FAST WAVE PROPAGATION IN THE EPIPHYSIS OF HUMAN FINGER PHALANGES – ASSOCIATIONS BETWEEN ULTRASOUND VARIABLES AND STRUCTURE OF TRABECULAR BONE

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Abstract

Quantitative Ultrasound (QUS) methods can be used for the estimation of bone fragility. Because ultrasound propagation also depends on architecture of trabecular bone additional features of the bone might be estimated, exceeding the potential of radiological measurements. We measured variables of a fast travelling part of the wave transmitted through the trabecular epiphysis of 32 human finger phalanges in vitro in comparison with density and structure.

Speed of Sound (SOS) and signal amplitude (AMP) correlated positively with bone volume fraction (BV/TV, R^2=0.39 resp. 0.55) and structure variables of the trabecular network (R^2=0.16 – 0.51). In a combined model SOS only correlated with trabecular thickness (R^2=0.55) while AMP correlated predominantly with BV/TV with a minor contribution of trabecular thickness (R^2=0.42). A combination of SOS and AMP could be used to estimate BV/TV at R^2=0.84 with a residual error of 13%.

QUS variables evaluated from a fast travelling part of a wave transmitted through the trabecular epiphyses of human finger phalanges are associated with bone volume fraction and thickness of the (predominantly plate-like) trabeculae.

Introduction

Within the last decade QUS measurements on the trabecular human calcaneus became popular for the estimation of osteoporotic fracture risk of the skeleton. Because ultrasound propagation depends on the architecture of the trabecular network it was expected that information about apparent mineral density and structure of the network could be obtained. However, density and structure appeared to be strongly correlated and only small information about bone structure, predominantly its anisotropy, could be obtained after adjustment for density.

Biot's theory predicts two waves, traveling with different velocities. However, these two waves cannot be separated in calcaneus measurements, potentially due to its high porosity as well as the predominant direction of the trabeculae perpendicular to the ultrasound beam direction in clinical measurements. The aim of our study was to measure ultrasound propagation in a network, where trabeculae are predominantly in alignment with the beam direction, and to investigate if associations with trabecular structure and density can be obtained different as in calcaneus measurements.

Methods

Distal epiphyses of 32 finger phalanges from female human donors were measured in dorso-volar transmission using a clinical device (DBMSonic 1200, Igea, Italy) originally designed for the measurements on the finger metaphysis. Two transducers mounted opposite to each other on a calliper at a fixed distance of 20 mm were immersed in a water bath with the bone positioned between them. Centre frequency was 1.25 MHz. One pulse cycle was used for the excitation of the sending crystal. Phalanges, which were fixed in formalin, were degassed prior to the measurements.

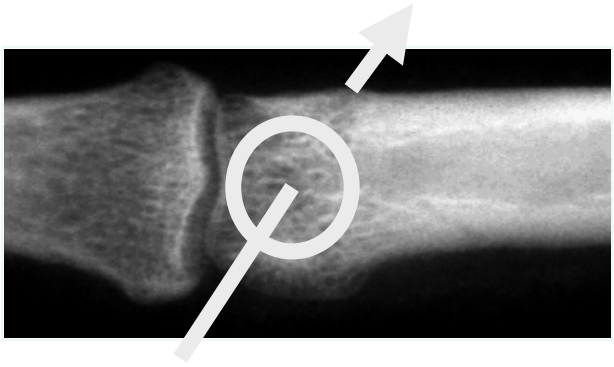


Fig.1: Direction of ultrasound beam penetration through the distal epiphysis of human finger phalanges (dorso-volar).

A typical signal received is depicted in figure 2. Inside the device the signal is rectified to achieve a better depiction on the screen, which has some advantages in clinical routine. Therefore, the negative half-cycles also appears positive.

We defined a cut-off time at 13.5 µs. This is the time at which a wave travelling through bone marrow or water only (velocity of 1480 m/s) would arrive at the receiver. Signal amplitude in the part of the wave arriving later in time usually is very high and cannot be measured correctly by the device (amplitude range limited to approximately 290 units). We only evaluated the part of the signal arriving earlier in time (dotted rectangle in figure 2).

Calculated ultrasound variables were:

1. ***Speed of Sound (SOS)***: ratio between transducer separation and time-of-flight of the signal, measured from the very first part in time of the signal received
2. ***Signal amplitude (AMP)***: average amplitude of the first oscillation (first 2 peaks).

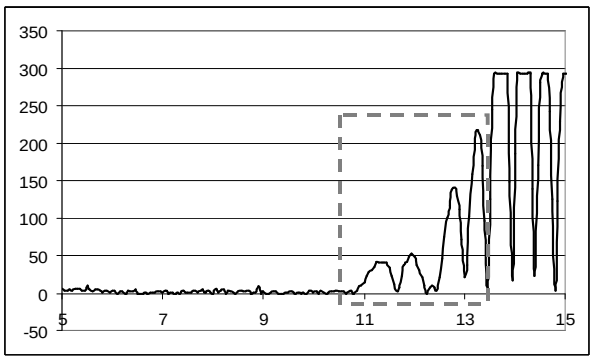
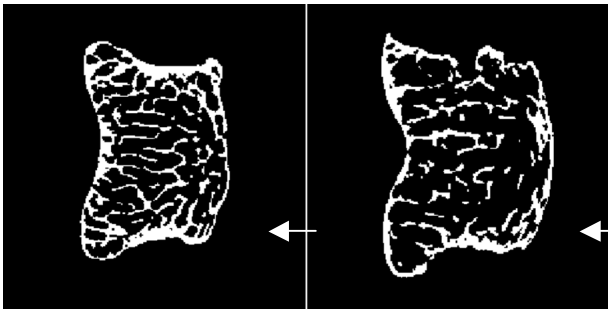


Figure 2: Typical signal received at the distal epiphysis of human finger phalanges. (Note: the signal is rectified inside the device, therefore, only positive values are stored.) The dotted rectangle marks the evaluated part of the signal.

Results were compared with 3D structure parameters assessed using micro computed tomography (Fan Beam µ-scope, Stratec, Germany). 130 slices perpendicular to the bone axis were obtained in the distal epiphysis with an isotropic voxelsize of 60 µm covering a length of 7.8 mm. Two examples of slices from different phalanges of different quality are depicted in figure 3. From the µ-CT measurements it could be seen, that the epiphyseal structure is rather plate-like than rod-like. Plates are aligned predominantly in dorso-volar direction, same direction as the ultrasound penetration.

Figure 3: Two slices of µ-CT measurements in the distal epiphyses of two different finger phalanges. Arrows mark the direction of sound propagation. Edge length's of the dark quadrates are 20 mm.



Structure calculations were performed using the software "Insight" developed in our lab (W.Timm). 3D structure variables were calculated from the three-dimensional dataset. Volume of interest was approximately the largest cuboid inside the epiphysis containing only trabeculae without touching the cortical surfaces.

Structure variables evaluated were:

1. ***Bone volume fraction (BV/TV)*** as a surrogate for apparent bone mineral density, assumed that mineral density inside the trabeculae is fairly constant.
2. ***Trabecular number (TbN)***
3. ***Trabecular thickness (TbTh)***
4. ***Trabecular separation (TbS)***
5. ***Degree of anisotropy (DA)***

Linear regression and stepwise regression techniques were used to assess associations between ultrasound and structure variables resp. density (JMP, SAS Institute Inc., Cary, NC). Pearson's correlation coefficient and the level of significance were calculated for the correlations.

Results

Descriptive statistics of the variables measured are summarized in table 1.

Bone volume fraction and all structure variables except degree of anisotropy correlated significantly with SOS and AMP. Correlation between trabecular separation and ultrasound variables were negative, all other correlations were positive (table 2).

Table 1: Mean and standard deviation of ultrasound and structure variables

	Mean ± SD
SOS / m/s	1724 ± 45
AMP A.U.	28 ± 14
BV/TV	0.26 ± 0.08
TbN / 1/mm	1.76 ± 0.32
TbTh / mm	0.14 ± 0.03
TbSp / mm	0.44 ± 0.13
DA	1.51 ± 0.11

Table 2: Correlations between bone volume fraction and structure variables on one side and ultrasound variables on the other side.
(ns: not significant, *: $p<0.05$, **: $p<0.01$, ****: $p<0.0001$)

	SOS	AMP
BV/TV	0.39 ****	0.55 ****
TbN	0.16 *	0.51 ****
TbTh	0.42 ****	0.27 **
TbS	0.24 **	0.48 ****
DA	0.03 ns	0.00 ns

In a stepwise regression model combining BV/TV and structure variables only trabecular thickness had a significant impact on SOS. AMP correlated strongest with BV/TV with a minor impact of trabecular thickness.

A combination of the QUS variables could be used to estimate bone properties except DA. Both SOS and AMP contributed significantly to the estimation of TbN, TbTh and TbS (R^2=0.61 – 0.65). Best estimation was for BV/TV at R^2=0.84 with a residual error of 13%.

Table 3: Significant correlations between combinations of bone volume fraction and structure variables on one side and ultrasound variables on the other side, calculated using stepwise regression.
(*: $p<0.05$, ****: $p<0.0001$)

	SOS	AMP
BV/TV	-	****
TbN	-	-
TbTh	****	*
TbS	-	-
DA	-	-
R^2	0.55	0.42

Discussion

QUS methods can be used to estimate osteoporotic fracture risk. Best evaluated are measurements on the calcaneus in transverse transmission mode. In this method the transmission of an ultrasound wave through the (predominantly trabecular) calcaneus is evaluated. Ultrasound variables speed of sound (SOS) and broadband ultrasound attenuation (BUA), which describes the increase in attenuation with frequency, are best correlated with bone mineral density (BMD), measured using dual energy x-ray analysis (DXA). DXA as a planar method measures an area density, e.g. values still depend on the thickness of the object. However, in the calcaneus BMD and structure variables strongly correlate with each other, and no substantial impact of structure on QUS could be found after adjustment for BMD (1,2).

The human finger phalanx is the other clinically used site for transverse transmission ultrasound measurements. Measurements are performed at the distal metaphysis which predominantly consists of compact bone. In a former study we could show that the first arriving part of the ultrasound wave travels as a guided wave through the compact shell while a later arriving part crosses the medullary canal (3). QUS variables of the first wave were correlated with geometrical properties of the long bone. However, the clinical significance of measurements on compact bone is not clear since the turnover of trabecular bone in disease and therapy is considered to be stronger due to its larger surface. Therefore, adding measurements on the trabecular epiphysis to (clinically evaluated) measurements on the cortical metaphysis might increase the amount of information about bone status and enhance the clinical significance of QUS measurements. Preceding investigations yielded the feasibility of QUS measurements in dorso-volar direction, while signal quality was insufficient in medio-lateral direction of penetration.

While in human calcaneus measurements the two by Biot's theory predicted waves cannot be separated, other studies e.g. in bovine bone yield a clear separation of these waves (4). In the epiphysis of finger phalanges we also found a signal part with a low amplitude preceding a second part with high amplitude. Although without further examinations we cannot claim that these are the fast and slow wave as predicted by Biot, it is interesting that the properties of the evaluated first part of the signal differs from signal properties in calcaneus measurements.

SOS correlates positively with bone volume fraction in the calcaneus as well as in the phalanx. Different is the behaviour of signal amplitude resp. attenuation. In the phalanx signal amplitude increases with bone volume fraction. In calcaneus measurements usually not signal amplitude resp attenuation is calculated but the increase of attenuation with frequency (BUA). However, our experience is that signal amplitude in the calcaneus decreases with increasing density. This is in agreement with the assumption, that a marrow wave is measured which is deteriorated by the trabecular network. In the phalanx signal amplitude is positively correlated with bone volume fraction indicating that not a marrow wave is measured but a wave which only exists in the presence of trabeculae.

Other differences between phalanx epiphyses and the calcaneus exist. While bone volume fraction is typically about 11% in the calcaneus (1) we measured 26% in the phalanx. Trabecular alignment in the calcaneus is typically perpendicular to the medio-lateral ultrasound beam direction. In the phalanx we observed a large part of plate-like trabeculae in dorso-volar direction, e.g. in direction of the ultrasound penetration. The ultrasound wave travels faster in direction of the trabeculae (5), which might be explained by the existence of bar waves in the trabeculae. Speed of sound of bar waves depends on the thickness of the rod or plate in which it travels. This might be an explanation for the strong correlation between SOS and trabecular thickness in our study.

No association with degree of anisotropy (DA) could be found. This might be due to the fact that the variation in DA is small and trabeculae are aligned predominantly in dorso-volar direction.

Our results should be verified using an independent data set. It would also be of advantage to use a bench top system to get access to the original signal (without rectification) to enable a reliable spectral analysis of the signal. Due to the limitations of spectral analysis in the rectified signal we abstained from citing corresponding results. Another limitation is a part wise mismatch of evaluated regions. Measurements were performed on complete phalanges while structure analysis was done in a cuboid inside the phalanges containing only trabecular bone. However, properties of the cortex and the outer shape might have an impact on ultrasound transmission.

Conclusion

Ultrasound propagation in the epiphysis of human finger phalanges could be evaluated quantitatively. The amplitude of the signal predominantly depends on bone volume fraction and speed of sound predominantly depends on trabecular thickness. The latter might be explained by a bar wave propagation through the plate-like trabeculae in alignment with the ultrasound wave. By combining SOS and amplitude of the signal received 84% of the variability of bone volume fraction could be explained. The residual error of 13 % is comparable with residual errors of clinically used radiological osteodensitometry measurements for the estimation of bone mineral density. It should be evaluated further if the finger epiphysis is a clinically relevant site and how sensitive ultrasound variables react on bone loss in the finger epiphysis, e.g. during perforation of the plate-like trabeculae.

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