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Quantitative anatomical imaging by ultrasound diffraction tomography

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Abstract: Ultrasound Computed Tomography using linear inversion methods fail to provide high resolution bone images. For children thin bone imaging, acquisition steps must be as fast as possible with a short-time exposure and low-intensity sonication. We have developed a fast-acquisition setup based on a cylindrical-focusing ring antenna, and a fast-protocol using Born approximation and spatial Fourier transform. But the result is still poor contrast-to-noise ratio (CNR) image. This work is concerning the improvement of CNR using a wavelet-based adapted method. Results will be presented and discussed on newborn arm phantoms and *ex vivo* complete organ.

Description of purpose

Current medical B-mode ultrasound does not allow imaging under subperiosteal cortical areas of bone. No information is available on cortical depth, underlying medullary tissue or marrow. Many authors have discussed ultrasonic imaging of bones. Their main objective was to evaluate the thickness of the diaphysis in axial and transverse mode, and/or was to estimate the velocity of the sound of a wave passing through the structure. Our group has been focusing on the cross-sectional radial imaging process using diffraction-mode Ultrasonic Computed Tomography (USCT). Although this method is known to provide a potentially valuable means of imaging objects with similar acoustical impedance, in the case of bone imaging, difficulties are bound with the higher acoustical impedance difference, which strongly alters the propagation of the ultrasonic waves, and generally induces low Contrast-to-Noise Ratio (CNR). It is necessary to change the methods used for the processing of the ultrasonic signals. Our group developed a wavelet-based coded-excitation (WCE) method enabling to process all the information available in frequency and time. The aim of this study is to investigate the feasibility of the WCE method as a mean of Contrast-to-Noise Ratio enhancement of diffraction-mode USCT. In this work, the WCE method is combined with inverse filtering that improves the image quality. Experimental results on newborn arm phantom and on an *ex vivo* chicken drumstick, are presented and the usefulness of the WCE method discussed.

Material and Methods

For the imaging of the upper limbs (arms) and lower limbs (legs), Ultrasound Computed Tomography (USCT) appears to be a possible alternative to the limitations of clinical B-mode ultrasound, allowing to take into account some of the physical phenomena induced by the presence of bones surrounded by soft tissues, and to access the significant acoustic parameters of the environment.

Diffraction-mode USCT exploits the information resulting from the diffraction of the incident acoustic field by the organ, and more specifically the mutual information between several transducers or several elements of an ultrasonic array. The basic principles of USCT have been clearly established in the case of weakly variable media such as homogeneous low contrast soft structures such as breast (Hopp et al. 2018). A constant reference medium is chosen and approximations will be made around a constant background. The problem can then be linearized using the first-order Born approximation, and a method to solve the inverse problem will be to perform an asymptotic far field development. The USCT is based on a simple (and fast) inversion by spreading filtered projections (Lasaygues 2006). A prototype has been developed (Figure 1), consisting of a crown (300 mm) of 8 transducers distributed every 45°. The ring can rotate around the object placed at the geometric center in increments of 1/100 degrees and move vertically to make several

slices. For a given height, it is thus possible to acquire sinograms of 64 signals (8 transmitters x 8 receivers), and to perform 45 rotations to obtain a complete sinogram (2880 projections).

The antenna transducers have a nominal frequency of 1 MHz. At this frequency, lower than that used in clinical B-mode ultrasound or soft-tissue USCT (> 2MHz), the physical phenomena of multiple scattering are less, and the penetration increases allowing to reach inter- or centro-diaphyseal areas. When propagating through an organ containing soft and hard tissues, the superposition of multiple signals due to internal reflections, or mixtures of propagation modes may not allow for proper discrimination of the transfer function of different tissues. Even when using short pulses as in conventional USCT (or B-mode ultrasound), the dispersion can be prohibitive, and the low-pass filtering effect can reduce the temporal resolution. FBP algorithms, even optimized, can cause images with low spatio-temporal resolution and contrast-to-noise ratio (CNR).

Our group has developed several signal (Lasaygues et al. 2018; Lasaygues 2006; Rouyer et al. 2015) and image (Marwa et al. 2019) processing methods. A multiscale wavelet-based coded-excitation (WCE) (Loosvelt and Lasaygues 2011) method has been adapted to the circular antenna (Lasaygues et al. 2017). The WCE method allows to process all local information in terms of frequency and time. Instead of using a regularization process to reduce the effect of Radon's inverse filter singularities, the wavelet transform can be directly used as an inverse regularization filter in the Filtered Back Projection (FBP) algorithm (Doveri et al. 2021; Holschneider 1991). The wavelet transform is suitable for the detection and discrimination of low amplitude signals embedded in noise or for the extraction of information such as the instantaneous frequency and evanescent properties of the medium. Even if efficient, the method requires delicate processing steps with a priori knowledge of the singularities of the medium and an optimized shaping of the transmitted signal associated with the incident wave propagating through the medium. In this work, the algorithm used to shape the transmitted wavelet was developed by Metwally *et al.* (Metwally et al. 2016). The processing time of a complete sinogram is approximately one minute.

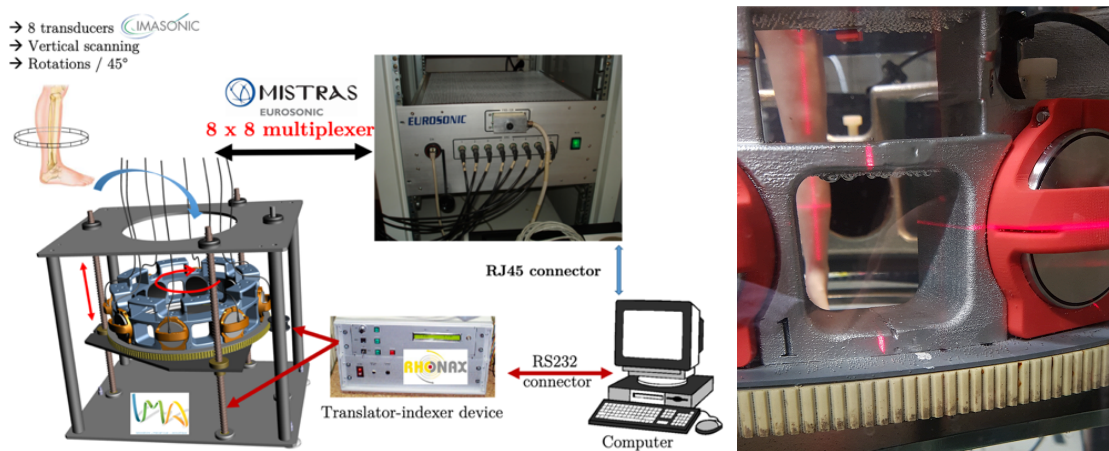


Figure 1: 8-channel circular antenna

Results

Experiments were conducted to confirm the interest of the WCE method. A newborn arm phantom (True Phantom Solution, Windsor, CA) containing blood vessels, single and joined bones was first studied at 6 and 14 mm from the elbow (Figure 2). The water tank temperature was 21°7 and the ultrasonic wave velocity in water was 1486 m/s.

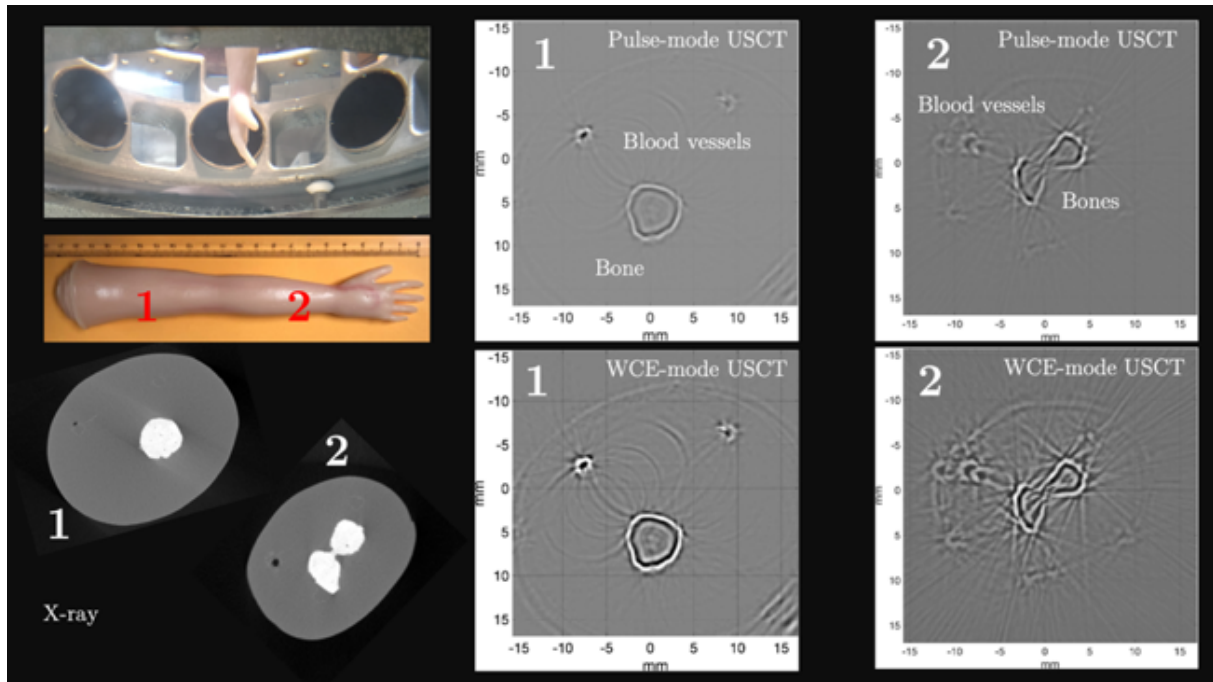


Figure 2: 1-MHz diffraction-mode USCT of a newborn arm phantom (True Phantom Solution, Windsor, CA) at 6 mm (left) and 14 mm (right) from the elbow.

A whole chicken drumstick with skin, different muscles, fat, tendons, nerves, tibia and fibula was also studied in the proximal area 25 mm from the upper tibio-fibular joint (Figure 3).

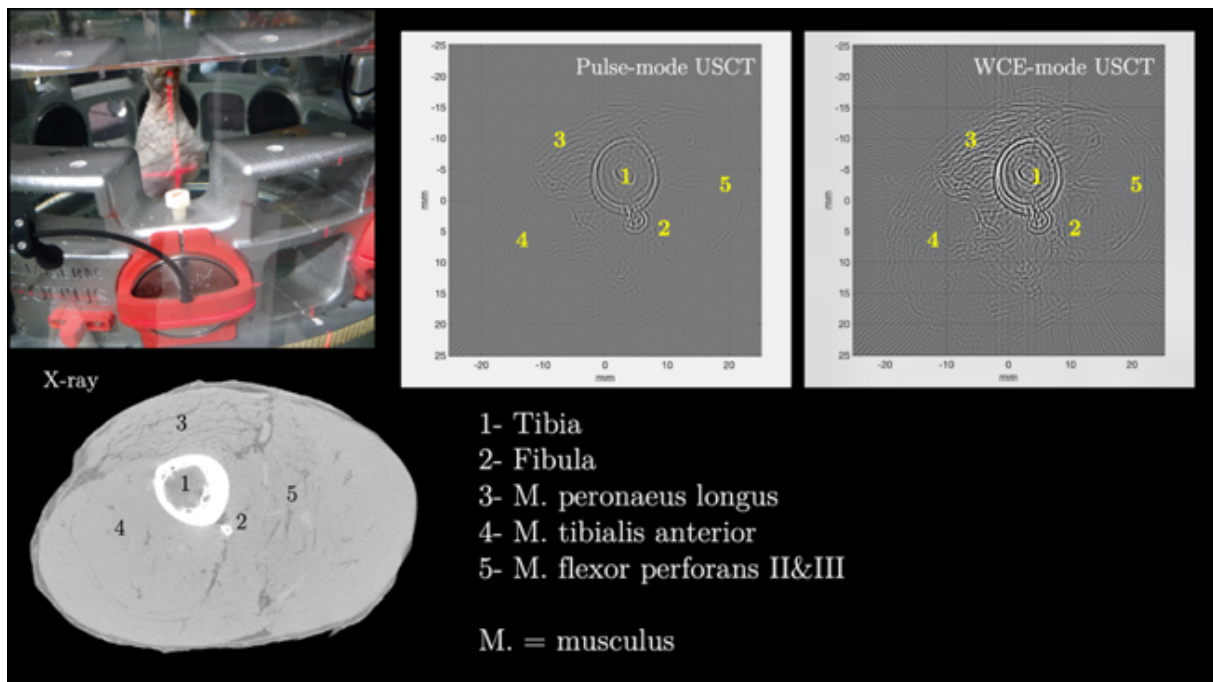


Figure 3: 1-MHz diffraction-mode USCT of a whole chicken drumstick

Comparison μ CT and USCT: On the newborn arm phantom images, the blood vessels appear clearly on the USCT image, and are difficult to discriminate on the μ CT. The different bone tissues, either single or joined, are visible. However, the dimensions are not realistic. The phantom is not developed for research but for training nurses to guide needles under B-mode ultrasound. So, the materials used to make the bones are not realistic, and the acoustic impedance contrasts are much higher than those between a human bone and the surrounding tissues. This is why signals due to multiple reflections are recorded, and the inversion algorithm which only takes into account a fluid model, cannot correctly process them. For the

chicken drumstick, the differences between USCT and μ CT are more significant. The tibia (1) and fibula (2) are visible on USCT but the resolution is not sufficient to distinguish them separately. The muscle (3), very well discriminated on the μ CT, is also visible on USCT with the fibrous structure and the tendinous ends (left and right of the area 3). However, the other muscles (4 and 5) are more difficult to visualize.

Comparison pulse-mode and WCE-mode USCT: To study the interest of the WCE method, the objects were initially imaged using a short pulse as transmitted signal. When comparing the two methods, the WCE-mode method enhances the CNR of the USCT significantly ($> 100\%$). This is more visible in the newborn arm phantom images than in the chicken drumstick, even though the CNR increases.

In conclusion, USCT in diffraction mode provides realistic morphological images of a complete organ, and an adaptation of a wavelet processing method improves image contrast and resolution.

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