Magnetic Resonance Elastography in Trabecular Bone: Preliminary Results

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Introductions:

Osteoporosis is a systemic skeletal disease characterized by low bone mass and microarchitectural deterioration of bone tissue leading to diminished biomechanical competence of the skeleton and low-trauma or atraumatic fractures. It is a major, increasing health problem causing approximately 2.3 million fractures annually at a cost of more than 23 billion dollars per year in the USA and Europe [1]. Although bone mineral density (BMD) is an important quantity for assessing the disease, the bone microstructure and architecture also contribute to the biomechanical properties of the bone [2]. Changes in collagen content or collagen cross-linking can increase fracture risk [3]. Therefore, assessing the overall biomechanical properties of the bone, based on the BMD and the trabecular bone matrix could be more valuable than BMD alone. Standard mechanical tests for measuring the characteristics of the bone matrix under laboratory conditions provides only limited information for clinical applications because of its invasive or ex vivo nature. Finite element analysis (FEA) can estimate the mechanical properties of the bone noninvasively, but is critically dependent on the boundary conditions in the FEA models [4]. Ultrasound velocity measurements have been demonstrated to be able to evaluate the bone architecture, but they are

Fig.1 (a) TB MRE setup. (b) TB SE MRE sequence.
FOV=20cm, Matrix=256X64, TR/TE=200/38ms, Slice thickness=10mm, BW=15.6kHz.

sensitive to the measurement directions [2]. Magnetic resonance elastograhy (MRE), has been successfully used in evaluating the biomechanical properties of soft tissues such as liver and brain [5-12] and has the advantage of noninvasively measuring the biomechanical properties of tissues in vivo. The goal of this work was to investigate the feasibility of using MRE to measure the stiffness of trabecular bone (TB).
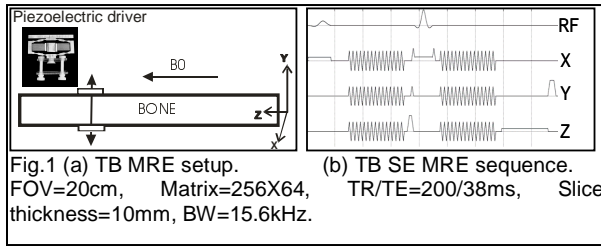
Methods and Materials:

(1) Bone. An entire porcine tibia with musculature removed was prepared, and kept in a moist state before the experiments. The weight of the entire bone was about 120g, the length was about 15cm. **(2) Mechanical vibration**. A piezoelectric stack mechanical driver was fabricated to apply mechanical vibrations to the bone at frequencies in the 1-10kHz range. The driver was rigidly clamped on the bone about 4cm from the condylar end and was secured to a supporting bar. Each specimen was put into a single-channel, quadrature, T/R head coil with the bone length parallel to the B_0 direction and the supporting bar was then fixed to the head coil. The vibration direction (polarity) of the driver was designed to be perpendicular to the long axis of the bone along the Y-axis of the physical coordinates (fig. 1a). **(3) Wave imaging sequence**. A spin-echo MRE sequence was developed for encoding high-frequency motion in the bone while accommodating the low T2 of trabecular bone. 15 cycles of 1500Hz triangular motion-encoding gradients (MEG, amplitude=2.4 Gauss/cm) were put before and after the 180° RF pulse. 45 cycles of 1500Hz mechanical motion were triggered by the sequence and were synchronized with the MEG to accumulate MR phase shifts due to the cyclic motion in the bone. 4 phase offsets evenly spaced over one period of the motion were implemented to image the mechanical motion though time. A tetrahedral arrangement was used for the MEG so the full vector motion could be measured. The designed wave imaging sequence has a sensitivity of 29.7 μm per π radians of phase. A standard 1.5T full-body MRI scanner (Signa, GE, Milwaukee, Wisconsin, USA) was used in the experiments. **(4) Inversion algorithms.** The bone stiffness was determined by inverting the 1D wave equation for a beam based on the flexural wave equation (Eq. 1) [13], where I=moment of inertia, E=Young's modulus, w= complex-valued displacements along the transverse direction at frequency f, S=cross-sectional area of beam, ρ=density of the TB (assumed to be 1100 kg/m^3) and ω=mechanical frequency (2πf). The obtained E is converted to shear modulus μ using the relationship E/2(1+ν), where ν= Poisson's ratio (assumed to be 0.3 for TB).
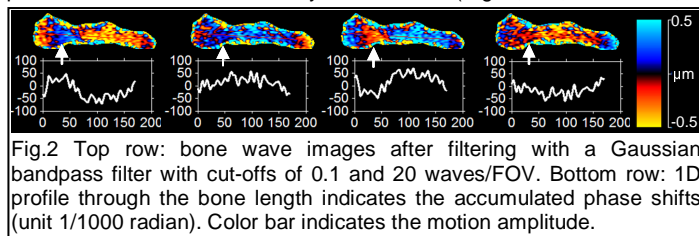

Fig.2 Top row: bone wave images after filtering with a Gaussian bandpass filter with cut-offs of 0.1 and 20 waves/FOV. Bottom row: 1D profile through the bone length indicates the accumulated phase shifts (unit 1/1000 radian). Color bar indicates the motion amplitude.

Results and Discussion:

The phase contrast images demonstrated propagating shear wave in TB, as illustrated in fig. 2. It is apparent that the soft tissue in the marrow space serves as marker material to report the high frequency cyclic motion of the trabecular bone. Transverse mechanical waves can be seen propagating from the vibration source (arrow) to the two ends of bone with a wavelength longer than the thickness of the bone, which indicates the need for a flexural wave inversion [13]. The wave data were processed with a beam inversion algorithm, generating quantitative stiffness maps (Fig. 3). The stiffness of the trabecular bone (thick arrow) is reported to be 0.8 GPa, which is in the range described in the literature [14]. The thin arrow indicates an invalid region in the elastogram where the wave source (driver) was located.
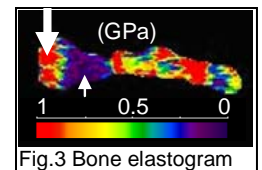

Fig.3 Bone elastogram

$$EI\left(\frac{\partial^4 w}{\partial x^4}\right) = \rho S \omega^2 w \quad (1)$$

Conclusion:

The preliminary results showed that MRE in TB is feasible in specimens. High-frequency mechanical flexural waves were induced in the bone with the motion direction dominated by the driver polarity. Spin-echo MRE successfully recorded the submicron mechanical motions in the bone, using the marrow soft tissue as a marker. The beam inversion yielded trabecular bone stiffness values that agree with results in the literature. Future work will focus on producing higher amplitude high-frequency mechanical vibrations and further optimizing the imaging sequence to obtain shorter wavelengths in the bone and better spatial resolution of the elastogram. More sophisticated inversion algorithms based on the flexural wave equations also show promise to improve the accuracy of the elastograms, and cross-validation with mechanical tests are underway. We speculate that with optimized drivers and sequences these MRE methods can be applied in vivo, to directly measure the stiffness of trabecular bone in extremities.

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