Fundamental Mechanisms of Thermoacoustic Imaging During Pulsed Microwave Ablation

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Microwave ablation (MWA) is a minimally-invasive treatment performed by introducing an interstitial antenna into the diseased tissue site and heating it by means of electromagnetic absorption. The goal is to raise the temperature of the target tissue to cytotoxic levels to induce coagulation necrosis. Real-time monitoring of the evolution of the ablation zone is essential for minimizing the risk of over- or under-treatment, particularly when MWA is used for treating a tumor. Accurate, safe, and low-cost real-time monitoring of the progress of ablation is currently an unmet need, and thermoacoustic imaging has the potential to meet these requirements. Thermoacoustic imaging utilizes the thermoelastic effect, in which the absorption of pulsed electromagnetic waves yields ultrasound waves that can be detected by traditional transducers at the tissue surface.

Recently, we investigated the feasibility of integrated pulsed microwave ablation and thermoacoustic signal generation for the purpose of ablation monitoring (J. Sawicki, et al., USNC-URSI National Radio Science Meeting, Boulder, Colorado, 2018). Our proposed system takes advantage of an MWA antenna's location in the center of the imaging region and uses it to provide pulses that both deliver ablative energy to tissue and launch thermoacoustic signals. The use of the MWA antenna itself as a pulse emitter ensures excellent energy transfer between the pulse microwave source and imaging region of interest. In our previous work, we showed that ablation zones generated in an egg white tissue phantom using high-power microwave pulses were similar in size and proportion to those generated by a continuous-wave source at the same frequency and with equal time-averaged power output. The narrow coaxial antenna components were shown to withstand the high electric fields to which they were subjected without undergoing damaging dielectric breakdown. Further, we analyzed thermoacoustic signal characteristics in a simulation environment in which the dielectric properties of the tissue surrounding the antenna changed over the course of ablation. We observed significant changes in electromagnetic absorption distributions, which led to corresponding changes in the thermoacoustic signals generated by that absorption.

In this work, we perform a thorough multi-physics analysis of thermoacoustic signal characteristics for pulsed microwave ablation. Water evacuation and tissue coagulation at ablative temperatures lead to significant changes in dielectric, thermal, and acoustic properties of tissue, all of which may impact the thermoacoustic signals that ultimately reach the tissue surface. Our presentation highlights the results of a literature survey of key tissue properties as well as temperature- and ablation state-dependent models. With these property models, we conduct numerical simulations with multiphysics-enabled software (COMSOL Multiphysics) to study the individual and combined impact of the changing tissue properties. We compare these findings with those from heating experiments on tissue phantoms, carried out using a pulsed magnetron generator and ultrasound detection equipment.