Measurement of exact wave-speed anisotropy in cortical bone with intra-osseous ultrasound imaging

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Background, Motivation and Objective

We recently showed [Renaud et al., Phys. Med. Biol., 2018] that ultrasound imaging of the cortex of a long bone is possible using compressional ultrasonic waves (P-waves), if refraction is taken into account during image reconstruction and if a model of weak elastic anisotropy is used. In this work, we show that the vertically-polarized shear ultrasonic waves (SV-waves), created by mode conversion in cortical bone, can also be exploited to image the bone cortex. Moreover we demonstrate how P-wave and SV-wave images can be used to estimate the four parameters describing exact wave-speed anisotropy in cortical bone. These four biomarkers may be of interest for the assessment of the quality of cortical bone tissue.

Statement of Contribution/Methods

We employed an acquisition procedure in which every element in a 2.5 MHz linear phased-array transducer subsequently transmits a quasi-spherical diverging wavefront, followed by a full array capture of the backscattered echo signals. The image is reconstructed with a delay-and-sum algorithm, using either echo signals related to pure P-wave propagation or to a path with SV-waves in cortical bone.
The elasticity of cortical bone can be approximated with a model of transverse isotropy, hence 4 independent parameters are required to describe wave-speed anisotropy [Thomsen, Geophysics, 1986]. Three parameters are found with a grid-search method by searching for optimal focus quality in the ultrasound images. For different tested values, metrics of image quality (intensity and sharpness) are evaluated in a region of interest (ROI) that encompasses the inner surface of the bone cortex. The fourth parameter is obtained by measuring the head-wave velocity along the axis of the bone. The method was tested in vivo on the forearm (radius bone) of one healthy volunteer. The acquisitions were repeated 5 times by repositioning of the probe.

Results/Discussion

Figure 1 shows images obtained with P-waves and mode-converted SV-waves, and the velocity model obtained with the estimated four parameters. The estimated values of the ultrasonic wave-speed and anisotropy in cortical bone are in agreement with ex vivo studies reported in the literature. The mean cortical thickness was 3.7+/-0.1 mm in P-wave-based images and 3.8+/-0.4 mm in SV-wave-based images, in good agreement with the thickness obtained with high-resolution CT (3.7+/-0.2mm).

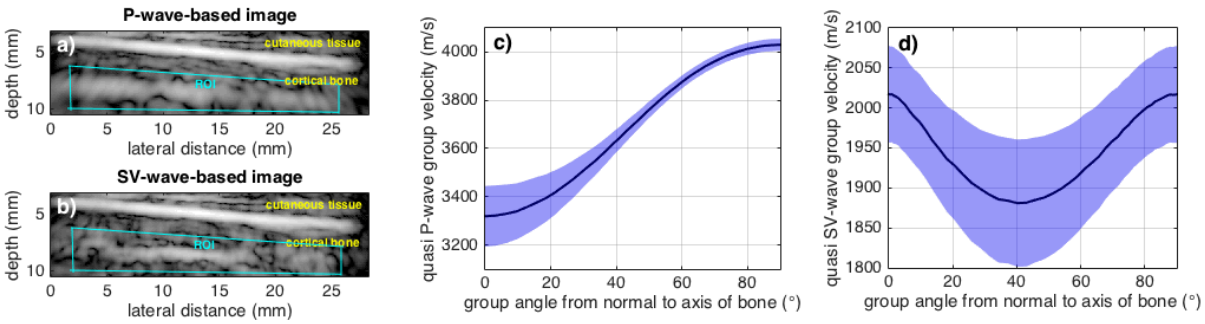

Fig. 1. Exemple of reconstructed image a) with P-waves in cortical bone and b) with SV-waves in cortical bone. Panels c) and d) show the estimated anisotropy of the group velocity of P-wave and SV-wave in cortical bone (solid black line depicts the mean value and +/- one standard deviation is shown about the mean value).