also use screws and anti-rotation features (40). In-vitro cyclic tests and finite element analysis studies reported that compressive forces caused deeper settling of the abutment within the implant body of conical connections, thereby minimising the micro gap and allowing the two-piece system to behave as a homogenous unit. This showed resistance to bending and rotational torque application, which reduced

the possibility of abutment screw loosening or fracture, when compared with other connection types (35, 41).

From a clinical perspective, a retrospective study of 1159 participants with single-unit implant-retained restorations employing internal and external connection, showed no significant difference in the clinical outcomes over a study period of five years (42). Additionally, a dental hospital-based retrospective study of 1289 participants over a 12 year study period demonstrated that there was no significant difference in the incidence of abutment screw fracture when comparing dental implants with an internal and external connection (43). In a recent systematic review, Lemos et al.(2018) concluded that the implant connection type had no influence on complication rates with dental implant-retained restorations (44).

1.3.3.2 The material of the abutment screw as a risk factor for abutment screw loosening and fracture.

The yield strength, modulus of elasticity and fatigue life are mechanical properties that determine the preload and influence the amount of strain in an abutment screw (15, 17), and the surface finish of the abutment screw has a significant effect on the ability of the screw threads to maintain a frictional contact with the internal threads of the implant, for a particular torque value (45). Using a finite element analysis techniques, Sakaguchi et al. (1995) reported that the factors responsible for the preload achieved within the implant components included the finish of the interfaces, the friction between the mating components, the geometry of the interface, and the mechanical properties of the abutment

screw and the implant (45). Abutment screws with treated surfaces were developed with the aim of increasing the preload value and reducing the risk of screw loosening. For example, the palladium-gold abutment screw surface of the Gold-Tite® (3i, Implant Innovations) screw was modified by adding a solid lubricant to decrease the coefficient of friction and increase the preload value (46). In addition, the TorqueTite (Steri Oss) titanium abutment screw surface underwent a treatment process to decrease friction and increase the fatigue strength (47). An in-vitro study of four commercially available abutment screws confirmed that the Gold-Tite® and TorqueTite abutment screws reduced the coefficient of friction between the mating components and enabled greater rotational angles and preload values than conventional (untreated) gold alloy and titanium alloy screws of the time (48).

1.3.3.3 Prosthesis design as a risk factor for abutment screw loosening and fracture.

The stress distribution within the implant abutment connection is dependent on the restoration design (9). A number of systematic reviews concluded that single-unit prostheses were associated with a higher risk of mechanical complications than implant-supported fixed partial dentures (22, 49), however, it was not clear if this conclusion included an increased risk of abutment screw fracture. Pjetursson et al. (2007) calculated a 12.7% incidence of abutment screw loosening for single-unit prostheses when compared with an incidence of 5.6% for implant-supported fixed partial dentures, during a five-year period (22). Cantilevered designs are used in implant supported fixed dental prostheses, and cantilevers also occur as a result of eccentric occlusal contact on single-unit

prostheses (17). In-vitro studies demonstrated that cantilevers increased the moment of force on the supporting dental implants, thereby exerting torque (9), which resulted in stress concentration at the screw joint and increased the risk of abutment screw loosening and fracture (50-52). However, a recent systematic review and meta-analysis concluded that although the frequency of hardware related complications were higher for prostheses with cantilevers (13.4%), than those without cantilevers (5.1%), the use of cantilevers can be used in implant-supported fixed partial dentures and do not interfere negatively with the survival or success of the prosthesis (53). As a result of limited sample sizes, uncontrolled variables and inconsistent observation periods, this systematic review failed to demonstrate a causal relationship between the presence of cantilevers and mechanical complications with dental implant prostheses.

Manufacturers of dental implant-related products recently introduced one-piece “angulated screw channel implant abutments”, in which deviations between the screw access channel and the long axis of the implant of up to 25° may be accommodated (54). In a laboratory-based study, Goldberg et al. (2019) demonstrated that there was no significant difference between the removal torque for gold abutment screws when compared with angulated screw channel abutment screws, which were tightened by the application of non-axially directed torque (55). On the other hand, Hu et al. (2019) carried out a laboratory-based study to compare the removal torque values of 0°, 10°, and 20° angulated abutment screws and reported that none of these screws reached the targeted value of 35 Ncm, when placed with an angulated abutment screwdriver. Therefore, it was concluded that the loss of preload was influenced by the screwdriver angulation and they postulated that the use of angulated screw channel abutment screws was a risk factor for mechanical complications (56).

However, the abutment screws were used on repeated occasions within both studies (58,59), and Byrne et al (2006) demonstrated that repeated loosening and tightening of abutment screws resulted in a progressive reduction in preload values (57). In a similar laboratory-based study, Opler et al. (2020) did not reuse the abutment screws and showed that the preload developed with angulated screw channel abutment screws was not affected when accommodating angular deviations of up to 15°. However, when attempting to correct for angular deviations of 25°, a significant reduction in preload was demonstrated (58). Sethi et al. (2002) and Koutouzis et al. (2007) carried out clinical studies related to the long-term survival of dental implants using angled screw access channel abutment screws and concluded that the long-term survival of the implants was not compromised. However, neither study reported information about mechanical complications (59, 60), and there are no clinical studies available that assess the performance of angulated screw channel abutment screws.

1.3.3.4 The use of third-party dental implant components as a risk factor for abutment screw loosening and fracture.

The manufacture of dental implant components requires a strict level of quality control to ensure an accuracy of fit within a defined tolerance (27). The designs and interfaces of screw joints, for example, at the implant-abutment connection, are matched carefully to optimise fit, tolerance and preload (15, 17), but are not guaranteed by third-party manufacturers of dental implant components.

Gigandet et al (2014) carried out an in-vitro study to evaluate the quality of third-party abutments for dental implants and reported variations in the design of the

mating surfaces, when compared with that of the original manufacturers. An increased level of rotational misfit was associated with the third-party components, which had the potential to compromise their biomechanical performance (61). Other in-vitro studies showed that the removal torque values of dental implant components from the original manufacturer were superior when compared with the use of third-party components (62, 63). However, there were no studies available to evaluate the effect of the use of third-party implant components on their clinical performance.

1.3.3.5 Implant platform width as a risk factor for implant abutment screw loosening and fracture.

When biomechanical principles are applied, wider diameter dental implant-abutment interfaces (wide prosthetic platforms) result in less tipping forces and therefore less stress application to the abutment screw, than the use of narrow diameter prosthetic platforms (9, 13). An in-vitro study demonstrated a 44% reduction in stress application to abutment screws when the diameter of the implant prosthetic platform was increased from 4 to 5 mm (64).

Another in-vitro study was aimed at evaluating the performance of single-unit prostheses on dental implants while varying the diameters of the prosthetic platforms. From a total of 15, five abutment screw fractures and one implant fracture were associated with the narrow-diameter implants as a result of load-fatigue testing. There were no failures associated with the wide prosthetic platforms, therefore, it was reported that the use of narrow-diameter prosthetic

platforms be avoided clinically, where significant functional demand on the prosthesis may increase the risk of fatigue failure of the abutment screw (7).

Similar recommendations were made in a recent systematic review and meta-analysis (68) and from working groups (69), that advised against the use of narrow-diameter implants in patients with parafunctional habits and severe malocclusions (65, 66).

1.3.3.6 Iatrogenic factors as a risk factor for implant abutment screw loosening and fracture.

The use of a calibrated torque limiting device is recommended for providing the optimal torque to abutment screws (17). However, it was postulated that the accuracy of the torque values delivered was negatively affected by continual use and following repeated sterilisation procedures of the device (67, 68). Gutierrez et al. (1997) showed that torque limiting devices can provide inaccuracies by as much as 455% higher than the intended torque value, and stated that corrosion of the device was responsible (68). Goldstein et al (2020) evaluated the accuracy of torque limiting devices, currently in use in a dental school. Five new and 46 used torque limiting devices were investigated. All of the devices correctly delivered the recommended torque values, and no significant differences were found amongst the groups. It was concluded that autoclaving and clinical use did not affect the accuracy of the torque limiting devices tested (69). In conclusion, the application of the correct torque value to the abutment screw is recommended to optimise the performance of the screw joint, despite a lack of validated clinical evidence (16).

During intraoral function, implant-supported prostheses are exposed to a range of forces. Chewing forces were reported to range from 108 and 299 N in the incisor region (70, 71). In an electromyographic study, the maximum biting force in the first molar region was reported to range from 446 and 1220 N (72). Therefore, dental implant components, including abutment screws and the prosthetic materials are required to withstand these forces to avoid complication or failure. Daily tooth contact during normal physiologic function has been approximated to last for a few minutes, however, during parafunctional activity, prolonged periods of tooth contact occur (73), thereby increasing the risk of mechanical complications, including tooth and prosthesis wear, loosening or fracture of the implant components and the prosthesis (27). Bruxism is a repetitive jaw-muscle activity that is mainly characterised by tooth grinding and clenching, while awake or during sleep (74). Bruxism was proposed to cause frequent, excessive, multi-directional load on implant-supported prostheses (13), where the proprioceptive mechanism with dental implants is reduced by a factor 10 when compared with vital teeth (75). Chrcanovic et al. (2017) reported a significantly higher prevalence of mechanical complications associated with dental implant prostheses in patients with parafunctional activity (bruxism), when compared with a control group of patients without parafunctional activity. The odds ratio of abutment screw fracture in the patients with parafunctional activity was reported as 40.991 (76). Although this study was retrospective, it proposed that bruxism and the exposure of implant-supported prostheses to high magnitude, high frequency and multidirectional forces was a risk factor for abutment screw fracture.

1.4 ASSESSMENT AND DIAGNOSIS OF ABUTMENT SCREW FRACTURE

A comprehensive assessment is required to manage the clinical complication of a fractured abutment screw (10). Mizumoto et. al. (2018) listed a number of techniques to assist the clinical assessment of abutment screw fracture (11):

- Direct visualisation.
- Intra-oral radiographic examination.
- Tactile assessment using an instrument.
- Comparison of the fractured screw with an undamaged abutment screw of the same system if the coronal fractured fragment is readily available.
- Attempting to engage an undamaged prosthetic component of the same system to investigate if the presence of a fractured abutment screw fragment precludes seating.

Clinical assessment is largely dependent on visibility of the screw fragment, which is affected by the location and depth of the implant, the depth of the fractured screw fragment inside the implant and the ability to illuminate the inside of the implant (11). Visibility may be further diminished if the implant-supported prosthesis has been missing for an extended period of time and the peri-implant soft tissue and plaque accumulation has obscured the screw access hole (10, 11). Reyhanian et al. (2010) described the use of a low-frequency Er:YAG diode laser to remove excess peri-implant tissue to effectively expose the implant prosthetic platform, without producing thermal side-effects to the dental implant or the surrounding tissues (77) (Figure 2). The use of high-power

magnification with a coaxial light source or a light-emitting diode headlamp to enhance visibility was also advocated to significantly enhance visibility, especially in situations where fractured screw fragments are located deep within the implant (78) (Figure 3).

1.5 FRACTURED SCREW RETRIEVAL TECHNIQUES

Numerous clinical reports and case series provide techniques for retrieving fractured abutment screw fragments from dental implants (33, 34, 79-111), and these techniques are categorised as conservative, where no modification of the fractured screw fragment is required, or invasive, requiring the use of rotary instrumentation to either manipulate or modify the screw fragment. Conservative techniques may be accomplished using standard instruments which are available in a clinician's armamentarium and may require modification to facilitate screw fragment retrieval. Alternatively, several commercially available screw retrieval kits are available for the same purpose (10, 11). The aim is to retrieve the fractured screw fragment safely and to avoid damaging the internal threads of the implant (10). If all conservative means have been unsuccessful, invasive solutions to remove fractured abutment screw fragments include obliteration of the screw fragment, implant modification or implant removal to facilitate replacement (83, 88, 89, 91, 95, 98, 99, 101, 104, 110).

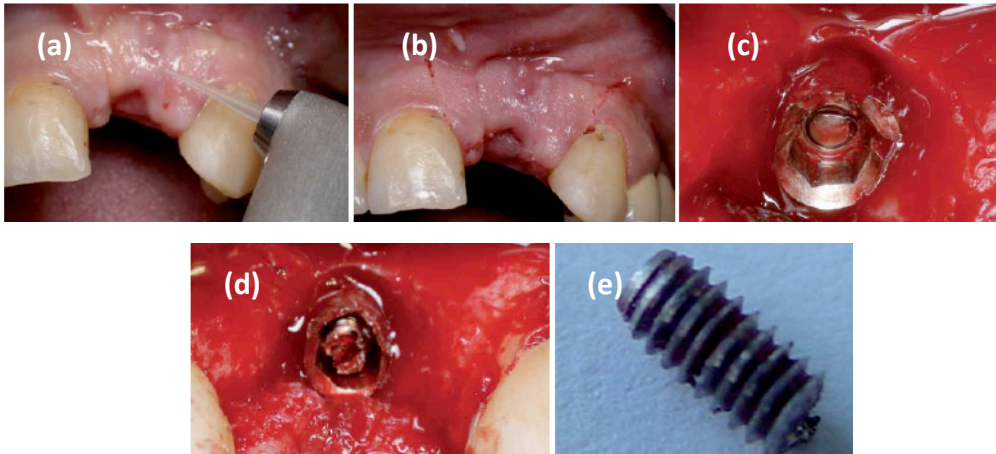


Figure 2: (a - b) A low-frequency Er:YAG diode laser being used to incise a mucoperiosteal flap. (c) The full thickness flap has been raised. Granulation tissue overlying the fixture containing the fractured screw fragment has been ablated safely and with minimal heat dissipation following use of the same diode laser. (d) A slot has been created on the coronal aspect of the fractured screw fragment. (e) The retrieved screw fragment. *Adapted from Reyhanian et al. (2010) (78).*

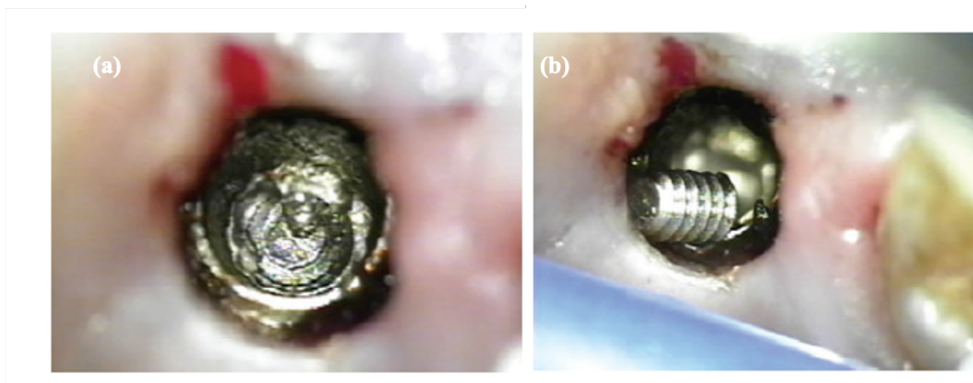


Figure 3: (a) A fractured abutment screw seen through surgical microscope. (b) Same view following removal of the fractured screw fragment. *Adapted from Patel et al. (2010) (79).*

1.5.1 Conservative management

Initial management usually begins by inserting a narrow rigid instrument, such as an endodontic or sickle explorer, into the internal well of the implant containing the fractured abutment screw and attempting removal by rotating the fragment in an anticlockwise direction (28) (Figure 4).

Mizumoto et al. (2018) suggested that screw fragments with oblique fractures are easier to remove by facilitating engagement of the screw fragment (11). In cases where it is not possible to engage or move the screw fragment with the use of a hand instrument, a piezoelectric ultrasonic scaler may be used (10, 11). Bhandari et al. (2013) recommended the application of gentle reverse torque, concomitant with the ultrasonic vibrations to prevent the screw fragment from being directed further into the implant. This technique is painless, requires minimal chair time and the instruments are readily available (82) (Figure 5).

The modification of instruments was advocated in situations where limited space within the implant prevented access for standard dental instruments or the tip of a piezoelectric ultrasonic scaler (103, 106). Satwalekar et al. (2008) reported the successful use of a spoon excavator which was modified by cutting the working end of the instrument to create a fork shape (103) (Figure 6). Yang and Wu (2019) described a technique where the tip of an 18-gauge hypodermic needle was bent and flattened to facilitate engagement of a fractured screw fragment (106) (Figure 7).



Figure 4: A sickle explorer being used to remove a fractured screw fragment by rotating the fragment in an anticlockwise direction. *Adapted from Misch et al. (2017) (28).*

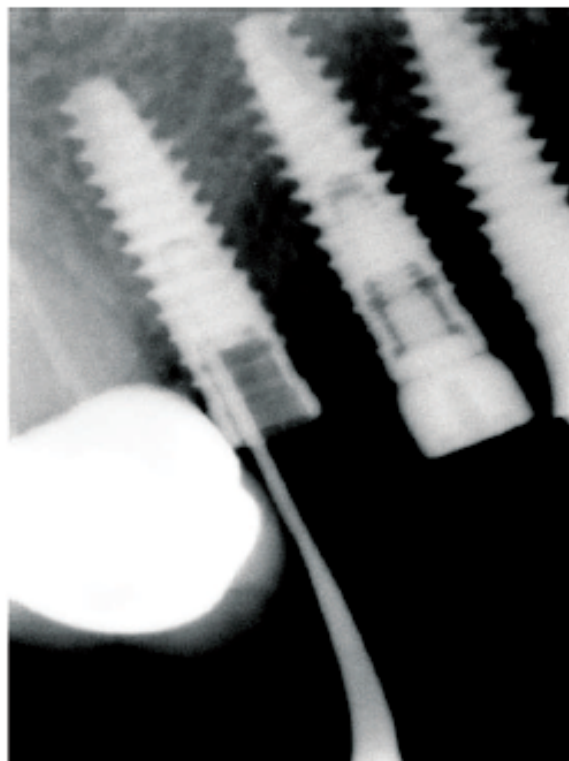


Figure 5: The application of gentle reverse torque, concomitant with the ultrasonic vibrations to retrieve a fractured screw fragment whilst also preventing the screw fragment from being directed apically in the implant. *Adapted from Bhandari et al. (2013) (83).*



Figure 6: An example of instrument modification: a spoon excavator has been modified by cutting the working end of the instrument perpendicularly to create fork shape, allowing it to engage the fractured screw fragment. *Adapted from Satwalekar et al. (2013) (104).*

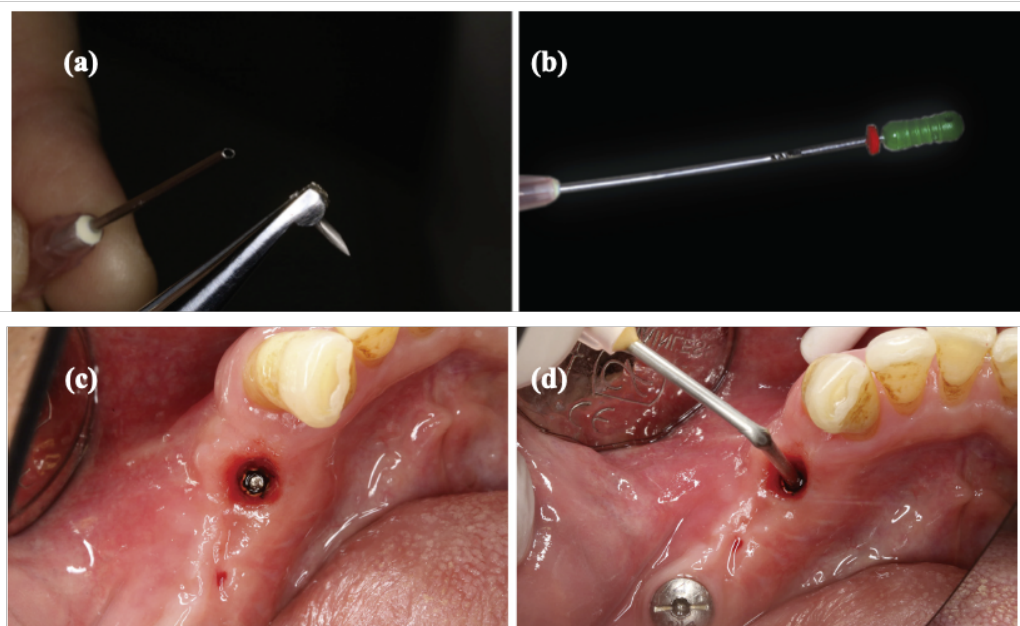


Figure 7: An example of instrument modification: **(a)** The tip of an 18-gauge hypodermic needle was cut off. **(b)** An endodontic file was used to round the tip to facilitate engagement of a fractured screw fragment. **(c)** View of fractured screw fragment inside the internal well of an implant. **(d)** The custom screwdriver has been bent to facilitate access and subsequently placed into the implant to engage the fractured screw fragment. *Adapted from Yang and Wu (2019) (106).*

Fractured screw fragments may be displaced from within the implant to the coronal level of the implant but remain difficult to remove (28, 81, 85). Misch (2017) suggested using an artery forceps to grasp the fragment and twist in an anticlockwise direction (28) (Figure 8). Alternatively, Barbosa et al. (2014) demonstrated the use of a cotton tip applicator as a driver to grip and remove the screw fragment (81) (Figure 9). Chen and Cho (2018) reported a case where an adhesive dental restoration-placement instrument was pressed against a fractured screw fragment and slowly rotated out of the implant (85) (Figure 10). The risk of damage to the implant threads was minimised with the use of the cotton tip applicator and the adhesive dental restoration placement instrument (81, 85).

In cases where the coronal fragment of the fractured screw is available and an oblique fracture pattern is observed, the screw shank of the fractured coronal fragment may be used as a retrieval tool. Azpiazu-Flores and Lee (2020) described a technique where the fractured coronal fragment was mounted onto a standard hexagonal driver and reintroduced into the screw access hole of the implant. This assembly was carefully approximated with the retained apical fragment and slowly rotated anti-clockwise to remove the apical portion of the abutment screw (79) (Figure 11).

In a case report, Yilmaz and McGlumphy (2013) described a clinical case where the apical portion of a fractured screw remained inside the implant and two screw washers were used to allow a new abutment screw to engage the prosthesis and to develop an adequate preload (110) (Figure 12).



Figure 8: A successfully retrieved fractured screw fragment using an artery forceps to grasp the fragment and twist it in an anticlockwise direction. Adapted from *Misch CE (2017) (28)*.

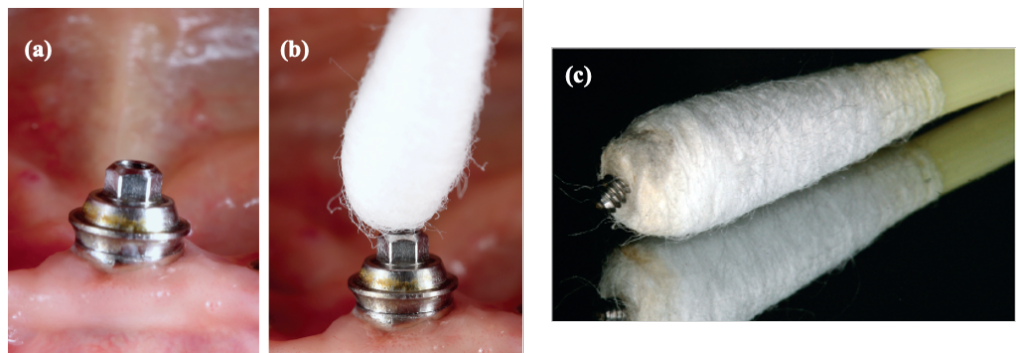


Figure 9: (a) An implant containing a fractured screw fragment. (b) A cotton tip applicator being twisted anticlockwise to engage the fractured screw fragment. (c) The retrieved screw fragment. Adapted from *Barbosa et al. (2014) (82)*.

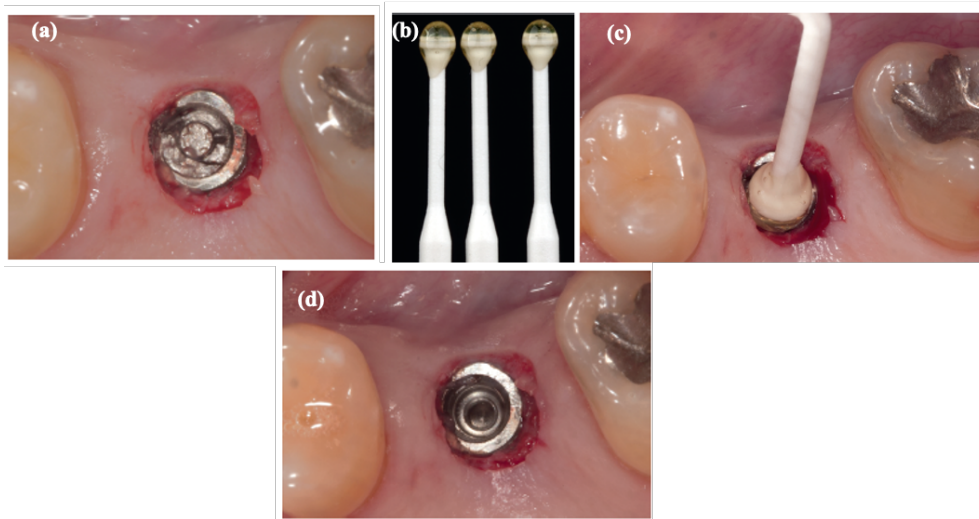


Figure 10: (a) Occlusal view of a dental implant containing a fractured screw fragment. (b) adhesive dental restoration placement instruments. (c) The instrument being pressed against a fractured screw fragment and slowly rotated out of the implant. (d) The fragment has been successfully retrieved. *Adapted from Chen and Cho (2018) (85).*

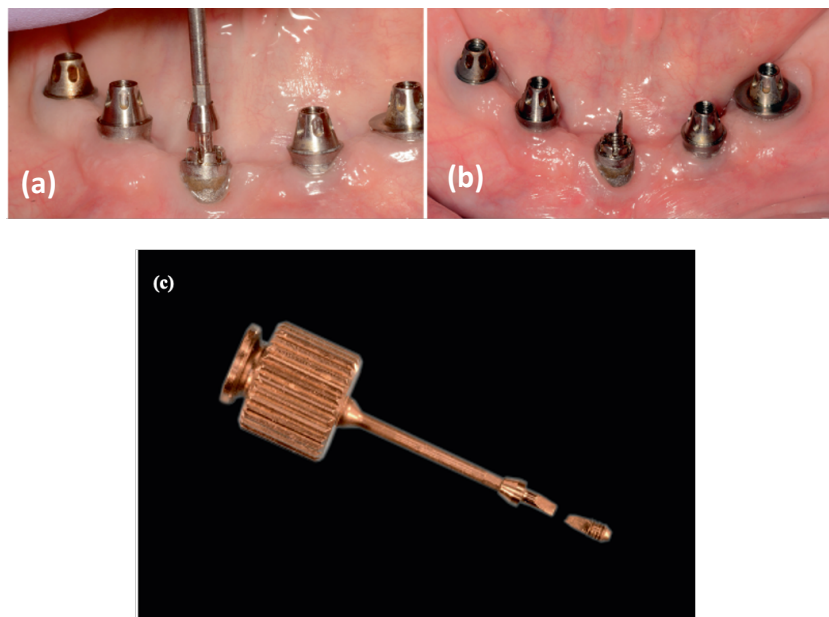


Figure 11: (a) The fractured coronal fragment of a one-piece abutment system mounted onto a standard hexagonal driver and reintroduced into the screw access hole of the implant. This assembly was carefully approximated with the retained apical fragment and slowly rotated anti-clockwise. (b) The apical portion of the abutment screw reversed out to be engaged with standard instruments. (c) The successfully retrieved screw fragment. *Adapted from Azpiazu-Flores et al. (2020) (80).*

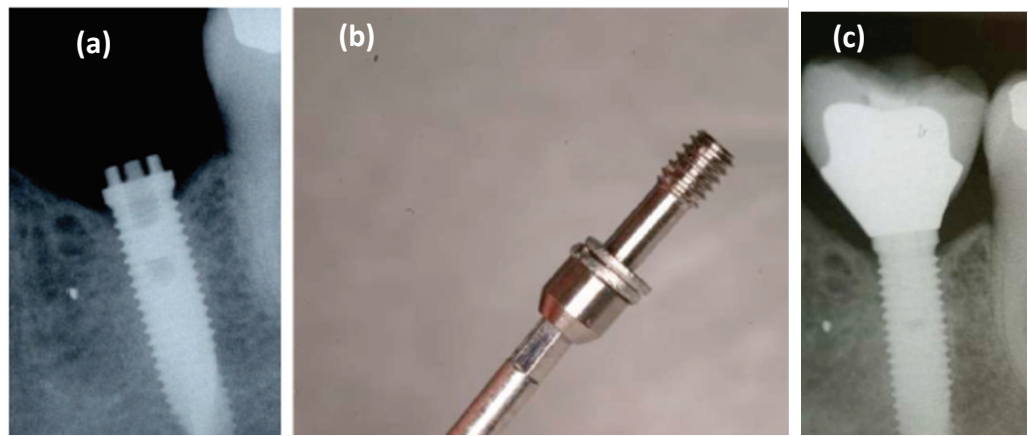


Figure 12: (a) A radiograph of a fractured abutment screw present in a dental implant. (b) Two screw washers were used with a new abutment screw. (c) This allowed the new screw to engage the prosthesis and to develop an adequate preload, thus still allowing an implant with an irretrievable fractured screw to be used. *Adapted from Misch et al. (2017) (28).*

Yi et al. (2020) presented a series of three cases where the apical portions of the fractured abutment screws remained *in-situ* and the prostheses were refitted using abutment screws that were shortened to engage the remaining coronal internal threads of the implant (107) (Figure 13). In-vitro studies investigating cyclic load testing of intentionally short abutment screws reported that for external connection implants, there is no relationship between the length of the abutment screw and screw loosening potential or yield strength, provided the screw is at least 1.4 mm in length, or has a minimum of 3.5 screw threads (112-115). However, these case series provided no evidence of long-term success, and would require further investigation.

Table 1 summarises the available evidence describing management techniques which may be considered conservative.

1.5.2 Rotary instrumentation and screw fragment modification

On occasion, the fractured abutment screw fragment was reported to retain the preload and was not amenable to removal by conservative means (28). It was recommended that a rotary instrument (bur or drill piece) be inserted inside the implant to engage the fractured screw fragment to attempt removal with an anticlockwise spin (28, 93, 105) (Figure 14). Because of the risk of damaging the implant threads through contact with the rotary instrument, Lau and Pang (1994) recommended removing sharp cutting edges present on the side of rotary instrument prior to use (93).

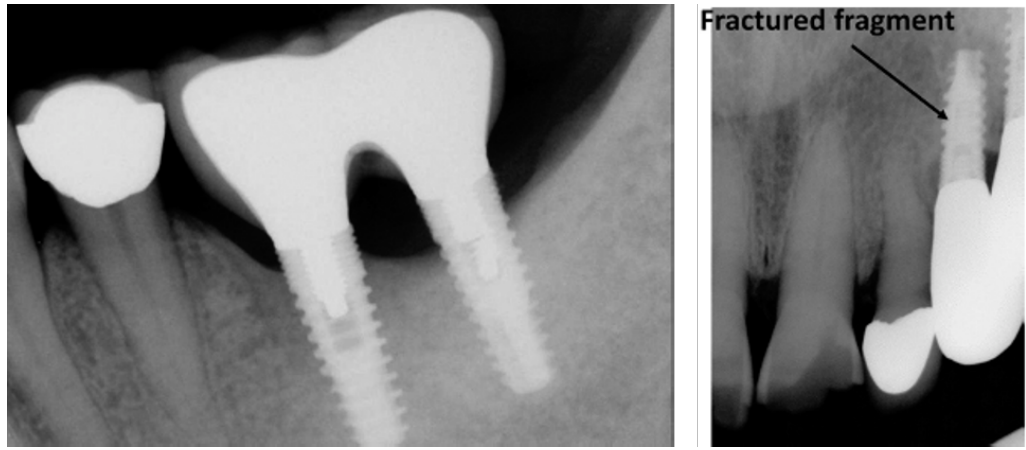


Figure 13: Examples of cases where the apical portions of the fractured abutment screws remained in-situ and the prostheses were refitted using abutment screws that were shortened to engage the remaining internal threads of the implant. *Adapted from Yi et al. (2020) (108).*

Table 1: Summary of reported conservative retrieval techniques in managing fractured abutment screws

Authors	Year	Summary of technique described
Satterwaite and Rickman	2008	Managed a loose cement-retained implant supported crown where the thread of the abutment screw had fractured away from the body of the screw and was retained within the implant. It was engaged and removed by using a curved endodontic file (103).
Bhandari et al.	2013	Used ultrasonic oscillations in a reverse torque manner to retrieve a fractured screw fragment without affecting the internal surface of the implant (83).
Satwalekar et al.	2013	Modified a spoon excavator to a fork shape and used it to unscrew a fractured abutment screw (104).
Yilmaz and McGlumphy	2013	Apical portion of fractured screw fragment left <i>in-situ</i> . Used two screw washers to allow a new abutment screw to engage the prosthesis and develop adequate preload (111).
Barbosa et al.	2014	Pressed a cotton tip applicator into the internal well of an implant and rotated anticlockwise to retrieve a loose screw fragment (82).
Chen et al.	2018	An adhesive dental restoration placement instrument was pressed against a fractured screw fragment and slowly rotated out of the implant (86).
de Souza Batista	2018	Used a sterile slice of rubber band interposed between a driver and the fractured screw fragment to create sufficient friction to unscrew the fractured screw fragment (81).
Yang et al.	2019	Used a custom screwdriver to unscrew a screw fragment by modifying an 18-gauge hypodermic needle (107).
Azpiaz-Flores et al.	2020	Described a conservative method of removing a fractured abutment screw with a diagonal fracture pattern using the screw shank as the retrieval tool (80).
Yi et al.	2020	Describes a conservative solution for the management of non-retrievable fractured screws by reconnecting the prostheses to the existing implants by using cut screws (108).

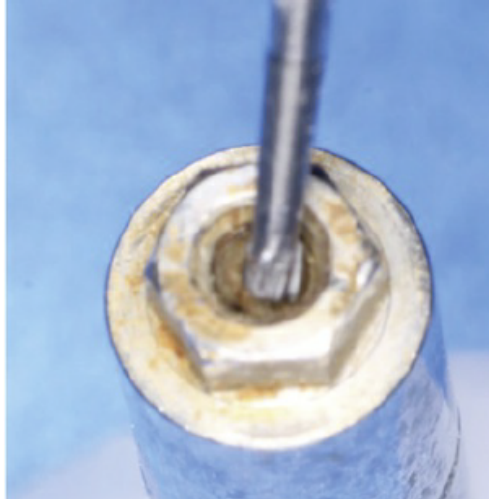


Figure 14: Demonstration of a rotary instrument being inserted inside the implant to engage the fractured screw fragment in an attempt to remove the screw fragment with the anticlockwise spin of the rotary instrument.
Adapted from Misch et al. (2017) (28).

Modification of the retained screw fragment may be required if the previous removal techniques failed. A slot may be created within the fractured edge of the retained screw fragment using a small round stainless-steel bur or a narrow tungsten-carbide fissure bur to facilitate engagement and anticlockwise rotation with a hand instrument (33, 34, 87, 92, 105, 111) (Figure 15).

Several commercially available screw retrieval kits are available to remove fractured screw fragments (10), and their use was documented in clinical reports (94, 96, 97, 100). The screw retrieval kits may be designed for use with all dental implant systems (universal screw retrieval kits), the components may be suitable for a single dental implant system (manufacturer specific screw retrieval kits) or the design may be specific to the general shape of a dental implant or connection type (internal connection, external connection, conical connection, trilobe connection) (10). Most of the commercially available screw retrieval kits aim to create a dimple in the centre of the retained screw fragment which is then removed using a proprietary drill piece that engages the dimple (94, 96, 97, 100). If it is not possible to remove the fractured screw fragment by engaging the dimple, it was recommended that the fragment be removed completely using rotary instrumentation, followed by re-tapping the implant threads with specialised screw-tapping tools (84, 91, 108).

The use of drill guides or sleeves were advocated to aid drill orientation and stabilisation of the drill piece, thereby reducing the risk of damage to the internal threads of the implant (10, 11). Drill guides may be custom made, using available implant prosthetic components found in a clinician's armamentarium (111) (Figure 16), or included in commercially available retrieval kits (10)



Figure 15: A dimple slot created within the fractured face of the retained screw fragment using a small round stainless-steel bur to facilitate engagement and anticlockwise rotation with a modified hand instrument. *Adapted from Williamson et al. (2001) (106).*

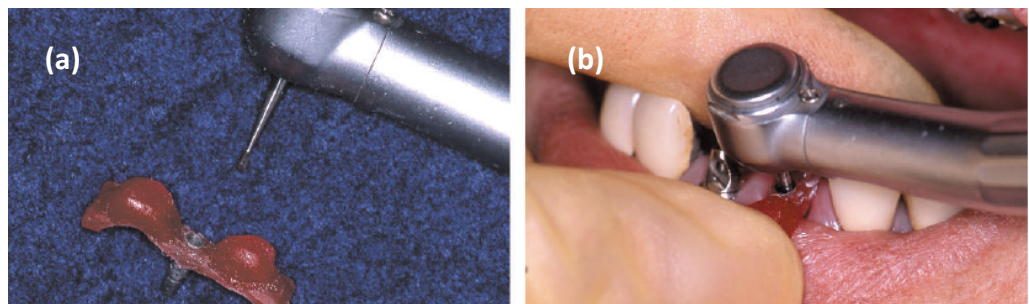


Figure 16: (a) A custom made drill guide made of autopolymerising acrylic resin. (b) The custom drill guide being used intra-orally to retrieve a fractured abutment screw. *Adapted from Taira et al. (2012) (112).*

(Figure 17). Copious irrigation and intermittent drill use was advised to prevent excessive heat transfer and damage to the peri-implant tissues (33, 94).

Table 2 summarises the available evidence describing techniques which involve rotary instrumentation to manipulate or modify screw fragments.

1.5.3 Implant modification

Under certain circumstances, for example following unsuccessful retrieval of a fractured abutment screw, or where damage has occurred to the internal threads of an implant, modification of the internal configuration of the implant may be required to facilitate subsequent use of the implant (10, 11).

Clinical reports described removal of fractured screw fragments with rotary diamond instruments, followed by preparation of the internal surface of the implant to enable an impression and cementation of a custom cast post and core to support a crown (Figure 18) or to retain an overdenture (Figure 19) (83, 88, 89, 98, 99, 104). It was reported that the decision to modify the dental implant in this way was made following consideration of dental implant removal (116). The modification of dental implants with alternative prosthetic solutions may be considered a non-surgical alternative to implant removal (101), or an alternative to submerging the implant with soft tissue, while accepting that there is no supporting clinical evidence for this form of treatment (11).

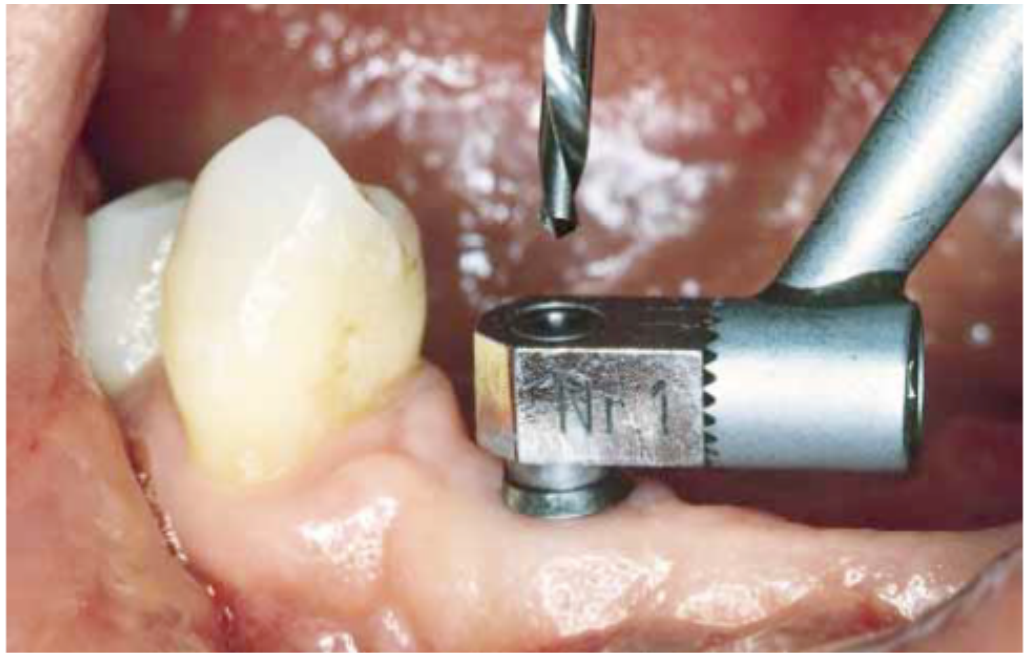


Figure 17: Sequential drill guide as part of a commercially available screw retrieval kit. Adapted from Luterbacher et al. (2000) (95).

Table 2: Summary of reported retrieval techniques which involve rotary instrumentation to manipulate or modify fractured abutment screws.

Authors	Year	Summary of technique described
Ow and Ho	1992	Described two methods of retrieving a fractured screw using either a screwdriver to engage an intentionally placed horizontal groove in a screw or by using a commercially available IMZ retrieval kit (98).
Lau and Pang	1994	The lateral blades of a low-speed short-shank tapered fissure bur were removed and the modified bur was mounted in a torque controlled electric handpiece before engaging a fractured screw fragment and rotating anticlockwise out of the implant (94).
Rosen	1995	Described the use of two common commercially available screw retrieval kits (101).
Luterbacher et al.	2000	Detailed the use of an ITI service set to retrieve two fractured abutment screws (95).
Williamson and Robinson	2001	Used a ¼ round bur to cut a slot in a fractured screw and then modified the ¼ bur to resemble a flat head screwdriver to rotate the screw out (106).
Nergiz et al.	2004	Described the use of an IMZ TwinPlus Repair Set to retrieve a fractured screw fragment successfully (97).
Yilmaz and McGlumphy	2011	Used an Ultratech Fragment Fork is used to successfully retrieve a fractured screw fragment (110).
Taira and Sawase	2012	Fabricated a custom drill guide and demonstrated its use to allow for safe screw modification without damage to the internal threads of the implant (33).
Walia et al.	2012	Used a fine tapered carbide bur to cut a notch in the periphery of a fractured abutment screw and to allow for a purchase point for piezoelectric ultrasonic use. The specific notch location was created to create a lever arm around the central axis of the screw to reduce effort required to reverse screw (34).
Kurt et al.	2013	Create a slot in a fractured screw and constructed a custom-made screwdriver to unscrew the fractured screw fragment (93).
Gooty et al.	2014	An ultrasonic scaler was used to remove a fractured screw fragment after the screw was modified by creating a slot (88)
Imam et al.	2014	Detailed the use of an Astratech Fragment Fork to initially screw a fractured screw fragment deeper so that damaged internal threads could be retreaded, allowing the fractured screw fragment to be retrieved successfully with the Fragment Fork (91).
Carneiro et al	2015	An unretrieved screw fragment was completely drilled out of the implant, and the internal threads of the implant were retapped successfully (85).
Yilmaz et al.	2015	Damaged internal threads were re-tapped after successfully removal of a damaged abutment (109).

Table 2 (continued): Summary of reported retrieval techniques which involve rotary instrumentation to manipulate or modify fractured abutment screws.

Yoon et al.	2015	Reported the use of a modified impression coping that acted as a drill guide to modify a screw fragment. The drill was then engaged into the modified screw and reverse torqued until the screw was successfully retrieved (112).
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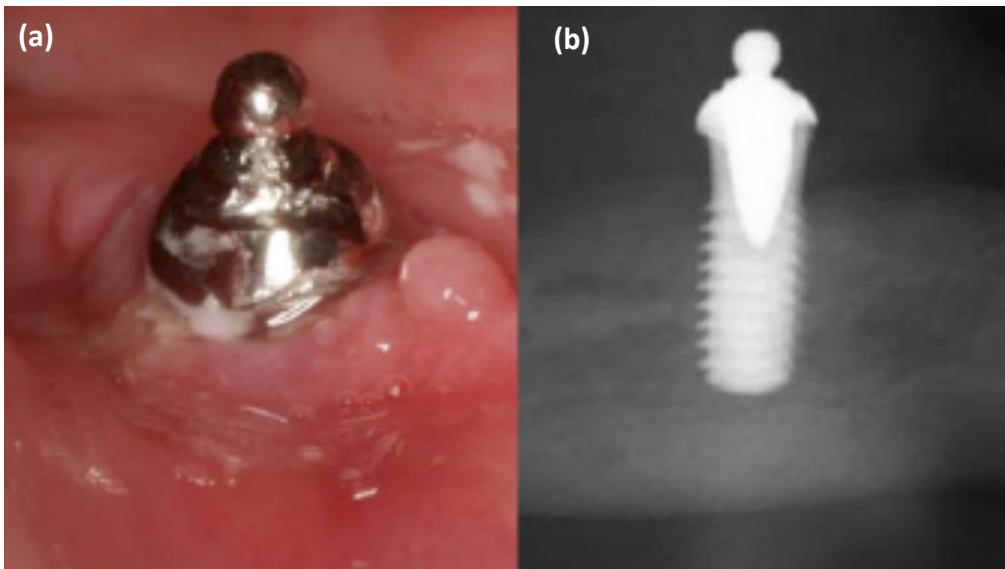


Figure 18: (a) A cast post with a ball attachment constructed and cemented within a modified dental implant to improve the retention of an overdenture. (b) Radiograph of the cemented cast post with a ball attachment within a modified dental implant. *Adapted from Canpolat et al. (2014) (84).*

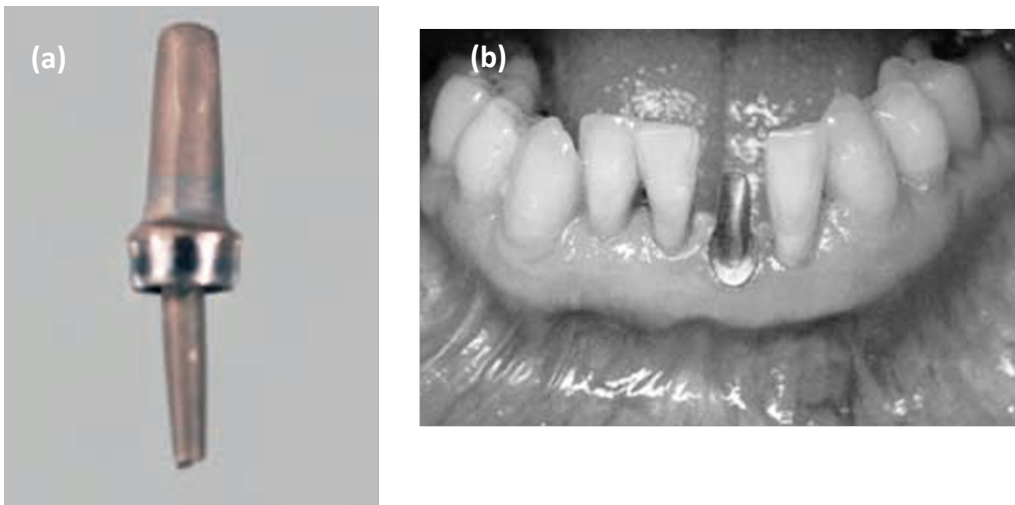


Figure 19: (a) Preparation was completed to the internal surface of the implant to enable an impression and fabrication of a custom cast post and core. (b) The custom cast post and core was cemented into the modified dental implant, allowing it to support a new crown. *Adapted from Pipko Et al. (2004) (99).*

Table 3 summarises the literature describing techniques which involve implant modification for dental implants with irretrievable fractured abutment screws or extensively damaged internal threads.

1.5.4 Efficacy of retrieval techniques

The aim of managing a fractured abutment screw is successful retrieval of the fragment with no damage to the internal surface of the dental implant in as simple, efficient and cost-effective manner as possible. (10, 11, 28). Despite the range of techniques reported in the literature that aim to retrieve fractured screw fragments, there is insufficient scientific evidence to evaluate the efficacy of these techniques (11).

Only two experimental in-vitro trials (117, 118) and one animal study (119) investigating the efficacy of fractured screw management techniques have been published.

An in-vitro study was carried out to investigate the relative efficacy of three different methods aimed at retrieving fractured abutment screw fragments from dental implants (118). One hundred thirty-five internal connection implants had fractured screw fragments intentionally placed at three depths in the dental implants (coronal third, middle third and apical third). These dental implant specimens containing the fractured screw fragments were distributed into three groups according to the screw retrieval methods:

Table 3: Summary of reported techniques which involve implant modification performed on salvaging dental implants with irretrievable fractured abutment screws and/or extensively damaged internal threads.

Authors	Year	Summary of technique described
Pikpo et al.	2004	Describes a technique for retrofitting a cast post and core into a salvaged dental implant (99).
Pow and Wat	2006	Details a technique to safely remove a fractured abutment screw and to restore the implant without sacrificing it by fabricating a custom post and core and a new crown restoration (100).
Maalhagh-Frad et al.	2010	Authors prepared a trough between the stripped head of the fractured abutment screw and the implant's platform using high speed rotary instrumentation with subsequent fabrication of a new restoration (96).
Canpolat et al.	2014	Drilled through an irretrievable fractured screw fragment and prepared a post space in the affected dental plant. An impression was made and a custom cast post and core with a laser-welded ball attachment was then luted to salvage the implant and retain the patient's existing overdenture (84).
Gupta et al.	2014	A technique to salvage a dental implant with an irretrievable fractured screw or extensively damaged internal threads by preparing the implant's body to receive a custom cast post and core (89).
Harshakumar et al.	2014	Reports a clinical case where the fractured screw fragment was drilled away using a #1/8 round ended tapered diamond bur with subsequent post space preparation. Used acrylic resin to fabricate a direct pattern for a custom titanium cast post and core which was subsequently luted and a new crown fabricated (90).
Shah and Lee	2016	The replacement of two fractured, irretrievable, Locator abutment screws of a mandibular implant-retained overdenture with two custom made cast post and laser welded Locator attachments. This method was successful in managing broken abutment screw fragments while using the existing prosthesis and implants (105).

- (a) conventional (conservative) methods using a sickle explorer and an ultrasonic scaler,
- (b) the use of a commercially available universal screw fragment retrieval kit with guide cylinders and
- (c) a commercially available universal screw fragment retrieval kit without guide cylinders.

A success rate of 93.3% and a mean retrieval time of 2 mins 56 secs $\pm$ 2 mins 9 secs was reported with the use of the universal retrieval kit without a guide cylinder. The conventional method had a success rate of 73.3% and a mean retrieval time of 3 mins 15 secs $\pm$ 1 min 48 secs. The universal screw fragment retrieval kit with the guide cylinder method had the lowest success rate of 20% with a mean retrieval time of 13 mins 34 secs $\pm$ 7 mins 25 secs. The internal threads of six implants were damaged as a result of attempted removal of the screw fragments, two from the group using the conventional methods, four from the group using the universal retrieval kit with the guide cylinder (118). On the basis of the results of this study, it was reported that the poorer performance of the universal retrieval kit with the guide cylinder was attributed to the complexity of the guide cylinder inhibiting the drill pieces from contacting the fractured screw fragments which were located in the middle or apical levels of the implants. Additionally, it was reported that omitting the guide cylinder enabled easy and efficient screw modification and effective removal with the second drill piece. However, the universal screw fragment retrieval kit with the guide used in the current study was not used without the guide cylinder for comparison, and the retrieval kit without the guide was acquired from another manufacturer and therefore of a different design. Therefore, a comparison made

between retrieval kits with and without the guides was not possible. The purpose of the guide cylinder is to prevent contact between the rotary instrument and the internal threads of the implant, thereby reducing the risk of damage, however, greater internal thread damage was associated with the use of the guide cylinder in that study (118). It was reported that a combination of the complexity and imprecise fit of the universal guide cylinder with the implant connection caused the drill pieces to touch the internal threads of the implant. However, the number of implants damaged was not sufficient to allow statistical analysis so a definitive conclusion could not be made. The depth of the screw fragment had no impact on the success rates or retrieval times.

More recently, another in-vitro study was carried out by Augustín-Panadero et al. (2020) to assess the relative efficacy of a commercially available universal screw fragment retrieval kit and conventional methods of screw fragment retrieval (117). Additionally, this study aimed to assess the influence of abutment screw morphology on success rates and the retrieval time required. Furthermore, the level of experience that the operators had in retrieving screw fragments was assessed. The success rates for screw fragment retrieval were more favourable for the commercially available kit, which was in agreement with the previous study of that author (118). The abutment screw morphology significantly influenced the retrieval time, where screws with a smooth shank and threaded apical portion required less time to retrieve than screws with a completely threaded body. However, the screw morphology did not influence success rates for retrieval. A small number of implants suffered damage to the internal threads. The level of experience of the operators did not influence the capacity to successfully retrieve fractured screw fragments. In general, the

results from both in-vitro studies suggested that the compatibility and ease of use of the commercially available screw fragment retrieval kits were important factors which affected their efficacy (117, 118).

Kulakov et al. (2018) published an investigation comparing the effectiveness of retrieving fractured abutment screws using ultrasonic instrumentation and a commercially available screw retrieval kit using an animal model (119). Twenty abutment screws were scored at three different levels within the implants (coronal third, middle third and apical third) before being torqued and intentionally fractured in dental implants which were placed in pig mandibles. The authors reported that the mean screw fragment retrieval times with ultrasonic instrumentation were less than with the retrieval kit. Furthermore, the authors stated that success rates correlated with abutment screw fracture level, where deeper fractured screw fragments were easier to remove. However, no statistical analysis was carried out for this study.

An in-vitro study was carried out to investigate the use of manufacturer-specific screw fragment retrieval kits on the quality of the implant-abutment connection (120). Following the successful retrieval of intentionally fractured abutment screw fragments using the retrieval kits, the inner threads of the implants were re-tapped, and new abutments were torqued. Following a period of thermocycling and mechanical loading, screw loosening was compared with a control group. The results indicated that no screw loosening was observed, and the integrity of the implant-abutment connection was not compromised following the retrieval procedure (125).

Several fractured screw retrieval methods employ a rotary instrument to modify and subsequently aid retrieval of the screw fragment (28, 93, 94, 96, 97, 100, 105). However a standardised protocol for drill speed and coolant irrigation is lacking (121). The drilling speeds recommended by manufacturers of the retrieval kits vary from 600 to 2000 rpm, and some systems do not provide information about the use of air and coolant irrigation. The high thermal diffusivity of titanium can cause the kinetic friction to generate a substantial amount of heat (122). High magnitudes of heat generation at the implant-bone interface may cause irreversible bone damage and compromise osseointegration (10, 11). Eriksson et al. (1984) reported that temperatures above 60° C can result in permanent vascular stasis and necrosis of bone tissue (123). An in-vitro study measured the temperature increase during the removal of fractured abutment screws from implants placed in a pig mandible using a commercially available screw retrieval kit operating at drilling speeds of 600 or 2000 rpm. The results indicated that mean peak temperatures were significantly higher with drilling speeds of 2000 rpm when compared with 600 rpm in the crestal and mid-body regions of the implants, but not in the apical region (121). At 2000 rpm, the mean peak temperatures in the mid-body area of the implant were above 60° C, therefore, the slower drilling speeds were recommended (121). An in-vitro investigation by Meisberger et al. (2015) reported that ultrasonic instrumentation used to retrieve fractured abutment screws caused a limited rise in the implant temperature, even without coolant (124).

1.5.5 Evaluating the integrity of the internal threads the implant after retrieval of the fractured screw fragment.

After a fractured abutment screw has been successfully retrieved, the presence of any residual fragments inside in the internal well of the implant and the condition of the internal threads must be determined to facilitate subsequent restoration of the implant. Fractured screw fragments may remain within the implant or damaged threads may prevent placement of an abutment.

In-vitro studies assessed the integrity of the internal threads of the dental implant by replacing the abutment screw to determine if the recommended preload could be achieved (117, 118). Alternatively, the successful seating of an impression coping was reported as another means of evaluating the integrity of the internal threads of the dental implant (10). Igarashi et al. (2018) described the “Bernese silicone replica technique” to evaluate the integrity of the internal threads of the dental implant by injecting a low viscosity thixotropic polyvinylsiloxane impression material into the internal well of the dental implant and supporting the unset material with a wooden wedge. After polymerisation, the pattern was retrieved from the implant and compared with a previously prepared control pattern to identify morphological discrepancies that would indicate damage to the threads of the implant, or to identify residual fragments (125). An in-vitro study was later carried out to compare the efficacy of this technique and two other techniques: the ability to successfully seat an impression coping and with direct visualisation of the internal surface of the implant using a dental microscope (126). They reported that after fractured screw removal, the impression coping technique had 100% sensitivity and 0% specificity, the

Bernese silicone replica technique showed 88.9% sensitivity and 100% specificity, and the dental microscope technique showed 100% sensitivity and 66.7% specificity. It was noted that impression copings used in this study remained 1.5 mm coronal to the bottom of the implant's internal well when fully seated and the presence of apical screw remnants would not be detected. However, the authors failed to determine the significance of the accumulation of debris from the drilled abutment screw at the apical extent of the implant internal well.

CHAPTER 2: STUDY AIMS AND HYPOTHESES

The aims of this in-vitro study were:

(1) To compare the efficacy of a commercially available universal screw retrieval kit with a homemade screw retrieval kit in retrieving fractured abutment screw fragments from dental implants.

(2) To assess the effect of dental implant system type, operator experience, screw fracture morphology, screw fracture torque and location of the implant on the ability to retrieve fractured abutment screw fragments from dental implants.

The null hypotheses:

(1) The commercially available implant abutment screw retrieval kit and the homemade abutment screw retrieval kit are equally effective in retrieving fractured abutment screw fragments from dental implants.

(2) The type of dental implant system, operator experience, screw fracture morphology, screw fracture torque and position of the dental implant does not influence the ability to retrieve fractured abutment screw fragments from dental implants

CHAPTER 3: MATERIALS AND METHODS

3.1 MATERIALS STUDIED

3.1.1 Dental implant systems investigated

Two endosseous dental implant systems were utilised for this experimental in-vitro study - the Straumann® Standard Plus Tissue Level (Ø 4.8 mm) implant (Straumann®, Basel, Switzerland) (Figure 20) and the Nobel Biocare® Brånemark Mark III TiUnite (Ø 4.0 mm) implant (Nobel Biocare®, Zurich, Switzerland) (Figure 21).

3.1.1.1 Straumann® Standard Plus Tissue Level

The Straumann® Standard Plus is a commercially pure grade IV titanium soft-tissue level dental implant (Figure 20). It is designed with a polished neck, 1.8 mm in height and with a regular (Ø 4.8 mm) or wide (Ø 6.5 mm) diameter prosthetic platform. The endosteal portion of the implant is manufactured with a diameter of 3.3, 4.1, or 4.8 mm.

The Straumann® Standard Plus implant is designed with an internal octagonal abutment connection with an 8-degree Morse taper, termed the Straumann® synOcta® connection. The dental implant specimens chosen for the current study had a regular diameter neck (Ø 4.8 mm) prosthetic platform. The diameter of the endosteal portion was 4.1 mm and of varying lengths.

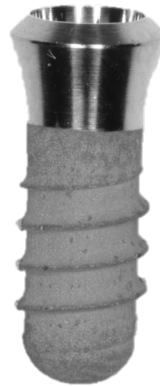


Figure 20: Straumann ® Standard Plus Tissue Level (Ø 4.8 mm) implant

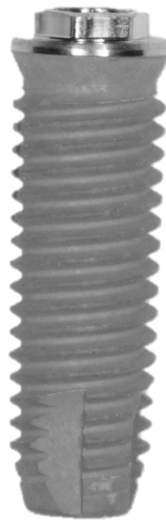


Figure 21: Nobel Biocare ® Brånemark Mark III TiUnite (Ø 4.0 mm)

3.1.1.2 Nobel Biocare® Brånemark Mark III TiUnite

The Nobel Biocare® Brånemark Mark III TiUnite is a commercially pure grade IV titanium dental implant (Figure 21). It is designed with parallel external surfaces, a collar with a machined surface, 0.8 mm in height with narrow (Ø 3.5 mm), regular (Ø 4.1 mm), or wide (Ø 5.1 mm) prosthetic platforms. In addition, a wide prosthetic platform (Ø 5.1 mm) alternative is manufactured with a machined collar and a height of 0.2 mm. The diameter of the endosteal portion varies with the width of the prosthetic platform; 3.3 mm for the narrow-platform implant, 3.75 or 4 mm for the regular-platform implant and 5 mm for the wide-platform implant.

The Nobel Biocare® Brånemark Mark III TiUnite implant is designed with an external hexagonal abutment interface which facilitates six abutment positions. The dental implants chosen for the current study had a regular diameter platform (Ø 4.1 mm). The diameter of the endosteal portion was 3.75 mm and of varying lengths.

3.1.1.3 Straumann® synOcta® Basal Screw RN

The abutment screw chosen for the Straumann® Standard Plus implant was the Straumann® synOcta® Basal Screw RN (Straumann®, Basel, Switzerland) (Figure 22). This abutment screw had a length of 6.7 mm and the head of the screw had a diameter of 2.2 mm. The design includes a tapered head incline, a polished screw-shank with parallel surfaces and a threaded apical portion, of six threads with a diameter of 2.0mm.



Figure 22: Graphic representation of a Straumann® synOcta ® Basal Screw.

The manufacturer's recommended torque value is 35 Ncm, applied utilising a Straumann® Screw Carrying System (SCS) driver tip (Straumann®, Basel, Switzerland).

3.1.1.4 Nobel Biocare® Titanium Abutment Screw for Brånemark System

The Titanium Abutment Screw (Nobel Biocare®, Zurich, Switzerland) for the Nobel Biocare® Brånemark Mark III TiUnite RP implant (Figure 23) was composed primarily of titanium alloy with a diamond-like carbon coating. This abutment screw had a length of 7 mm and the head of the screw had a diameter of 1.9 mm. The screw was designed with a polished parallel-sided screw-shank, and a threaded apical portion with seven threads, and a diameter of 1.5mm.

The manufacturer's recommended torque value is 35Ncm, applied utilising a Nobel Biocare® Unigrip™ driver tip (Nobel Biocare®, Zurich, Switzerland).

3.1.2 NeoBiotech Screw Remover (SR) Kit-II Version 1

The NeoBiotech Screw Remover (SR) Kit-II Version 1 (NeoBiotech, Seoul, South Korea) was selected as the commercially available universal screw retrieval kit in this study (Figures 24 and 25). This kit was introduced in 2015, for the purpose of efficient and safe removal of fractured abutment screws from dental implants. The components are fabricated from stainless steel and arranged in an autoclavable plastic cassette in ascending order of size.



Figure 23: Graphic representation of a Nobel Biocare® Titanium Abutment Screw for Brånemark System RP.

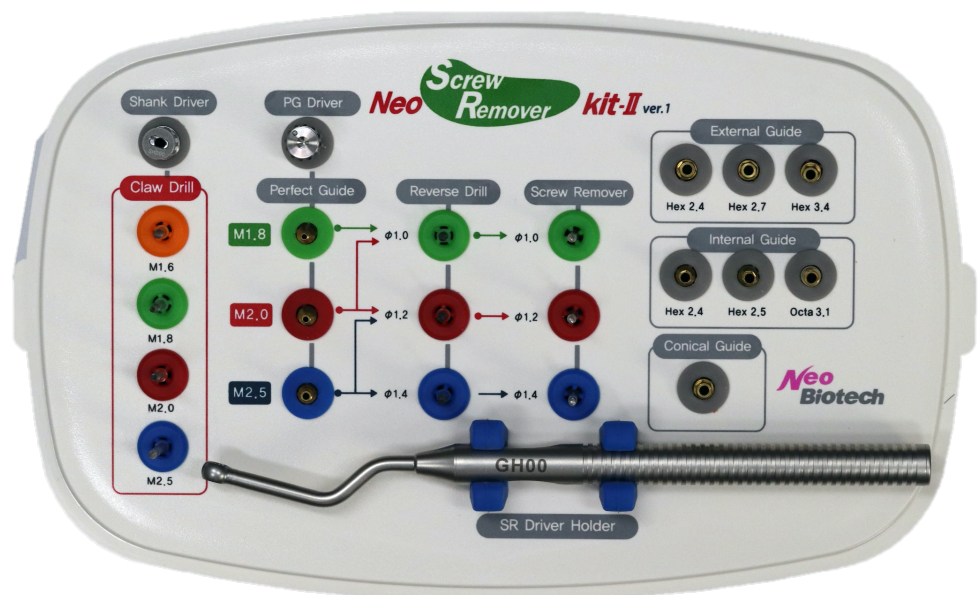


Figure 24: NeoBiotech Screw Remover (SR) Kit-II Version 1

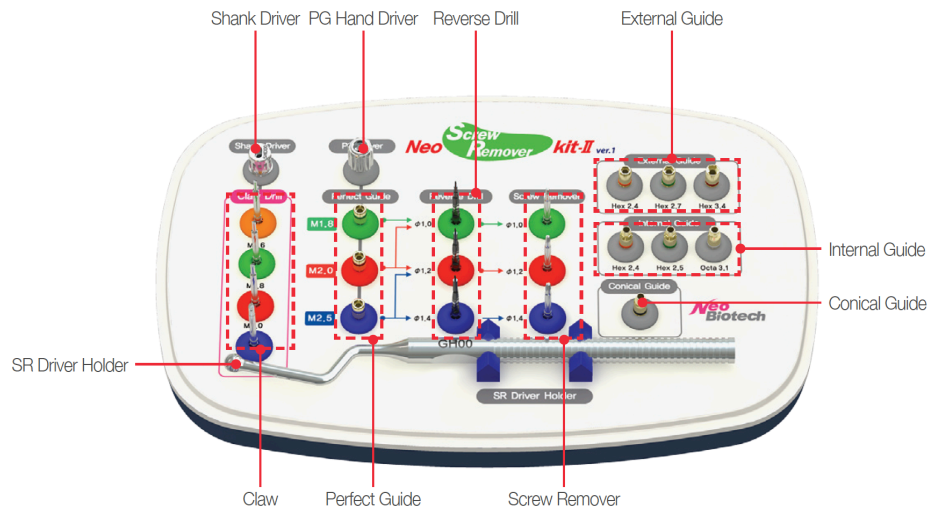


Figure 25: Graphic representation of NeoBiotech Screw Remover (SR) Kit-II Version 1 with labelled categories of components

The components of this kit include:

a) Claw:

A manual hand tool used to remove fractured abutment screw fragments inside the internal well of a dental implant (Figure 26) with a reaming action. It derives its name from the geometric form of the head of the instrument.

The claw is available in four sizes, according to the diameter of the fractured screw fragment; CD16 M1.6, CD18 M1.8, CD20 M2.0 and CD25 M2.5 for removal of fractured screw fragments with diameters greater than 1.6, 1.8, 2.0 and 2.5 mm, respectively (Figure 27).

A latch grip type connection is present in the Claw's coronal terminus (Figure 27b) for use with the Shank Driver SHD00 (Figure 28). The Claw is used in conjunction with a connection guide. A range of connection guides are supplied to match the Claw size and the implant abutment interface of commercially available dental implants (Figure 29a). The SR driver holder GH00 (Figure 29b, 29c) facilitates a convenient grip on the connection guide.

b) Reverse Drill:

An end-cutting stainless-steel bur with a nickel-titanium coating to cut a hole in the fractured abutment screw fragment.

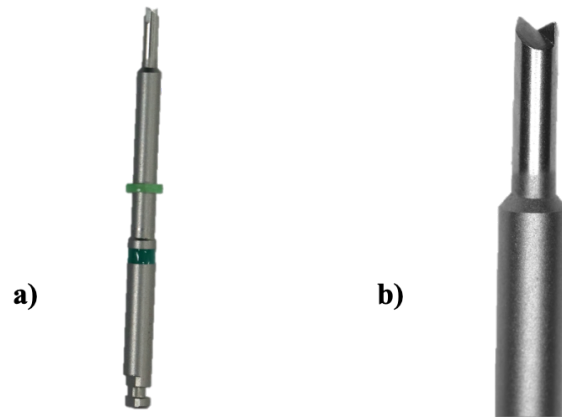


Figure 26: a) CD18 M18 Claw instrument b) Magnified view showing geometric form of the instrument's head

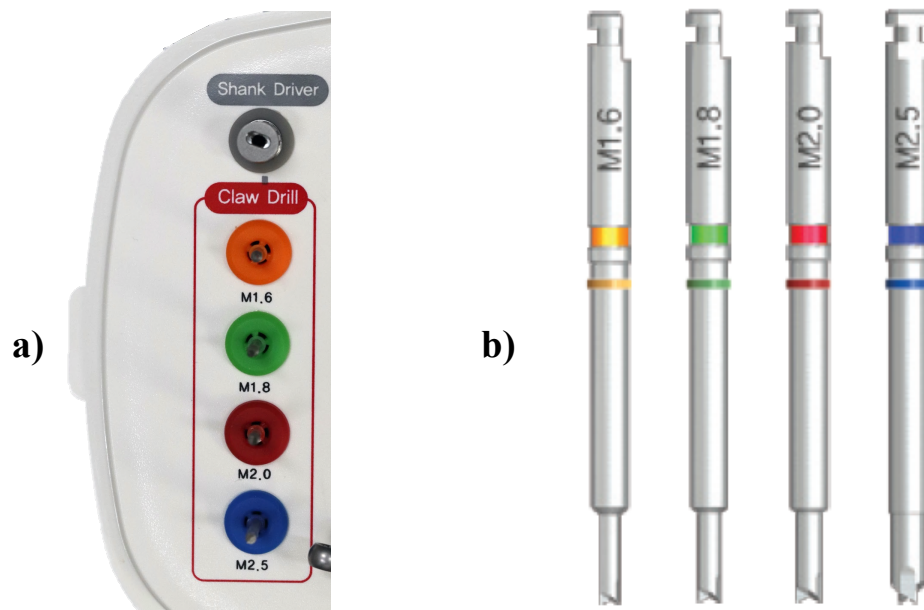


Figure 27: a) Arrangement of the four claw components in the cassette b) Graphic representation of the claw instruments CD16 M1.6, CD18 M1.8, CD10 M2.0 and CD25 M2.5

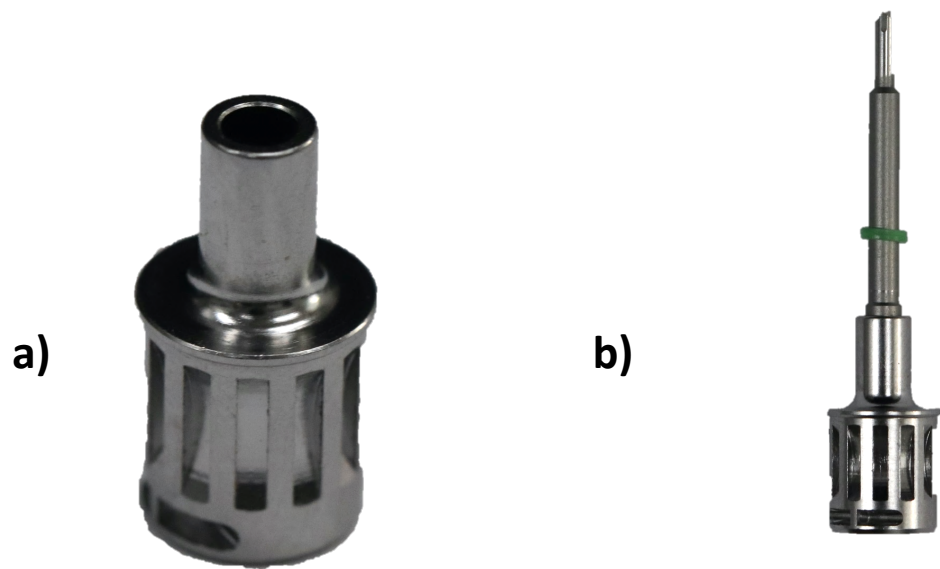


Figure 28: a) Shank Driver SHD00 b) CD18 M1.8 Claw connected to the Shank Driver SHD00

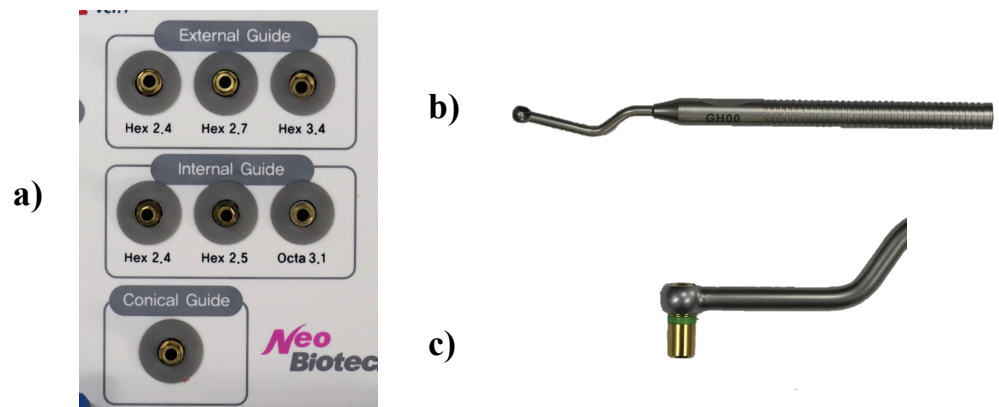


Figure 29: a) Connection guides available in the cassette which are compatible with the Claw b) SR Driver Holder GH00 c) Conical Guide connected to SR Driver Holder GH00

A range of sizes of the Reverse drill are available: RCD10 (1.0 mm in diameter), RCD12 (1.2 mm in diameter) and RCD14 (1.4 mm in diameter) for use in fractured screw fragments with diameter of 1.8, 1.2 and 2.5 mm, respectively (Figure 30a, b).

The Reverse Drill is used in conjunction with the connection guide (Figure 31a, b). The choice of connection guide to use depends on the depth of the fractured screw fragment. The PG Hand Driver PGHD25SS is connected to the Perfect Guide to enable the operator to engage the inner implant threads (Figure 32a-c).

A latch grip -connection on the coronal terminus of the Reverse Drill is connected to a torque-controlled implant surgical handpiece. The manufacturers recommend the Reverse Drill as a single-use component.

c) Screw Remover:

A tool to remove a fractured screw fragment (Figure 33a) after cutting a hole with the Reverse Drill.

The screw remover is available in three sizes: SR10 (1.0 mm in diameter), SR12 (1.2 mm in diameter) and SR14 (1.4 mm in diameter) for removal of fractured screw fragments with diameters of 1.0, 1.2 and 2.5 mm, respectively (Figure 33b).

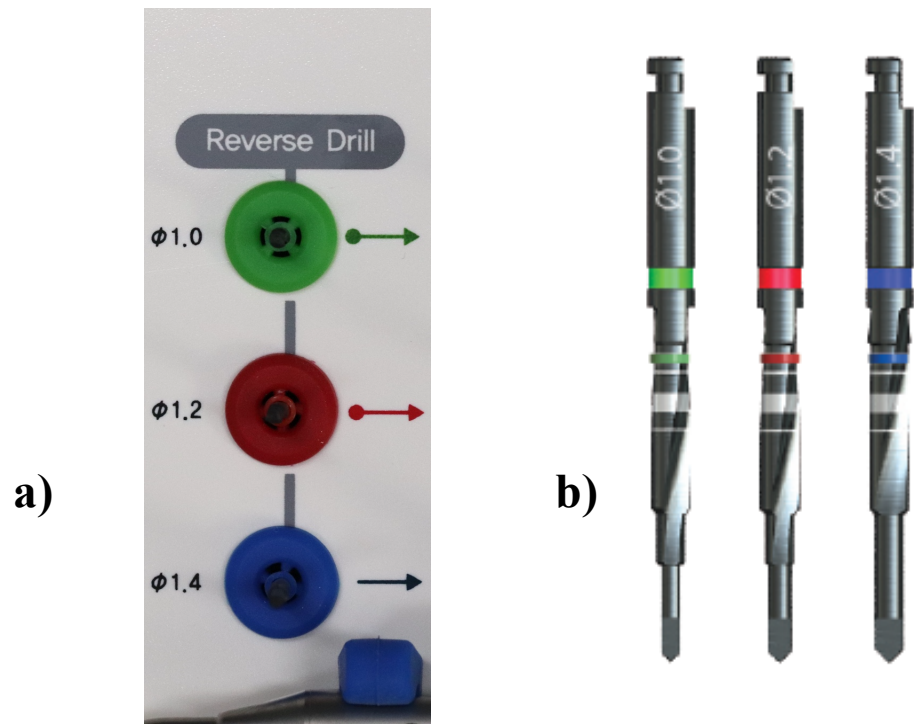


Figure 30: a) Arrangement of the three Reverse Drills in the cassette **b)** Graphic representation of Reverse Drills RCD10, RCD12, RCD14 respectively

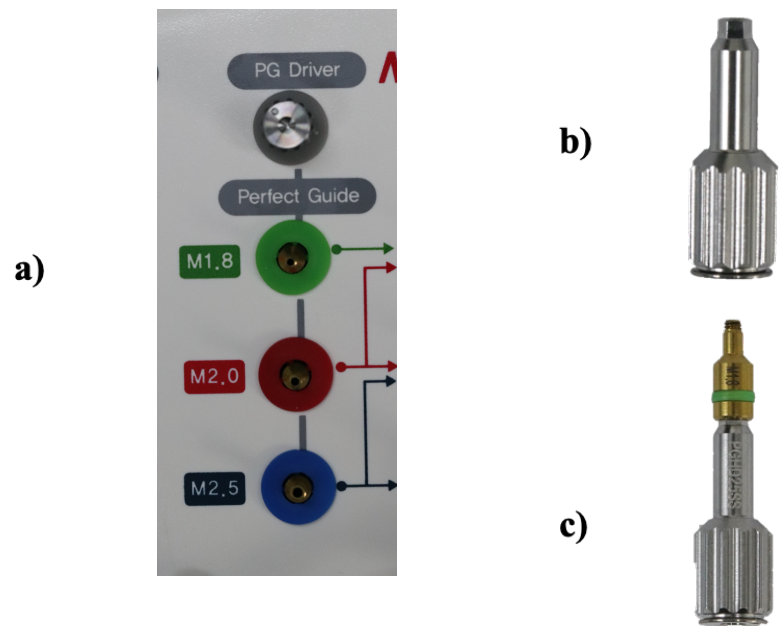


Figure 31: a) Connection guides available which are compatible with the Reverse Drill burs **b)** PG Hand Driver PGHD25SS **c)** Conical Guide connected to PG Hand Driver PGHD25SS

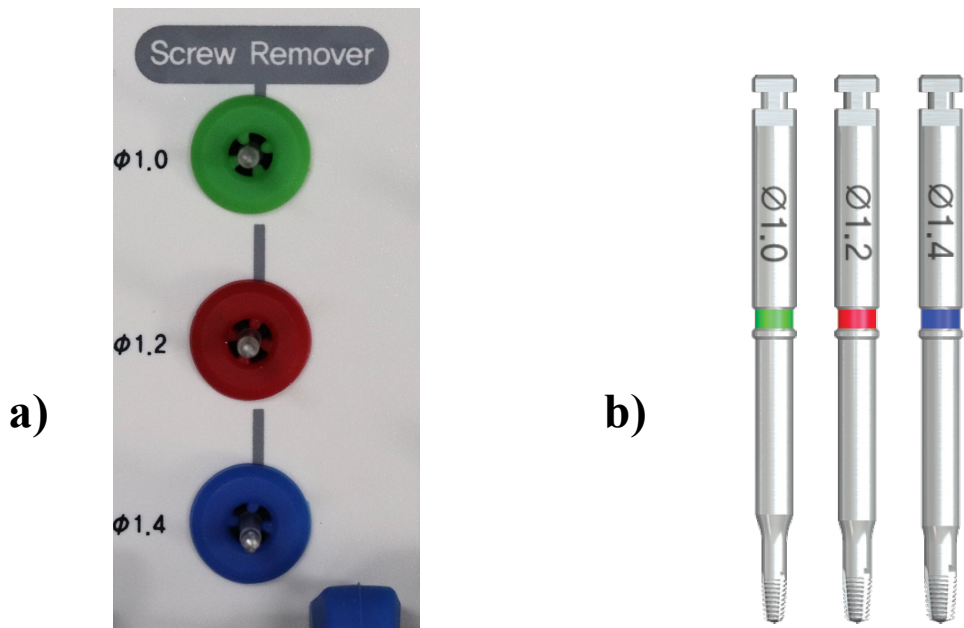


Figure 32: a) Arrangement of the three Screw Removers in the cassette **b)** Graphic representation Screw Removers SR10, SR12, SR14 respectively

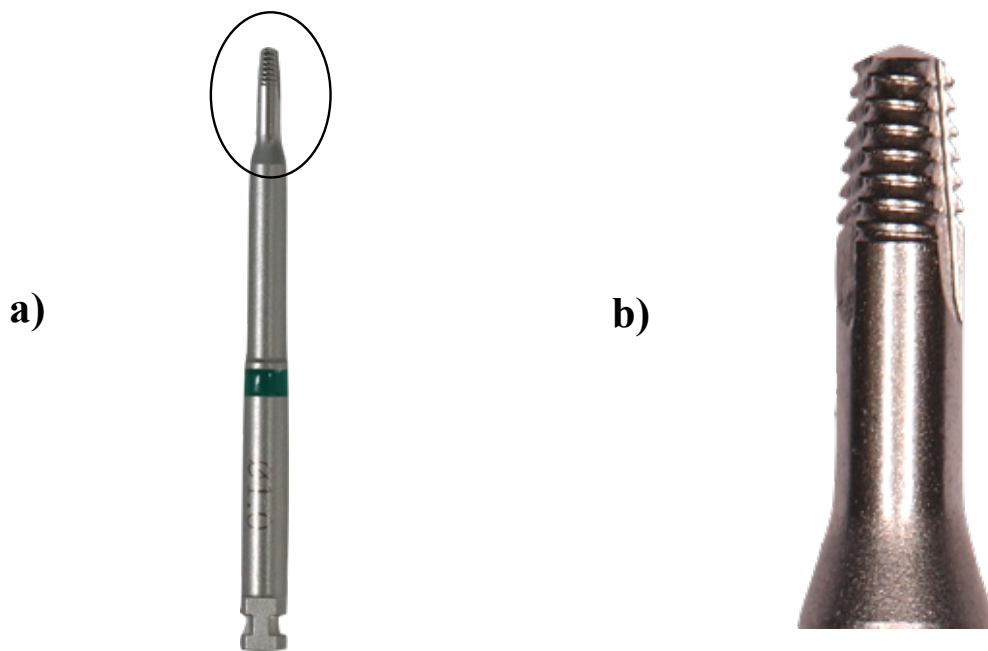


Figure 33: a) Screw Remover SR10 **b)** Tapered head design of SR10 with a minor diameter of $\phi 1.0\text{mm}$

A latch grip connection on the coronal terminus of the Screw Remover facilitates its use as a manual instrument in conjunction with Shank Driver SHD00, or as a rotary tool when connected to a torque-controlled implant surgical handpiece. The apical tip of the screw remover is tapered apically and consists of eight threads of similar pitch (Figure 33a, b). This tool is not used with a guide.

3.1.3 Homemade Screw Retrieval Kit

The homemade screw retrieval kit consisted of eight tools (Figure 34). Four of the tools were standard dental instruments:

- a standard single-sided dental mouth mirror (#3 HD Mouth Mirror MIR3HD, Hu-Friedy®, Hu Friedy Co., Frankfurt, Germany)
- a DG16 endodontic explorer (9EXDG166, Hu-Friedy®, Hu Friedy Co., Frankfurt, Germany)
- a spoon excavator (EXC14, Hu-Friedy®, Hu Friedy Co., Frankfurt, Germany)
- #3 curved mosquito forceps (H3 Hemostat Halsted, Hu-Friedy®, Hu Friedy Co., Frankfurt, Germany)

In addition, the homemade kit contained:

- a homemade connection guide (Figure 35a)
- two homemade claw tools (Figure 35b).
- a hand driver for use with the homemade claw tools (Figure 35b)

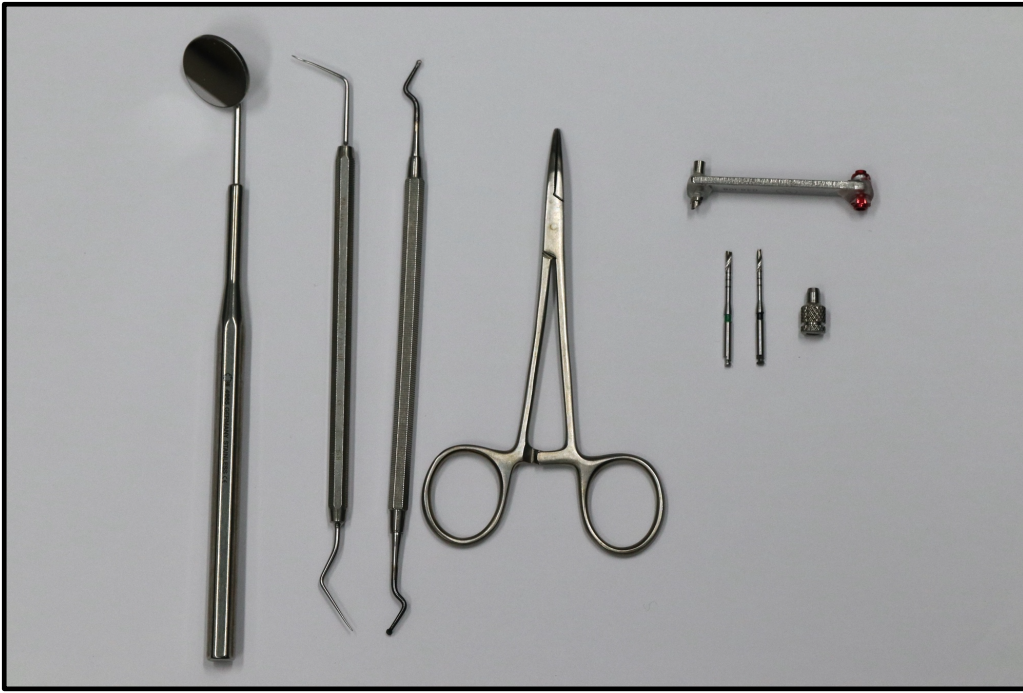


Figure 34: The homemade retrieval kit; *from left-to-right:* mouth mirror, DG16 explorer, spoon excavator, curved mosquito forceps, homemade connection guide (top), homemade claw tools (bottom) and hand driver

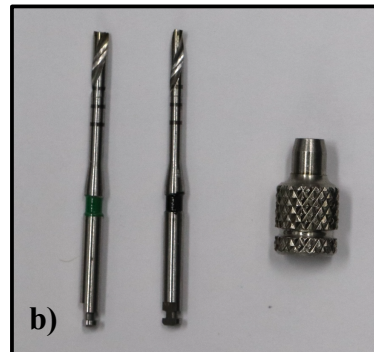


Figure 35: a) Homemade connection guide b) Homemade claw tools and driver handle

The homemade connection guide (Figure 35) was constructed by modifying and amalgamating three different items – a service instrument (Straumann® Service Instrument 046.108, Straumann®, Basel, Switzerland), an RN synOcta® Impression Coping and an Impression Coping Open Tray Brånemark System RP (Nobel Biocare®, Zurich, Switzerland).

The lumens in the Service Instrument were widened with a cross-cut tungsten carbide bur (9C.79K.104.040, Frank Dental, Gmund, Germany) mounted in an electric straight laboratory handpiece, operating at 30,000 rpm (K5Plus™, KaVo Dental, Biberach, Germany) to allow both impression copings to be engaged passively. They were then embedded in the Service Instrument with clear autopolymerising acrylic resin (MP2 Orthodontic Cold Cure Acrylic, Ortho-Care®, Ortho-Care Ltd, West Yorkshire, UK).

The homemade claw tools consisted of a modified Ø 1.50 mm and Ø 1.75 mm tri-fluted ParaPost® drills (Coltène/Whaledent, Coltène/Whaledent Ltd., Altstätten, Switzerland).

The tip of the drill pieces were modified using a grinding disc (FINODISC GRIND, FINO, Mangelsfeld, Germany) (Figure 36a, b) attached to an electric straight handpiece, and operating at a speed of 10,000 rpm to form serrations, similar to the Claw of the Neobiotech retrieval kit (Section 3.1.4). The homemade claw tools were inserted into the hand driver (ParaPost® L590 Universal Hand Driver, Coltène/Whaledent, Coltène/Whaledent Ltd., Altstätten, Switzerland) before use.

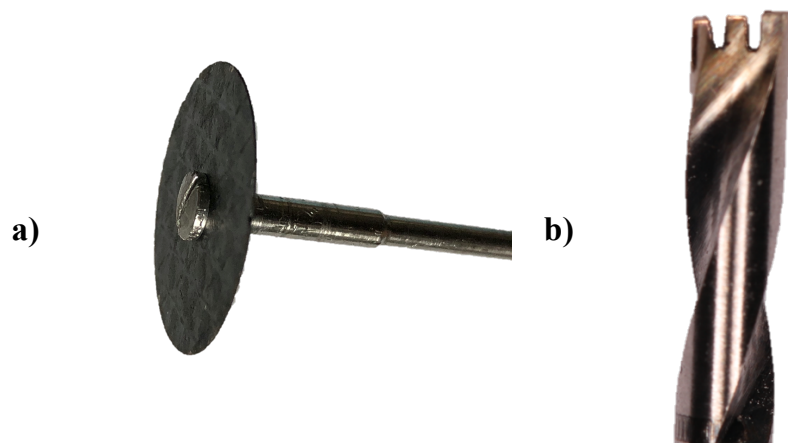


Figure 36: a) Grinding disc b) Modified Ø 1.75mm tri-fluted ParaPost ® drill

3.2 PREPARATION OF THE WORKING CAST

3.2.1 Power calculation

To determine a suitable sample size for the current study, a power calculation was based on the study of Agustín-Panadero et al. (2017) (118). With comparable efficacy and success of the retrieval kits, a sample size of 16 in each experimental group would yield a power of 80% to detect a difference between the group mean and hypothetical mean of 5 minutes (difference in successful screw fragment retrieval time) with a significance level α of 0.05 (two-tailed). Considering that the dental implant system, abutment screw, retrieval kit, fracture level and morphology and operator experience were different, it was decided to double the sample size to 32 for each experimental group to improve the probability of determining a difference somewhat escalated the chance of using the appropriate number, thus making meaningful statistical comparisons.

3.2.2 Construction of gypsum casts

A pair of edentulous maxillary and mandibular typodont models were (B-3 NM, B-3 NMB, Frasco ®, Frasco GmbH Ltd., Tettnang, Germany) (Figure 37a, b) placed in rigid duplicating flasks (WaSil soft Duplicating Flask, WASSERMANN ®, WASSERMAN LTD, Hamburg, Germany) (Figure 38). An autopolymerising addition-vulcanizing duplicating silicone material (WaSil soft, WASSERMANN ®, WASSERMAN LTD, Hamburg, Germany) was auto-mixed (Sidomix, WASSERMANN ®, WASSERMAN LTD, Hamburg, Germany) and dispensed into both duplicating flasks containing a typodont

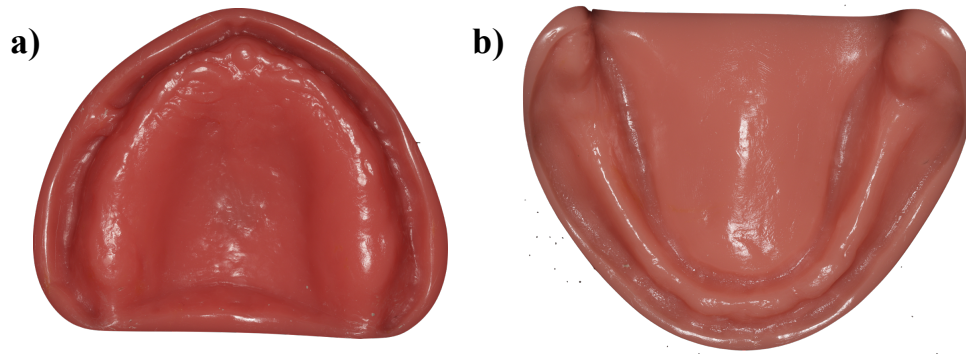


Figure 37: a) Edentulous maxillary typodont b) Edentulous mandibular typodont

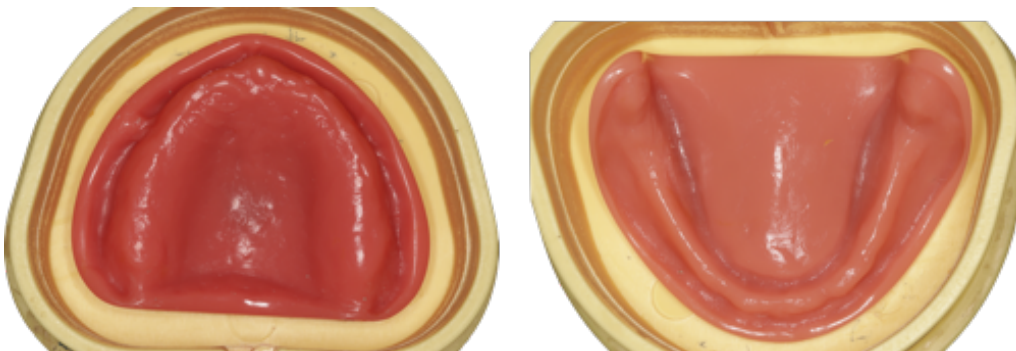


Figure 38: Edentulous typodonts inside duplicating flasks.

model to fill the flask. The silicone material was allowed to polymerise for 45 mins, prior to removal of the typodont models from the polymerised duplication moulds (Figure 39). ISO Type V dental stone (Jade Stone, WHIP MIX CORPORATION, Kentucky, USA) was prepared according to the manufacturer's powder: liquid ratio and mixed using a vacuum mixer (VPM2, WHIP MIX CORPORATION, Kentucky, USA). The vacuum-mixed dental stone was poured into each mould using a spatula and the aid of a stone vibrator (Power Vibrator K-56, WASSERMANN®, WASSERMAN LTD, Hamburg, Germany). Following a setting time of 60 mins, the casts were removed from the duplicating moulds and excess stone at the base of the cast was removed using a model trimmer (Trimmer HSS-ZA, WASSERMANN®, WASSERMAN LTD, Hamburg, Germany).

Cylindrical cavities (5.0 mm in diameter and 15.0 mm in length) were prepared in the maxillary and mandibular casts at four sites (Figure 40) using a long parallel-sided cross-cut tungsten carbide bur (C.79LKSG.104.060, Frank Dental, Gmund, Germany) in an electric, straight laboratory handpiece, operating at 30,000 rpm. A total of eight maxillary and eight mandibular casts were made in a similar manner. Prior to the initial setting reaction of the dental stone, a circular magnetic disc (Splitex Retention Disc, Amann Girrbach AG, Koblach, Austria) was magnetically attached to the centre of a magnetic typodont mounting plate (1260M/J, Frasaco®, frasaco GmbH Ltd., Tett nang, Germany) (Figure 41). This assembly was inverted and placed into the unset dental stone (Figure 42). Following setting of the dental stone, the cast was removed from the duplicating mould and the magnetic mounting plate was carefully separated from the stone cast, to reveal a recess for placement of the



Figure 39: Duplication molds

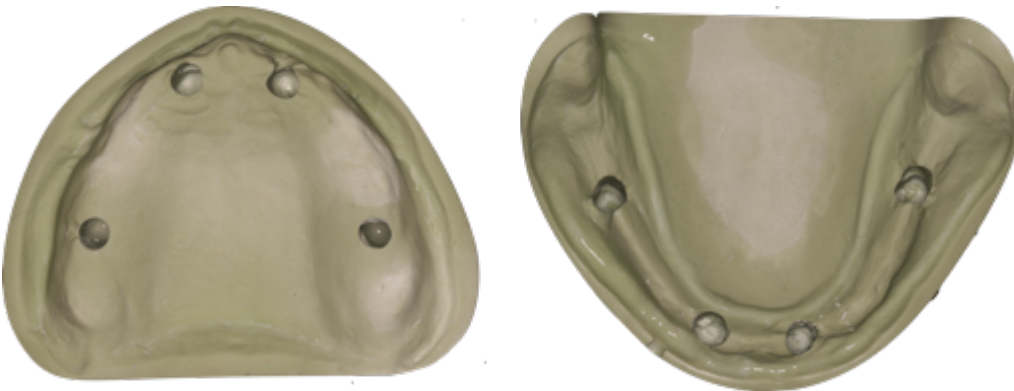


Figure 40: Cavities prepared at four sites on each cast

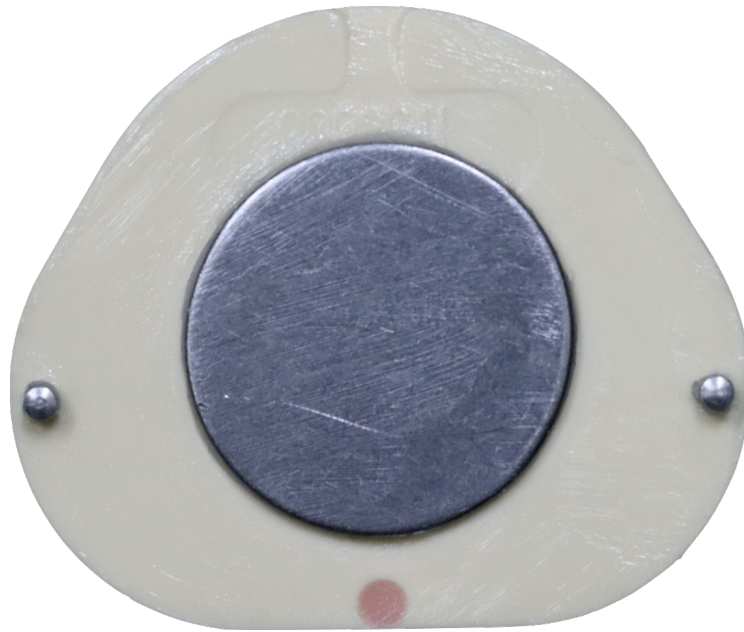


Figure 41: Magnetic disc attached to mounting plate

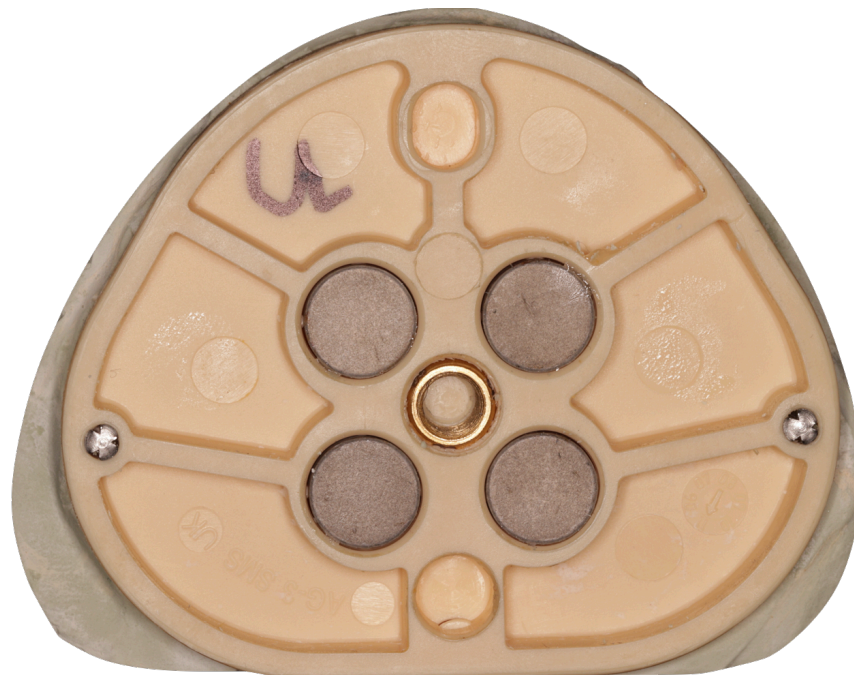


Figure 42: Magnetic disc-plate assembly embedded in dental stone

positioning pins of the magnetic mounting plate on the cast, and a depression to allow a magnetic disc to be adhered to the base of the cast (Figure 43).

3.2.3 Fracture of dental implant abutment screws

A total of 64 abutment screws were partially sectioned through the second coronal thread using a grinding disc, in an electric straight laboratory handpiece, for the purpose of mechanically weakening the screw. The screws were equally distributed into four groups and partial sectioning of the abutment screws was carried out using one of four methods. Method 1 involved a single cut with the grinding disc as shown in Figure 44(a). Method 2 involved two diametrically opposing cuts placed in the abutment screw as shown in Figure 44(b). Method 3 and 4 involved the placement of three and four cuts, respectively, around the circumference of the abutment screw (Figure 44c, d). The partially sectioned abutment screws were used to connect prefabricated implant abutments to the implant specimens. RN Variobase® titanium base abutments (Straumann®, Basel, Switzerland) were connected to the Straumann® Standard Plus implants with the partially sectioned Straumann® synOcta® Basal Screw RN (Section 3.1.2), and UCLA-type abutments (GoldAdapt Engaging Brånemark System RP, Nobel Biocare®, Zurich, Switzerland) were connected to the Nobel Biocare® Brånemark Mark III TiUnite implants using the Nobel Biocare® Titanium Abutment Screw (Section 3.1.3). Each abutment screw was hand tightened until resistance was felt. An independently calibrated torque driver (Tohnichi, Japan) (Appendix 1) was used to deliver torque to the abutment screws while the implant was secured in a bench vice until the abutment screw fractured. The four methods used to partially section the abutment screws

produced characteristic cross-sectional morphologies of the fractured abutment screws (Figure 44). The torque value at which the abutment screws fractured, and the fracture morphology was recorded.

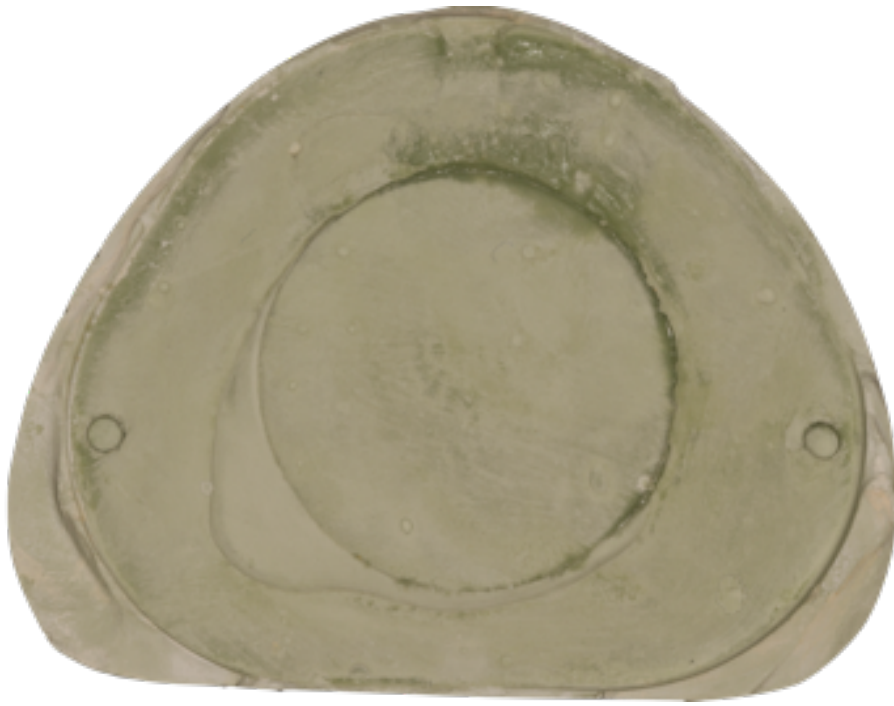


Figure 43: Underside of model base revealing recesses for mounting plate pins and relief in the center for attachment of a metal disc

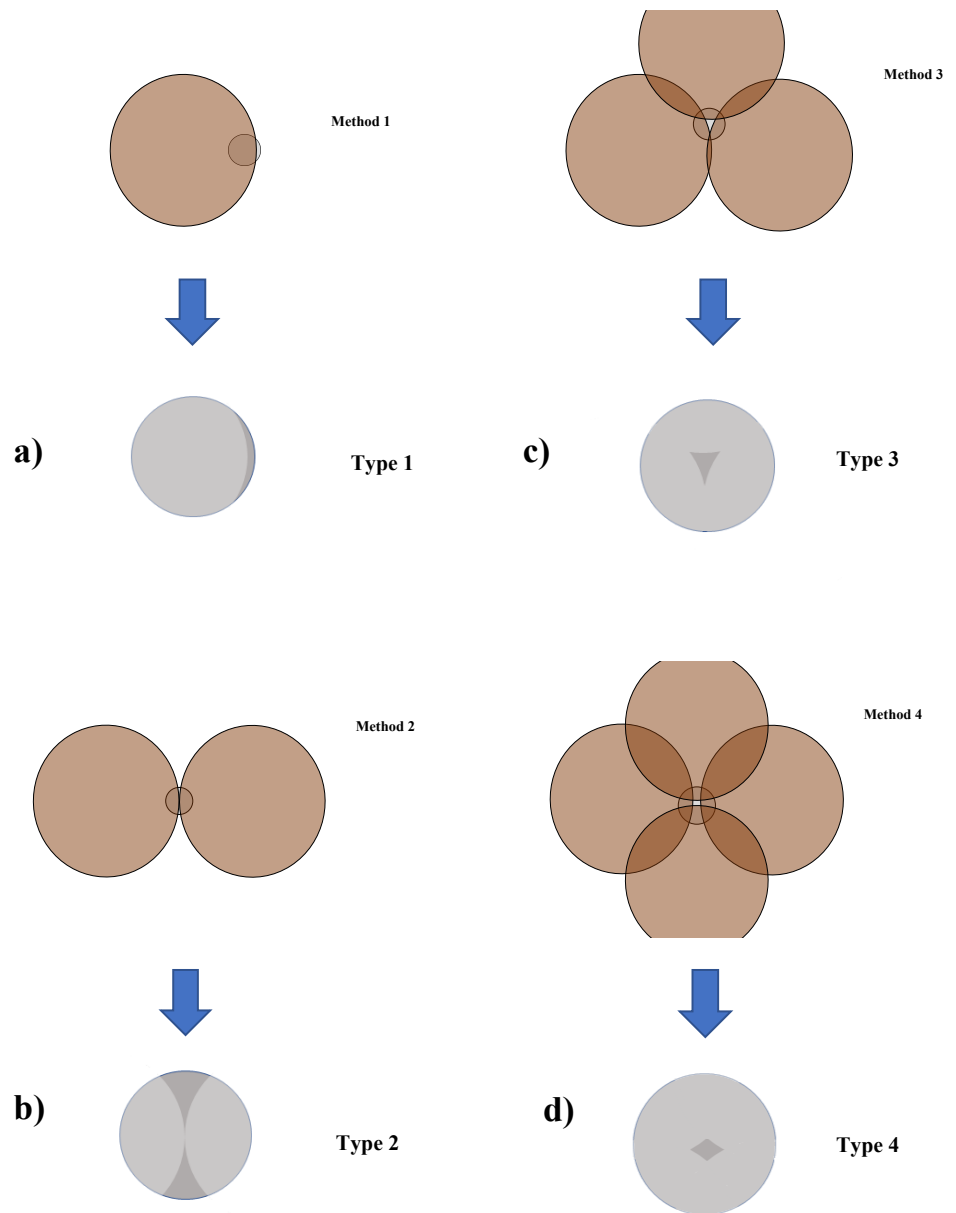


Figure 44: Schematic representation of the four methods use to cut the abutment screws. The smaller grey circle denotes the abutment screw viewed from the occlusal perspective. The brown circle represents the cutting location of the grinding disc. The overlap of the grey and brown circle(s) shows the depth of cuts. **(a)** Type 1 fracture morphology. **(b)** Type 2 fracture morphology. **(c)** Type 3 fracture morphology. **(d)** Type 4 fracture morphology.

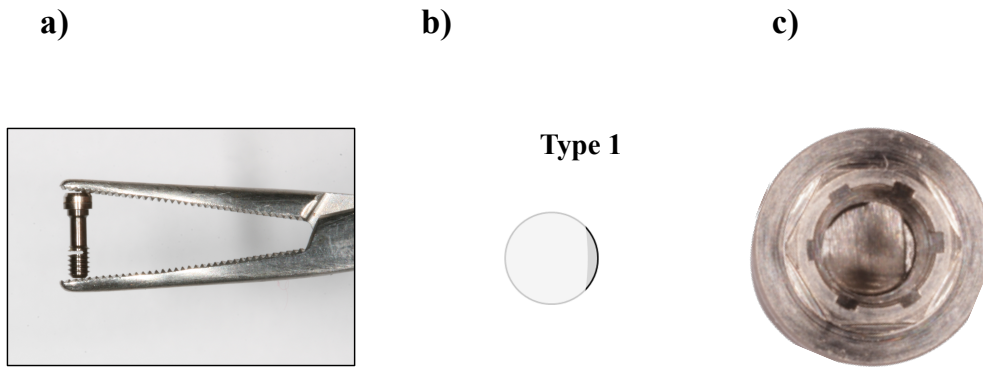


Figure 45: a) A Nobel Biocare® Titanium Abutment Screw cut by Technique 1: b) Graphic representation of a Type 1 fracture morphology occurring in an abutment screw from the occlusal perspective c) Nobel Biocare® Brånemark Mark III TiUnite dental implant containing a fractured screw fragment with a Type 1 fracture morphology

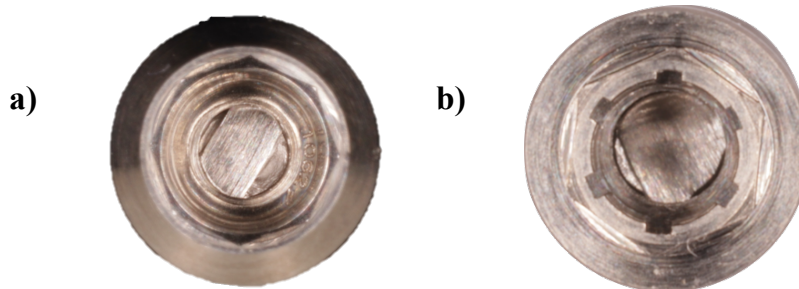


Figure 46: a) Straumann® Standard Plus dental implants containing a fractured screw fragment b) Nobel Biocare® Brånemark Mark III TiUnite dental implants containing a fractured screw fragment

3.2.4 Embedding dental implants containing fractured dental implant abutment screws

Four maxillary casts and four mandibular casts (Section 3.2.2) were assigned to receive four Straumann® Standard Plus dental implants each containing a fractured screw fragment (Figure 46a). Similarly, 4 maxillary casts and 4 mandibular casts were assigned to receive four Nobel Biocare® Brånemark Mark III TiUnite dental implants each containing a fractured screw fragment (Figure 46b).

The Straumann® Standard Plus and Nobel Biocare® Brånemark Mark III TiUnite dental implants containing fractured screw fragments were embedded in the cavities of their respective stone casts to the level of the prosthetic platform using autopolymerising acrylic resin (Figure 47a). The casts were submerged in an activated pressure polymerisation unit (Polyquick260, WASSERMANN®, WASSERMAN LTD, Hamburg, Germany) at a temperature of 55°C, under a pressure of 5 bar for 15 mins, to polymerise the acrylic resin. After 15 mins, the stone casts were allowed to bench cool for 24 hours to facilitate further polymerisation of the acrylic resin.

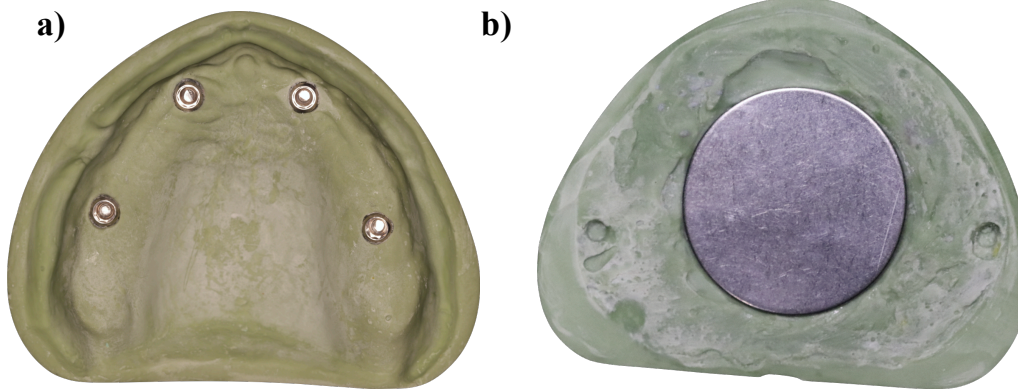


Figure 47: a) A maxillary stone cast with four Straumann® Standard Plus dental implants containing a fractured screw fragment embedded in acrylic resin **b)** Circular metal disc adhered to the base of the cast

The metal discs were bonded to the central depression on the underside of the base of the cast using a polyurethane-based adhesive (GORILLA GLUE®, The Gorilla Glue Company, Ohio, USA) (Figure 47b).

3.2.5 Specimen Distribution

Eight of the Straumann® Standard Plus dental implants and eight of the Nobel Biocare® Brånemark Mark III TiUnite implants containing the fractured screw fragments were each distributed to two clinicians with extensive experience with implant-supported prosthodontics (operators with high experience) (32 implants). Eight of the Straumann® Standard Plus dental implants and eight of the Nobel Biocare® Brånemark Mark III TiUnite implants containing fractured screw fragments were each distributed to two postgraduate students with low experience with implant-supported prosthodontics (operators with low experience) (32 implants). This in-vitro study took place concurrently with another D.Ch.Dent. research project as part of a wider investigation examining fractured abutment screw retrieval methods in other dental implant systems. A designated and organised sample flowchart (Appendix 2) was made which would rotate operator type, implant system, implant location and retrieval kit to be used, in an even manner in order to equalise any potential effects of improved operator competence as the experiment progressed.

3.3 RETRIEVAL OF FRACTURED DENTAL IMPLANT ABUTMENT SCREW FRAGMENTS

3.3.1 In-vitro experimental setup and simulation of clinical environment

This in-vitro experimental study took place in a designated dental chair unit (Planmeca Compact™ i5, Planmeca, Helsinki, Finland) in the Dublin Dental University Hospital. The head rest in the dental chair unit was removed and replaced with a phantom head (P-6/3 Standard Mannequin System; Frasaco®, frasaco GmbH Ltd., Tett nang, Germany).

The cast containing the dental implant to be investigated was attached to the magnetic mounting plate in the phantom head (Figure 48). The operators used loupes with a magnification of x3 (HDL™ 3.0, Orascoptic, USA) and an LED-powered headlight (Endeavour™, Orascoptic, USA).

The following data were recorded for each experimental specimen:

- Operator experience level (inexperienced or experienced)
- Dental implant system (Straumann® or Nobel Biocare®)
- Implant position (maxillary anterior, maxillary posterior, mandibular anterior or mandibular posterior)
- Fracture morphology type of the fractured screw fragment (Type 1, 2, 3 or 4)
- Type of retrieval kit used (commercially available screw retrieval kit or homemade retrieval kit)

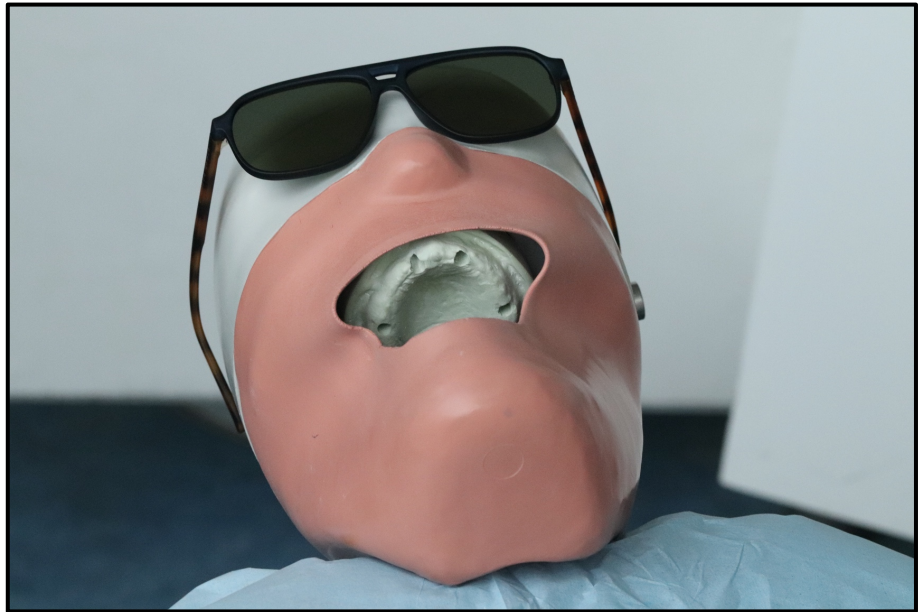


Figure 48: Phantom head fixed on the dental chair unit head rest with the maxillary stone cast magnetically attached.

- Torque at which the screw fractured (Ncm)
- Retrieval outcome (screw fragment retrieved: Yes/No)
- Time taken to retrieve the screw fragment (secs)
- Presence of damage to implant threads (Yes/No).

A period of 15 min was allowed for the removal of each screw fragment, and if the screw fragment had not been retrieved within this time, it was recorded as not retrieved. A successful outcome was defined as retrieval of the screw fragment in less than or equal to 15 mins with no damage to the implant's internal threads.

3.3.2 Retrieval of fractured dental implant abutment screws utilising the Neobiotech Screw Remover (SR) Kit-II Version 1

The following procedure was used when attempting to retrieve fractured screw fragments with the Neobiotech Screw Remover (SR) Kit-II Version 1:

- (1) The abutment connection, dental implant width and diameter of the fractured screw fragment were established. The appropriate connection guide and Claw tool (Figure 27) were selected. For the Straumann® Standard Plus dental implants, the Conical Guide CG00 (Figure 25) was chosen, attached to the SR Driver Holder (Figure 25) and inserted in the Straumann® Standard Plus implant. The CD20 Claw tool (Figure 27) attached to the Shank Driver was then selected because it matched the diameter of the fractured screw fragment. The claw tool was inserted in the Conical Guide, stabilised by the SR Driver Holder on the implant

prosthetic platform. When the tip of the CD20 Claw tool engaged the fractured screw fragment, it was rotated in an anti-clockwise direction (Figure 49). For the Nobel Biocare® Brånemark Mark III TiUnite dental implants, the EHG34 External Guide (Figure 29a) was used with SR Driver Holder and the CD20 Claw tool in a similar manner. If the fractured screw fragment was not removed with the Claw tool, the Reverse Drill was employed.

- (2) The depth of the screw fragment was visualised. If the fragment was located deeper than 2 mm, or if the fragment was superficial such that there were no threads coronal to the fragment, the Conical guide CG00 was used. Otherwise, the Perfect Guide PG1220 (Figure 31a) was selected for use with Straumann® Standard Plus implants or the Perfect Guide PG1018 for the Nobel Biocare® Brånemark Mark III TiUnite dental implant. The Perfect Guide was torqued to a value of 15 Ncm onto the dental implant using the PG Hand Driver (Figure 31b, c). The RCD10 Reverse Drill (Figure 32b) was connected to a torque-controlled implant surgical handpiece (DU900, Zimmer Biomet™, Biomet 3i Ltd, Florida, USA), passed through the connection guide, and operated at 2,000 rpm in an anti-clockwise direction with saline irrigation to cut a hole in the coronal aspect of the fractured screw fragment (Figure 50).

A screw remover was selected to match the size of the hole in the fractured screw fragment that was cut by the Reverse Drill. For the Straumann® Standard Plus and the Nobel Biocare® Brånemark Mark III TiUnite dental implants, the SR10 Screw Remover was used in the

torque-controlled implant surgical handpiece, without a connection guide (Figure 51) to engage the hole in the fractured abutment screw fragment. The implant surgical handpiece was operated at 80 rpm in an anticlockwise direction, with saline irrigation until the screw fragment was removed from the implant (Figure 52 and 53).

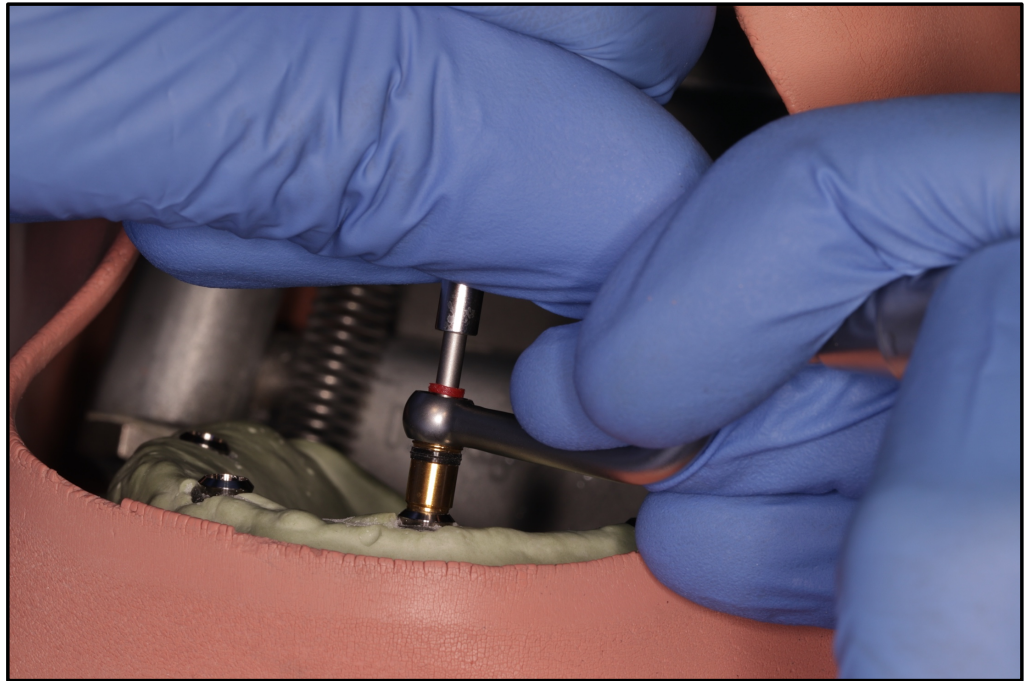


Figure 49: CD20 Claw tool being used in conjunction with a conical connection guide in an anticlockwise direction

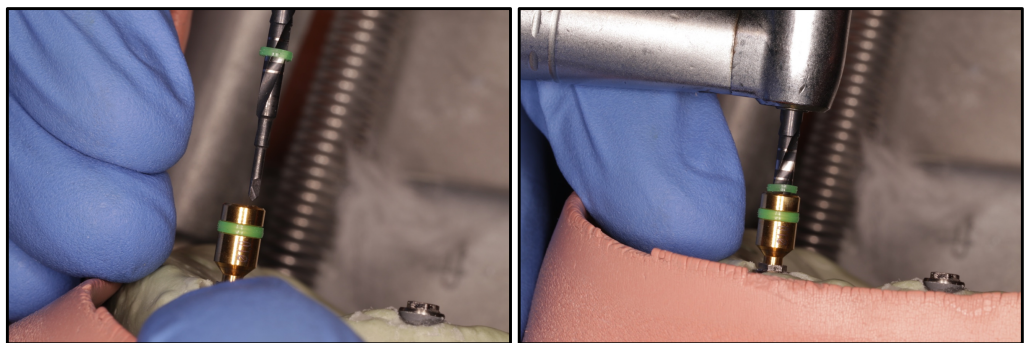


Figure 50: Reverse Drill RCD10 passing through Perfect Guide PG1018 in order to create a hole in Nobel Biocare® Titanium Abutment Screw

3.3.3 Retrieval of fractured dental implant abutment screw fragments utilising the homemade screw retrieval kit

A choice of tools was available to retrieve fractured screw fragments with the homemade screw retrieval kit (Figure 34):

- (1) The tip of the DG16 endodontic probe was used to rotate the fractured screw fragment in an anti-clockwise direction and to move the fragment coronally (Figure 54).
- (2) The oscillation of the ultrasonic scaler tip was used to loosen the fractured screw fragment and to facilitate the use of the other instruments.
- (3) The spoon excavator was used to move the screw fragments in an anti-clockwise direction coronally.
- (4) The curved mosquito forceps was used to hold screw fragments that had become situated coronally and were rotated from the implant in an anticlockwise direction.

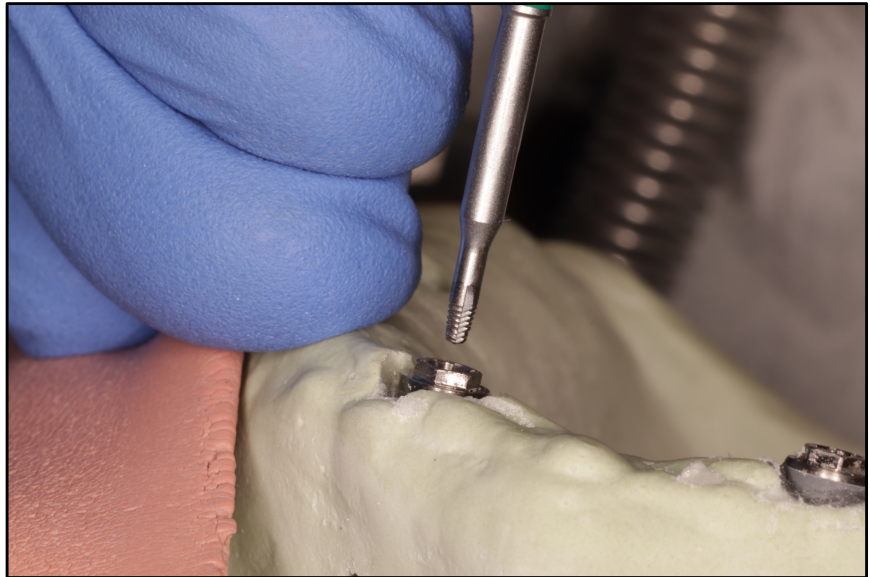


Figure 51: SR10 Screw Remover being used without a connection guide



Figure 52: The Screw Remover SR12 with a basal screw fragment attached



Figure 53: Successfully retrieved fractured screw fragment

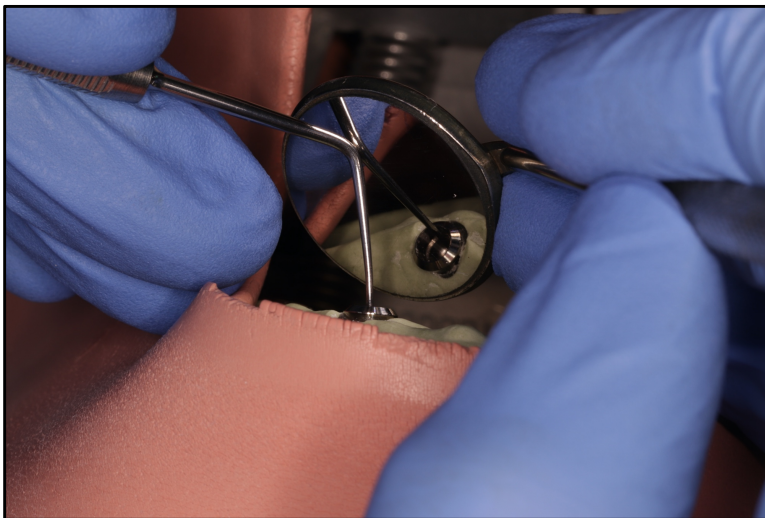


Figure 54: The DG16 endodontic probe used to rotate the fractured screw fragment in an anti-clockwise direction.

(5) The homemade claw tools (Figure 35b) and the homemade connection guide (Figure 35a) were connected to the dental implant and used manually to engage the fractured screw fragment by rotating in an anti-clockwise direction (Figure 55).

3.4 ANALYSIS OF DAMAGE TO THE INTERNAL THREADS OF THE IMPLANTS

After successfully retrieving a fractured screw fragment, the same operator immediately assessed the integrity to the respective dental implant by hand-torquing an impression coping into the implant to verify correct seating, visually and by touch. An RN synOcta® Impression Coping was used with the Straumann® Standard Plus Tissue Level implants (Figure 56) and an Impression Coping Open Tray Brånemark System RP was the used for Nobel Biocare® Brånemark Mark III TiUnite implants (Figure 57). Seating of the impression coping on the prosthetic platform confirmed the integrity of the dental implant, however, if the impression coping did not seat because of damage to the threads of the implant, the integrity of the implant was considered unsatisfactory.

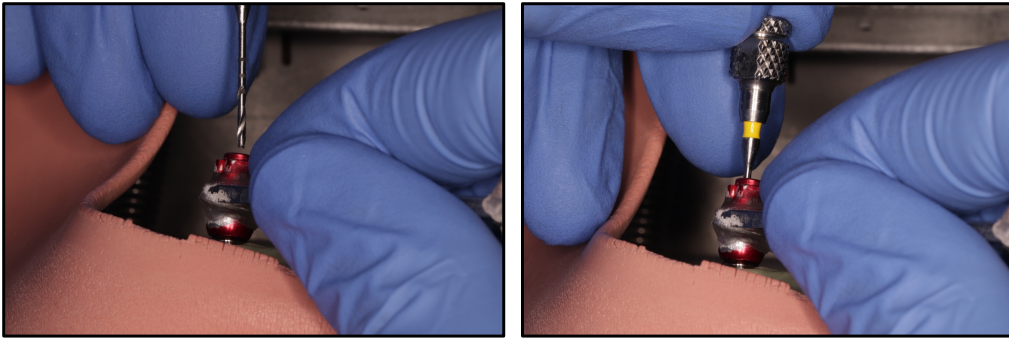


Figure 55: The homemade claw tool used in conjunction with the homemade connection guide to retrieve a fractured Straumann® synOcta ® Basal Screw.

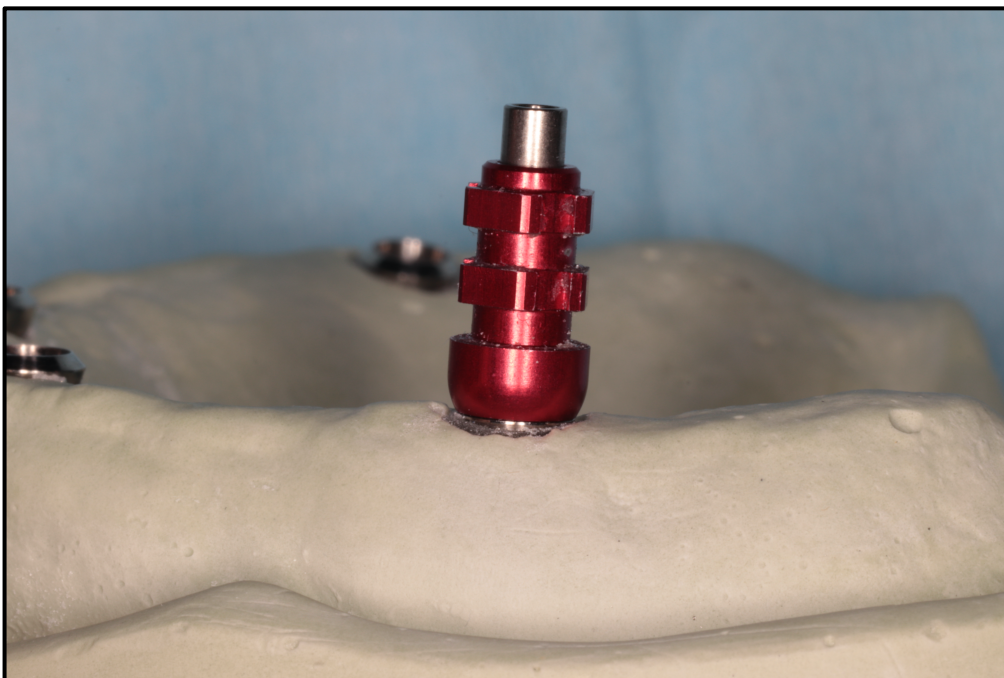


Figure 56: RN synOcta® Impression Coping fully seated after removal of a fractured screw fragment.



Figure 57: Impression Coping Open Tray Brånemark System RP fully seated after removal of a fractured screw fragment.

3.5 DATA HANDLING

The data were transferred to an Excel spreadsheet (Microsoft Excel, Microsoft Corporation, USA). A statistical analysis was carried out using an SPSS statistical analysis software program (IBM SPSS Statistics, v26.0, IBM Corp, USA).

The independent variables likely to predict the dependent outcomes were collected, along with measures for those variables and the appropriate statistical tests employed (Table 4).

Table 4: Summary of variables collected and statistical tests employed.

	Dependent variables			
		<i>Level</i>	<i>Categorical dichotomous</i>	<i>Continuous</i>
Independent variables	Variable		Retrieval outcome	Time taken for a successful retrieval outcome
	Retrieval kit used	<i>Categorical dichotomous</i>	Chi-square/ Fisher's Exact, binary logistic regression	Mann-Whitney U
	Implant system	<i>Categorical dichotomous</i>	Chi-square/ Fisher's Exact, binary logistic regression	Mann-Whitney U
	Operator experience	<i>Categorical dichotomous</i>	Chi-square/ Fisher's Exact, binary logistic regression	Mann-Whitney U
	Fracture morphology	<i>Categorical nominal</i>	Chi-square, binary logistic regression	Kruskal-Wallis
	Implant location	<i>Categorical nominal</i>	Chi-square, binary logistic regression	Kruskal-Wallis
	Screw fracture torque	<i>Continuous</i>	Binary logistic regression	Spearman's rank-order

Descriptive statistics were calculated to report success rates for overall screw fragment retrieval and between the different categorical variables. The efficacy of the screw fragment retrieval kits, the effects of the different dental implant systems, the implant position, the screw fracture morphology and the operator experience were analysed by chi-square tests (≥ 5 counts) or Fisher's Exact tests (≤ 5 counts) where feasible. The level of significance was set at 5% ($p < 0.05$).

Relationships between the dependant variable primary outcome and one or more independent variables were analysed using a binary logistic regression analysis model. The level of significance was set at 5% ($p < 0.05$).

Retrieval times were observed overall and for each independent variable. Times were summarised as mean, standard deviation, median and interquartile range.

Mann-Whitney U tests were applied to test for significances between non-parametrically distributed times recorded for the successful retrieval of screw fragments by the retrieval kit used, the operator's experience and the implant system being used. The level of significance was set at 5% ($p < 0.05$).

To investigate the significance of screw fracture morphology and the implant position on non-parametrically distributed times recorded to retrieve a fractured screw fragment, a Kruskal-Wallis association test was applied, followed by paired grouped comparisons using a Bonferroni post-hoc analysis. The level of significance was set at 5% ($p < 0.05$).

The presence of damage to any of the implant specimens was observed and reported.

Screw fracture torque values were observed as mean, standard deviation, median and interquartile range overall, for each fracture morphology type, overall for each implant system and for each fracture morphology type with its respective implant system. A Spearman's rank-order correlation test was used to determine the relationship between torque at which the abutment screw fractured, and the time taken to retrieve the fractured screw fragment. The level of significance was set at 5% ($p < 0.05$).

CHAPTER 4: RESULTS

A total of 64 implants had fractured abutment screws placed (Section 3.2.3) and 57 abutment screw fragments were successfully retrieved from their respective implants, within the time limit of 15 mins (Table 5), with no damage to the internal screw threads of the implants being detected (Section 3.4), thereby representing a success rate of 89.1% (Section 3.3.1).

The use of the commercially available screw retrieval kit resulted in the successful retrieval of 28 fractured abutment screws from a total of 32 (Table 5), thereby representing a success rate of 87.5%. The use of the homemade screw retrieval kit resulted in the successful retrieval of 29 fractured abutment screws from a total of 32 (Table 5), thereby representing a success rate of 90.6%. A Fisher's Exact test for the comparison of counts of the categorical variable of successful retrieval by retrieval kit used did not demonstrate a statistically significant difference ($p = 1.000$).

Twenty-nine fractured abutment screws, of an allocated total of 32 were successfully retrieved from the Straumann® Standard Plus Tissue Level implant system (Table 5), representing a success rate of 90.6%, and 28 fractured abutment screws, from an allocated total of 32 were successfully retrieved from the Nobel Biocare® Brånemark Mark III TiUnite system (Table 5), representing a success rate of 87.5%. A Fisher's Exact test for the comparison of counts of the categorical variable successful retrieval by implant system did not find a statistically significant difference ($p = 1.000$).

Table 5: Raw data collected. SM = Straumann system; NBC = Nobelbiocare system; CAK = commercially available retrieval kit; HK = homemade retrieval kit.

Sample	Was the screw retrieved?	Time taken (min:sec)	Was there damage present to the implant's internal threads?	Implant system	Torque (Ncm) at which screw fractured	Fracture morphology (Type)	Operator experience	Retrieval kit used	Position
2A	Yes	03:57	No	SM	18	1	Inexperienced	CAK	Upper anterior
2P	Yes	03:42	No	SM	40	3	Inexperienced	CAK	Upper posterior
4A	Yes	02:38	No	NBC	35	1	Inexperienced	CAK	Upper anterior
4P	Yes	03:15	No	NBC	28	1	Inexperienced	CAK	Upper posterior
6A	Yes	03:05	No	SM	30	4	Inexperienced	HK	Upper anterior
6P	No			SM	35	1	Inexperienced	HK	Upper posterior
8A	Yes	07:24	No	NBC	32	1	Inexperienced	HK	Upper anterior
8P	Yes	11:33	No	NBC	35	3	Inexperienced	HK	Upper posterior
10A	No			SM	28	4	Experienced	CAK	Upper anterior
10P	Yes	03:57	No	SM	18	1	Experienced	CAK	Upper posterior
12A	Yes	00:54	No	NBC	43	3	Experienced	CAK	Upper anterior
12P	Yes	07:03	No	NBC	20	1	Experienced	CAK	Upper posterior
14A	Yes	04:49	No	SM	40	4	Experienced	HK	Upper anterior
14P	No			SM	35	2	Experienced	HK	Upper posterior
16A	Yes	00:58	No	NBC	22	4	Experienced	HK	Upper anterior
16P	Yes	01:56	No	NBC	25	4	Experienced	HK	Upper posterior
18A	Yes	14:45	No	SM	35	1	Experienced	HK	Upper anterior
18P	Yes	00:39	No	SM	16	2	Experienced	HK	Upper posterior
20A	No			NBC	33	4	Inexperienced	CAK	Upper anterior
20P	Yes	02:38	No	NBC	25	3	Inexperienced	CAK	Upper posterior
22A	Yes	00:37	No	SM	35	4	Experienced	CAK	Upper anterior
22P	Yes	01:56	No	SM	36	2	Experienced	CAK	Upper posterior
24A	Yes	01:10	No	NBC	36	4	Inexperienced	HK	Upper anterior
24P	Yes	11:00	No	NBC	38	4	Inexperienced	HK	Upper posterior
26A	Yes	01:50	No	SM	18	2	Inexperienced	HK	Upper anterior
26P	Yes	00:34	No	SM	25	3	Inexperienced	HK	Upper posterior
28A	Yes	04:06	No	NBC	41	2	Experienced	HK	Upper anterior
28P	Yes	07:30	No	NBC	40	3	Experienced	HK	Upper posterior
30A	Yes	03:16	No	SM	35	2	Inexperienced	CAK	Upper anterior
30P	Yes	01:14	No	SM	15	3	Inexperienced	CAK	Upper posterior
32A	No			NBC	42	2	Experienced	CAK	Upper anterior
32P	Yes	09:53	No	NBC	35	3	Experienced	CAK	Upper posterior
34A	Yes	00:43	No	SM	14	3	Inexperienced	HK	Lower anterior

Table 5 (continued): Raw data collected. SM = Straumann system; NBC = Nobelbiocare system; CAK = commercially available retrieval kit; HK = homemade retrieval kit.

34P	Yes	00:25	No	SM	22	2	Inexperienced	HK	Lower posterior
36A	Yes	05:02	No	NBC	38	3	Inexperienced	CAK	Lower anterior
36P	Yes	01:07	No	NBC	19	2	Inexperienced	CAK	Lower posterior
38A	Yes	00:53	No	SM	15	2	Inexperienced	CAK	Lower anterior
38P	Yes	02:35	No	SM	18	3	Inexperienced	CAK	Lower posterior
40A	Yes	01:59	No	NBC	19	3	Inexperienced	HK	Lower anterior
40P	Yes	07:45	No	NBC	36	1	Inexperienced	HK	Lower posterior
42A	Yes	01:33	No	SM	39	3	Experienced	CAK	Lower anterior
42P	Yes	01:36	No	SM	18	2	Experienced	CAK	Lower posterior
44A	Yes	00:43	No	NBC	35	2	Experienced	HK	Lower anterior
44P	Yes	02:07	No	NBC	29	2	Experienced	HK	Lower posterior
46A	Yes	00:53	No	SM	35	2	Experienced	HK	Lower anterior
46P	Yes	01:38	No	SM	17	4	Experienced	HK	Lower posterior
48A	Yes	03:11	No	NBC	23	3	Experienced	CAK	Lower anterior
48P	Yes	02:27	No	NBC	12	4	Experienced	CAK	Lower posterior
50A	Yes	00:58	No	SM	33	2	Experienced	HK	Lower anterior
50P	Yes	00:16	No	SM	28	3	Experienced	HK	Lower posterior
52A	Yes	01:52	No	NBC	26	3	Inexperienced	HK	Lower anterior
52P	No			NBC	28	3	Inexperienced	HK	Lower posterior
54A	Yes	01:21	No	SM	15	3	Experienced	CAK	Lower anterior
54P	Yes	02:59	No	SM	10	4	Experienced	CAK	Lower posterior
56A	Yes	10:00	No	NBC	33	4	Inexperienced	CAK	Lower anterior
56P	No			NBC	19	1	Inexperienced	CAK	Lower posterior
58A	Yes	00:14	No	SM	35	2	Inexperienced	CAK	Lower anterior
58P	Yes	00:24	No	SM	38	3	Inexperienced	CAK	Lower posterior
60A	Yes	03:46	No	NBC	26	2	Experienced	CAK	Lower anterior
60P	Yes	02:52	No	NBC	22	2	Experienced	CAK	Lower posterior
62A	Yes	00:50	No	SM	15	2	Inexperienced	HK	Lower anterior
62P	Yes	00:14	No	SM	12	4	Inexperienced	HK	Lower posterior
64A	Yes	03:57	No	NBC	25	2	Experienced	HK	Lower anterior
64P	Yes	01:55	No	NBC	20	1	Experienced	HK	Lower posterior

The inexperienced operators successfully removed 28 fractured abutment screws of an allocated total of 32 (Table 5), which represented a success rate of 87.5%. The experienced operators removed 29 fractured abutment screws of an allocated total of 32 (Table 5), which represented a success rate of 90.6%. A Fisher's Exact test for the comparison of counts of the categorical variable successful retrieval by operator experience did not find a statistically significant difference ($p = 1.000$).

A total of eleven fractured abutment screw fragments were classified as having a Type 1 fracture morphology (Section 3.2.3), and 9 of these screw fragments were successfully retrieved, thereby representing a success rate of 81.8% (Table 4). Twenty fractured abutment screw fragments were classified as having a Type 2 fracture morphology (Section 3.2.3), and 18 of these screw fragments were successfully retrieved, thereby representing a success rate of 90% (Table 5). Nineteen fractured abutment screw fragments were classified as having a Type 3 fracture morphology (Section 3.2.3), and 18 of these screw fragments were successfully retrieved, thereby representing a success rate of 94.7% (Table 5). Fourteen fractured abutment screw fragments were classified as having a Type 4 fracture morphology (Section 3.2.3) and 12 of these screw fragments were successfully retrieved, thereby representing a success rate of 85.7% (Table 5). A comparison of counts of the categorical variable successful retrieval by screw fracture morphology could not be performed due to the low number of counts for an unsuccessful retrieval outcome.

A total of sixteen implants with fractured abutment screws were placed in each sextant (Section 3.2.4). Thirteen screw fragments were successfully retrieved

from the maxillary anterior sextant, representing a success rate of 81.25% (Table 4). Sixteen screw fragments were successfully retrieved from the maxillary posterior sextant, representing a success rate of 100% (Table 5). Sixteen screw fragments were successfully retrieved from the mandibular anterior sextant, representing a success rate of 100% (Table 5). Fourteen screw fragments were successfully retrieved from the mandibular posterior sextant, representing a success rate of 87.5% (Table 5). A comparison of counts of the categorical variable successful retrieval by implant position could not be performed due to the low number of counts for an unsuccessful retrieval outcome.

A binary logistic regression was calculated to predict the retrieval outcome based on the retrieval kit, the implant system, the experience of the operator, the screw fracture torque, the screw fracture morphology and the implant location. No significant regression equation was found.

The mean, median, standard deviation and interquartile range for the successful retrieval times for each categorical independent variable was collected (Table 6). A non-normal distribution for the overall successful retrieval times was observed (Figure 58).

The mean time required to successfully retrieve the fractured screw fragments was 3 mins 12 secs (SD: 3 mins 13 secs) (Table 6).

Table 6: Summary of the mean, standard deviation, median and interquartile range for the successful retrieval times for each categorical independent variable. SD = standard deviation, IQR = interquartile range, CAK = commercially available retrieval kit; HK = homemade retrieval kit; SM = Straumann system; NBC = Nobelbiocare system; IE = inexperienced; E = experienced.

	Mean (SD)	Median (IQR)
Overall	3 mins 12 secs (3 mins 13 secs)	1 min 59 secs (3 mins 1 sec)
Retrieval kit		
CAK	3 mins 2 secs (2 mins 28 secs)	2 mins 38 secs (2 mins 29 secs)
HK	3 mins 22 secs (3 mins 50 secs)	1 min 52 sec (3 mins 41 secs)
Implant system		
SM	2 mins 8 secs (2 mins 45 secs)	1 min 21 secs (2 mins 24 secs)
NBC	4 mins 19 secs (3 mins 19 secs)	3 mins 2 secs (2 mins 34 secs)
Operator experience		
IE	3 mins 16 secs (3 mins 18 secs)	2 mins 17 secs (3 mins 3 secs)
E	3 mins 9 secs (3 mins 11 secs)	1 min 56 secs (2 mins 59 secs)
Fracture morphology		
Type 1	5 mins 51 secs (3 mins 59 secs)	3 mins 57 secs (4 mins 38 secs)
Type 2	1 min 47 secs (1 min 17 secs)	1 min 22 secs (1 min 30 secs)
Type 3	3 mins 10 secs (3 mins 18 secs)	1 min 56 secs (3 mins 11 secs)
Type 4	3 mins 24 secs (3 mins 33 secs)	2 mins 12 secs (3 mins 22 secs)
Implant location		
Anterior maxilla	3 mins 48 secs (3 mins 48 secs)	3 mins 5 secs (3 mins 24 secs)
Posterior maxilla	4 mins 46 secs (3 mins 53 secs)	3 mins 29 secs (6 mins 20 secs)
Anterior mandible	2 mins 22 secs (2 mins 28 secs)	1 min 27 secs (2 mins 47 secs)
Posterior mandible	2 mins 1 sec (1 min 55 secs)	1 min 47 secs (2 mins 15 secs)

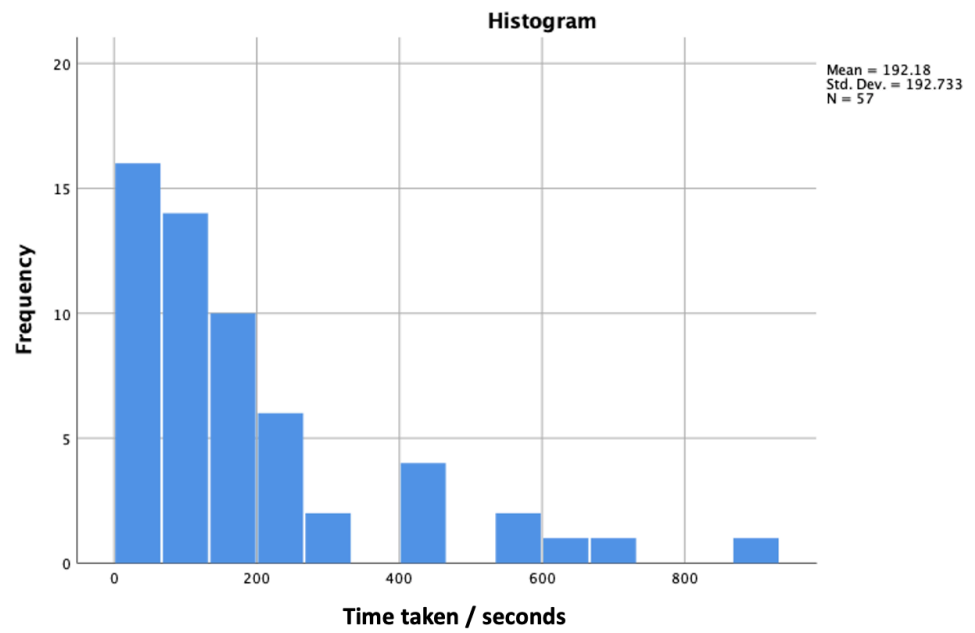


Figure 58: Histogram showing the skewed, non-normal distribution of overall successful retrieval times.

The mean time required to successfully retrieve fractured screw fragments using the commercially available universal screw retrieval kit was 3 mins 2 secs (SD: 2 mins 28 secs) and 3 mins 22 secs (SD: 3 mins 50 secs) for the homemade screw retrieval kit. A Mann-Whitney U test was applied to test for associations between the non-parametrically distributed times recorded for successful retrievals of screw fragments by the type of retrieval kit used. The test showed no significant differences in the retrieval times for the retrieval kit used ($U = 359.500$, $p = 0.458$) (Figure 59).

The mean retrieval time required for the fractured screw fragments from the Straumann® Standard Plus implant system was 2 mins 8 secs (SD: 2 mins 45 secs) and for the Nobel Biocare® Brånemark Mark III TiUnite system was 4 mins 19 secs (SD: 3 mins 19 secs). A Mann-Whitney U test was applied to test for associations between the non-parametrically distributed times recorded for successful retrievals of screw fragments by the type of implant system. The test showed that the retrieval time for the Nobel Biocare® Brånemark Mark III TiUnite system was significantly longer than for the Straumann® Standard Plus implant system ($U = 615.500$, $p = 0.001$) (Figure 60).

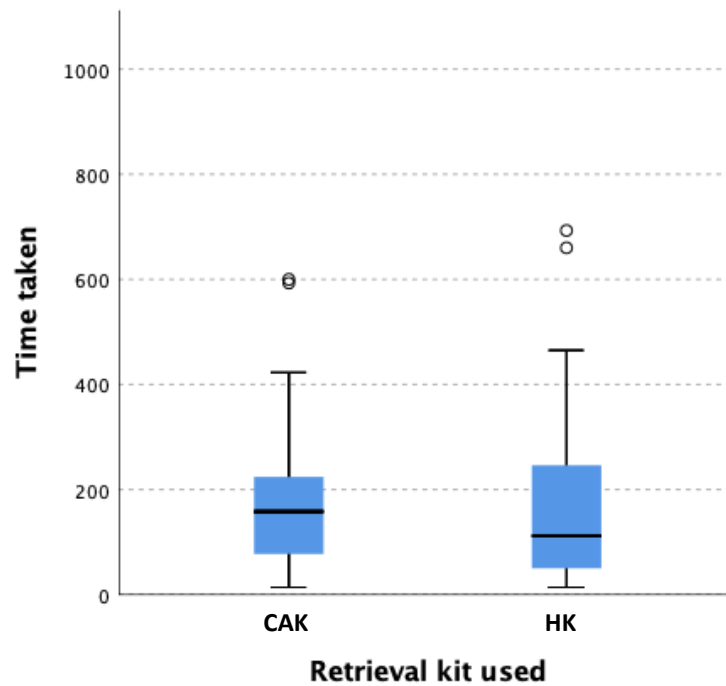


Figure 59: Box plot showing the retrieval time (in seconds) for each retrieval kit used. CAK = commercially available universal screw retrieval kit; HK = homemade screw retrieval kit.

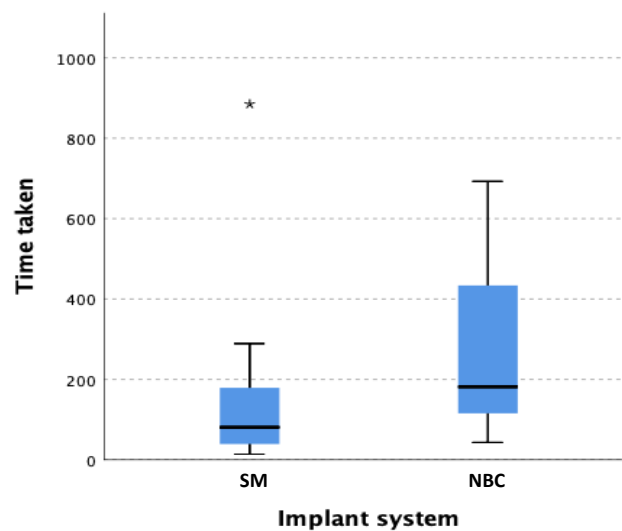


Figure 60: Box plot showing the retrieval time (in seconds) for each implant system investigated. SM = Straumann system, NBC = Nobel Biocare system.

For inexperienced operators, the mean retrieval time to retrieve fractured screws fragments was 3 mins 16 secs (SD: 3 mins 18 secs) and 3 mins 9 secs (SD: 3 mins 11 secs) for experienced operators. A Mann-Whitney U test was applied to test for associations between the non-parametrically distributed times recorded for successful retrieval of screw fragments by operator experience, and no significant difference was observed ($U = 420.000, p = 0.823$) (Figure 61).

The retrieval times for successfully retrieved fractured screw fragments with Type 1, 2, 3 and 4 fracture morphology were 5 mins 51 secs $\pm$ (SD: 3 mins 59 secs), 1 min 47 secs (SD: 1 min 17 secs), 3min 10 secs (SD: 3 mins 18 secs), 3min 24 secs (SD: 3 mins 33 secs), respectively. A Kruskal-Wallis association test was applied to test for associations between the non-parametrically distributed times recorded for successful retrievals of screw fragments by fracture morphology types and showed that significant differences in retrieval time were found between the different fracture morphology types. A Bonferroni post-hoc analysis showed that fractured abutment screw fragments with a Type 1 fracture morphology took significantly longer to retrieve than those with a Type 2 fracture morphology ($p = 0.002$) (Figure 62).

The mean retrieval time for successfully retrieved fractured screw fragments in the maxillary anterior, maxillary posterior, mandibular anterior and mandibular posterior locations was 3 mins 48 secs (SD: 3 mins 48 secs), 4 mins 46 secs (SD: 3 mins 53 secs), 2 mins 22 secs (SD: 2 mins 28 secs) and 2 mins 1 sec (SD: 1 min 55 secs), respectively. A Kruskal-Wallis association test was applied to test for associations between the non-parametrically distributed times recorded for successful retrievals of screw fragments by the four different implant locations,

and no significant differences in retrieval times were found between the implant positions ($p = 0.078$) (Figure 63).

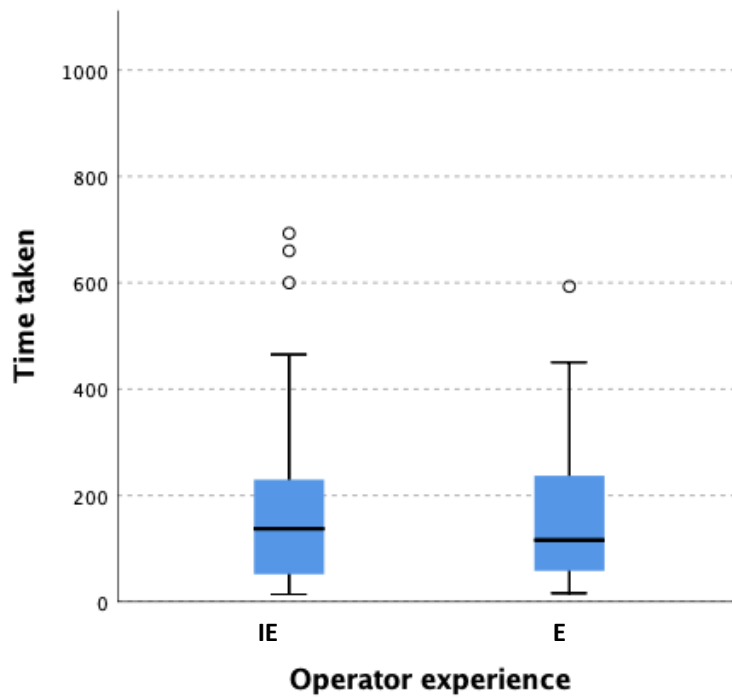


Figure 61: Box plot showing the retrieval time (in seconds) for operator type. SM = Straumann system, NBC = Nobel Biocare system. IE = inexperienced, E = experienced.

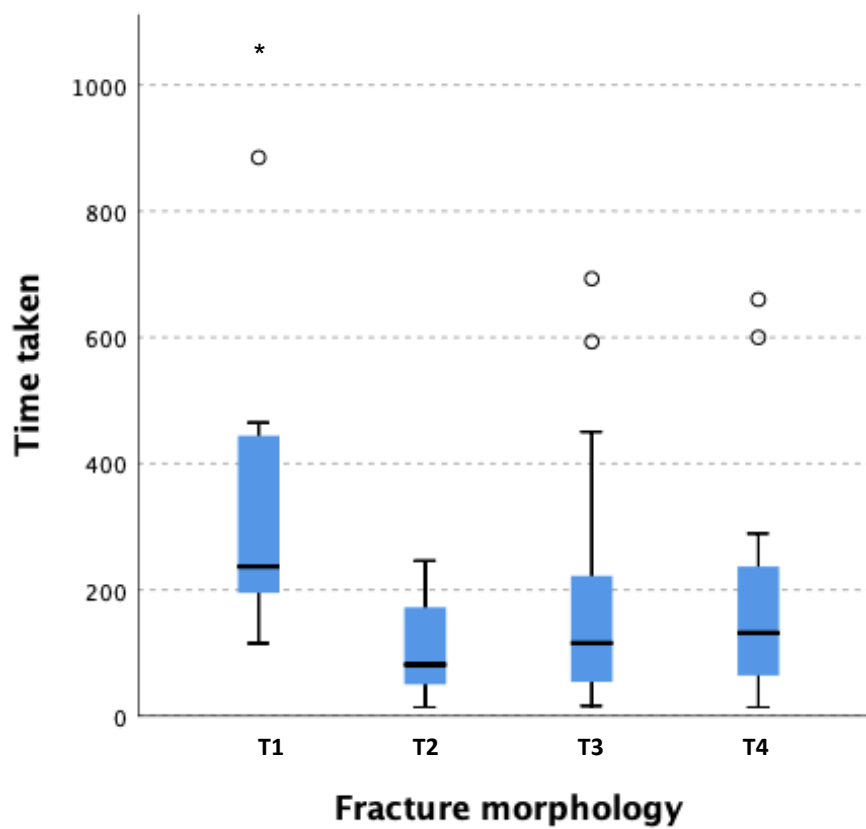


Figure 62: Box plot showing the retrieval time (in seconds) for each fracture morphology type of the fractured abutment screw being retrieved. T1 = Type 1, T2 = Type 2, T3 = Type 3, T4 = Type 4.

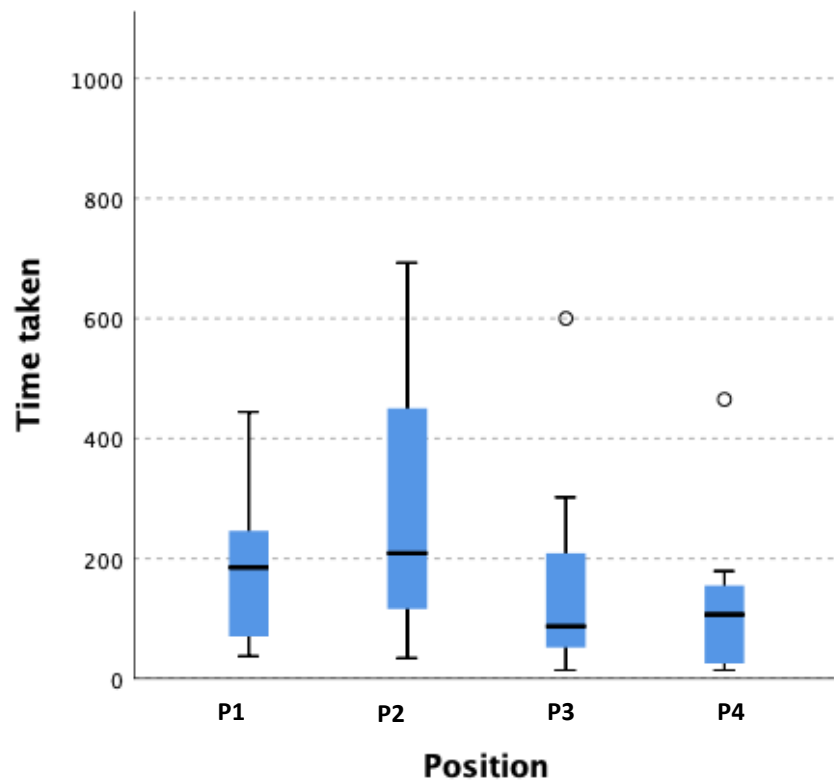


Figure 63: Box plot showing the retrieval time (in seconds) for each implant location. P1 = maxillary anterior, P2 = maxillary posterior, P3 = mandibular anterior and P4 = mandibular posterior.

An unsuccessful attempt to retrieve a fractured screw fragment occurred upon failure to remove the screw fragment within 15 mins or if the attempt to retrieve the screw fragment resulted in damage to the internal threads of the implant. A total of seven fractured screw fragments were not retrieved successfully within 15 mins. However, these fragments were later retrieved after the 15 minute mark had passed and damage to the internal threads of the implants did not occur.

Screw fracture torque values were collected as mean, standard deviation, median and interquartile range overall, for each fracture morphology type, overall for each implant system and for each fracture morphology type with its respective implant system. (Table 7). A non-normal distribution for the overall screw fracture torque values was observed (Figure 64).

Table 7: Summary of the mean, standard deviation, median and interquartile range for screw fracture torque values overall, by implant system and fracture morphology type. SD = standard deviation, IQR = interquartile range; SM = Straumann system; NBC = Nobelbiocare system; FM = fracture morphology.

	Mean (SD) / Ncm	Median (IQR) / Ncm
Overall	27.55 (9.15)	28 (16)
Type 1 FM	26.91 (7.89)	28 (16)
Type 2 FM	27.60 (27.5)	27.50 (17)
Type 3 FM	28.63 (9.68)	28 (19)
Type 4 FM	26.50 (10.31)	29 (20)
Implant system		
Overall SM	25.72 (9.90)	26.50 (19)
SM Type 1 FM	26.50 (9.81)	26.50 (17)
SM Type 2 FM	26.08 (9.33)	27.50 (19)
SM Type 3 FM	25.78 (10.98)	25 (24)
SM Type 4 FM	25.57 (11.66)	28.0 (23)
Overall NBC	29.38 (8.08)	28.5 (14)
NBC Type 1 FM	27.14 (7.45)	28 (15)
NBC Type 2 FM	29.88 (8.59)	27.5 (17)
NBC Type 3 FM	31.20 (8.05)	31.50 (24)
NBC Type 4 FM	28.42 (9.25)	33 (14)

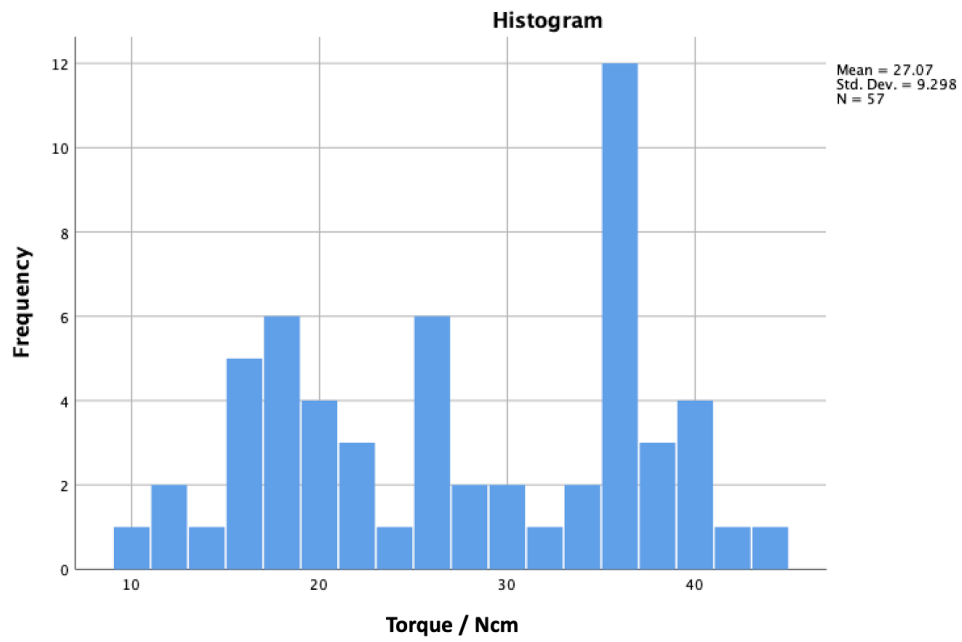


Figure 64: Histogram showing the non-normal distribution of screw fracture torque values.

Due to the monotonic relationship between the continuous dependent variable of successful retrieval time and the continuous independent variable of screw fracture torque, a Spearman's rank-order correlation test was applied to determine the relationship between the torque at which the abutment screw fractured, and the time taken to retrieve the fractured screw fragment. The test showed that there was a weak positive correlation between the torque at which the abutment screw fractured, and the time taken to retrieve the fractured screw fragment ($r_s = 0.300, p = 0.023$).

CHAPTER 5: DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

This present study compared the efficacy of a commercially available universal abutment screw retrieval kit (Section 3.1.2) with a homemade abutment screw retrieval kit (Section 3.1.4) in retrieving 64 fractured abutment screw fragments from 64 dental implants under in-vitro testing conditions. The effect of dental implant system type (Section 3.1.1), operator experience (Section 3.2.5), screw fracture morphology (Section 3.2.3), torque value at which the screw fractured (Section 3.2.3) and location of the implant within the mouth (Section 3.2.5) on the ability to successfully retrieve fractured abutment screw fragments from dental implants was also analysed. A successful attempt to retrieve a fractured screw fragment was defined as the complete removal of the screw fragment within 15 minutes with no damage to the internal threads of the implant. An unsuccessful attempt to retrieve a fractured screw fragment occurred upon failure to remove the screw fragment within 15 mins or if the attempt to retrieve the screw fragment resulted in iatrogenic damage to the internal threads of the implant.

5.1.1 Sample preparation

The cutting of the abutment screws (Section 3.2.3) occurred at the second coronal thread to allow for the depth of the fractured screw fragments to become standardised after intentional fracturing. In a previous study, the level at which the fractured screw was located within the implant was shown to have an impact on the successful retrieval, whereby screw fragments situated in a more coronal position within the implant were more readily retrievable (117). The design of

the Straumann® synOcta® Basal Screw RN (Figure 22) and the Nobel Biocare® Brånemark Titanium Abutment screw (Figure 23) both included a polished screw-shank and a threaded apical portion consisting of six threads and seven threads, respectively. However, morphological design differences between the respective dental implants resulted in the Straumann® synOcta® Basal Screw RN screw fragments being situated deeper within the dental implant specimens. Due to the low number of screw fragments that were not successfully retrieved, an analysis of screw fragment depth within the dental implant specimen and successful retrieval outcome was not possible.

Embedding the dental implants containing fractured dental implant abutment screws within the stone casts using acrylic resin was required because direct placement of the implants into the cast prior to fracturing the abutment screws would have resulted in the fracture of the cast. The abutment screws in the present study were fractured in a continuous torque to failure manner which resulted in predictable fracture at the level that the screws were cut. Augustín-Panadero et al. (2017 & 2020) fractured the screws using cyclic torque application, which resulted in the screws fracturing at varying fracturing depths within the implants (117, 118).

There is no documented evidence available that analyses the morphological pattern of abutment screw fracture encountered clinically. The present study demonstrated four fracture morphologies in an attempt to represent the unpredictable nature of fracture morphologies encountered clinically.

5.1.2 Testing conditions

For ethical reasons, it is impossible to conduct clinical studies to compare techniques aimed at the management of fractured implant abutment screws. Numerous clinical reports have been published which presented techniques to address specific complications (Section 1.5). However, upon review of these techniques, coupled with the general consensus of published authors in this area, it is evident that the undesirable complication of a fractured abutment screw is managed by tentatively, and no consensus on a standardised management protocol currently exists (10, 11). Both currently available in-vitro studies (117, 118) and one animal study (119) evaluating fractured abutment screw fragment retrieval methods were completed at a laboratory bench-top setting, which do not provide a valid simulation of the clinical environment. Additionally, bench-top studies of this nature allowed for easy access and visualisation of the fractured screw fragments, which is rarely encountered clinically, and which was cited as a challenge to overcome clinically (10, 11, 78). To simulate the clinical conditions and the accessibility within the clinical scenarios where fractured abutment screws are encountered, the present in-vitro study took place in a designated dental chair unit with a modified head rest where a phantom head containing the specimen was attached (Section 3.3.1). The location of the implants was varied to simulate clinical scenarios whereby a fractured abutment screw could occur in any sextant. While retrieval of fractured screw fragments in the mandibular anterior sextant may be amenable to direct visualisation under proper lighting conditions, indirect visualisation, with the additional use of a dental mirror would be required for all other sextants.

5.1.3 Outcomes

The first null hypothesis stated that the commercially available implant abutment screw retrieval kit and the homemade abutment screw retrieval kit were equally effective in retrieving fractured abutment screw fragments from dental implants. The results showed that the success rates and the retrieval times for both retrieval kits were similar. Seven fractured screw fragments were not retrieved successfully because the retrieval time was exceeded. Following retrieval of the fractured screw fragment, no damage to the internal threads of the implants was detected. Consequently, this study failed to reject the first null hypothesis. Damage to the implant's internal threads is a major complication that may not be correctable and in some scenarios necessitated implant removal and replacement with a new implant (101). Misch and Resnik (2017), Leung (2017) and Mizumoto et al. (2018) all stated that the goal of managing a fractured abutment screw is successful retrieval of the fragment with no damage being made to the internal threads of the dental implant in a time efficient, easy and cost-effective manner (10, 11, 28). Since there was no difference between the results for the screw fragment retrieval kits, the homemade abutment screw fragment retrieval kit was more cost-effective because it contained a combination of standard and modified dental instruments already found in the clinical armamentarium (Section 3.1.4). Furthermore, the four operators reported that during testing conditions, the majority of successful screw fragment retrieval involved only the use of the CD18 M18 Claw instrument (Figure 28b) in conjunction with a Connection Guide (Figure 29). The manufacturers of screw retrieval kits stated that the specialised nature and design of the instruments were aimed at reducing the risk of damage to the internal

threads of the implant and maintaining a serviceable prosthesis. On the other hand, the homemade kit provided no means of modifying the screw fragment, if this were to be required. In-vitro studies that assessed methods of retrieving fractured screw fragments demonstrated superior success rates with the commercially available kit when compared with the conventional (homemade) kit (117, 118). One in vitro study showed that damage to the internal threads of the implant was more likely to occur with the use of cylinder (118). The purpose of the guide cylinder was to reduce the risk of damage to the implant threads by preventing contact with the rotary instruments, however, greater internal thread damage was demonstrated with the use of the guide cylinder. In general, the results from both in-vitro studies suggested that the compatibility and ease of use of the commercially available screw fragment retrieval kits were important factors which affected their efficacy, with the authors postulating that the complexity and imprecise fit of the universal guide cylinder with the implant platform resulted in contact between the drill pieces and the threads of the implant (117, 118).

The conventional (homemade kit) retrieval instruments used were limited to an unmodified explorer and an ultrasonic scaler, with no connection guide. The homemade kit used in the current study employed a simple and cost-effective homemade connection guide (Section 3.1.3) which precisely fit the implant systems being investigated and allowed it to be used in conjunction with its various components, including the ultrasonic scaler, which was reported as a commonly used retrieval instrument (103). It was postulated that the effective homemade connection guide prevented damage to the internal threads of the implant.

On the basis of this study's results, the type of dental implant system, operator experience, screw fracture morphology, screw fracture torque and position of the dental implant did not influence the ability to retrieve fractured abutment screw fragments from dental implants, and therefore, failed to reject the second null hypothesis.

There was no difference between the implant types when the success rate of fractured screw fragment retrieval was considered, however, the retrieval time for the screw fragments from the Nobel Biocare® Brånemark Mark III TiUnite system was longer than for the Straumann® Standard Plus implant system. Despite this difference, the retrieval times during testing conditions were within the time limit of 15 mins and the differences were therefore clinically insignificant. It was postulated that the wider internal well of the Straumann® Standard Plus implant permitting easier access and visibility, in addition, to having a wider abutment screw facilitated easier retrieval and a shorter retrieval time than the Nobel Biocare® Brånemark Mark III TiUnite implant.

In the current study, the results indicated that the success rates for screw fragment retrieval and the retrieval times for inexperienced operators were similar to the experienced operators. Similar findings were reported in the study by Augustín-Panadero et al. (2020) where the level of operator experience had no influence on the ability to retrieve screw fragments with any of the retrieval methods used (117). These results suggested that inexperienced operators have the ability to remove fractured abutment screw fragments with either the commercially available kit or with standard dental instruments.

The purpose of generating specimens with varying morphologies of the fractured screw surface was to simulate clinical scenarios whereby screws would fracture unpredictably, and not based on the propagation of a standard flaw introduced into the screw. The resultant fracture morphologies varied according to the pattern of occlusal projections of the uncut cross-sectional portions of the fractured screws (Figure 44). The results indicated that the retrieval time for fractured screw fragments with a type 1 fracture morphology was longer than those with a type 2 fracture morphology. It was postulated that the pattern of occlusal projections of the uncut cross-sectional portions of the fractured screws had an influence on the ability of the retrieval instrument to physically engage the irregularity on the fractured surface and to rotate the screw fragment from the implant. Despite statistically significant differences in the retrieval times of fractured screw fragments based on the fracture morphology of the screw fragment, all of the retrieval times were within the time period of 15 mins, which was considered an acceptable period of clinical chairside time to overcome this clinical complication. An analysis of the influence of fracture morphology type on successful retrieval outcome was not possible to deduce due to the low sample size within this categorical variable.

The results of this study showed that a positive correlation was evident between the torque at which the abutment screw fractured, and the time taken to retrieve the fractured screw fragment with those abutment screws fracturing at higher torque values taking longer to retrieve. Although positive, the correlation between the torque value at which the abutment screws fractured and the retrieval time was weak and therefore no conclusion could be made.

Lastly, no statistically significant differences in retrieval times were found between the different implant positions. Additionally, the influence of the position of the dental implant on successful retrieval outcome was not possible to deduce due to the low sample size within this categorical variable. There is no documented evidence available that analyses the effect of dental implant position on fractured abutment screw retrievability

5.1.4 Limitations of the current study

The results reported in this study must be interpreted giving consideration to the clinical validity of the testing conditions reported. Efforts were made to ensure that the simulation of the clinical presentation of a fractured abutment screw fragment and the clinical operating conditions of retrieving such a fragment were achieved, however, due the absence of teeth, oral mucosa, peri-implant soft tissue and saliva, visibility and access during testing conditions were relatively less challenging.

It was not known whether the methods used in the present study, or in the available in-vitro research, to intentionally fracture the abutment screws accurately represented the clinical mechanism of abutment screw fracture. In addition, it is unknown whether the fracture morphologies of the retrieved specimens in the present study actually represented clinically similar fracture morphologies.

Several potential areas of bias were noted. Firstly, although the intention of the designated sample flowchart (Appendix 2) was to rotate operator type, implant

system, implant location, fracture morphology type and retrieval kit used, in an even manner to equalise any potential effects of improved operator competence as the experiment progressed and to thus avoid chronology bias, the effects of improved operator competence and its implications on the results could not be eliminated. Furthermore, additional bias cannot be ruled out as it was impossible to blind the operators to what retrieval kit was being used and also to what implant system was being investigated. Additionally, following the retrieval of a fractured screw fragment, expectation bias could not be eliminated as the same operator that retrieved the fragment evaluated the conditions of the implant's internal threads. During testing conditions, an independent observer was not present to verify that all operators adhered to the protocol for screw fragment retrieval.

Although a power calculation was completed, the present study yielded poor statistical power for some independent variables and would have benefited from a larger sample size of fractured screw fragments for both dental implant systems, however, this was not feasible due to the high costs of the materials involved.

5.1.5 Future work

Future work related to this study should be aimed at:

1. Improving our understanding of the aetiology and mechanism of fracture of dental implant abutment screws by studying fracture surfaces through fractography and finite element modelling. These avenues may help design a clinically valid laboratory testing method to simulate the clinical presentation of fractured abutment screw fragments.
2. Investigating the conditions which present as risk factors for abutment screw fracture in the clinical environment, e.g., abutment screw material and design, prosthesis material and design, implant body design, implant/abutment connection, and the effects of occlusal loading. Potential risk factors may be identified through analysis of appropriate clinical parameters of patients treated with implant restorations as part of prospective longitudinal multi-centre clinical trials.
3. Investigating in-vitro the effects of abutment screw torque on the integrity of the internal threads of the dental implant.
4. Investigating additional fractured abutment screw retrieval techniques and additional commercially available abutment screw retrieval kits as currently reported in the literature, in addition, their application to a broader range of dental implant systems, and also with retrieving

fractured abutment screws from novel angulated screw channel abutment screw systems.

5. Assessing the effect of access and visibility in retrieving fractured abutment screw fragments.

5.2 CONCLUSIONS

Under the testing conditions described in the current study, the following conclusions were made:

1. Fractured abutment screw fragments may be removed safely and in a reasonably short period of clinical time using the instruments and techniques described.
2. The combination of standard dental instruments and modified standard dental instruments used in the current study are as effective in the retrieval of fractured abutment screw fragments as the commercially available universal abutment screw retrieval kit.
3. Operators that are inexperienced in retrieving fractured abutment screw fragments from dental implants may overcome this clinical complication as easily as experienced operators.

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APPENDICES



NSAI

National Metrology Laboratory

Certificate of Calibration

Issued to Dublin Dental University Hospital
Lincoln Place
Dublin 2

Attention of Advan Moorthy

Certificate Number	190925
Item Calibrated	Torque Meter
Serial Number	503817J
Client ID Number	N/A
Manufacturer	Tohnichi
Model	6BTGN
Range	0-60 cNm
Resolution	1 cNm
Units	cNm
Order Number	Advan Moorthy
Date Received	11 Mar 2019
NML Procedure Number	D4P-NM-04
Calibration Standards	Transducer & Display, ID No.: 0708, Due Date: 21 Jul 2019

Calibrated by

Graham Thomas

Graham Thomas

Approved by

P. Hetherington

Paul Hetherington

Date of Calibration

20 Mar 2019

Date of Issue

22 Mar 2019

Appendix 2: Sample flowchart

A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:	A YES NO Time: P YES NO Time:
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Biomet Right Mandible Advan Code:57 LENGTH: A: P: Prof Kit	ITI Right Mandible Suha Code:58 LENGTH: A: P: Prof Kit	Biomet M Right Mandible Ioannis Code:59 LENGTH: A: P: Prof Kit	Nobel Right Mandible Brendan Code:60 LENGTH: A: P: Prof Kit	Biomet Left Mandible Advan Code:61 LENGTH: A: P: Home Kit	ITI Left Mandible Suha Code:62 LENGTH: A: P: Home Kit	Biomet M Left Mandible Ioannis Code:63 LENGTH: A: P: Home Kit	Nobel Left Mandible Brendan Code:64 LENGTH: A: P: Home Kit
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Biomet Right Maxilla Suha Code:9 LENGTH: A:	ITI Right Maxilla Brendan Code:10 LENGTH: A:	Biomet M Right Maxilla Advan Code:11 LENGTH: A:	Nobel Right Maxilla Ioannis Code:12 LENGTH: A:	Biomet Left Maxilla Suha Code:13 LENGTH: A:	ITI Left Maxilla Brendan Code:14 LENGTH: A:	Biomet M Left Maxilla Advan Code:15 LENGTH: A:	Nobel Left Maxilla Ioannis Code:16 LENGTH: A:

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Biomet Right Mandible Brendan Code:49 LENGTH: A: P: Home Kit	ITI Right Mandible Ioannis Code:50 LENGTH: A: P: Home Kit	Biomet M Right Mandible Suha Code:51 LENGTH: A: P: Home Kit	Nobel Right Mandible Advan Code:52 LENGTH: A: P: Home Kit	Biomet Left Mandible Brendan Code:53 LENGTH: A: P: Prof Kit	ITI Left Mandible Ioannis Code:54 LENGTH: A: P: Prof Kit	Biomet M Left Mandible Suha Code:55 LENGTH: A: P: Prof Kit	Nobel Left Mandible Advan Code:56 LENGTH: A: P: Prof Kit
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Biomet Right Maxilla Brendan Code:17 LENGTH: A: P: Home Kit	ITI Right Maxilla Ioannis Code:18 LENGTH: A: P: Home Kit	Biomet M Right Maxilla Suha Code:19 LENGTH: A: P: Home Kit	Nobel Right Maxilla Advan Code:20 LENGTH: A: P: Prof Kit	Biomet Left Maxilla Brendan Code:21 LENGTH: A: P: Prof Kit	ITI Left Maxilla Ioannis Code:22 LENGTH: A: P: Prof Kit	Biomet M Left Maxilla Suha Code:23 LENGTH: A: P: Prof Kit	Nobel Left Maxilla Advan Code:24 LENGTH: A: P: Home Kit
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Biomet Right Mandible Suha Code:41 LENGTH: A:	ITI Right Mandible Brendan Code:42 LENGTH: A:	Biomet M Right Mandible Advan Code:43 LENGTH: A:	Nobel Right Mandible Ioannis Code:44 LENGTH: A:	Biomet Left Mandible Suha Code:45 LENGTH: A:	ITI Left Mandible Brendan Code:46 LENGTH: A:	Biomet M Left Mandible Advan Code:47 LENGTH: A:	Nobel Left Mandible Ioannis Code:48 LENGTH: A:

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Biomet Right Maxilla Advan Code:25 LENGTH: A: P: Home Kit	ITI Right Maxilla Suha Code:26 LENGTH: A: P: Home Kit	Biomet M Right Maxilla Ioannis Code:27 LENGTH: A: P: Home Kit	Nobel Right Maxilla Brendan Code:28 LENGTH: A: P: Home Kit	Biomet Left Maxilla Advan Code:29 LENGTH: A: P: Prof Kit	ITI Left Maxilla Suha Code:30 LENGTH: A: P: Prof Kit	Biomet M Left Maxilla Ioannis Code:31 LENGTH: A: P: Prof Kit	Nobel Left Maxilla Brendan Code:32 LENGTH: A: P: Prof Kit
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Biomet Right Mandible Ioannis Code:33 LENGTH: A: P: Prof Kit	ITI Right Mandible Advan Code:34 LENGTH: A: P: Home Kit	Biomet M Right Mandible Brendan Code:35 LENGTH: A: P: Home Kit	Nobel Right Mandible Suha Code:36 LENGTH: A: P: Prof Kit	Biomet Left Mandible Ioannis Code:37 LENGTH: A: P: Home Kit	ITI Left Mandible Advan Code:38 LENGTH: A: P: Prof Kit	Biomet M Left Mandible Brendan Code:39 LENGTH: A: P: Prof Kit	Nobel Left Mandible Suha Code:40 LENGTH: A: P: Home Kit