Rapid MR Elastography Methods During MRI guided Focused Ultrasound Surgery

Y. Le[1], K. J. Glaser[1], J. P. Felmlee[1], O. Rouviere[2], A. Manduca[1], S. Chen[1], R. L. Ehman[1]

[1]Mayo Clinic Foundation, Rochester, MN, United States, [2]Department of GenitoUrinary and Vascular Radiology, Hopital Edouard Herriot, Lyon, Cedex, France

Introduction: Focused ultrasound surgery (FUS) is a promising new treatment for breast cancer since it affects only the targeted tumor and does not require surgical or radiotherapy intervention [1-3]. MR temperature mapping has been shown to help guide and control FUS ablation [4]. However, tissue temperature rise is a transient effect that does not directly indicate tissue viability. MR elastography (MRE) represents a promising method to monitor FUS [5]. Previous studies have shown that pulsed FUS can induce shear waves, the shear waves can be detected by MRE, and the MRE-measured stiffness of FUS-ablated tissues are significantly different from normal tissue [5]. Our goal was to assess a time-efficient 1D version of the MRE pulse sequence [6] offering data at rates that can be used to interactively monitor FUS therapy. Displacement amplitude change will be used as indication of the shear stiffness change of the material in this technique, so the sensitivity in displacement measurement of 1D MRE was investigated in this paper and two main limiting factors were considered: 1) the partial volume effect due to the difference in size of the 1D excited beam and FUS focus, and 2) variations of the displacement measured during FUS treatment.

Materials and Methods: The system setup is shown in Figure 1. Bovine gelatin phantoms made with evaporated milk [7] were used for the 1D-2D displacement comparison and reproducibility studies. A 1.5-MHz ultrasound wave modulated by a 100-Hz rectangular envelope induced periodic displacement at the transducer focus and created shear waves that propagated in the x-y plane. The MRE pulse sequence was used to control the data acquisition and FUS delivery. In 1D technique, 2D selective RF pulse was applied to excite a column or beam of spins with the focus point at the center. Two-dimensional images of the beam were acquired to visualize the position of the beam and the wave in the beam (Figure 2). 1D displacement profiles were acquired from the beam by performing spatial encoding only along the axis of the beam (Figure 3). After the images and 1D data were acquired, the displacement amplitude was calculated from a small region of interest at the focus by fitting a sine wave to the displacements over time. To assess the sensitivity of 1D MRE to detect FUS-induced shear wave motion, the partial volume effect was evaluated by comparing the 1D MRE measured displacement amplitudes with those measured by 2D MRE. The reliability was studied by investigating the curve fitting error and the standard deviation of the displacement measured in 10 repeated experiments. In all acquisitions, TR = 90 ms, TE = 20 ms, 1 sinusoidal motion-sensitizing gradient pair with an amplitude of 1.76 Gauss/cm, 2 pre-encoding ultrasound pulses, and 8 phase offsets were used. Variable transducer power was used to provide a range of displacements and was varied in 1D-2D comparison (Figure 4) from 0.37 W to 37 W (acoustic intensity of 31.5-1256.9 W/cm^2 at the focus), and in reliability test (Figures 5 and 6) from 0.37 W and 5.9 W (acoustic intensity of 31.5-199.9 W/cm^2). The curve fitting error was evaluated by SSE/SSY, where Y is the measured displacement at the eight time offsets, $\hat{Y}$ is the value corresponding to the same offset on the fitted curve, and $\bar{Y}$ is the mean value of Y:

$$SSE\ /\ SSY = \sum (Y-\hat{Y})^2 / \sum (Y-\bar{Y})^2 \quad (1)$$

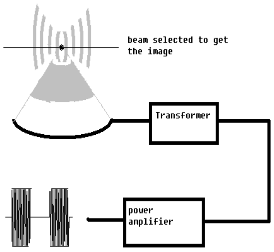

Figure 1.

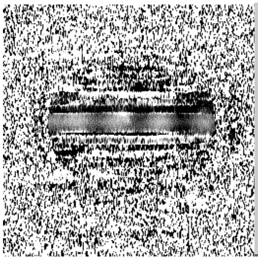

Figure 2

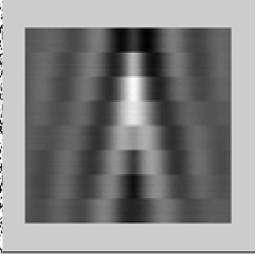

Figure 3

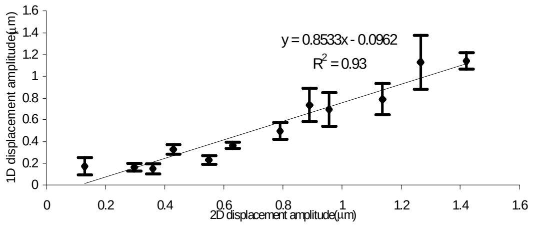

Figure 4

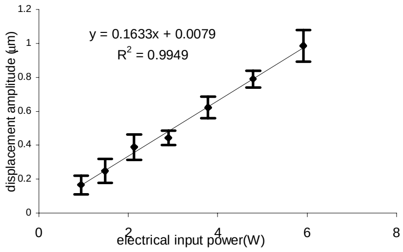

Figure 5.

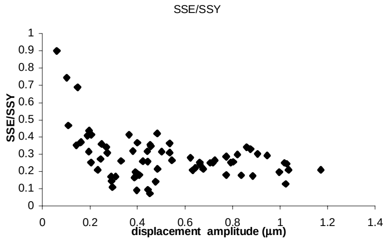

Figure 6

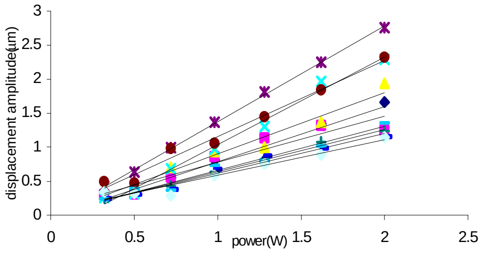

Figure 7

Results: Figure 4 compares the displacement amplitudes measured by 1D and 2D MRE in gel phantoms at different power levels. The results are highly correlated, with slope of 0.85 and a correlation coefficient of 0.93. Figure 5 indicates 1D displacement measurements that are highly correlated with the ultrasound power and are highly reproducible. The average displacement standard deviation is 0.05 µm, yielding a 95% confidence interval of 0.2 µm. Figure 6 shows the error function SSE/SSY, which decreases dramatically for displacements exceeding the 0.2 µm sensitivity threshold.

Discussion: The results show that the displacement amplitudes from 1D and 2D MRE are highly correlated, and have the sensitivity to reliably measure 0.2 µm displacement in our phantoms. Similar experiments (ten tests at different locations in tissue) conducted using ex vivo porcine muscle (Figure 7) yielded a sensitivity of 0.4 µm, The variability of the slopes reflects the variation in mechanical properties caused by tissue heterogeneity. Since the expected shear stiffness change that will occur during the FUS treatment is up to 100 kPa [5], the expected displacement change during treatment of tissue should be greater than 5 µm, which can be detected with our system. These studies imply that 1D methods have the potential to interactively monitor FUS therapy.

References: [1]. Lynn, J. et al. Gen. Physiol. 1942 (26): 179-93. [2]. Oka, M. Wakayama Medical Report (Japan) 1977 (20): 1-50. [3]. Hill CR, ter Haar GR: BJR 68:1296-1303, 1995. [4]. Gianfelice, D. et al. Radiology 227(3):849-855, 2003. [5] Wu T, et al. MRM. 2001 Jan; 45(1):80-7. [6]. Glaser KJ, et al. Proc. ISMRM. 10 (2002). [7]. Madsen EL, et al. Ultrasound Med Biol. 1998(4):535-42.