A fast thermal imaging sequence for focused ultrasound ablation of the liver

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Introduction: We developed an ultra fast scan and processing algorithms that will be implemented in a clinical MRI guided focused ultrasound (FUS) tissue ablation of moving organs such as the liver and kidneys. The pulse sequence is a restricted Field Of View (rFOV) EPI acquired at a rate of about 20 images/second. The signal from outside the FOV is suppressed with a dual band polynomial phase [1] RF pulse. The point to be treated is tracked continuously, and the information is sent in real-time to a FUS transducer.

Method: The approximate location of the area to be treated is known, so we use this information and limit our imaging FOV. This enables us to significantly reduce the number of phase encoding lines and hence increase imaging speed. As the speed increases the SNR decreases. Applying a low-pass filer to each voxel along the time axis restores the SNR, but also enable us to enhance the information by using the high frequency content of the filter, as explained below.

The advantages of the sequence are: 1) the motion of the object is tracked continuously at a very high rate. 2) The readout time per image is < 20 msec because we use a small number of lines, therefore image distortions due to field inhomogeneity are negligible. This is critical because spatial location from the image is fed in real time to the FUS transducer, so the coordinates from the image must be accurate within 1 mm to the true spatial coordinates. 3) Temperature measurement is more accurate because the moving object is fully stationary during the short imaging time. 4) We can image up to 3 slices simultaneously, as explained below. 5) Spatial resolution must be < 1.8 mm, otherwise intra-voxel dephasing around the FUS beam (with large temperature and phase gradients) creates signal void and wrong temperature reading. For a given imaging speed, we can decrease resolution by decreasing the size of the rFOV or by using the UNFOLD technique (see below). 6) The short readout time reduces/eliminates the ghost artifact of the EPI reconstruction [2]. The disadvantage is that a wide band RF pulse must be applied to saturate the signal outside the FOV. This increases SAR and is sensitive to b1 inhomogeneity. In another abstract we explain the design of a low SAR b1-insensitive wide band saturation RF pulse designed to suppress signal from outside the FOV.

Filter optimization: Low pass filtering of each pixel is done in the time domain with an IIR elliptic filter using a linear combination of previous and current data points [3]. The maximum frequency is 1/TR where TR is the time between images. To maximize SNR we use the lowest possible filter bandwidth without smearing the point-spread function of fast moving tissue. Therefore the filter bandwidth depends on the maximum speed of the tissue and TR. To test the filter we used a Gaussian 2D RF pulse [4] in conjunction with the EPI sequence, and saturated a pencil beam with 10 mm diameter and a parabolic profile over a stationary water phantom. We moved the beam in a sinusoidal movement across the phantom and measured the beam profile vs. speed and amplitude. Respiratory motion analysis with healthy volunteers showed that the maximum in-plane amplitude and speed of the liver motion is about 3.0 cm and 1.5 cm/sec respectively. Therefore we moved the pencil beam at a speed of 3.0 cm/sec and sinusoidal amplitude of 5.0 cm, twice the maximum liver motion, with a TR of 50 msec. A profile through the images vs. time before and after filtering is shown in Figure 1. The width and shape of the beam profile is preserved in the filtered image with a delay of two points, and SNR increases by a factor of 2.9 for TR = 50 msec. The frequency response of the filter is shown in Figure 2.

The unused parts of the spectrum that are rejected by the low-pass filter can be used to extract additional information. This is done with the UNFOLD technique [5], where even and odd lines are acquired in alternate scans. The spectrum of the ghosts is centered at a normalized frequency of 0.5, and is eliminated by the filter. UNFOLD enables us to reduce spatial resolution and/or TR by a factor of 2. Another application is simultaneous multi-slice imaging, where different slices are modulated in such a way, that the spectrum of each slice is located at a different normalized frequency. By using the filter we can separate up to 3 slices simultaneously. This is essential for FUS ablation, because the center of the heated spot is moving as the temperature increase.

Results: The technique was applied successfully on phantoms and the liver of 4 volunteers during free breathing, at a rate of 14 images/second with 3 simultaneous slices, i.e. 42 images/second. The SNR of the filtered images was 2.6 times higher than the unfiltered images with temperature noise of 1º. In all cases we used sagittal scans to reduce inter-slice movement. The movement in the liver was correctly depicted in each slice, and image tracking was successful in all cases.

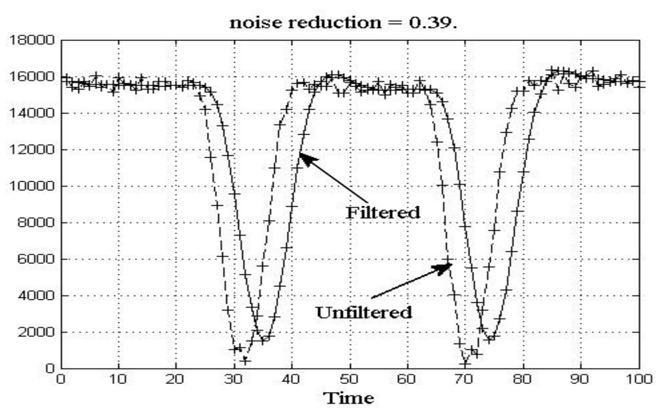

Figure 1

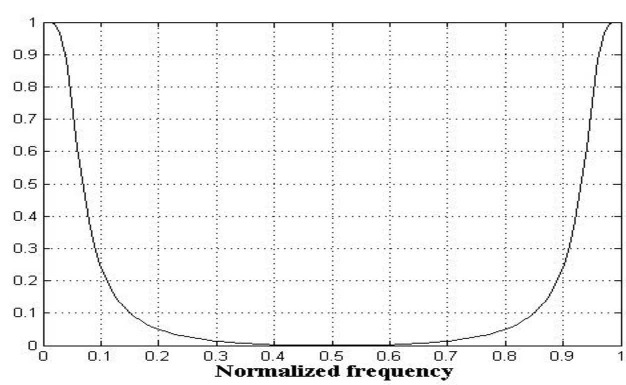

Figure 2

References: [1] R. Schulte et al, J. Mag. Res. 186, p. 167 (2007). [2] Y. Zur US Patent 7375519 B2 (2008). [3] Numerical Recipes, 1986 Ch. 12.9. [4] J. Pauly et. al. J. Mag. Res. 81, p 43 , (1989). [5] B. Madore et al., Mag. Res. Med. 42, p 813 (1999).