Fast imaging sequence for temperature monitoring in moving objects

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Introduction: MR thermometry is a very promising technique for guiding thermal ablation procedures. The demands on the imaging technology are both diverse and challenging: A temporal resolution of at least 0.5 s to resolve respiratory-induced motion, a temperature resolution of about one degree Celsius would be desirable, possibly 3D coverage to ensure no materials outside the targeted region are being inadvertently heated to dangerous levels, and reasonable spatial resolution must be maintained. While EPI can be fast enough to resolve motion, it provides relatively low quality images for temperature measurements, and while gradient-echo sequences can provide good-quality temperature measurements in static objects they may prove too slow to resolve motion and may require navigator-echo correction schemes. Such navigator-echo schemes may not be capable of capturing complicated motion (e.g., stretching).

In the present work, we present an approach based on a modified steady-state free precession sequence capable of capturing both motion and temperature changes, with sufficient speed and accuracy. Hargreaves et al presented a modified SSFP sequence robust in the presence of field inhomogeneities [1]. Due to steady-state effects, the image takes on a striped appearance, and k-space becomes double-peaked (see Fig. 1) [1]. In the presence of inhomogeneities, including temperature-induced resonance offsets, these bands will warp slightly, providing a novel way of measuring temperature. With high SNR and short TR, an SSFP sequence tolerant but yet sensitive to frequency offsets might be the ideal sequence for fast motion and temperature monitoring. The approach was implemented for both 2D and 3D sequences, and tested on a moving phantom.

Theory: The modifications to the SSFP sequence proposed in [1] create a band pattern within the object through steady-state effects, leading to a double-peaked k-space (Fig. 1). While temperature could be measured by detecting temperature-induced warping in the banding pattern, a computationally more efficient processing is used here instead, to avoid the large amounts of zero filling involved in [1] and to allow more exact measurements of band warping. The two k-space halves can be reconstructed separately (Fig. 1), leading to separate images $\mathbf{I_1}$ and $\mathbf{I_2}$. Within the width of a single pixel (e.g., red and green dots in Fig. 1), the k-space shift between the two peaks creates the phase ramps indicated in Fig. 1. The crest of a band happens where signals from $\mathbf{I_1}$ and $\mathbf{I_2}$ add constructively, and the value of this maximum is simply $|\mathbf{I_1}| + |\mathbf{I_2}|$. The location of the crest, which is temperature dependent, is determined by the phase of $\mathbf{I_1}$ and $\mathbf{I_2}$ (for example, a phase shift in $\mathbf{I_1}$ and $\mathbf{I_2}$ by $\Delta\varphi_1 = -\Delta\varphi_2 = \pi/2$ would displace the crest by half a pixel). A temperature-induced phase shift of $\Delta\varphi$ in $\mathbf{I_1}$ (and $-\Delta\varphi$ in $\mathbf{I_2}$) corresponds to a temperature change of $\Delta\varphi/(\pi \cdot TR \cdot 1.27)$ at 3T.

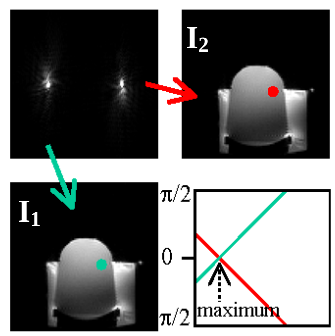

Fig. 1

Methods: A gel phantom placed in water and sitting on an ultrasound transducer was imaged using a 3T GE Signa system. The transducer was turned on for a minute and then stopped, while temperature was monitored with our proposed approach. The patient table was made to rock by 2 cm with a period of about 5 s, typical of liver motion during free breathing. The method was implemented on a 3D SSFP sequence (matrix size = 96x96x8, FOV = 25x25x2.4 cm, resolution = 2.6x2.6x3 mm, TR=4.9 ms, TE=TR/2, Δt=96x8xTR=3.8 s) and a 2D SSFP sequence (64x96, FOV=13x26 cm, resolution=2.0x2.7x8.0 mm, TR=5.2 ms, TE=TR/2, Δt=96xTR=500 ms). A standard single-slice 2DGRE sequence was also used to validate the measured temperature measurements. Cross-correlation was used to register the images of the moving phantom, and a self-referenced processing closely related to that from [2] was used to remove motion-induced phase variations.

Results: 3D results are presented in Fig. 2a-c. A temperature curve for a 2x2x2 ROI is shown in (c), along with a control from a single typical pixel out of the target zone (σ of 0.47°C). With the 2D sequence, temporal resolution (500 ms) was sufficient to resolve motion. Cases with and without motion are presented in Fig. 2. Although motion clearly degraded the temperature measurements, similar images and curves were nonetheless obtained. Using fast imaging techniques such as parallel imaging, we plan to bridge the gap between the 2D and 3D applications, acquiring *n* slices with an acceleration of *n* while keeping temporal resolution as in the 2D case.

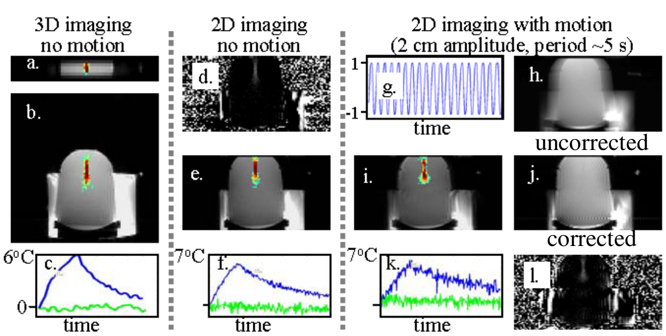

Fig. 2

References: [1] Hargreaves, ISMRM 2008, p. 1357. [2] McDannold et al. JMRI 2008;28:1026.

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