ACOUSTIC RADIATION FORCE IMAGING (ARFI) BASED ON FAST SPIN ECHO

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<u>Introduction:</u> MR-guided Focused Ultrasound (MRgFUS) is used to treat noninvasively many brain disorders, e.g. essential tremor, psychiatric disorders and tumors. The heterogeneities of biological tissue and skull bone in the brain induce significant distortions of the ultrasonic wave field. Therefore it is necessary to measure the acoustic field and correct it, such that the focus is obtained at the desired location with 1mm accuracy. A few algorithms (1, 2) were suggested to correct these aberrations by iteratively measuring the acoustic field and modifying the power and phase of the ultrasound (US) transducers. Since it takes many iterations to converge, a fast and accurate map of the acoustic field is required. This field is measured with Acoustic Radiation Force Imaging (MR-ARFI) (3), where the US induced tissue displacement (~20 μm) in conjunction with a strong gradient generate a phase shift which is read with a fast 2D imaging sequence such as EPI. The phase shift φ generated by an ultrasound pulse of T sec, a tissue displacement Δx and a gradient G is

$$\varphi(ARFI) = \gamma G \cdot T \cdot \Delta x \qquad [1]$$

The ARFI signal-to-noise ratio (ASNR) is defined as the ratio between the ARFI induced phase and the phase noise. In this abstract we describe a new ARFI sequence based on Fast Spin Echo (FSE) which is advantageous over the existing spin-echo EPI sequence.

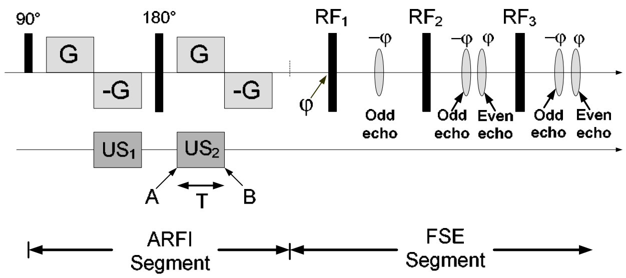

Fig. 1

<u>Theory:</u> Fig. 1 shows the MR-ARFI sequence. During the first segment (ARFI segment) we apply two ultrasound excitation pulses and the tissue motion is encoded by the two pairs of bipolar gradients generating a phase φ prior to RF1. The second segment (FSE segment) is FSE readout with N equidistant refocusing pulses. The signal during each sampling window in the train can be divided into two pure echoes (4): An even echo that experience an even number of phase inversions and an odd echo with odd number of inversions. Consequently, φ before the first refocusing pulse phase-shifts each even echo by φ and each odd echo by -φ. We calculate φ by separating all even and odd echoes and measuring the phase 2φ between them. These echoes are separated by phase cycling with two shots, where the phase of the initial 90° pulse is set to 0° and to 90° in shot 1 and 2 respectively. Images I1 and I2 are reconstructed from shot 1 and 2. Images $\mathbf{I}_{\mathbf{even}}$ and $\mathbf{I}_{\mathbf{odd}}$ from all the even and odd echoes are calculated by adding and subtracting I1 and I2 (4), and the phase difference between them is 2φ. To remove the background phase we run an identical reference sequence without US excitation and subtract its phase (reference phase) from the phase of the ARFI image. The tissue displacement Δx is calculated from Eq. [1]. In order to maximize φ, the direction of the ARFI gradients is controlled by the user to be always in the direction of the applied US beam. Note that the ARFI image is not affected by b0 inhomogeneity because it is fully refocused during data acquisition. In addition, the ARFI phase is not affected by b0 drift because the ARFI segment is a spin echo.

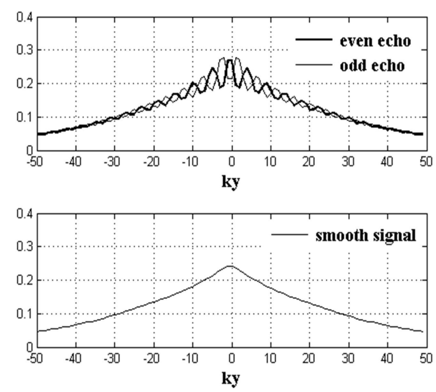

Fig. 2

<u>Data Processing:</u> To enable a long echo train we modulate the RF flip angles along the echo train. The flip angles optimization is similar to 3D Cube (5). The ky lines are acquired in a centric order, where the first acquired echo is at ky = 0. The amplitudes of the even/odd echoes oscillate along the train (6). Since the oscillations are the same (up to a global phase) for the reference and the ARFI images, we calculate the oscillations from the reference image and subtract it from the ARFI images. To obtain smooth signal decay we 1) ignore the first three echoes in the train. 2) Subtract the oscillation from the images. The simulated signal and smooth signal (after removing the oscillations) vs. ky is shown in Fig. 2. The data processing steps are a) separate the reference images and the ARFI images into even and odd echoes. b) Subtract the (low resolution) reference phase from the phase of the ARFI images. Repeat for both even and odd echoes. c) Remove the oscillatory signal. d) Calculate the phase difference 2φ between the processed even and odd echoes.

<u>Acquisition Parameters:</u> The ARFI acquisition matrix is 100 x 128, rectangular FOV of 20 x 26 cm (2 mm resolution) with 5 mm slice. Each ARFI gradient lobe is 2.9 G/cm with duration T of 7 msec. The echo train length is 53 echoes with 50 acquired echoes, echo space of 4.3 msec and 31 kHz receiver bandwidth. 4 shots are required to sample 100 ky lines because each echo train is acquired twice (phase cycling). The total scan time to scan 3 slices is 3.2 sec. The TE (from the 90° RF pulse to the first acquired echo) is 45 msec.

<u>ASNR Comparison of FSE and EPI ARFI:</u> We compared the ASNR of FSE and EPI. We ran EPI ARFI with a 50 x 128 acquisition matrix and rectangular FOV of 10 x 26 cm (2 mm resolution), 5 mm slice and the same ARFI gradients as with FSE, echo space 1.0 msec and TE of 60 msec. For EPI the rectangular FOV is essential in order to obtain a reasonable TE due to the long acquisition window. To prevent image aliasing we use two wide saturation bands. The total scan time to acquire 3 slices is 1.0 sec. To simulate the ARFI-induced phase we switched the receiver frequency by Δf at time point A (Fig. 1) and reset it back to 0 T sec later at point B. This was done for Δf = 0 and Δf = 25 Hz with T = 7 msec. The images were acquired using transmit/ receive Head coil at 1.5T with a 17 cm diameter spherical water phantom (T1/T2 = 200/130 msec). The expected phase difference for FSE is 4π□ΔfT = 2.2 rad and for EPI 2π□ΔfT = 1.1 rad. The ASNR is the ratio between the mean and r.m.s. of an ROI centered on the phase-difference image. The results are shown in the Table below.

<u>Discussion:</u> In practice, the ARFI EPI sequence is often useless because 1) It is very sensitive to b0 inhomogeneity (spatial distortion). 2) Spatial distortions are induced by eddy currents from the ARFI gradients whenever an ARFI gradient has a component along the phase encode direction due to the low bandwidth of EPI in the phase direction. 3) Noticeable artifacts from incomplete RF saturation of signal from outside the rectangular FOV. 4) Ghost artifact at oblique slices. The FSE ARFI is artifact-free. Due to its insensitivity to b0 drift (explained above) we run the reference scan only ones for a full set of ARFI experiments. This is a significant time saving compared to EPI, where a reference scan must be acquired before each ARFI measurement.

<u>Conclusion:</u> The FSE ARFI sequence provides a reliable, accurate, artifact-free and high ASNR alternative to the EPI ARFI sequence used today. The advantage of EPI ARFI is its high imaging speed of 1 image (with 3 slices)/sec.

sequence	σ(phase)	Mean phase	ASNR	Scan time, sec	slices
EPI	0.082	1.1	13.4	1.0	3
FSE	0.042	2.2	52.4	3.2	3

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