In Vitro Visualization of Ultrasonic Wave Fronts Interacting with Heel Bones Using Refracto-Vibrometry

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Abstract. Ultrasonic measurements of the heel bone (calcaneus) are used commonly for osteoporosis screening. Pulses emitted by an ultrasound transducer are incident on the calcaneus, and the transmitted wave fronts are detected with a separate transducer. In the current study, full field videos were obtained using refracto-vibrometry of ultrasonic pulses interacting human calcaneus samples in an in vitro environment. Pulses were emitted by a 500 kHz Panametrics V303 transducer. The measurement beam from a Polytec PSV-400 scanning laser Doppler vibrometer laser was directed through a water tank towards a stationary retroreflective surface. Acoustic wave fronts (density variations) which pass through the measurement laser cause variations in the integrated optical path length. The time-varying signals detected by the vibrometer at numerous scan points were used to determine the time evolution of ultrasonic wave fronts. The resulting videos enable visualization of the propagating wave fronts and the backscattered and transmitted wave fronts. These videos enable direct investigation of wave front distortion due to reflection, refraction and diffraction effects.

Keywords: Ultrasound, Sonometry, Refracto-vibrometery
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INTRODUCTION

Osteoporosis is a degenerative bone disease afflicting millions, especially those of advanced age.[1] Osteoporotic bone is of lower density than healthy bone. This weakens the bone's structure, leading to an increased risk of fractures. Clinical diagnosis of osteoporosis is based on measurements of hip and spine bone mineral density (BMD) using a technique called dual-energy x-ray absorptiometry (DXA). Because x-ray absorption is dependent on the medium the x-rays travel through, measuring the absorption of x-rays through the bone provides indicators of their mineral composition and health. While DXA has found use as an osteoporosis diagnostic tool, BMD is only a proxy for bone strength, not completely describing fracture risk. Additionally, a DXA scan results in exposure to x-ray radiation.

Ultrasound shows great promise as an alternative for determining bone health because the propagation of ultrasonic waves in bone depends on the physical and mechanical properties of the tissue. Currently, ultrasonic heel bone sonometry has achieved clinical relevance as an economical method to pre-screen patients for osteoporosis. It functions by measuring the speed and attenuation of ultrasonic pulses propagated through the heel bone (calcaneus).[2] The heel bone is chosen because both sides of the bone are readily accessible, allowing for ultrasound transmission and reception. While deployed in clinics and health services around the world, there are still fundamental physical questions remaining regarding how ultrasound interacts with the complex geometry of the heel bone. Resolving these questions requires visualization of ultrasound waves reflecting and transmitting through the heel bone.

Refracto-Vibrometry for Ultrasound Visualization

Refracto-vibrometery is an emerging optical technique for creating full acoustic field visualizations. A scanning laser Doppler vibrometer is the instrument utilized for this technique. A vibrometer is designed to measure the Doppler shift of laser light after it is reflected from a vibrating surface.[3] However, in refracto-vibrometry the vibrometer is directed towards a motionless retroreflective surface. Acoustic (pressure) waves cause fluctuations in the density of a medium, changing its index of refraction. Therefore, as an ultrasound pulse traverses through the laser, the optical path length of the laser continuously changes. The time varying modulation of the laser detected by the vibrometer relates directly to the acoustic pulse passing through the laser, providing a method for noninvasively sampling a localized region of an acoustic field.[4] By repeatedly emitting ultrasound pulses from a transducer and compiling time-series data at numerous sampling locations, the vibrometer software can reconstruct an image of the traveling wavefront, display how this wavefront evolves over time, and show how it interacts with its environment.

METHODS

The aim of the current study is to visualize ultrasound interacting with a human calcaneus heel bone, mimicking the setup of a clinical ultrasound heel bone scanner. An excised calcaneus was suspended in a water tank. A 0.5 MHz ultrasound transducer, placed one focal length away from the surface of the bone, ensonified this specimen. On the back side of the water tank a retroreflector was placed, and a Polytec PSV-400 scanning laser Doppler vibrometer laser faced the heel sample from the other side of the tank. An image of this setup is shown in Figure 1. Figure 2 presents a depiction of the experimental configure from different perspectives. In Figure 2a, the setup is shown as seen from above. By sweeping the laser back and forth, locations across the entire acoustic field could be sampled. Figure 2b shows this sampling grid pattern from the vibrometer perspective. In all, 15000 different locations were sampled to reconstruct the sound field map. At each location, 100 pulsing cycles took place, and the time series were averaged.

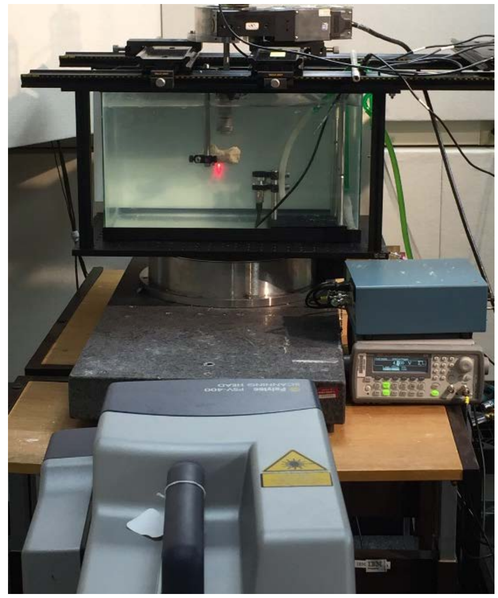

FIGURE 1. The experimental configuration, as pictured from the scanning laser Doppler vibrometer.

RESULTS

An initial comparison was performed between the signal received by the vibrometer and a traditional piezo-electric transducer. Figure 3 presents a time trace obtained using the refracto-vibrometery technique (a) and piezo transducer (b) for a location on the other side of the bone from the transmitting transducer. Therefore, these traces capture the sound after it has propagated through the bone itself. The two traces are in general agreement with one another, offset only by the slight difference in location of the vibrometer beam and receiving transducer.

While each individual refracto-vibrometry measurement is limited to sampling over the small cross-section of the laser path, by interpolating between points, and combining each sampling location in the region surrounding the heel, a video of the time evolution of the acoustic field in the area is found.[5] This helps show the interactions between the ultrasound pulse and the bone structure. Figure 4 represents a single frame taken from this video. On the left of the image is the transmitting transducer. The image shows some of the wave having passed through the bone to the right side of the image, while a significant portion of the original outbound signal has been reflected off the bone back towards the transducer. Each band in the image represents the variation in index of refraction of the water medium caused by the wave's pressure fluctuations.

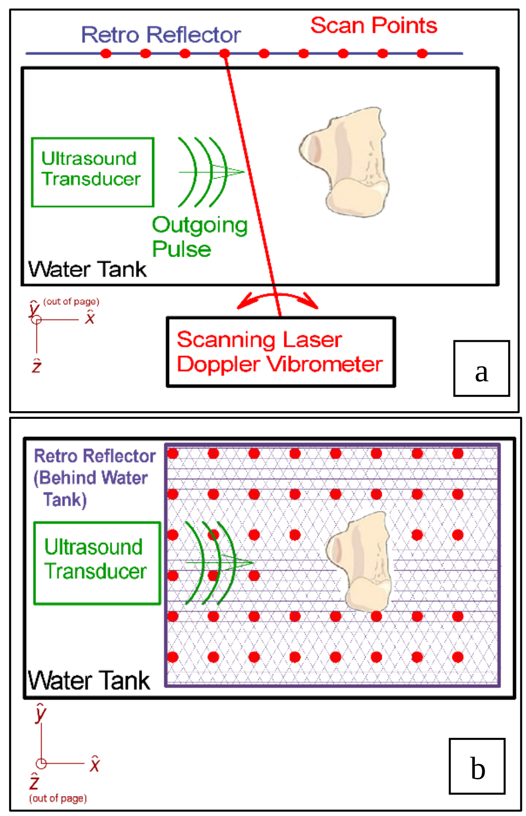

FIGURE 2. a) A top-down view of the experimental configuration. b) The view of the experimental setup from the vibrometer. The dots represent individual scan points. This depiction is simplified to show only the general layout of the scanning grid. In the experiment, 15000 data points were scanned.

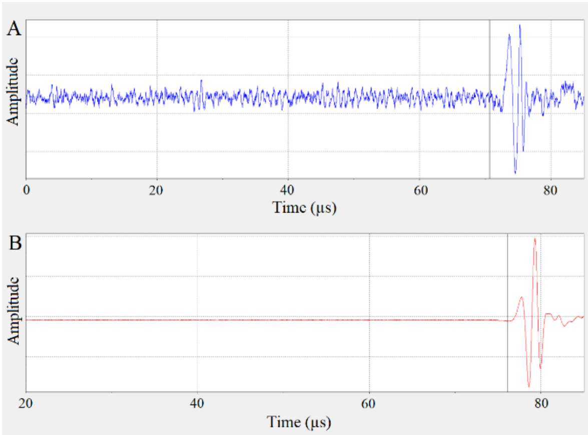

FIGURE 3. Time-series readouts of the a) vibrometer's and b) transducer's time-series measurement. In these graphs, amplitude corresponds to the voltage output of each instrument and has not been scaled to acoustic intensity.

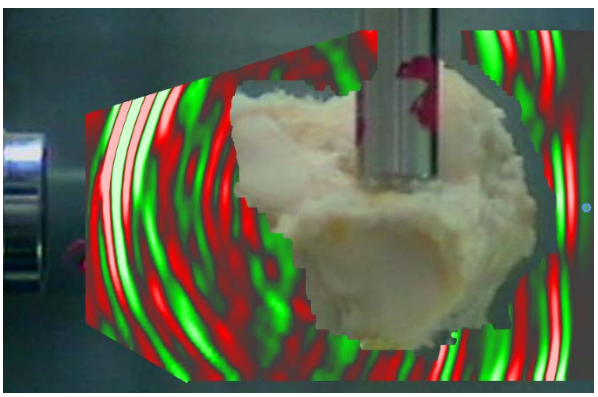

FIGURE 4. Still frame from a video of the ultrasound wave interacting with the heel bone. Green and red regions correspond to areas of increased and decreased pressure, respectively. The pulse originated from the transducer at the left of the image. In this image, the original wave pulse is being both transmitted through and reflected from the bone. For scale, the vertical metal support rod is 1cm in diameter.

DISCUSSION

Comparing the vibrometer trace and transducer trace shown in Figure 3, the vibrometer measurement has a significantly lower signal to noise ratio. With repeated measurements and averaging, some of this noise can be reduced, albeit at the expense of longer sampling times. Despite the higher noise, the vibrometer measurement offers several advantages to traditional transducer measurement. First, the vibrometer measurement is non-invasive. Additionally, the vibrometer is sensitive to all frequencies, while transducers are more constrained in their bandwidth. The vibrometer beam can also be scanned anywhere in the acoustic field, as long as it has an unobstructed path to the retroreflector and back. The transducer requires moving the detector to a new location, constrained by where it can be physically located. An additional major difference is that the vibrometer samples a single line of data running through the field, while the transducer integrates over its entire face area.

The resultant waves seen from the video produced by refracto-vibrometry indicate a complex backscatter pattern contained in the reflection from the heel. However, the transmitted waveform is nearly planar. Therefore, the attenuation and time-of-flight speed of sound measurements traditionally done in ultrasound heel scanners are likely quite robust, with interference at the face of the receiving transducer not having a major impact on the resultant measurement.

CONCLUSIONS

Refracto-vibrometery provides a method for noninvasively sampling an acoustic field. The signals obtained by this measurement, while noisier than the traditional transducer measurements, are advantageous when mapping a complete sound field, as in this study. Applying refracto-vibrometer to the geometry used in a heel-bone ultrasound scanner provides the opportunity to better understand the wave dynamics in this complex system, offering the potential to improve the measurements done by these systems, or increase confidence in their results.

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