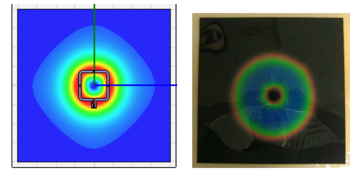
3T MR Phased Array as a Hyperthermia Applicator

S. B. Bulumulla[1], A. Arunachalam[1], K. J. Park[1], T. K. Foo[1], and Y. Zhu[1]
[1]GE Global Research Center, Niskayuna, New York, United States

Introduction
Overlapping loop elements (i.e. surface coils) have been used as phased array receivers to obtain larger field of view with better signal to noise ratio in MR imaging [1]. These elements have also been used as transmit elements in parallel transmit schemes to obtain selective excitations as well as improved B1 homogeneity [2].

In this work, we consider surface coil arrays excited by continuous wave RF sources as RF hyperthermia applicators for oncology. Using numerical analysis and experimental work, we study the heating patterns from loop elements and demonstrate the feasibility of selective heating from surface coils. The resulting array has the potential to function as parallel transmitters and phased array receivers for diagnostic imaging as well as an applicator for hyperthermia oncology therapy.



(a) (b)
Fig. 1 Heating pattern from a single surface coil (a) simulated pattern, with higher temperature in red, lower temperature in blue (b) pattern from experiment, where heat sensitive sheet shows higher temperature in blue color and lower temperature in red color.

Methods
A well-known model for the temperature dynamics in tissue is the Pennes Bio-Heat equation [3], which relates temperature rise to energy from metabolism, energy from external sources, and energy loss through thermal conduction

$$\rho c \frac{\partial T}{\partial t} = \nabla \bullet (k \nabla T) - \rho_{blood} w c_{blood} (T - T_{core}) + Q_m + Q_e$$

and blood perfusion. In our short duration phantom experiments, the temperature rise is dominated by external RF energy. Therefore, we can eliminate the terms describing blood perfusion and thermal conduction terms to obtain an equation that directly relates the temperature rise to material parameters and specific absorption rate.

$$\Delta T = \frac{\sigma}{\rho c} \frac{E^2}{2} \Delta t = \frac{1}{c} SAR \, \Delta t \, .$$

In this final equation, ΔT is the temperature rise, c is the specific heat capacity, SAR is the specific absorption rate and Δt is the RF pulse duration.

In studying the heating patterns of coils, we use the finite element method (HFSS, Ansoft Corp, USA) to simulate the electromagnetic fields and estimate specific absorption rates. We consider two overlapped coils at 3T, with varying relative phase between the coils. We also consider an array with four elements, constructed on a former for breast imaging (P/N 1085BR, GE Healthcare, Waukesha, WI). The interior of this former is modeled as being filled with material of lower conductivity (0.12 S/m) representing breast tissue. At the center of this material is a 2-cm diameter sphere of higher conductivity material (0.7 S/m) representing tumor cells. These material properties are based on [4].

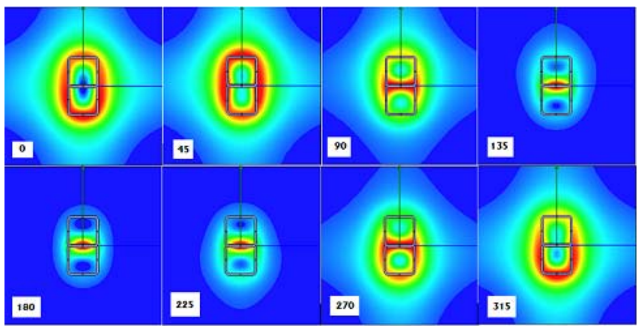
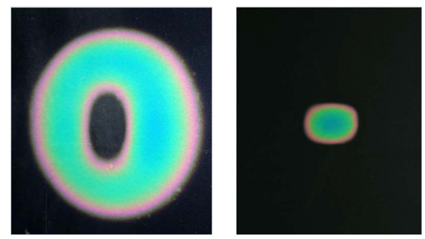


Fig.2. Simulated heating pattern from two overlapped coils as relative phase is varied in steps of 45 deg. Higher temperature is shown in red color, lower temperature in blue color.



(a) (b)
Fig. 3 Experimental verification of heating patterns (a) Coils with current in-phase, (b) Coils with current 180 out of phase. The heat sensitive sheets show higher temperature in blue color and lower temperature in red color.

In order to verify the results from simulations, we have gathered experimental data. For two coils, the coils are overlapped to cancel out mutual coupling, placed next to a Plexiglas container with Agarose and salt mixture, tuned and matched. Then a heat sensitive liquid crystal sheet (Edmund Optics, Barrington, NJ) is placed over the solidified mixture. The coils are energized with a continuous wave RF amplifier (Mini-Circuits, Brooklyn, NY). As the coils heat up the phantom, the color changes on the liquid crystal sheet indicate the heating pattern. For the four-element array, the interior of the former is filled with Agarose and salt mixture. To create the higher conductivity region, an Agarose mixture with higher concentration of salt is added. Again, a liquid crystal sheet is used to record the temperature pattern.

Results
The heating pattern of a single surface coil is shown in figure 1. This pattern follows the electric field pattern of the coil. The heating patterns of two overlapped coils are shown in figure 2. The plots show the specific absorption rate, which is proportional to the temperature rise, as the phase of current in one coil is varied in increments of 45 deg relative to the phase of current in the other coil. When the currents are in phase (top left), the electric field cancels near the overlapping region. Therefore the heating pattern is similar to heating from a larger coil with dimensions equal to the outline of the two overlapped coils. When the currents are 180deg out of phase (bottom left), the electric field adds near the overlapping region, creating a localized 'hot spot'. Figure 3 shows experimental results with the two overlapping coils, for the two cases of in-phase and 180deg out phase currents. These experimental results confirm the heating patterns predicted by simulations. The specific absorption rate in the breast coil model is shown in figure 4. The four coils are energized so that the electric field adds constructively at the center. The results indicate the feasibility of heating the 2cm diameter 'tumor' region.

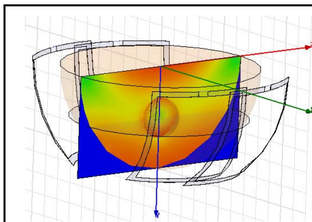


Fig. 4. SAR pattern from breast array. The sphere at center has higher conductivity, representative of malignant tissue.

Conclusions
Using numerical analysis and experimental data, we have studied heating patterns of surface coils for hyperthermia treatment. With two coils, a heating pattern over a distributed area or a localized area (i.e. hot spot) can be created by adjusting the relative phase between currents in the coils. The breast array simulation indicates the feasibility of treating deep-seated tumors using surface coils.

References:
[1] Roemer, P. B. et. al., Magnetic Resonance in Medicine 16, 192-225, 1990 [2] Zhu, Y., Magnetic Resonance in Medicine, 51: 775-784, 2004 [3] Pennes, H. H., Journal of Applied Physiology, 1, 93-122, 1948 [4] Fear, E. C., et. al., IEEE Microwave magazine, Mar 2002.

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