Thermo-Acoustic Ultrasound Detection of RF Coil and Tip SAR

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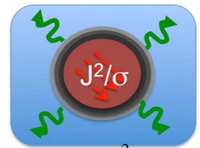
Target Audience: *MRI RF device safety researchers, clinicians of patients with implants undergoing MRI.*

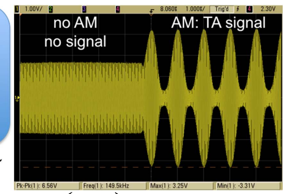
Purpose: Non-invasive technology for assessing RF heating from MRI transmit coils and device implants is quite limited. Recipients of deep brain stimulators (DBS), or pacemakers often have restricted access to MRI [1,2] due to RF tip heating concerns. MR interventional device visualization of EP catheters or dipole micro-transceivers [3], must also limit RF tip currents, and hot spot generation is a concern in transmit arrays. However, if low-level rapid RF heating occurs, tissue undergoes rapid thermal expansion and generates ultrasound (Fig. 1). We demonstrate the feasibility of thermo-acoustic ultrasound to non-invasively sense RF power absorption at 64MHz from RF tip heating and by an RF strip-line coil.

Theory & Methods: Thermo-acoustic waves are generated by time-modulating RF power density at ultrasonic frequencies (Fig 1). If an RF power impulse increases temperature by 1.25uK, it launches ~1 Pa pressure step that propagates at 1500m/s. Classic US impulse trains can be used, but with finite RF power, considerable averaging time is needed to increase total signal energy. Instead, by continuously modulating the RF amplitude at a frequency corresponding to an ultrasound detector, continuous wave (CW) ultrasound is generated. The CW modulation can be linear frequency modulation (FMCW) to frequency encode depth, or in stepped frequencies (SFCW) to phase encode depth (Fig. 2) [4,5]. To demonstrate thermo-acoustic ultrasound, we modulated a 64 MHz carrier over a 375kHz span centered at 1 MHz (Fig. 3) producing a ~100% AM signal. This span offers about 5mm range resolution. This drove a 100W RF power amplifier with an output either to a toroid-coupled exposed wire tip in saline [3] for tip-heating, or to a 6.5in strip-line coil under the saline phantom for coil heating. The data was hanning windowed for good side-lobe suppression. CW schemes allow simultaneous transmission of RF and detection of ultrasound. For both modulation schemes, the integrated total duration of RF was 1 second. Signal transmission and detection were programmed with a Medusa control system [6] with 500kHz Rx bandwidth. An Olympus V303 detected the ultrasound in bench tests, but has ferrous matching precluding magnet use.

Results: Fig. 4 shows averaged thermo-acoustic signals generated by FMCW (250x4ms chirps), and by SFCW (250 tones x2ms x2nex) from the toroid-driven wire tip, and strip-line coil at 8-10cm depth. Thermo-acoustic signals have been detected for tip currents below 100 mA. SFCW aliases at 1m range but FMCW has no range aliasing. Preamp nonlinearity creates a demodulated leak-thru at 0cm depth. Reverberation at the top and bottom surface of the saline container exists for the strip-line case because the bottom acoustic absorber was removed.

Conclusions: RF tip heating and RF coils can definitely generate thermo-acoustic signals. To be used in MRI, the scanner must be capable of modulation at ultrasound frequencies. For head, passage through the skull may require <500kHz modulation. Conversely, a prescreening system could be constructed, and could allow low SAR detection of aberrant conditions such as fractured leads, even before entry into the MRI bore. Phased array transducers and larger spans will further improve sensitivity and range resolution.





$$SAR = |J|^2 / \rho\sigma$$

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\left(\frac{\beta}{C_p}\right)\frac{\partial}{\partial t}\frac{|J(r,t)|^2}{\sigma}$$

Fig.1 Rapid RF heating causes thermal expansion. If MRI RF is AM modulated at 1 MHz, a continuous 1 MHz thermo-acoustic (TA) pressure wave is created.
Cp~4e3 J/kgK, β=4e-4K^{-1}, c~1500m/s,

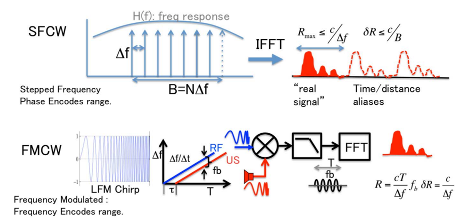


Fig 2: Stepped frequency (SFCW) phase encodes depth, but exhibits range aliasing. Frequency modulated continuous wave (FMCW) frequency encodes depth without aliasing. We used 375 kHz spans for both.

References:
[1] Rezai AR, et al., Invest Radiol 2004; 39:300–303. [2] Nyenhuis JA, et al., IEEE Trans Dev Mat Rel 2005; 5:467–80. [3] M. Etezadi-Amoli, MRM 2014 DOI: 10.1002/mrm.25187. [4] M. Aliroteh, Elec. Lett, 50,790,2014. [5] H. Nan Appl Phys Lett 104, 224104, 2014. [6] P. Stang, IEEE TMI, 31:370- 379, 2012. NIH Grant support: R01EB008108, P01CA159992, DARPA MEDS program.

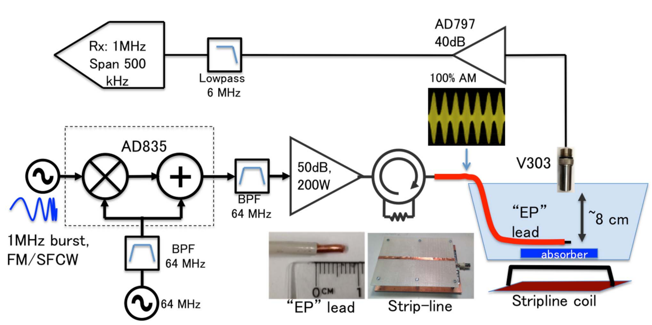


Fig 3: Setup to amplitude modulate (AM) 64 MHz carrier at 1 MHz center with 375 kHz span. Tip lead is toroid driven in saline, or strip-line coil excites below saline phantom.

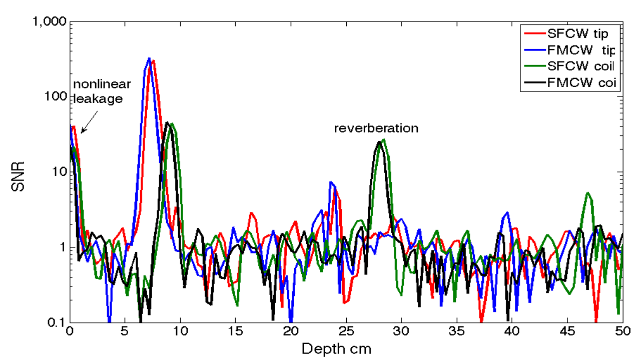


Fig 4:) FMCW (250x4ms, 375 kHz chirps) and SFCW (250 tone x 2ms x 2 Nex,) of strip-line SAR, and RF tip-heating TA signal.