Analysis of focused ultrasound hotspot appearance on EPI and Spiral MR Imaging

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Introduction

While 2DFT MR thermometry is clinically acceptable for temperature mapping during focused ultrasound (FUS) therapy of stationary tissues such as uterine fibroids, there is considerable interest in speeding up MR thermometry with EPI and/or spiral sequences for other applications. MR thermometry relies on the proton resonance frequency shift seen with temperature [1], but this can produce off-resonance artifacts in EPI and spiral sequences. The purpose of this work was to analyze the appearance of the FUS hotspot on imaging performed with these trajectories.

Methods

The FUS hotspot was modeled as a Gaussian temperature distribution in x and y dimensions, with a size of 2 mm full width half maximum, and maximum temperature rise of 20°C at the center (resulting in 25 Hz off-resonance at 3T). Simulations were performed using 2DFT, EPI and Spiral k-space trajectories, and compared to experimental results. The trajectories used and their imaging parameters are listed in Table 1.

FUS sonications were performed on a polyacrylamide gel phantom using the Insightec ExAblate 2000 HIFU system in a 3T GE scanner. Each sonication delivered 40 W acoustic power for 10 seconds. Imaging was performed throughout the sonication, using the same trajectories as in the simulation. Images were acquired in the x-z plane, transverse through the center of the FUS spot. An image acquired pre-heating was used as a reference for phase subtraction.

Results and Discussion

The appearance of the FUS hotspot matched well between simulation and MR imaging (Fig. 1). For the 2DFT and EPI trajectories, the hotspot on the magnitude image appears as bright pixels adjacent to dark pixels, consistent with the signal being shifted due to off-resonance. For the 2DFT trajectory, the shift is in the frequency encode direction, while for EPI it is primarily in the phase encode direction. This shift can be several mm for the single shot sequences. The temperature variation over the hotspot leads to an arrow shaped appearance of the spot on the single shot EPI magnitude images. For the spiral trajectory, the off-resonant signal is blurred out resulting in a ring artifact on the image.

In general, the magnitude images are distorted more than the temperature maps, and the peak of the magnitude is shifted more than the peak of the phase, in both experiment and simulation. In addition, the hotspot may be distorted from the expected Gaussian shape due to the non-uniform shift of the signal. The spins experiencing the peak temperature are shifted more and may be averaged with spins from a voxel with a lower temperature leading to an underestimation of the temperature. Examples of these effects are shown in Fig. 2.

Table 1 lists the temperature rise estimated by the simulation, given the 20ºC input. All the single shot trajectories show significant under-estimation of the simulated temperature. The low-resolution EPI single shot techniques underestimate the actual temperature due to the large temperature variation across a voxel. With the long TE of the higher resolution Flyback EPI-1 shot, even a small temperature variation across the voxel would produce a wide phase distribution. This combined with the large 5.5 mm shift of the off-resonant spins at the hotspot peak probably results in underestimation of the temperature. In the spiral-1 shot case, the signal is shifted outward from the hotspot center, producing a dip in the center and hence an under-estimation of temperature.

Conclusion

There can be significant distortion of the FUS spot with single shot EPI and Spiral imaging for the high temperature changes used in ablation, and multi-shot sequences can be used to reduce the shifts/distortion to a tolerable level. Single shot trajectories can be useful for applications employing a smaller temperature rise, or potentially when used with techniques such as parallel imaging or reduced FOV imaging to reduce the scan duration and off-resonance sensitivity.

	Resolution (mm)	Expected shift (mm)	TE / TR (ms)	Readout duration (ms)	Scan time (ms)	Simulated temperature rise (ºC)
2DFT	1.56 x 1.56	0.2 (readout direction)	20/40	9.4	5000	20.4
EPI-8 FB	1.56 x 1.56	0.8	16/40	35	320	19.6
EPI-8 NoFB	1.56 x 1.56	0.4	10/28	23	224	19.9
EPI-RS-3 FB	1.56 x 1.56 (FOV=8x20)	1.6	7.9/60	55	80	19.5
EPI-1 FB	2.2 x 3.2	4.8	40/85	80	85	14.2
EPI-1 NoFB	1.9x2.4	2.6	39/83	78	83	15.8
EPI-1 FB 'high res'	1.56 x 1.56 (FOV=16)	5.5	96.5/200	186	200	5.8
Spiral-8 shots	1.56 x 1.56	blur	20/100	8	800	21.2
Spiral-1 shots	1.56 x 1.56	blur	20/100	61.5	100	12.5

Table 1: Trajectories used in the simulation and MRI experiment. FB = Flyback design. EPI-8 FB refers to Flyback EPI with 8 shots. EPI-RS-3 = readout-segmented EPI with 3 shots and saturation bands to reduce field of view (FOV) in phase encode direction. FOV was 20 cm for all trajectories, except the 2 cases listed. The readout bandwidth was 8 kHz for 2DFT and 125 kHz for all others. The single-shot EPI sequences were designed for lower resolution to keep the TE short. The expected shift is calculated for a 20ºC temperature rise based on the gradient trajectory in each case. The shift is in the phase encode direction for all EPI trajectories. The last column lists the maximum temperature rise estimated in the simulation, given the 20ºC input.

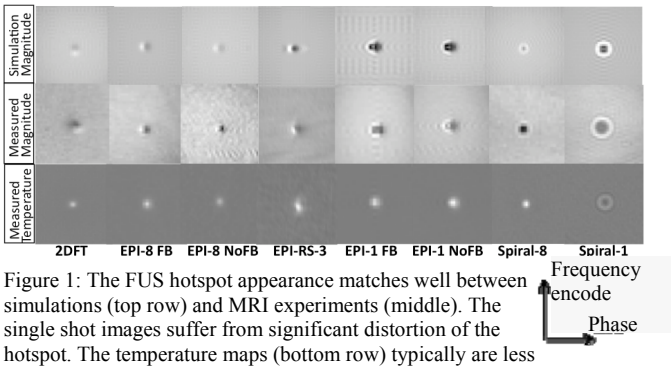

Figure 1: The FUS hotspot appearance matches well between simulations (top row) and MRI experiments (middle). The single shot images suffer from significant distortion of the hotspot. The temperature maps (bottom row) typically are less distorted than the magnitude images. The images are displayed at separate window/level for optimum contrast.

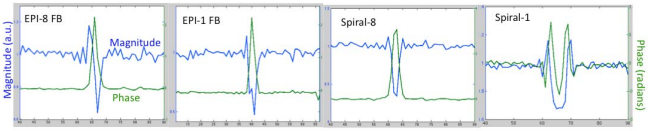

Figure 2: Line plots from the MR images through the center of the hotspot In general, the peak of the magnitude is shifted more than the peak in the phase images. In the spiral-1 case, the signal is shifted outward, resulting in a dip in the hotspot center.

References:[1] Ishihara Y. et al, 1995 Magn Reson Med 34: 814-823

Acknowledgements: NIH grants P41 RR09784, RO1 CA121163