Tissue Impedance Implications of Performing RF Ablation at 64 MHz

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Introduction: RF ablation and microwave ablation are minimally invasive thermal therapies for treatment of tumors, particularly in the liver. If ablation were instead performed at the Larmor frequency of an MRI scanner, the RF magnetic field generated by the ablation current can be measured using B1 mapping techniques[1] to augment MR thermometry. The biophysics of the tissue impedance response has implications for ablation at MRI frequencies. We compare the impedance response of liver tissue during RF ablation at 460 kHz and 64 MHz and show that the impedance-temperature curves are similar, but with impedance changes more muted at 64 MHz. This less drastic impedance swing at 64 MHz may allow more controlled, microwave-like ablations.

Tissue Impedance: Tissue properties during RF ablation (RFA) at 64 MHz can be expected to fall between those observed during typical RF ablation at 460 kHz and microwave ablation (MWA) at 915 MHz or 2.45 GHz[2]. Figure 1 shows the complex conductivity (admittivity) of liver, derived from Gabriel[3,4]. Below the β dispersion (~500kHz), the conductivity is primarily due to extra-cellular fluid. Above the β dispersion, cell membrane capacitances become short-circuited, allowing intra-cellular fluid to increasingly participate in current conduction. Displacement current should progressively dominate over conduction current by 128 MHz (3T MRI), after which power deposition approaches MWA behavior. At high frequency, tissue permittivity, ε, should "permit" a capacitive bypass even if conductivity drops during ablation. Ablation-induced conductivity changes have previously been shown to be larger at low frequencies (10 Hz versus 1 MHz)[5].

Multi-Frequency RF Ablation Methods: Two RF ablation procedures were performed, one at the typical frequency of 460 kHz, and the other at 64 MHz, matching the Larmor frequency of 1.5T MRI. Porcine liver phantoms were ablated with bipolar ablation electrodes. We designed a custom multi-frequency ablation apparatus in which a Medusa parallel-transmit system[6] generated the ablation current waveforms. The impedance was measured by an inline voltage and current coupler at 64 MHz and by a bidirectional coupler at 460 kHz. Single point temperatures adjacent to the electrode were measured with an m3300 fluoroptic Biomedical Lab Kit (LumaSense, Santa Clara, CA, USA). The ablation power was adjusted manually based on real-time impedance and temperature readings displayed in a GUI developed in Matlab. The ablations proceeded until the impedance achieved roll-off at temperatures around 100°C. After roll-off, the ablations were briefly paused and then restarted until a second roll-off was achieved.

For 64 MHz, the ablation currents generate an RF magnetic field at the Larmor frequency of 1.5T. This RF field can be used as the B1 field for MRI[1]. Using the AFI sequence[7] with an adiabatic partial passage pulse[8], B1 maps were acquired before and after ablation (Fig. 2), with the post-ablation maps acquired after the tissue cooled. Scans were periodically stopped for MR PRF thermometry[9]. A 3-inch diameter surface coil was used for receive. The sequence parameters were: TR1=18ms, TR2=180ms, FOV=8cm, 1mm in-plane resolution, TE=4ms, 32 slices, 2mm slice thickness, sagittal orientation (with the length of the electrodes contained in the slice).

Results: The impedance and temperature readings during the ablations are shown in Fig. 3. The measured impedance depended strongly on the temperature. At temperatures below about 95°C, the resistance decreased (conductivity increased) and the reactance increased as the temperature rose. The transient drops of the 64 MHz thermal data occur when ablation is paused for MR thermometry. At temperatures near to or above the boiling point of water, the impedance exhibited a sharp change in the opposite direction, with increasing resistance and decreasing reactance, resulting in part from vapor generation, which electrically insulates. The strength of this change was much larger at 460 kHz than at 64 MHz. The B1 fields (Fig. 4) became weaker after ablation, indicating lower current due to a permanent increase in tissue impedance.

Discussion and Conclusions: Our 460 kHz data are consistent with previous ablation studies: tissue conductivity increases of ~2%/°C[10] for heating below the point of coagulation necrosis[11], with an extreme excursion of impedance at high temperatures[12]. Most significantly, at 64 MHz, the impedance response is similar but suppressed. Tissue impedance at 460 kHz underwent a very steep impedance rise when temperatures reach 100°C as tissue vaporization likely prohibited energy transfer, limiting the ablation[13]. We suspect that at higher frequencies, a contact capacitance remains, allowing displacement current even if conduction current is blocked. It may be that for RFA at 64 MHz, impedance roll-off is less of a limiting factor than at 460 kHz.

This argument is supported by previous studies comparing microwave and RF ablation [2,14], where microwave ablation has been shown to create faster and larger ablation lesions than RFA. Tissue temperatures can exceed 100°C with less impedance disruption to power flow. This allows higher temperatures during ablation, decreasing treatment time and limiting the heat-sink effect of nearby blood vessels. MRI-guided ablation has the potential to retain these impedance properties.

References: [1]Shultz et al, IEEE TMI, In press. [2]Simon et al, Radiographics, 25:S69, 2005. [3]Gabriel et al, Phys Med Bio, 41:2251, 1996. [4]Gabriel et al, Phys Med Bio, 41:2231, 1996. [5]Haemmerich et al, Physiol. Meas., 30:459, 2009. [6]Stang et al, Proc. 15th ISMRM, p925, 2007. [7]Yarnykh, MRM 57:292, 2007. [8]Shultz et al, Proc. 19th ISMRM, p2834, 2010. [9]Ishihara et al, MRM 34:814, 1995. [10]Vorst et al, *RF/Microwave Interaction with Biological Tissues*. 2006. [11]Huang: *Radiofrequency Catheter Ablation of Cardiac Arrhythmia*. 1995. [12]Curley et al, An Surg, 230:1, 1999. [13]Haemerich, Crit Rev Biomed Eng, 38:53, 2010. [14]Andreano et al, Med Phys, 37:2967, 2010.

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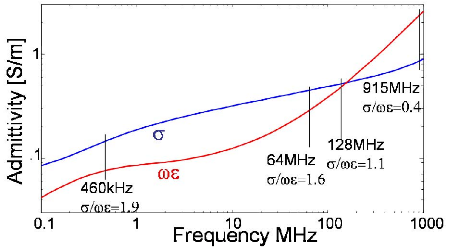

Figure 1: *Admittivity ($\sigma+j\omega\varepsilon$) of liver tissue at a variety of frequencies. As frequency increases, the ratio of conduction to displacement current will decrease. Above 3T, displacement current becomes the dominant impedance mechanism.*

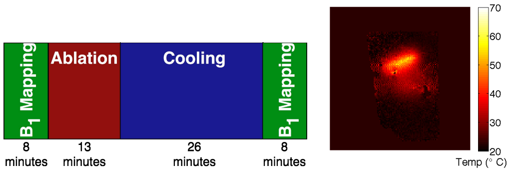

Figure 2: *MRI ablation timing (left) and representative temperature image (right) for 64 MHz ablation. B1 maps are acquired before and after ablation. MRI temperature maps were acquired periodically during ablation and cooling, while electric impedance and fluoroptic thermal sensing can be monitored continuously.*

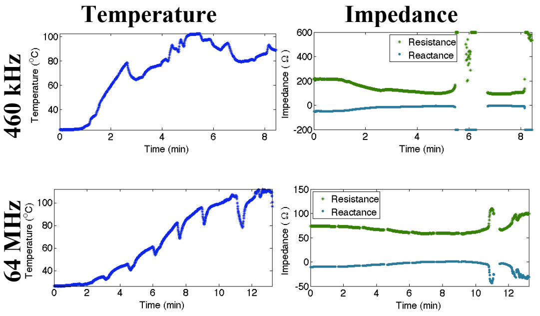

Figure 3: *Impedance and temperature measurements during ablation. At both frequencies, the resistance initially decreases as temperature increases, with a corresponding increase in reactance. At 460 kHz (top), the resistance increases very sharply as temperatures approach 100°C. At 64 MHz, there is also a resistance increase at 100°C, but the effect is significantly muted.*

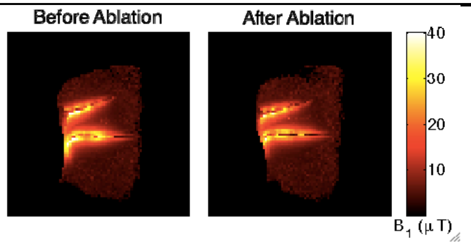

Figure 4: *Maximum intensity projections of B1 maps. The field strength (and current quantity) decreased along the length of the electrodes. The post-ablation image shows decreased RF field strength, due to a permanent increase in tissue impedance.*