Development of a Patient-Specific, Three-Dimensional, Heterogeneous, Radio Frequency Thorax Phantom

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Target audience: This work targets MR researchers who require geometrically complex tissue-mimicking phantoms for the development and validation of SAR and thermal simulations, MR thermometry techniques, multi-channel transmit RF excitation techniques, SAR mitigation approaches, and safety protocols for implantable devices.

Purpose: To date, substantial effort has led to the development and experimental validation of MR-specific and multi-modality tissue-mimicking phantoms [1,2,3]. Further, phantoms and numerical simulations have been developed to model tissue hyperemia and specific absorption ratio (SAR) [4,5,6,7]. However, current approaches are not accurate for applications like 7T MRI. To improve phantom designs, pulse excitation techniques, and RF safety evaluation at 7T, tissue-mimicking phantoms must reflect the complexity of human anatomy. Therefore, the goal of this work is to construct a robust radiofrequency (RF) tissue-mimicking phantom derived from 3D anatomical models [8,9] with a one-to-one anatomical mapping to the numerically simulated, three-dimensional (3D), patient-specific MR model. We hypothesize that multiple tissue types [10] can be corroborated between simple experimental and numerical phantom. To predict outcomes on a patient specific basis a, truly patient-specific, 3D, heterogeneous, RF phantom is required.

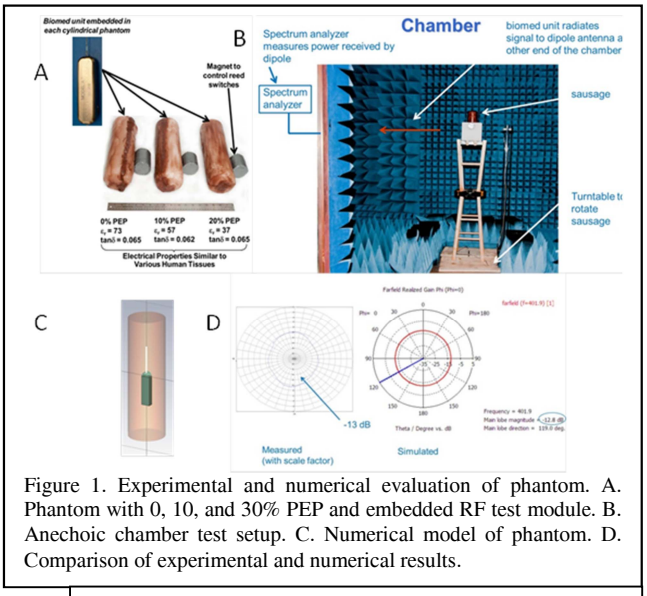

Figure 1. Experimental and numerical evaluation of phantom. A. Phantom with 0, 10, and 30% PEP and embedded RF test module. B. Anechoic chamber test setup. C. Numerical model of phantom. D. Comparison of experimental and numerical results.

Methods: ***Material Development:*** Two anatomically-accurate RF phantoms were developed: one using a previously described agar base [11], and a second with polyvinyl alcohol (PVA) substituting agar. Potassium chloride phosphate-buffered saline (PBS) was used to modify the conductivity (σ) of the phantoms. Polyethylene Powder (PEP) was used to modify the permittivity (ε') of the phantoms. ***Material Characterization:*** Phantoms were tested using two methods, the first, a previously described surface probe method [11] using a Agilent 8722ES Vector Network Analyzer (VNA) and Agilent 8570B dielectric probe, and the second a co-axial method using a Agilent 8510C VNA and a Damaskos 14MT coaxial fixture. ***Phantom Experimental Measurements and Numerical Simulations:*** A wireless implantable RF test module controlled by a low-power microprocessor was developed and used as a calibrated RF source for phantom experiments. Initial experiments consisted of cylindrical phantoms placed inside a 12x12x24 ft^3 broadband RF anechoic chamber, and then rotated, and the radiated power from the RF module was measured versus angle. From the measured radiated power, the test module antenna gain while inside the phantom can be estimated. A simplified numerical model of the sample cylinder with embedded RF-module was created and evaluated within CST Microwave Studio. The numerical model antenna gain can then be compared to the experimental gain. Figure 1 demonstrates steps taken to calibrate the experimental and numerical models. The agreement between measured and simulated gains provides additional validation of the phantom electrical properties. ***Organ Model Development:*** 3D female complex geometry molds of organs (Figure 2) were printed using a ZCorp Spectrum 510 3D printer using the segmented organ anatomy of the virtual human [9]. PVA models were then filled with the experimentally determined PBS and PEP concentrations that mimicked the organ of interest. A method to coat each organ with a thin platinum silicone (PS) shell provides long-term phantom stability.

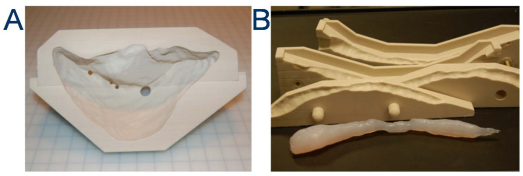

Figure 2. Organ molds. A. Liver and B. Esophagus.

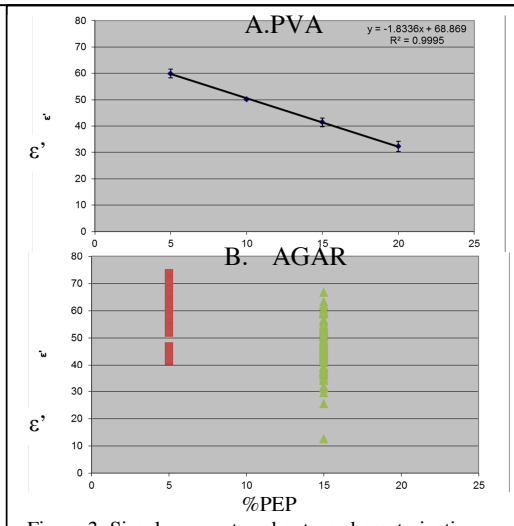

Figure 3. Simple geometry phantom characterization.

Results & Discussion: Figure 3a demonstrates the precise nature of the permittivity measurements obtained by using PVA and the Damaskos coaxial probe, versus the relatively unreliable results obtained in Figure 3b using agar and the Agilent dielectric probe. PVA phantoms of various sizes and shapes were generated and found to be physically robust. Through repeated experiments, we were able to demonstrate a reproducible process for generating a uniform suspension of the PEP in PVA. Repeatability of material electrical/RF properties was validated with a coaxial probe and anechoic RF chamber. Phantom and numerical simulations of RF properties were highly correlated across PEP concentrations. The RF effect of the PS skin on the phantoms was demonstrated to be negligible. Further, PS is self-healing allowing for repeated intervention on the phantom without degradation. MRI of the phantom revealed the need to control T1 and T2 properties of the different organs.

Conclusion: We have demonstrated a new method to develop a patient specific, 3D, heterogeneous, RF phantom for safety evaluation of implanted devices. Additional efforts are underway to create more complex phantom structures and evaluate them using EM-thermal simulations and MR thermometry in a MR parallel transmit environment.

References: [1] Kato, et al. 1986. [2] Marchal, et al. 1989. [3] D'Souza, et al. 2001. [4] Gellermann, et al. 2004. [5] Paulides, et al. 2007. [6] Suzuki, et al. 2010. [7] Yuan, et al. 2012. [8] McGurk, et al. 1997. [9] Ackerman, M.J.:, "The Visible Human Project," Proceedings of the IEEE , vol.86, no.3, pp.504-511, Mar 1998. doi: 10.1109/5.662875. [10] Andreuccetti, et al. 2000. [11] Baker-Jarvis, J. "DRAFT: Characterization of High-Frequency Tissue-Equivalent Materials From 200 MHz to 20 GHz DRAFT".