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Designing Microwave Ablation Applicators for Breast Cancer: Difficulties Associated with Heterogeneous Tissue

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Abstract. Microwave ablation has been designed as a minimally invasive thermal therapy for treatment of breast-localized tumor. From a systems point of view the overall performance is not to be determined solely by one given parameter but rather the combination and synergistic effects of applicator design, EM coupling, thermal transport processes as well the inhomogeneity of breast tissue. Herein we review MWA systems for the treatment of breast cancer, with a specific focus on applicator design geometry, electromagnetic–thermal modeling techniques and experimental validation procedures and investigate how tissue heterogeneity affects power deposition and temperature profile. The energy delivery, temperature control and treatment prediction limitations associated with the shift from idealized numerical models to realistic ex vivo and in-vivo studies are addressed. Finally, several open engineering questions and future directions are considered in the context of design optimization and treatment planning under variability in tissue.

Keywords: Microwave ablation, breast cancer, heterogeneous tissue.

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1. Introduction

The incentive of breast cancer to create new therapeutic methods with the reducing invasiveness while maintaining precision has not yet abandoned [1]. The heating method in thermal-based modalities Microwave ablation, among various heat-based modalities, has recently received interest in being able to provide a rapid volumetric heating using applicators which are small-sized and flexible in nature [2].

At the system layer, treatments performed by microwave ablation systems cannot be considered energy-dumping instruments [3]. Their entire behavior is due to the interplay between several parameters, such as applicator geometry, electromagnetic coupling, tissue dielectric properties, and thermal diffusion mechanisms [4]. In practice, relatively small fluctuations of any one of these factors can lead to the large changes in the size, configuration and isotropy of the ablated zone which tend to compromise treatment repeatability [5].

Microwave ablation refers to application of electromagnetic energy—at typically microwave frequencies—to biological tissues via either a coaxial or antenna-driven applicator. On interacting with the dielectric properties of tissue, absorption and thermal conversion into heat occur with thermocoagulation and cell necrosis [3].

The process depends on a number of physical parameters such as the operating frequency, input power, impedance matching and the standing wave ratio (SWR) [1]. Optimized energy delivery can be achieved through close consideration of applicator design to minimize reflected power and localize heating around the treatment site [4].

2. Electromagnetic and Thermal Modeling Approaches

When combined with thermal models, electromagnetic simulations can be used to predict the temperature distribution and ablation zone evolution in time [5]. Such imposed couplings are generally associated in these models with frequency-dependent dielectric properties and temperature dependent thermal parameters to enhance the reality [6].

Recent studies have emphasized the need to validate computational models with phantom-based and experimental studies, especially in breast applications [11–13]. This kind of validation serves in diminishing contradictions between simulated predictions and experimental measurements, which is particularly impacting in the case of heterogeneous tissues [7].

3. Breast Microwave Ablation and Tissue Inhomogeneity

The dielectric and thermal properties of breast tissue, which is a mixture of adipose, glandular, and tumoral tissues vary spatially to a large extent. This diversity directly affects the microwave penetration and energy absorption [6].

Several studies have in fact proved that the ignorance of the tissue heterogeneity may lead to a bias in estimating ablation zone size and geometry. Regions with higher water contents, for instance, typically absorb microwave energy more without necessarily resulting in evenly heating patterns and regular ablation boundaries.

In close practice, the heterogeneity in tissue still is among the most challenging issues for design of microwave ablation systems and provides a strong motivation to transversally develop adaptive applicators, as well as personalized treatment planning methodology.

4. Experimental and Preclinical Validation Strategies

Experimental verification of microwave ablation systems usually includes tissue-mimicking phantoms, excised tissues and a more controlled laboratory setting [8]. Phantoms have been developed to simulate the dielectric and thermal properties of biological tissues, so that repeated and reproducible testing conditions can be achieved [9].

Recently, there have been a number of reports that describe combined numerical, phantom-based and ex vivo validation of microwave ablation applicators for breast applications demonstrating feasibility of the technique and the difficulty associated in real tissue conditions [10]. These results shed vital light on the constraint we are facing between numerical simulations and actual experiments [11].

Recent pilot ex vivo studies using mastectomy tissue have further demonstrated the technical feasibility of MA prior to in vivo investigation and also identified practical end-user system-level limitations due to power delivery and thermal management [12]. It is therefore an ongoing and critical effort to bridge the gap between simulation prediction and experimental observation [13].

However, several of the system level challenges in microwave ablation for breast cancer applications are still unresolved even as technology continues to improve [14]. Of the longstanding challenges, poor control on ablation boundaries is especially significant in the presence of tissue heterogeneities that cause distortions in electromagnetic fields patterns and temperature gradients.

Under practical test conditions the mismatch and reflected power was found to be larger than it would have been calculated from numerical simulation. Although simulations often assume homogeneous tissue models, phantom and ex vivo investigations show strong local differences, which have a direct influence on power deposition and heating efficiency [15]. This discrepancy emphasizes the distance that exists between idealized modeling conditions and reality.

A further important drawback is the impossibility of real-time monitoring. Multiple methods of temperature monitoring have been proposed, but none support the required spatial resolution and robustness to provide fast ablation dynamics tracking in heterogeneous tissues [10]. Consequently, treatment predictability often depends on esthetically less satisfactory safety distances rather than accurate control of the feedback loop.

5. Future Perspectives and Research Directions

Future research in this area will concentrate on optimization of applicator geometries, joint modelling with advanced simulation tools, and personalized ablative treatment plans based upon patient-specific tissue properties. Advances in biomedical and computational modeling should help realize more predictable effective microwave ablation systems supported by experimentally validated FEM-based approaches [11–13].

6. Conclusions

This analysis provided an overview "on technologies" of microwave ablation for breast cancer based on a system approach and bioelectronic point of view, focusing specifically in the applicator design, electromagnetic–thermal modeling and tissue heterogeneity. Instead of presenting microwave ablation as a mature technique, the we have demonstrated some outstanding limitations with impact on its dependability and predictivity.

Results of numerical, phantom and ex vivo studies suggest that tissue heterogeneity is still a leading factor which could not yet be sufficiently accounted for by simplified models only. Hence, the further development of microwave ablation technology will be based on realistic tissue characterization, adaptive designed strategies and experimentally validated modeling tools.

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