Temperature mapping close to the surface of ultrasound transducers using susceptibility-compensated MRI

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Introduction. Non-invasive temperature measurement is a critical component of thermal therapies such as high intensity focused ultrasound (HIFU) [1,2], laser [3], radiofrequency [4], and microwave [5] ablation. MRI has found extensive use as a thermal monitoring method. The proton reference frequency (PRF) method is well-established [6] and is used in the majority of studies. Typically, the heated volume is a large distance from the heating source, making imaging simple. However, there are applications in which it is desirable to measure temperature very close to the heating device. For example, we have worked extensively with a class of transducers used for drug delivery, which are placed directly onto the skin [7]. Since the elements of these "cymbal arrays" are made of brass, image artifacts preclude temperature mapping using conventional imaging sequences. Here, we show how susceptibility compensation sequences [8] can be adapted to measure temperatures very close to the transducer surface.

Imaging sequence. In the presence of spatially dependent magnetic field inhomogeneities caused by, in this case, metal elements of the transducer, an additional intra-voxel dephasing term is present. Typically, this intra-voxel dephasing is most significant in the slice select dimension, since the slice-thickness is normally larger than the in-plane pixel resolution. If one assumes for simplicity (though not losing generality) a linear susceptibility-induced gradient ($dB/dz=G_z^{susc}$) across the slice, then an additional phase encoding term is introduced into the imaging equation:

$$S(k_x,k_y) \propto \iiint_{slice} \rho(x,y)e^{-jk_x x}e^{-jk_y y}e^{-jk_z z}dxdydz, \quad k_z = \frac{\gamma}{2\pi}G_z^{susc}TE$$

The effect of G_z^{susc} is to shift the echo from the center of k-space: if the echo lies outside the data acquisition window there is a complete loss of signal. The echo can be shifted back into the acquisition window by applying a compensation gradient G_z^{comp} in the slice dimension. Since different voxels experience different values of G_z^{susc}, a number of different values of G_z^{comp} can be used to produce separate data sets, with these images being combined to produce a final composite image [8].

Materials and Methods. Agar (1% w/v) was placed in a hemispherical plastic holder. An ultrasound array, Figure 1(a), with diameter 4 cm and four brass capped cymbal transducers each of diameter 1 cm, was placed directly in contact with the top surface of the phantom. The transducer, matched to 50 Ω was driven at 20 kHz with an input voltage 160 mV fed into a 25W amplifier. MRI at 7 tesla was performed using a Varian Direct Drive Console. A quadrature birdcage coil was used for transmission and reception. Heating was performed continuously for 30 minutes. Images were acquired with TR 22 ms, TE 20 ms, slice thickness 1 mm, 1 signal average with four different values of the slice select refocusing gradient (-2, +3, +4 and +8 gauss/cm). A composite thermal map is obtained by using a weighted average of the individual phase maps, converted to temperature [6].

Results and Discussion. Figure 1(b) shows the heating images obtained after 30 minutes using a conventional gradient echo sequence, with the slice positioned ~1 mm below the transducer surface (the dotted white line represents the transducer): there are large areas containing essentially no information. In contrast, Figure 1(c) shows the composite thermal map using four values of compensation gradient, with the signal voids largely restored. Figure 1(d) plots the temperature measured at the centre of the array throughout the experimental run. Data using the conventional sequence represent essentially random noise, whereas data from the compensated sequence was consistent with thermocouple measurements performed separately (data not shown).

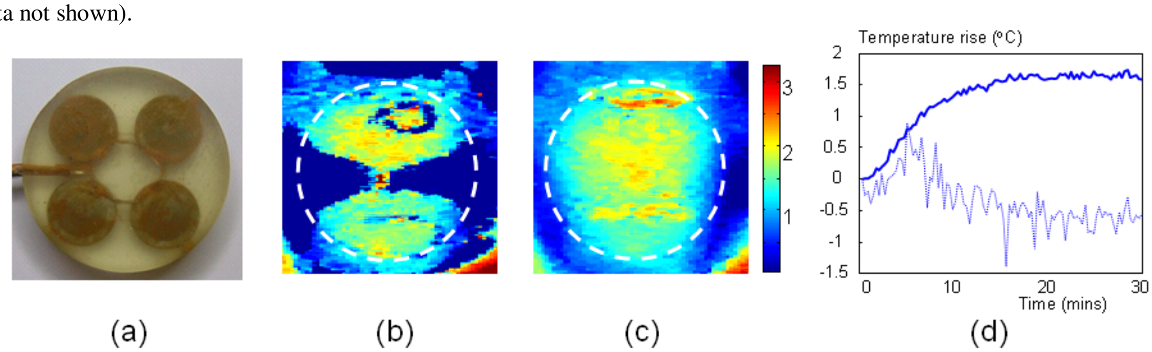

Figure 1. (a) Photograph of four-element cymbal ultrasound transducer, (b) temperature map obtained at 1 mm below transducer surface using a conventional gradient echo sequence (bright red represents 3°C), (c) corresponding temperature map from susceptibility-compensated sequence, (d) plot of temperature vs time at the centre of the array for conventional (dotted line) and compensated (solid line) sequences.

Conclusion. Susceptibility-compensated gradient-echo sequences allow temperature measurement very close to the surface of an ultrasound transducer. The cost in time is that extra images have to be acquired, meaning that the temporal resolution is not as high as for conventional imaging. In this particular application, this was not a major issue since heating occurs over a relatively long period of time. For applications where imaging speed is important, we are investigating the use of multiple echoes, in which each echo corresponds to a different value of the compensation gradient.

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