Preliminary results of vibro-acoustography evaluation of bone surface and bone fracture

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Background: Vibro-acoustography (VA) uses two co-focused ultrasound beams with slightly different frequencies. The beams interact and generate a low-frequency focus to excite an object.

Methods: A two-element confocal ultrasound transducer with central frequency at 3.2 MHz was used to generate the low-frequency excitation (30 kHz) and the response of the bone to that excitation was acquired by a dedicated hydrophone. The face of the confocal transducer was positioned parallel to the surface of the bone at a focal length of 7 cm. The hydrophone was fixed to the side of the transducer, out of the path of the ultrasonic beam.

Results: The resulting image clearly showed the bone fracture with resolution of 0.25 mm and high contrast with well-defined borders.

Conclusions: In this paper, we present preliminary results of VA imaging of bone surface and of bone fracture using an experimental set-up. Our results encourage future studies using VA to evaluate bone fractures.

Keywords: Bone; fracture; vibro-acoustography (VA); ultrasound

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Introduction

Diagnostic ultrasonography is widely used in medicine to image internal structures in the body. The ultrasound penetration and image resolution are frequency-dependent, which impose a trade-off in the frequency selection. Thus, superficial structures such as muscles and tendons can be imaged at higher frequencies (7–18 MHz) with higher resolution than deeper structures such as liver and kidney, typically imaged at 1–6 MHz (1). In addition, the maximum response of quantitative ultrasound methods is usually associated with tissue resonance frequency, for example, soft tissues 30–400 Hz (2) and stiffer structures such as human dentin 0.5–1.4 MHz (3).

Vibro-acoustography (VA) is an imaging technique that combines multiple co-focused ultrasonic beams with different frequencies at the mega-hertz range to generate high spatial resolution focus of lower frequencies (hertz to kilo-hertz) (4,5). As a result, this technique allows access specific regions at different depths applying selected frequencies such that excited tissue will have maximum response. Assemblies using distinct types of transducers show that it is possible to obtain low frequency foci with lateral resolution of tenths of millimeters (6).

The nonlinear interaction between two ultrasonic beams of near frequencies, equal to $\omega = \omega_0 \pm \Delta\omega/2$ (being $\Delta\omega$ the difference-frequency), gives rise to a pressure field with frequency $\Delta\omega$. The difference-frequency pressure field $P_{\Delta\omega}$ presents contributions from the parametric array (7), the interaction of sound-with-sound (4,7), and induced

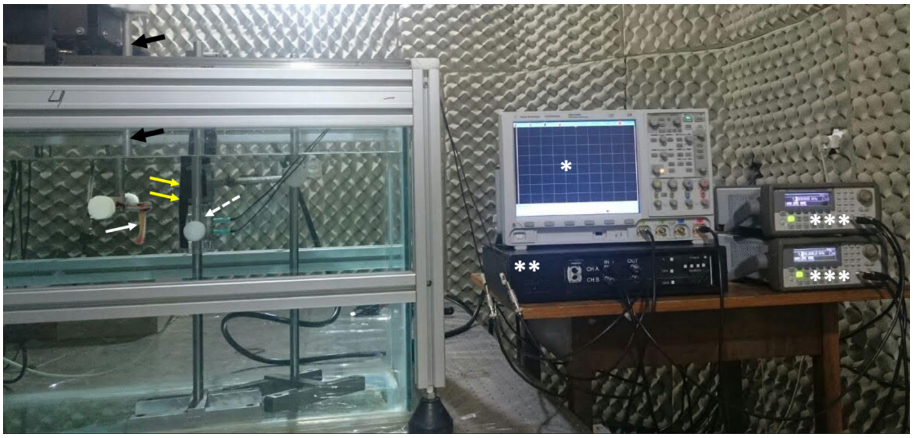

Figure 1 Acoustic tank where the experiments were made. Black and thick arrows indicate the positioning system. Thin white arrow indicates the femur. White dashed arrow points the confocal transducer. Yellow arrows indicates hydrophone. *, oscilloscope; **, power amplifier; ***, function generators.

acoustic emission (8) by a time-modulated radiation force (9-12). The quantification of all contributions can be found in (13).

The VA signal is weighted by the mechanical properties of the sample, such as density, speed of sound, structural characteristics, and viscoelastic parameters. Clinical feasibility studies of VA were previously performed for detection of macrocalcifications in breast (14) and prostate (15). In addition, the use of fundamental frequencies (ω_1 and ω_2) with values lower than 1 MHz allows the generation of VA images of trabecular bone structures to aid in the diagnosis of osteoporosis (16). Using frequencies higher than 2 MHz, it is also possible to select superficial regions of bone structures and implants with generation of three-dimensional VA images to monitor postoperative total hip arthroplasty (17).

When a bone is fractured, its mechanical properties and vibrational characteristics (18) and, consequently, its acoustic scattering and resonant frequencies are changed. The aim of this study is to investigate the potential of VA imaging in the evaluation of bone surface and bone fracture. Preliminary VA images of excised fractured bones using high frequency primary beams are reported.

Methods

This pilot study was conducted using two fresh and cleaned chicken (Gallus gallus domesticus) femur bones. The approval of the Institutional Review Board was not necessary because no animal was sacrificed or submitted to experimental investigation. The bone samples were prepared removing the flesh from chicken thigh obtained in the supermarket. One femur was fractured in its distal region, resulting in a longitudinal separation with maximum cleft width of 2.5 mm. The other femoral bone was intact.

Images were generated in an acoustic tank with degassed water in controlled temperature environment (23 ℃) (*Figure 1*). A confocal two-element transducer with a focus length of 7 cm, a lateral resolution of 0.7 mm, and an axial focus size of 1 cm generated two ultrasound beams. The ceramics were driven by function generators (model 33220A, Agilent Technologies, Palo Alto, CA, USA) with slightly different frequency signals $f \pm \Delta f/2$, where f is the central frequency of the ceramic equal to 3.2 MHz and Δf the frequency difference equal to 30 kHz. The signals were amplified by a homemade power amplifier before going to the ceramics. To detect the low frequency response, we used a wideband-preamplified hydrophone (frequency bandwidth: 0.03–70 kHz, sensitivity: −157 dB/1V/µPa, model ITC-6050C, International Transducer Corporation, Santa Barbara, CA, USA).

The face of the confocal transducer was positioned parallel to the surface of the cleft bone at a focal length of 7 cm. The hydrophone was fixed to the side of the transducer, out of the path of the ultrasonic beam (*Figure 2*). A picture showing the placement of the bone sample relatively to the confocal transducer can be seen in *Figure 3*.

To generate the images, the transducer focus was traced to the bone, according to the pattern shown in *Figure 4*, with a resolution of 0.25 mm, covering an area of 50 mm ×

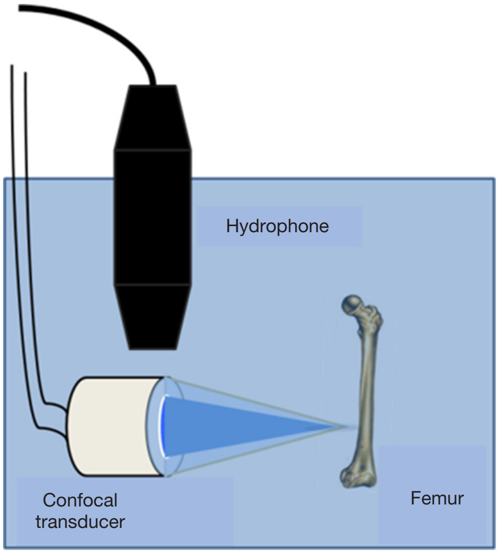

Figure 2 Experimental setup for VA image generation. The hydrophone was positioned to the side of the confocal transducer and the bone sample was positioned in its focal region. VA, vibro-acoustography.

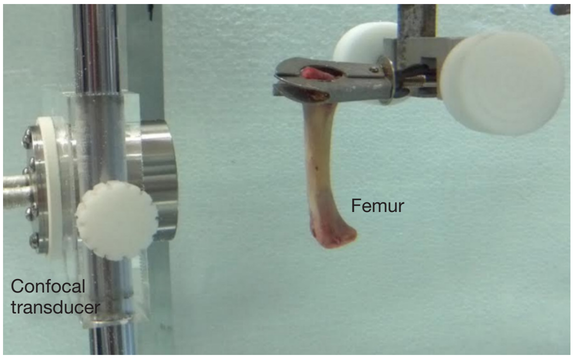

Figure 3 Placement of the bone sample relatively to the confocal transducer.

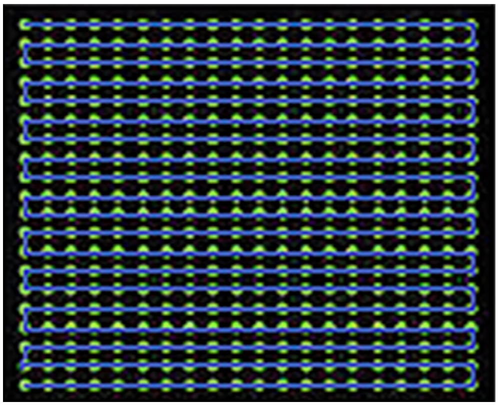

Figure 4 Pattern of VA imaging scan. The blue line represented the path scanned by the focus of the confocal transducer and the green points the acquisition position. VA, vibro-acoustography.

50 mm. Using the same experimental set-up five images of an intact femoral bone were generated for distances between the confocal transducer and bone: 6, 7, 8, 9 and 10 cm.

Results

This pilot study showed that VA images might be suitable to evaluate bone tissue at least in the experimental setup. The acquired images correspond to scanned regions of 2.5 cm × 2.5 cm, with acquisition time for high-resolution VA images (0.25 mm) of approximately 35 minutes.

In *Figure 5* it is possible to observe the fracture of the distal femur both in the original bone (A) and generated image (B,C). In the intermediate region of the fracture, there is a blurring of the image related to the focus positioning.

Figure 6 shows images of intact bone using different distances between the confocal transducer and the bone, which entails different positions of the transducer focus on the bone. At 10 cm bone image was completely unfocused.

Discussion

According to this preliminary study, VA may be suitable for the diagnosis of bone fractures *in vitro*. The acquisition time for high-resolution VA images (0.25 mm) is approximately 35 minutes using the current acquisition system. The acquisition time can be significantly reduced with the implementation of VA in clinical systems (19) using multi-element transducers (20). Future studies are encouraged to test if the technique may be suitable for the diagnosis *in vivo* of small bone fractures.

The contrast in the VA image when the bone was placed at different distances to the transducer, suggest the potential of VA image to evaluate the mineralization of internal structure of the bone. The dark contour around the bone is due to the scattering of the beam at the edge of the bone.

Unlike X-ray techniques, in VA there is no overlay of images when using high fundamental frequencies (greater than 1 MHz). The use of fundamental frequencies f_1 and f_2 of the order of 3 MHz allowed selective image generation

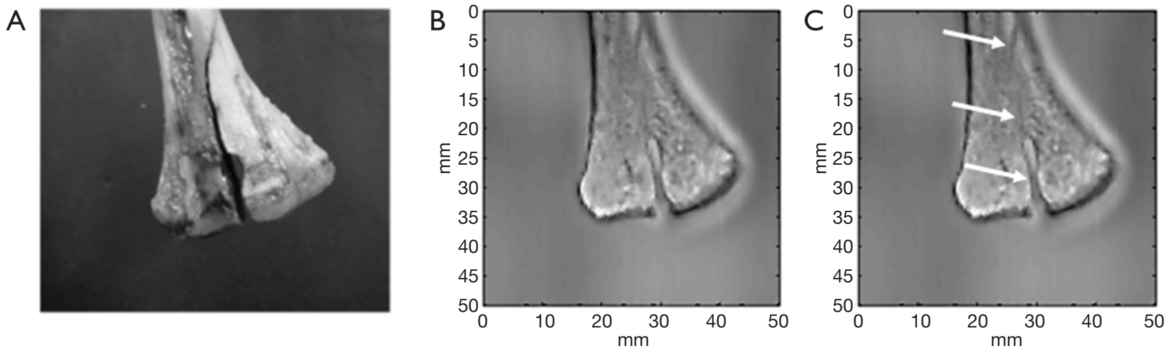

Figure 5 Bone fracture detection with VA. (A) Photograph of fractured bone. The maximum width of the fracture gap was 2.5 mm; (B) VA-generated image with a 30 kHz beat frequency and a resolution of 0.25 mm; (C) same image of (B) with white arrows indicating the fracture. VA, vibro-acoustography.

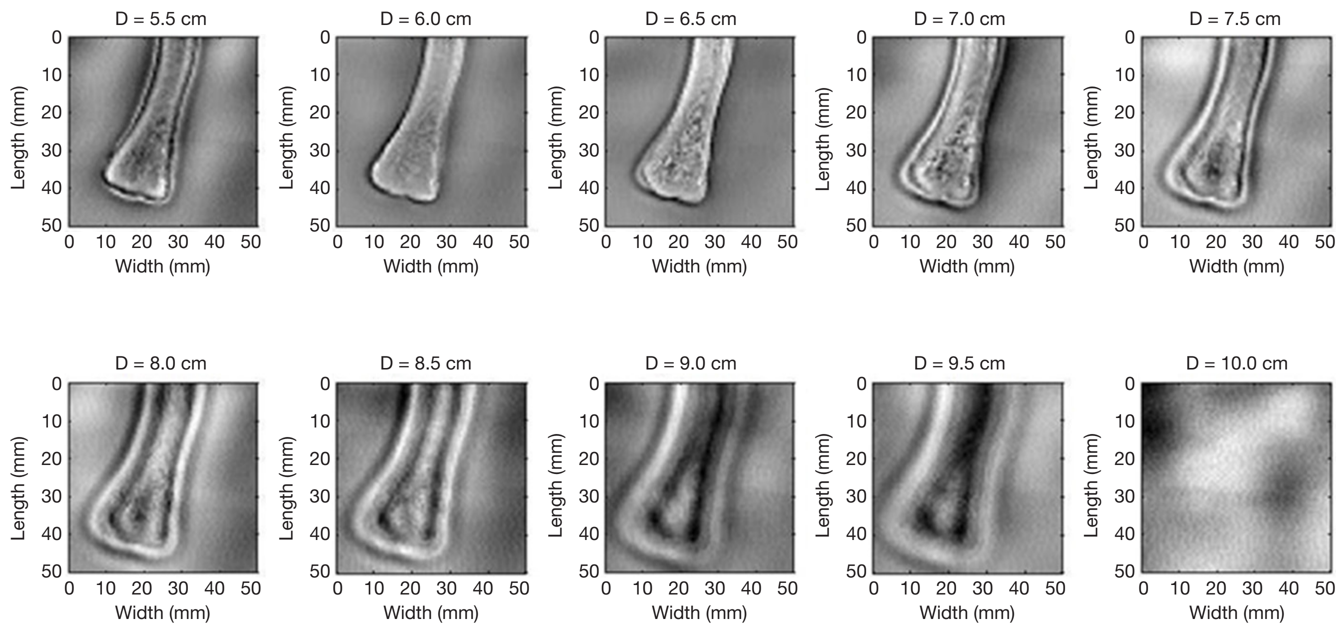

Figure 6 Series of VA bone images obtained with different distances (D) between the transducer and a bone surface. VA, vibro-acoustography.

focusing on the superficial region of the bone. This is because frequencies above 1 MHz have little penetration of the beam in bone, preventing the response of more internal regions. *Figure 5* shows the possibility of selecting the region responsible to generate the image details by changing the transducer focus position.

Non-linear acoustic measurements were used to assess micro cracks in trabecular bone (21). More recently nonlinear resonant ultrasound spectroscopy technique has been used to monitor fatigue cortical bone micro damage (22). Ultrasonometry may be used to identify bone fractures in experimental and *in vivo* studies and to monitor fracture healing (23-27). To our knowledge, we found no previous papers showing VA images of bone fractures.

Our study has limitations that deserve mention. First, we evaluated only one case of femoral fracture. The evaluation of different types of fracture morphology should be performed to confirm the potential use of the technique. Second, the time for image acquisition need to be decreased to allow future clinical application. The current set-up is not suitable for clinical use, though the preliminary results should encourage further research and development.

VA use would prevent patient exposure to ionizing radiation inherent to X-ray techniques used for bone fracture diagnosis in the clinical routine. The high contrast generated by differences in the trabecular structure in the bone potentiates the use of this technique to evaluate the trabecular variation in osteoporotic bones.

Conclusions

The results reported here show that VA is capable of detecting bone fractures *in vitro* in high resolution images. Furthermore, the VA signal is associated with mechanical properties of the tissue. Thus, the acoustic parameters can be tuned to bring structural information of bones and help detecting conditions such as osteoporosis, as previously reported by other groups. VA is a promising technique and its implementation in a clinical system may bring a relatively low-cost and ionizing radiation-free alternative to X-ray to the clinical routine.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

Ethical Statement: The approval of the Institutional Review Board was not necessary because no animal was sacrificed or submitted to experimental investigation.

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