2022 International Workshop on Antenna Technology (iWAT) | 978-1-6654-9449-6/22/$31.00 ©2022 IEEE | DOI: 10.1109/iWAT54881.2022.9811065

# Identifying Microwave Antenna Design Limitations for Radar-based Breast Imaging

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Abstract—Clinical trials using ten different Microwave Breast Imaging systems have been published including both academic and industrial systems. While trials with over 200 participants show promising detection results, substantial technical differences exist between the systems in terms of the antenna designs, antenna array designs and antenna performance specifications. In this work, the current state-of-the-art in operational microwave systems in terms of antennas are reviewed and preliminary limits on dimensions are identified. Gaps in understanding regarding the optimal number, configuration and performance of antennas are highlighted and future work regarding the impact of these design decisions on imaging performance identified.

Index Terms—microwave breast imaging; microwave imaging; propagation

## I. Introduction

In the last five years alone, clinical trials of microwave breast imaging systems from more than seven operational systems have been published with both academic and industrial interest of which many reviews exist, not least [1]–[4]. While many consistent and promising trends are evident in terms of the potential to detect early-stage or otherwise difficult to detect cancers, many technical differences exist between the systems [2].

Specifically, differences exist in terms of the numbers of antennas in the system, the antenna positions and ability or neccessity of antennas to move, how the full microwave scan of the breast is acquired and in the design of the antennas themselves. Few studies have examined the optimal antenna parameters in terms of antenna dimensions, type or performance in terms of required bandwidth, frequency range or adaptability, although preliminary work suggests that antenna layout and orientation can affect performance [5].

Many open-source and shared resources are available for microwave breast imaging research, including:

- numerical breast phantoms [6];
- shared 3-d printed breast phantoms and experimental datasets [7]–[9];
- and open-source imaging toolboxes [1], [9], [10].

However, no open-source antenna designs, shared antenna resources or electromagnetic simulation platforms exist for the acquisition of data.

In this work, basic design parameters for antennas for microwave breast imaging systems are reviewed and identified, specifically, preliminary limitations on the antenna dimensions required to cover a microwabe breast imaging radome. Finally, other uses of similar non-invasive biomedical microwave imaging systems are reviewed.

## II. Existing Implementations

Many antenna types have been used in operational systems, not least:

- monopole antennas in [11];
- cavity-backed slot antennas [12].
- Vivaldi antennas [13], [14];
- planar slot antennas [15];
- horn antennas [16];
- and flexible microstrip antennas [17].

These antennas have been incorporated into flexible wearable arrays, rigid fixed housing, moveable subarrays or moveable antennas. The frequency ranges of use have varied from 0.5 GHz to 9 GHz with bandwidths as small as 2 GHz in [17] to much larger in [13].

Antennas have been designed which operate entirely in air [9], directly in contact with the breast [15], [17], in contact with a solid coupling shell [12], in contact with an immersion

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tank [14], and immersed in a tank of varying fluids [11], [13].

While some work has considered the optimal frequency ranges in terms of penetration [18], investigations of inherent assumptions in [19], comparisons using different patient orientations in [20] and some other analyses not least in [1], [3], no comprehensive guidelines on minimum performance standards of antenna arrays for microwave breast imaging have been established.

## III. Design Goals

Broadly speaking, the antenna array should be able to:

- illuminate the object of interest from multiple aspects;
- sample the scattered field from multiple aspects;
- and couple sufficient energy into the object of interest.

The majority of microwave breast imaging antennas operate either in air, in direct contact with a coupling shell or tank, or immersed in a tank of coupling liquid. The coupling liquids or coupling shells are typically designed to secure the breast, to match the dielectric properties of the skin ($\varepsilon_r \approx 30$), or to provide a consistent operating envirnoment.

To estimate the necessary maximum dimensions to ensure a minimum number of antennas, a simplified model of an acquisition surface is examined consisting of a hemisphere of radius $R$, similar to MARIA [12] and other systems comprehensively reviewed in [2]. Typically in these systems, the antennas $\mathbf{a}_i \in \mathcal{A}$ are arranged in concentric rings of decreasing radius $R_n$ in the coronal plane, meaning the maximum number of antennas can be calculated as:

$$|\mathcal{A}| = \sum_{n}^{N} \left\lfloor \frac{\pi}{\arctan\left({}^{w}\!/_{2R_n}\right)} \right\rfloor \qquad (1)$$

where the number of coronal rings, $N$ can be calculated:

$$N = \left\lfloor \frac{{}^{\pi}\!/_{4}}{\arctan {}^{h}\!/_{2R}} \right\rfloor \qquad (2)$$

and the radius of each ring is:

$$R_n = R \cos n\theta \qquad (3)$$

For a square antenna where $w = h$, the maximum number of antennas for hemispheres between with radii between 6 to 9 cm is shown in Figure 1 with the 60 antennas of the MARIA system shown for reference. As can be seen, even for large arrays of 9 cm in radius, the total antenna assembly including supports and separators must be less than 3 cm × 3 cm to fit greater than 60 antennas in the hemisphere.

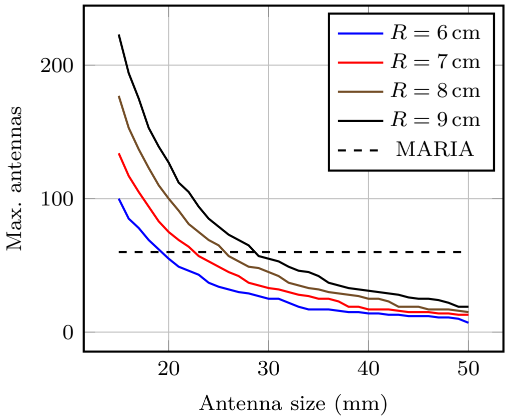

Fig. 1. The maximum number of square antennas which could form a conformal hemispherical antenna array for radomes of four different radii are shown. For reference, the number of antennas in in the MARIA system in [12] are also shown.

For antennas with differing widths and heights, few studies have examined if an optimal antenna arrangement exists or what the minimum number of acceptable antennas is. For example, narrower but tall antennas allow for more antennas in the coronal rings at the expense of fewer rings which may be desirable. In some cases such as in [11], [14], data is collected in successive coronal slices, meaning that the antenna width alone determines the number of antennas in the array.

Further discretisations of the acquisition surface are possible and some studies suggest that non-regular or randomised arrays might improve performance [21]. Enhanced understanding of the effects of antenna positioning on performance may refine the understanding.

Directivity of the antennas also varies, from omnidirectional monopoles in the tomographic system in [11] to more directive antennas in the other radar-based systems. However, few studies have examined the desirable characteristics in terms of directivity. Limits on the directivity based on minimum power levels within the imaging volume are calculated in [22].

## IV. Related Applications

Active microwave systems are also used in other applications, not least:

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- non-invasive systems for monitoring or treatment;
- endobronchial systems for treatment;
- and percutaneous systems for treatment.

Focusing solely on external, non-invasive systems, many cross-overs exist. For example, active microwave hyperthermia systems are in use which couple focused microwave energy into the head and neck to raise the temperature of shallow tumours as part of a treatment regime [23]. Typically the antennas are submersed in a water bolus [24] and often consist of a single ring of antennas for shallow tumour treatment.

Active microwave systems have also been investigated for hydration monitoring [25], [26] using easily accessible limbs and also for bone health monitoring using joints such as the ankle [27]. However, in these applications, three dimensional images or imaging arrays are not required. While microwave breast imaging of the head has been proposed, few similarities exist between these applications due to the hair, desired targets and the presence of the skull.

## V. Conclusion

As microwave breast imaging is used with larger and more diverse populations, it may be necessary to identify performance specifications and key design decisions to ensure adequate and consistent imaging performance. However, substantial gaps in the literature remain regarding many aspects of the antenna array design specifically in the optimal size, arrangement and performance characteristics of the antennas. In this work, preliminary size limitations on the antennas are identified, however, further examinations of how the arrangement and sizes of the antennas might impact on the imaging performance is warranted.

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