Uncertainty Quantification of a Microwave Ablation Simulation with Spatial and Transient Responses
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Introduction: This study presents a statistical approach for prediction and uncertainty quantification of a hepatic tumor Microwave Ablation treatment simulation with a spatial and transient response. The study will examine the variation in the volume of necrotic tissue in a human liver tissue model during Microwave Ablation/Coagulation therapy due to tissue property variation as a function of wattage and treatment time. The analysis will also assess the effects of tissue variation on the size, shape, and percentage of necrotic tissue as a spatially distributed field rather than as a single-value parameter like cross-sectional area or volume. Data with spatial and functional correlations can often be modeled with fewer training data points using machine learning techniques. This approach also has the advantage of representing the entire spatial-transient field, which allows analysis on a greater range of results such as the percentage of necrotic tissue around an ablation region or areas in which tissue was unaffected. The surrogate models developed in this study are used to determine the most sensitive model parameters and perform uncertainty studies to assess the variation in volume and shape of necrotic tissues due to variations in human tissue properties and treatment procedures.

Materials and Methods: This study utilizes COMSOL Multiphysics 5.3a to model and simulate a region of hepatic cancer tissue. A commonly used coaxial microwave ablation antenna, with the corresponding slotted catheter, is positioned in the center of the cylindrical tissue section. The antenna operates at 2.45 GHz, a frequency widely used in microwave ablation therapy. The DOE contains both biological and treatment factors to generate proper training data for the surrogate model. The biological factors include temperature, conductivity, permittivity and specific heat of cancerous hepatic tissue, each varying based on what is suggested in the literature [1-3]. The DOE was generated using a sliced design, allowing iterative implementation of the simulation to validate and converge the surrogate model. The DOE and surrogate model generation, as well as the sensitivity and uncertainty studies, were performed using SmartUQ Software Version 5.0.

Results and Discussion: The surrogate models developed in this study accurately mimic the model behavior of the COMSOL simulation. The Continuous Response Emulator, which models summary outputs such as volume of necrotic tissue, percentage of unaffected tissue, etc., converged with a standardized RMSE of less than 0.15 for all output parameters. The Functional Emulator, which models the spatially and transiently distributed field of responses for ablation, converged with a standardized RMSE, averaged across all nodes, of less than 0.1. These surrogate models were then used to produced sensitivity results and uncertain margins due to expected variation in human tissue properties corresponding to a mock set of liver tumor scenarios.

Translational Impact: This study presents a novel methodology for both transient and spatial-transient simulation of tumor ablation treatment using surrogate modeling. This surrogate model will help ensure a microwave ablation device is able to produce predictable ablation zones while keeping ablation time to a minimum. The techniques presented with this case study can be implemented to a wide variety of other medical devices to deliver similar results and improve treatment predictions on a case-by-case basis for patients.

Disclosure Statement: There are no real or perceivable conflicts of interest with this study.

Reference Section: