MR ARFI using the Keyhole technique: Acceleration of MR-guided adaptive focusing for transcranial ultrasonic brain therapy

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Introduction

Magnetic resonance acoustic radiation force imaging (MR ARFI) [1] has been recently introduced as a promising method to monitor and plan therapeutic applications of magnetic resonance guided high intensity focused ultrasound (MRgHIFU). MR ARFI measures the displacement induced by the ultrasonic radiation force, and provides the location of the focal spot without significant heating effects. Quantitative displacements maps obtained with MR ARFI provide an indirect estimation of the acoustic beam intensity at the target, which is essential in the context of adaptive focusing procedures of transcranial HIFU [2-4]. It can also be used to achieve beam correction, by maximizing the displacement at focus. In that case, a significant amount of serial MR ARFI images (>1000) is required and thus, a partial k-space updating method, such as keyhole [5-6] appears as a method of choice. The purpose of this work is to demonstrate the efficiency of the keyhole technique combined with a two-dimensional spin-echo MR ARFI pulse sequence. Our approach aims at reducing scan time and ultrasound (US) energy deposition during MR-guided adaptive focusing procedures, with limited image distortion.

Theory, Materials and Methods

The peculiarity of our approach relies on the assumption that the displacement profile can be described by a Gaussian function [7] (Figure 1), which is well-known to have straightforward Fourier Transform (FT) properties. Typically, a broad Gaussian in the image space generates a sharper Gaussian in the reciprocal space and *vice-versa*. Thus, the *a priori* knowledge of the spread of the Gaussian profile taken along the phase-encoding (PE) direction determines *in-fine* the extent of the keyhole technique for MR ARFI. In addition, the orientation of the PE direction and the imaging plan must be properly chosen since the focal spot is a 3D anisotropic object (ellipsoid pattern or cigar-shaped).

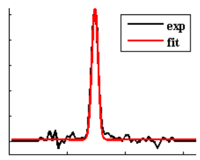

Figure 1. *(black line) Experimental profile of the displacement obtained via MR ARFI (here taken along the phase-encoding dimension with R = 1). (red line) Gaussian fit.*

A 2D spin-echo MR ARFI sequence was developed to sample a keyhole range δk_y, such as $\delta k_y/\Delta k_y = 1/R$, with Δk_y the complete phase-encoding range and R the acceleration or keyhole factor. Imaging acquisitions were performed on a 3T Siemens Verio MR scanner (Siemens Healthcare, Erlangen, Germany). The measurements were performed in a calf brain immersed in an agar gel (4 % w/v). Experimental parameters were: TE = 43 ms, TR = 900 ms. Square fields of view (FOV) of 160×160 mm^2 were acquired with a 64×64 matrix size and isotropic resolution of ~2.5 mm. Reference data without US bursts were recorded and keyhole data were acquired with 5 ms US bursts. The US burst were emitted during the second half of the Motion Sensitive Gradients of the MR-ARFI sequence [4] and were generated with a 1 MHz 512 channels prototype (SuperSonic Imagine, Aix en Provence, France). Each keyhole data was merged with complementary peripheral lines taken from the first reference data, and both magnitude and phase images were reconstructed. Background phase variations were removed by subtracting the second reference image. The protocol was completed for a transversal (TRA) view and a sagittal (SAG) view with the phase-encoding axis being collinear to the longest axis of the US focal spot.

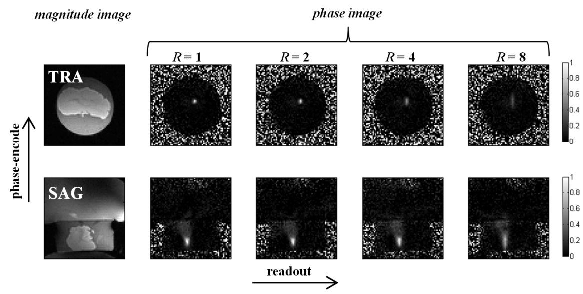

Figure 2. *Experimental MR ARFI keyhole (phase) images obtained in calf brain by varying the keyhole factors R with transversal (TRA) and sagittal (SAG) imaging plans.*

Results

Figure 2 shows the MR ARFI images generated by changing the keyhole factor R. The keyhole technique results in a low resolution image of the change, i.e., the displacement, in the phase-encode dimension. Mathematically, this corresponds to the convolution of the Gaussian profile by a sinc function. Figure 3 shows that the loss of spatial resolution is accompanied with a decrease of intensity at the focal spot. This deleterious impact is limited using the SAG imaging conditions. For R = 8, the intensity keeps ~75 % of the original value (R = 1), while it falls to ~ 35 % for the transversal view. To validate our initial hypothesis, simulations have been handled to reproduce the keyhole technique onto a Gaussian profile encoded into the phase image of a spherical phantom object. The spread of the Gaussian input in the simulations were equal to those measured experimentally using the TRA and SAG imaging plans. An excellent match is observed between experiments and simulations, which could thus be used as a prediction tool.

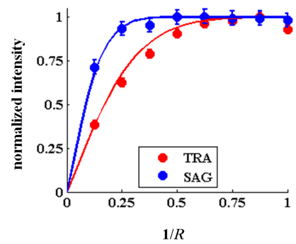

Figure 3. *Plots of the normalized intensity at the target versus 1/R. (Dots) experimental data. (Line) Simulated data.*

Discussion and conclusion

The keyhole performance is strongly dependent on the US focal spot size. The coincidence between the phase-encoding orientation and the longest axis of the focal spot allowed preserving up to 75 % of the original intensity at the focal spot with a keyhole factor of eight. Simulations and experiments were in good accordance. The MR ARFI keyhole technique using suitable settings improves the temporal resolution and provides rapidly undistorted two-dimensional images and accurate localization of the focal spot. The method offers a compromise between spatial resolution, SNR and scan time and could be valuable for adaptive focusing procedures.

References

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