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Coaxial Slot Antenna for Microwave Ablation in Breast Tissue: A Simplistic Axisymmetric Finite Element Method Model Employing State-of-the-Art Advanced Multiphysics Simulation Software

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Abstract. Microwave energy holds significant potential for medical applications, especially in treating breast carcinomas. Its effectiveness lies in its ability to selectively target and heat tissues with high water content, such as cancerous cells, while causing minimal heating in lower-water-content tissues like adipose and glandular tissues in the breast. This selective heating is further enhanced by the distinct difference in electrical properties between normal and cancerous tissues, resulting in focused electromagnetic energy deposition and targeted thermal elevation within tumors. The aim of this work is to use the latest version of the commercial software COMSOL Multiphysics, to solve some of our earliest axisymmetric models developed by the research group, with the purpose of verifying whether there are significant changes in the computational modeling results. To achieve this, we employed a detailed axisymmetric finite element method for computer modeling. This theoretical approach was complemented by practical experimental ablation conducted on ex vivo swine adipose-dominated breast tissue. This comprehensive analysis aimed to provide a deeper understanding of the ablation process, enhancing the precision and safety of microwave ablation as a treatment method, regardless of the software's improvements or updates over time.

Keywords: Microwave ablation, High-Water-Content Tissues, Adipose and Glandular Tissues, Breast cancer.

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1. Introduction

Microwave ablation (MWA) leverages localized heating to induce tissue necrosis, showing great promise in targeting high-water-content breast carcinomas. This method is advantageous due to its selective heating of cancerous tissues while minimally affecting adipose and glandular tissues with lower water content [1]. The effectiveness of this heating is primarily influenced by power deposition in the tissue, commonly measured as the Specific Absorption Rate (SAR). It also depends on the dielectric and thermal properties of the tissue undergoing ablation. The lesion size produced by MWA is generally constrained by the available power and duration of treatment [2].

2. Computer Modeling

Building upon our previously published research conducted with COMSOL Multiphysics version 3.5a [3], we developed the same computational model but using the latest version of the advanced Multiphysics software, COMSOL 6.1. Given the coaxial slot antenna's rotational symmetry around its longitudinal axis, an axisymmetric model was employed to streamline computation. The antenna's inner and outer conductors are simulated using perfect electric conductor (PEC) boundary conditions, with axial symmetry along the z-axis, enhancing the model's accuracy. All non-axial boundaries are configured to have low reflection properties. The antenna, operating at 2.45 GHz, is assumed to be immersed in homogeneous breast tissue, ensuring a realistic simulation environment.

3. Antenna Design

The antenna is crafted from a 50Ω UT-085 semirigid coaxial cable with an SMB connector. Its outer conductor is copper, featuring a precisely cut 1-mm-wide ring slot near the short-circuited distal tip to facilitate electromagnetic wave propagation. The inner conductor comprises silver-plated copper wire (SPCW), and the dielectric is made of low-loss polytetrafluoroethylene (PTFE). Additionally, the antenna is wrapped in Teflon tape to prevent adhesion to desiccated tissue post-ablation, as shown in Figure 1 [4].

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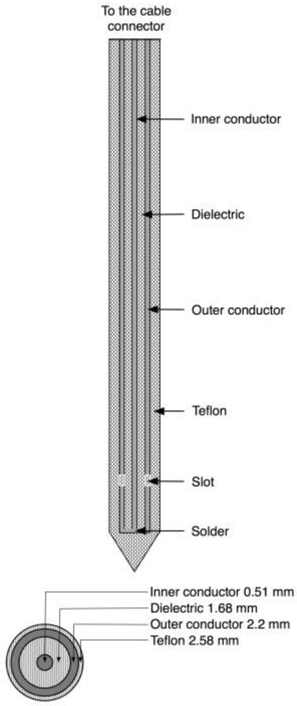

Figure 1. Enhanced Schematic Representation of the Coaxial Slot Antenna, Showcasing Both Cross-Sectional and Axial Views.

4. Experimental Validation

Before ablation procedures, the dielectric properties of adipose-dominated breast tissue were characterized at 2.45 GHz using a precision open-ended coaxial probe and an Agilent E5071B network analyzer. After preparing the breast tissue, a cavity was created for the coaxial slot antenna, which was then inserted into homogeneous adipose-dominated tissue. The setup included an Aethercomm SSPA 1.0-2.5-50 power amplifier and a Rohde & Schwarz SML03 2.45-GHz microwave generator [5].

5. Results

There were no significant variations between the two versions of the software used. The results from the computer modeling indicated a significant difference in dielectric properties and thermal parameters between malignant and normal adipose-dominated tissues, leading to preferential tumor heating during MWA. Experimental ablations were conducted at 10 W for 3 minutes. Microwave Ablation (MWA) has proven to be an effective technique for treating breast carcinomas with high water content, due to its ability to selectively heat these tissues while minimizing the impact on lower-water-content adipose and glandular tissues. This specificity

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represents a significant advancement in the precision of tumor treatment. The effectiveness of MWA largely depends on the dielectric and thermal properties of the tissue being treated. The study underscores the importance of understanding these properties to optimize the application of the treatment and maximize its efficacy. The design of the coaxial slot antenna, particularly in terms of its materials and structure, has played a crucial role in enhancing the treatment. The use of materials such as copper, PTFE, and SPCW in the construction of the antenna has contributed to better electromagnetic wave propagation and increased efficiency in ablation. Computer Modeling and Experimental Validation: The combination of advanced computer modeling and experimental validation has provided a deeper understanding of the ablation process and its impact on tissues. This has allowed for a more targeted and potentially safer approach to treatment.

6. Conclusion

Regardless of both versions of the computational modeling software used, the experimental results, including the measurement of the reflection coefficient, the maximum temperature achieved, and the lesion size, have demonstrated the potential of MWA in treating cancerous tissues. These findings could guide future clinical applications and improvements in ablation technology.

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