Shear Wave Diffraction Fields Generated by Longitudinal MRE Drivers

M. Yin[1], O. Rouvière[1], R. L. Ehman[1]

[1]Radiology, Mayo Clinic College of Medicine, Rochester, MN, United States

Introduction MR Elastography (MRE) is a noninvasive phase-contrast technique for estimating the shear stiffness of tissues by imaging propagating shear waves [1]. Typically, electromechanical drivers [2] have been used to introduce shear waves by applying cyclic *transverse* vibration at the surface (Fig. 1-a). These drivers can have disadvantages in some applications, due to heat deposition, artifacts, and inflexible orientation. These limitations have motivated our lab to develop drivers based on a pneumatic design [3]. In their basic configuration, these pneumatic drivers apply cyclic *longitudinal* vibration at the surface (Fig. 1-b). The longitudinal vibration does not generate simple planar shear waves parallel to the skin surface, as seen with conventional drivers. Instead, the longitudinal waves generated by the driver are mode-converted to shear waves that propagate obliquely away from the driver in a distribution governed by diffraction principles, as shown in Fig.1-b. The goals of this work were: (1) to visualize the diffraction field of shear waves generated by pneumatic longitudinal drivers within a homogeneous medium; (2) to optimize the imaging plane selection by investigating the reliability of shear stiffness estimation for different imaging planes.

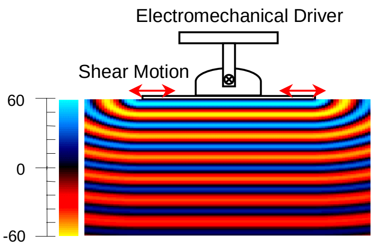


Fig. 1-a

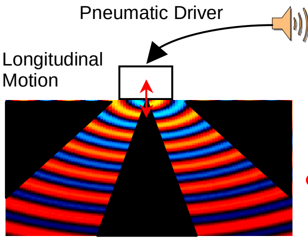


Fig. 1-b

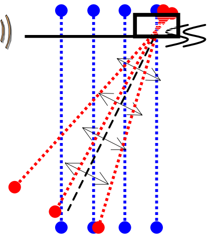


Fig. 2

Materials and Methods Two different types of cylindrical pneumatic longitudinal drivers, 3-cm and 8-cm in diameter with 100Hz and 90Hz resonances, respectively, were used. Both drivers performed continuous low frequency harmonic longitudinal vibration on a 15%B-gel, 25-cm diameter cylindrical phantom. A gradient echo MRE pulse sequence was used to acquire phase difference images in three sensitizing directions: 1) X: in-plane parallel to the driver surface; 2) Y: in-plane perpendicular to X; 3) Z: through plane. *Step 1:* At room temperature (20°C), for each driver operating at its resonant frequency, X, Y, and Z-sensitized phase difference images were obtained for two imaging orientations as shown in Fig. 2: vertical imaging planes located, at distances d, 0 to 60 mm from the driver's center at10 mm increments; and oblique imaging planes tilted, at angles θ, 0 to 60 degrees from the driver's central axis at 10 degree intervals. Shear stiffness estimations for each data set were obtained using the Direction Inversion algorithm [5]. *Step 2:* The phantom from *Step 1* was cooled to 4 degrees Celsius to stiffen it and the procedures were repeated. *Step 3:* Using a phantom at 20°C, X-sensitized phase difference images were obtained in the central imaging plane with both drivers operating at different driving frequencies. For each frequency, the diffraction fields were quantified using displacement maps to give both amplitude and distribution of shear motions, and corresponding diffraction angles α were also measured.

Results *Steps 1 and 2:* X-sensitized images (Xs) showed two lobes of shear waves propagating out-of-phase, separated by a certain diffraction angle α with no shear motion observed along the central axis. The maximum displacement of Xs images was observed in the central vertical imaging planes. Z-sensitized images (Zs) could be deduced from the performance of corresponding orthogonal Xs images and their maximum displacement was observed in the planes located roughly a quarter diameter away from the driver's center. The shear stiffness of gold standard, measuring from well-performed planar shear waves, was 2.67 ± 0.057 kPa at 20°C, and 23.68 ± 0.825 kPa at 4°C. Experiments showed that only oblique Xs and Zs images tilted with an angle approximate to diffraction angle α were optimum for correct estimation (3-cm driver: 2.68± 0.085 kPa at 20°C; 23.6 ± 0.551 kPa at 4°C. 8-cm driver: 24.0 ± 0.746 kPa at 4°C) on diffracted shear waves. *Step 3:* Diffraction quantification with different driver size and driving frequency illustrated that the diffraction angle increased when either the driving frequency or the driver size was decreased. Fig. 3-a, b, c, d showed examples of Xs images in center planes. The white lines indicate the direction of propagating shear wave. The measured diffraction angles α and the driving parameters were shown in the figure text.

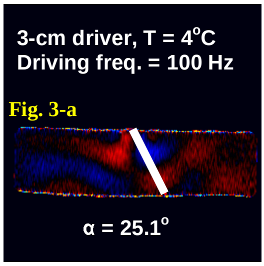


Fig. 3-a

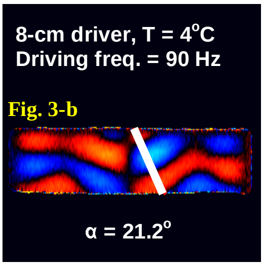


Fig. 3-b

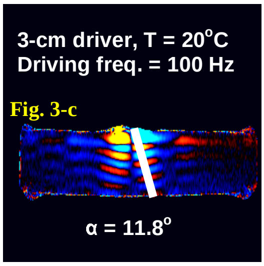


Fig. 3-c

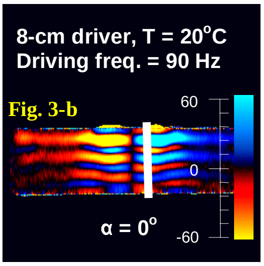
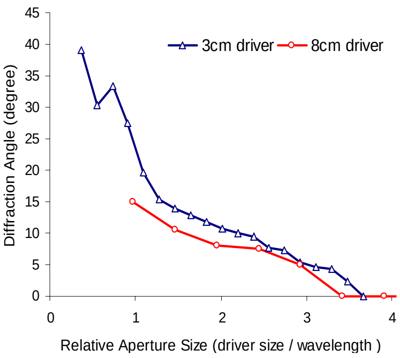


Fig. 3-b

Fig. 4 Diffraction Angle in the Near Field



Discussion The generated shear waves were hemispherically symmetric about the central axes of the cylindrical pneumatic drivers. In the Y sensitizing direction, very complicated motion was observed, composed of projection of shear waves, Rayleigh waves and bulk motion. Shear stiffness estimation varied with the imaging plane. These variations had three main causes: 1. poor SNR; 2. partial volume effects; 3. geometric distortion as shown in Fig. 2. Only geometric distortion could be easily corrected mathematically by multiplying $\cos^2(\theta-\alpha)$. Combining all the effects from the driving frequency, driver's size and shear stiffness, relative aperture size $a = r/\lambda$ (the ratio between the driver's size r and the wavelength λ) was used for analysis. Fig. 4 showed that diffraction angle increased when relative aperture size was decreased. Furthermore, nearly no diffraction was observed above the relative aperture size 4, and the maximum diffraction angle was approximately 35° [4], which was identical to the theoretical diffraction angle generated from a point source.

Conclusion Pneumatic longitudinal drivers are an effective approach to generate shear waves within an object. However, optimum imaging planes for accurate shear stiffness estimation depend on shear wave diffraction fields. Our results show that the amount of diffraction is merely determined by relative aperture size. Hence, the optimum imaging planes for a highly diffracted shear wave field are oblique ones tilted with angle α. For the least diffracted or planar shear waves, imaging planes orthogonal to the driver's surface are optimum. In order to obtain planar shear waves for easy handling, the relative aperture size should be no less than 4. These results offer potential improvements in both slice selection and planar shear wave generation for MRE data acquisition using a longitudinal driving modality.

Reference [1] R.Muthupillai, Science 1995, 269: 1789-1936. [2] R.Muthupillai, MRM 1996, 36: 266-274. [3] M.A.Dresner, ISMRM 2004. [4] Karl F. Graff, Wave Motion in Elastic Solids, 1991, ISBN 0-486-66745-6: 312-393. [5] T.E. Oliphant, MRM, 2001, 45: 299-310