Towards rapid planar MR elastography of the human brain: A 3D analysis of in vivo shear wave propagation

U. Hamhaber[1], J. Rump[2], S. Papazoglou[2], D. Klatt[2], I. Sack[2], J. Braun[1]

[1]Charite, CBF, Institute of Medical Informatics, Berlin, Germany, [2]Charite, CCM, Institute of Radiology, Berlin, Germany

Introduction: To investigate the mechanical properties of the human brain *in vivo* with dynamic magnetic resonance elastography (MRE) [1] low frequency (50-100 Hz) shear waves are applied [2]. Usually, the vibration of brain tissue is indirectly induced via skull, meninges and liquor. The exact transfer mechanisms are still not clear. This complex process results often in convolute wave fields with non-negligible deflections in all three spatial directions. Thus, a correct determination of the mechanical properties requires the spatially and temporally resolved measurement of all motion components of the wave field. Because MRE is a relatively time consuming acquisition technique it is often impossible to measure the complete wave field especially for patients. Therefore, in this study the full wave field was analyzed to determine regions where the wave propagation is in good approximation within the image plane. This is a prerequisite to get reliable values for elastic properties of the brain from time-resolved single slice 2D wave images.

Methods: To minimize the acquisition time for brain MRE, a single shot spin-echo EPI sequence was implemented which allowed motion encoding in arbitrary orientations [3]. Mechanical waves (frequency 83.33 Hz) were coupled into the brain of a healthy volunteer by an electromagnetic actuator attached to a bite bar resulting in a nay motion of the head (deflection amplitude < 0.5 mm). Steady state was achieved by applying 10 wave cycles before the start of the sinusoidal shaped motion sensitizing gradients (MSG). To cover the 3D wave propagation, 23 contiguous transversal slices with a thickness of 6 mm were acquired three times with two MSG cycles (amplitude 35 mT/m) in head-feet (hf), left-right (lr) and anterior-posterior (ap) direction, respectively. As wave images encoded in ap-direction showed the best penetration of the brain, 20 time points equally spaced over one oscillation cycle were acquired for this direction. Further acquisition parameters were: TR 2s, TE 164 ms, FOV 192 x 192 mm and 1.5 x 1.5 mm in-plane resolution. Using a phase contrast technique to eliminate scanner dependent effects, the total acquisition time was about 15 min for the time-resolved data set. All examinations were performed on a 1.5 T (Siemens Magnetom Sonata) scanner using a standard head coil.
The time-resolved 3D data was temporally filtered for the excitation frequency and 3D spatially band pass filtered to eliminate noise and effects of compression waves. A set of 29x29 rays (3.75 cm length) arranged in a spherical sector (orthogonal aperture angles: 84°) with the central ray pointing to the centroid of the brain was analyzed for each surface point of the brain. The brain surface was determined by interactive segmentation. Spatio-temporal images constructed by interpolation for each ray allowed the determination of the shear wave speeds using an edge detection algorithm. Slopes of all detected edge segments were calculated and averaged. The direction of rays connected to the smallest wave velocity was assumed to correspond to the direction of wave propagation for each sector respectively. The directions of wave propagation were determined and analyzed for transversal, coronal and sagittal slices. The whole data analysis was implemented in MATLAB® 7 (R14).

Results: Mechanical waves propagated concentrically from the skull and the meninges into the brain showing very strong damping (Fig.1). The largest amplitudes with 40 µm were found in parts of the cerebrum and the cerebellum adjacent to the tentorium cerebelli. The averaged value for white and gray matter of all shear wave velocities in the directions of wave propagation was about 1.75 m/s which corresponds to a shear modulus of about 3 kPa assuming density of 1000 kg/m³ for brain tissue. For transversal, coronal and sagittal slices the averaged deviation angles of the directions of wave propagation to the in-plane direction showed minima near the center of the brain and a strong increase towards the outer regions (Fig. 2). For transversal slices the minimum deviation angle was about 10° and for coronal and sagittal slices about 20° respectively. The standard deviation was for each slice about 10-20°.

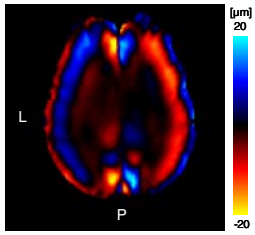

Fig. 1: wave image in an axial slice with motion component in ap-direction.

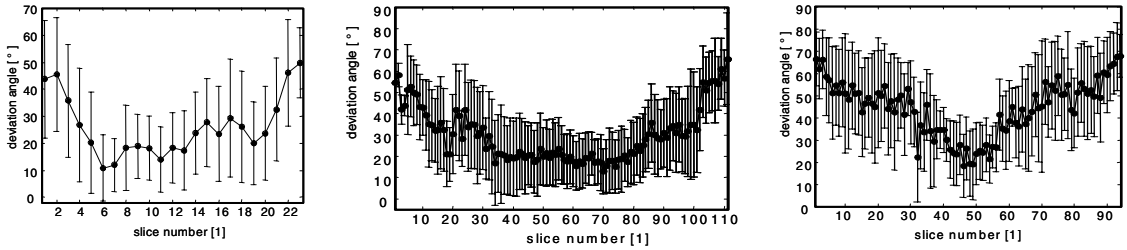

Fig.2: Averaged deviation angles for transversal, coronal and sagittal slices from left to right respectively. Error bars indicate the standard deviation.

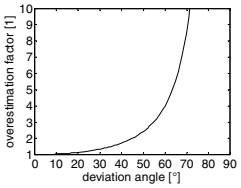

Figure 3: Overestimation factor of the shear modulus versus deviation angle.

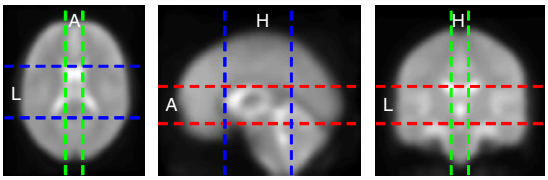

Fig. 4: Regions with moderate overestimation of the shear modulus for transversal (red lines), coronal (blue lines) and sagittal (red lines) slices.

Fig. 3 shows the overestimation factor for the shear modulus over the deviation angle which results from the projection of the direction with shortest wave velocity to the corresponding in-plane direction. It can be seen, that up to 25° the overestimation is relatively negligible. Therefore, in Fig. 4 the regions for transversal, coronal and sagittal slices with the averaged deviation angles lower than 25°±10 and hence moderate overestimation factors (<1.25±0.25) of the shear modulus are displayed on a standardized brain.

Discussion: The acquired wave images showed that all motion components of the propagating waves can be measured in the entire brain in good quality in a reasonable amount of time. The motion component with the best penetration of the brain was chosen for analysis. However, strong damping only allowed the analysis of rays with a length of 3.75 cm [Fig. 1]. To get reliable results no distinction between gray and white matter was made. The averaged shear modulus of 3 kPa is in good agreement to the results of Green et al. who used a 3D inversion algorithm [4]. For all analyzed slices an averaged deviation angle of the direction of wave propagation of at least 10° out of slice was observed which increased strongly to the outer regions of the brain. This deviation angle may explain the differences to the stated values for the shear modulus in [5-7] where single slice inversion algorithms were used. Transversal, coronal and sagittal slices near the center of the brain showed relatively moderate overestimation factors of 1.25±0.25 for the shear modulus. Hence, with our EPI-MRE technique we are able to get fairly reliable values of shear modulus from single slice acquisition and 8 time steps over one oscillation cycle with a total acquisition time of 16 s which should be acceptable even for patients with brain diseases.

References: [1] Muthupillai R et al, Science 1995, 269: 1854-1857 ; [2] Kruse SA et al, Proc. of ISMRM 2003, 1084 ; [3] Braun J et al, Proc. of ISMRM 2002, 2597 ; [4] Green M et al, Proc. of ISMRM 2005, 2176 ; [5] Kruse SA et al, Proc. of ISMRM 1999, 258 ; [6] Uffmann K et al, Proc. of ISMRM 2003, 1768 ; [7] McCracken PJ et al, MRM 2005, 53:628–639