MR-ARFI for the Quantification of Tissue Elastic Properties

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Introduction

High intensity focused ultrasound (HIFU) under MR guidance allows for pre-treatment planning, real-time temperature monitoring during treatment, and post-treatment assessment in ablative hyperthermia of tumors. In addition to heating, the focused ultrasound (US) causes micrometer transient displacement in the tissue in the direction of the US beam by the so-called acoustic radiation force. Tissue displacement is proportional to the HIFU intensity, and is, thus, most pronounced at the US focal spot. Using short HIFU pulses in combination with motion encoding gradients, the displacement can be visualized with MRI (acoustic radiation force imaging, ARFI) which can be used to localize the US focal spot prior to sonication [1].

The time-dependency of the displacement during the US pulse can be described by an overdamped harmonic oscillator model, which has two parameters: the maximum tissue displacement Δx, and the rise time tissue constant τ. The rise time is related to the mechanical tissue properties, and it is specific for each tissue type. Quantification of τ is needed for modelling of the tissue response during ARFI, and to distinguish tissues based on their stiffness (remote palpation). In this work we developed a method to measure τ from MR-ARFI data. The method can be used to assess the changes of the tissue elastic properties during treatment and to optimize ARFI protocols for different clinical applications.

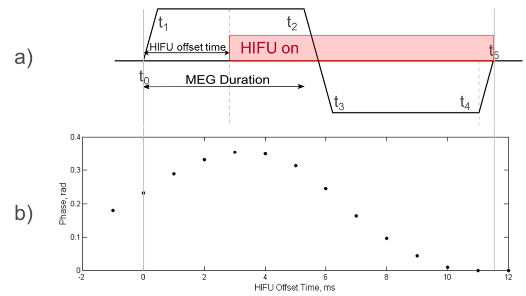

Fig. 1: (a) ARFI motion encoding gradient pair with a delayed HIFU sonication (b) phase difference for different delay times. Note, that the highest phase difference is in this case achieved for a delay of about 3 ms.

Materials and Methods

To determine τ, the MR phase offset φ caused by the tissue displacement $x(t)$ and the motion encoding gradients (MEG) $G(t)$ were simulated as a function of HIFU offset time (delay between the beginning of the HIFU pulse and the first gradient pulse, cf. Fig. 1a):

$$\varphi = \gamma \cdot \int G(t) \cdot x(t)dt, \quad (1)$$

Tissue displacement was described by an overdamped oscillation:

$$x(t) = \Delta x \cdot e^{-\frac{t-t_{offset}}{\tau}}, \quad (2)$$

where t_{offset} is the HIFU offset time. For a gradient amplitude of G_0 = 37 mT/m, a ramp duration of 0.6 ms and a plateau time of 4.4 ms phase differences of up to 0.4 rad can be expected with Δx = 7µm and τ = 5ms (Fig. 1b). Note, that with these parameters the maximal phase change occurs at t_{offset} = 3 ms.

To measure τ, a double-echo echo planar imaging (EPI) sequence [2] was modified to include the MEG gradients with interleaved polarity (Fig. 2) to be able to measure ARFI displacement and temperature simultaneously [3]. Temperature control during ARFI is required, because heating can occur during the ARFI sonication. The phase images are acquired with different polarities of the MEGs, and are later subtracted to remove background phases. The MEGs were oriented parallel to the HIFU beam using the same parameters as in the simulation. A fixed-focus HIFU transducer with an operating frequency of 1.7 MHz was used. The experiments were done in an ex vivo porcine muscle sample. ARFI experiments were performed in 4 different locations in the sample. To assess whether tissue stiffness changes with heating, ARFI measurements were preceded by HIFU sonication with different thermal doses [4] (cf. Tab. 1).

ARFI experiments were performed on 3T MR system (Siemens Tim Trio) using the following parameters: TE_1 / TE_2 = 26 / 32 ms, TR = 100 ms, α = 26°, ETL = 3, BW = 240 Hz/px, matrix = 64×128, FOV = 150×300 mm², slice thickness = 3 mm. ARFI phase images were acquired for offset times from -4 to 8 ms with 1 ms step. The phase at the focal spot was plotted as a function of HIFU offset time and equations (1) and (2) were used to fit Δx and τ.

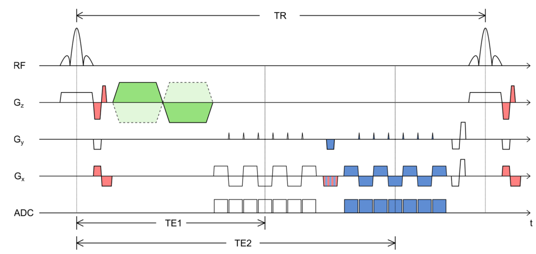

Fig. 2: Schematic of MR pulse sequence. The bipolar MEGs are shown in green. Blue elements correspond to the second echo; red elements show the motion correction.

Results and Discussion

The results of the simulation are shown in Fig. 1b. The highest phase is achieved if the displacement plateau starts with the beginning of the second MEG, which corresponds to the HIFU offset time of 3 ms. The rise time tissue constant affects how the displacement evolves with time, and, therefore, the optimal HIFU offset time will vary for different tissues.

The measurements and fit results are presented in Fig. 3. The values of Δx and τ calculated from the fit for four cases of ARFI experiment are presented in Table 1. The maximum phase value is achieved for the t_{offset} = 2 ms. τ is decreasing with the increase of thermal dose, except for the highest thermal dose (case 4), which is the only dose where necrosis would be expected in a clinical setting (> 240 CEM). Further experiments in an in vivo setting are required to evaluate the change in τ as a function of dose.

In this work we calculated the tissue elasticity dependent time constant τ using the MR-guided ARFI in four regions of a porcine muscle ex vivo phantom, which received different thermal dose. Time constant τ could be used for construction of elasticity/stiffness map of the tissues. Such maps could be used before the treatment to ensure the tumor location, during treatment for HIFU focal spot location optimization, and after the treatment to check if the necessary tissue ablation level was achieved.

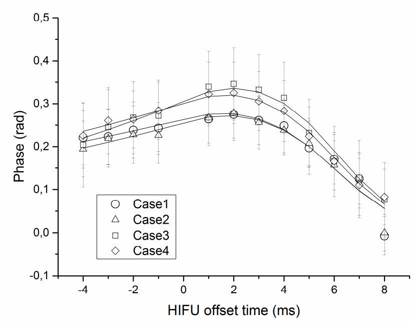

Fig. 3: Change in phase as a function of HIFU offset time and fit. Four different cases are presented, based on HIFU heating duration / thermal dose achieved.

Case	HIFU heating duration, s	Thermal dose, CEM	Δx, µm	τ, ms
1	0	0	15.2	23.9
2	10	<10	12.8	19.7
3	30	>50	12.8	15.0
4	60	>240	15.7	20.7

Table 1: Details of four cases of ARFI experiment.

References

[1] McDannold N, Maier SE. Med Phys **35**(8):3748-58 (2008) **[2]** Dadakova T, et al. MAGMA 2014 (In print) **[3]** Auboiroux V, at el. Magn Reson Med **68**(3):932-46 (2012) **[4]** Sapareto SA, et al. Int J Radiat Oncol Biol Phys **10**(6):787-800 (1981)

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