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Estimation of cortical thickness and speed of sound using refraction and phase aberration corrected pulse-echo ultrasound

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Background, Motivation and Objective

We have developed a method that uses a conventional US transducer to determine Ct.Th and Ct.SOS using a refraction-corrected multi-focus imaging approach of the outer (periosteal) and inner (endosteal) cortical bone surfaces. The method was validated on plastic reference materials and on cortical bone.

Statement of Contribution/Methods

Four parallelepiped cortical bone samples (thickness: 1.5 to 5 mm) were extracted from bovine tibiae below the periosteal surface. Two polycarbonate (PC), one polyvinylchloride (PVC) and three polymethylmethacrylate (PMMA), and four short glass fiber reinforced epoxy (Sawbones®, Malmoe, Sweden) samples with thickness values between 4 and 8 mm served as reference materials. Reference values of $Ct.Th^{Ref}$ and $Ct.SOS^{Cep}$ were measured by means of a micrometer screw (accuracy: ± 0.002 mm) and by 5-MHz plane wave pulse-echo measurements, respectively. One in-vivo measurement was performed on a young healthy volunteer.

Multi-focus imaging was performed using a medical ultrasound scanner SonixTOUCH equipped with a 3D linear array transducer 4DL14-5/38 (center frequency 8 MHz), and a SonixDAQ single-channel data acquisition system (Ultrasonix, Richmond, Canada). Conventional B-mode imaging sequences with a 32-element transmit aperture were repeated with gradually increasing focus distances (16 steps; step size: 2 mm). Pre-beamformed echo signals were captured using all 128 elements. Beamformed images were reconstructed using the same aperture and focus distance as for the transmit beams. The times of flight ($TOF_{\mathrm{f}}(x,z)$, $TOF_{\mathrm{b}}(x,z)$) and amplitudes ($V_{\mathrm{f}}(x,z)$, $V_{\mathrm{b}}(x,z)$) of reflections from the sample's front and backsides, respectively, were tracked for each array scan position and focus depth (Fig. 1 a and b). The time of flight difference ΔTOF and focus shift ΔF_z between confocal front and backside were used to calculate Ct.Th and Ct.SOS for each scan position [1,2].

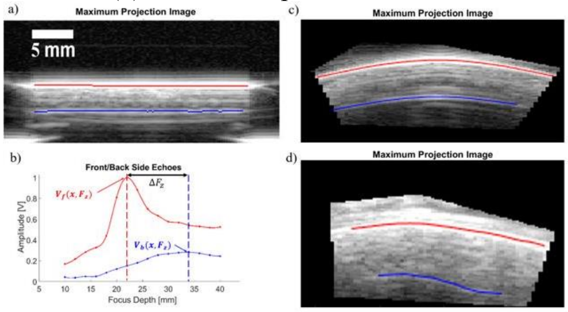
Results/Discussion

Table 1 summarizes the values obtained with the reference and the multi-focus methods. The accuracy of the multi-focus method was 0.04 mm for Ct.Th and 17 m/s for Ct.SOS. The measurement precisions of the multi-focus method were comparable to those of the reference methods: $Ct.Th^{MF}$ = 0.83%, $Ct.SOS^{Cep}$ = 0.36%, $Ct.SOS^{MF}$ = 0.42%. Ct.Th and Ct.SOS can be estimated reliably using multi-focus ultrasound imaging. For in-vivo application further work is required to implement a local phase aberration correction that accounts for the non-flat periosteal bone surface. The developed technique is anticipated to have high clinical potential since it uses conventional US technology, is non-invasive and non-ionizing and can assess Ct.Th and Ct.SOS locally with image guidance.

References

[1] Maev et al., IEEE Trans. Ultrason., Ferroelect., Freq. Contr., 44: 1224-1231, 1997.
[2] Raum et al., Proceedings of ICU, 31, 2003.

Fig.1: Max. projection B-mode image reconstructed from all focus distances with tracked front (red line) and backside surfaces (blue line) of a bovine sample (a), of a cylindrical Sawbone® sample (c) and human tibia volunteer (d). Tracked amplitudes of front and backside surface reflections of a 4.78 mm bovine sample (b).



Tab.1: Ct.Th and Ct.SOS estimated with reference and the multi-focus methods

Shape of sample	Material	$Ct.Th^{Ref}$ (mm)	$Ct.Th^{MF}$ (mm) Mean ± SD	CV (%)	$Ct.SOS^{Cep}$ (m/s) Mean ± SD	CV (%)	$Ct.SOS^{MF}$ (m/s) Mean ± SD	CV (%)
parallelepiped	Bovine	1.55	1.54 ± 0.02	1.2	3318 ± 18	0.5	3287 ± 11	0.3
		2.01	1.98 ± 0.02	1.0	3267 ± 9	0.3	3253 ± 16	0.5
		2.56	2.49 ± 0.06	2.4	3308 ± 36	1.1	3225 ± 52	1.6
		4.78	4.71 ± 0.05	1.0	3279 ± 36	1.1	3224 ± 19	0.6
	Sawbone®	1.12	1.12 ± 0.01	0.9	2805 ± 5	0.2	2806 ± 7	0.2
		1.76	1.77 ± 0.04	2.3	2843 ± 17	0.6	2827 ± 3	0.1
		2.80	2.74 ± 0.02	0.7	2792 ± 3	0.3	2795 ± 2	0.1
		4.74	4.72 ± 0.07	1.5	2960 ± 4	0.1	2942 ± 23	0.8
	PMMA	0.86	0.86 ± 0.01	0.4	2737 ± 6	0.2	2715 ± 5	0.2
		1.95	1.94 ± 0.01	0.5	2702 ± 2	0.1	2699 ± 3	0.1
		4.04	4.00 ± 0.01	0.3	2708 ± 4	0.1	2701 ± 4	0.2
	PVC	8.20	8.21 ± 0.03	0.4	2204 ± 4	0.2	2325 ± 3	0.1
	PC	6.24	6.24 ± 0.03	0.5	2244 ± 8	0.4	2244 ± 8	0.4
		7.18	7.15 ± 0.03	0.4	2218 ± 3	0.1	2218 ± 5	0.2
curved	Sawbone®	5.80	5.9 ± 0.3	0.5	2838 ± 3	0.9	2787 ± 16	0.5
curved	Tibia (volunteer)		6.88 ± 0.11	1.6			3425 ± 97	2.8