# Direct SAR Mapping by Thermoacoustic Imaging: A Feasibility Study

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**Target Audience:** MR scientists and engineers with focus on high field safety monitoring and assessment.

**Purpose:** We propose a new concept for direct measurement of specific absorption rate (SAR), to be used as a safety assessment / monitoring tool for MRI. The concept involves the use of short bursts of RF energy and the measurement of the resulting thermoacoustic excitation pattern by an array of ultrasound transducers, followed by image reconstruction to yield the 3D SAR distribution.

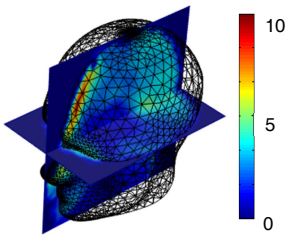

Fig. 1: IEC/CENELEC SAM head model with registered SAR pattern from Ella.

**Methods:** SAR is a key safety consideration in high field MRI, given the potential for tissue damage at locations of SAR hotspots. SAR prediction is therefore increasingly important, especially in the light of parallel transmit techniques, in which an unconstrained combination of the power output of multiple transmit channels can potentially cause strong local heating effects that depend not only on transmit coil and body characteristics but also on RF pulse characteristics. To date, no practical methods to measure local SAR *in vivo* exist; the only quantity that is routinely measured is average (global) SAR. Thermoacoustic signals are ultrasound waves generated through the absorption of pulsed or modulated RF/microwave energy [1,2]. A high intensity RF source is used to irradiate the tissue using short RF pulses, and absorbed RF energy then causes thermoelastic expansion with resulting pressure waves. In particular, for short pulses, the pressure wave equation is directly related to the SAR as follows: $\left[\nabla^2 - \frac{1}{v_s^2}\frac{\partial^2}{\partial t^2}\right] p = -\frac{\rho\beta}{C_p}\widetilde{SAR}(\mathbf{r})\frac{\partial I}{\partial t}$ (1), where $p(\mathbf{r},t)$ is the acoustic pressure field, ρ is the density, β is the volume expansion coefficient, $v_s$ is the speed of sound, and $C_p$ is the specific heat of the tissue. The quantities $\widetilde{SAR}(\mathbf{r})$ and $I(t)$ are the spatially varying SAR pattern and the unitless RF pulse temporal modulation, respectively.

Guided by the above theory, we propose to use thermoacoustic imaging to map SAR, using the RF transmit coil for delivery of the pulsed RF energy, and an ultrasonic transducer array to detect the thermoacoustic signals. The above governing equation can then be solved for $\widetilde{SAR}(\mathbf{r})$ assuming measurement of $p(t)$ at a number of locations surrounding the anatomy of interest, assuming knowledge of all other equation parameters.

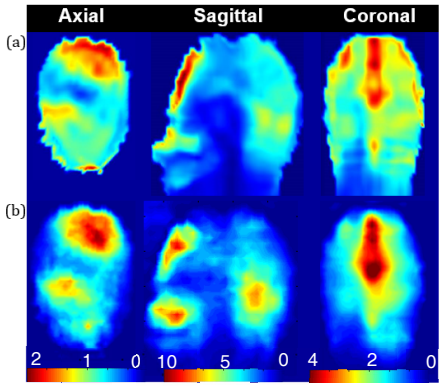

Fig. 2: (a) original 2D SAR pattern in W/kg, (b) 2D SAR pattern after reconstruction from thermoacoustic data.

**Modeling:** We studied the feasibility of the proposed technique via simulation, using a human head model with acoustically uniform tissue properties, an RF pulse of carrier frequency 298 MHz (i.e. 7T) with a rectangular pulse modulation $I(t)$ of width 1 μs and rise/fall times of 100 ns. The concept was studied using two simulation packages; the RF analysis was carried out using an finite difference time domain electromagnetic simulation package (SEMCAD, SPEAG GmbH, Zürich, Switzerland), while a finite element multi-physics simulation package (COMSOL, COMSOL Inc., Burlington, MA, USA) was used for the thermoacoustic analysis. The three-dimensional SAR distribution throughout the human head was computed in SEMCAD, using a standard head-sized birdcage coil model and a member of the Virtual Family (Ella, IT'IS, Zürich, Switzerland). This 3D SAR pattern was subsequently registered to an IEC/CENELEC SAM head model, which is available for use in COMSOL. This SAR pattern then served as the spatial excitation distribution for the thermoacoustic simulation according to Eq. (1) (Fig. 1). The head was modeled as a uniform material of constant speed of sound (1500 m/s), volume expansion coefficient (30 ppm/K) and heat capacity (3700 J/(kg·K)) [3]. Given that the 3D analysis problem becomes computationally very large, the calculations for axial, sagittal, and coronal planes were carried out in 2D. The time-domain acoustic pressure signals were recorded at 32 points distributed around the head boundary. Spatial maps of the SAR distribution were then reconstructed from these 32 time-domain signals using a delay-and-sum (DAS) algorithm implemented in Matlab (The MathWorks, Natick, MA).

**Results:** Fig. 2 shows that the reconstructed thermoacoustic SAR patterns are in good agreement with the input SAR patterns in all three planes. Further improvements can be achieved with more advanced image reconstruction techniques and improved pulse excitation waveforms. The final absolute SAR distribution can be computed by scaling to the measured global SAR.

**Discussion:** The presented simulation study suggests the feasibility of thermoacoustic SAR mapping. Experimental confirmation is underway. The two quantities relevant for ultrasonic detection sensitivity are the pulse energy needed for heating tissue (or in other words for generating the $SAR(\mathbf{r})$ excitation term) and the pulse rise time (the $\partial I(t)/\partial t$ excitation term), which determines the initial instantaneous pressure rise at each point. The former is mostly limited by the peak power of the RF system due to the short pulse thermal confinement requirement. The RF transmitter on most 7T scanners can deliver a peak power of 8 kW, which in a non-attenuated thermoacoustic experiment yields an ultrasound pressure of approx. 1 Pa. This preliminary study used acoustically homogeneous tissue parameters and tissue expansion coefficients. Advanced post-processing techniques readily available from thermo/photoacoustic imaging can be applied to overcome heterogeneity and other non-idealities not described by the proposed model. The human skull would be a significant challenge for diagnostic thermoacoustic imaging, where mm-scale resolution is desired, in which case a much higher ultrasound frequency would be required (e.g. >1 MHz). In our proposed lower resolution SAR mapping scenario, we expect that the skull will not pose a significant problem, given the use of ultrasound frequencies in the range of 200 kHz. This relatively low frequency can be selected to overcome ultrasound waveform aberration and absorption by the human skull, yet should still permit spatial resolution in the range of 1.5 cm in the resulting SAR maps.

**Conclusion:** A novel thermoacoustic method for in-vivo mapping of local SAR patterns in MRI has been proposed and verified in simulation.

**References:** [1]Gross, P, US pat 20100076298 (2010). [2]Foster KR, et al, Science 185:256 (1974). [3]Guo B, et al, CRC Press, Photoacoustic Imaing and Spectroscopy:165 (2009).

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