4^{th} European Symposium on Ultrasonic Characterization of Bone

ESUCB 2011

Department of Physics
University of Jyväskylä
Jyväskylä, Finland
20–21 June 2011

Scientific Committee

Local Organizer	Petro Moilanen
International Scientific Committee	Pascal Laugier (France) Frederic Padilla (France) Claus-C. Glüer (Germany) Reinhard Barkmann (Germany) Kay Raum (Germany) Michal Pakula (Poland) Emmanuel Bossy (France) Keith A. Wear (USA) Jonathan J. Kaufmann (USA) Mami Matsukawa (Japan) Dean Ta (China) Jussi Timonen (Finland) Sulin Cheng (Finland) Jukka Jurvelin (Finland) Patrick Nicholson (UK)

Scientific Program Information

Oral Presentation

All the oral presentations will take place in the lecture hall FYS 1 in the Department of Physics at the University of Jyväskylä. The time reserved for each presentation is 15 minutes. The recommended time for the actual presentation is 10 minutes, as approximately 5 minutes should be reserved for questions and discussion. Proper discussion and questions are essential for the students, who are expected to form a large part of the attendees.

30 minutes have been reserved for introductory and plenary presentations. 5 minutes of this should again be used for questions and discussion.

The session chairs are responsible for maintaining the schedule and guiding the discussion. They should also be present to organize the session 15 minutes before the scheduled time.

Poster Presentations

A space in the hallways directly outside the lecture hall will be reserved for the poster presentations. The length of the poster session will be 90 minutes and it will be during the last coffee break on Monday. Maximum size for the posters is one A0 sheet (portrait oriented).

At least one of the authors should be available to present the results of the poster during the poster session. Sufficient space will be reserved for all of the submissions, so posters need not be removed after the session. The hallways reserved for poster sessions can be used by the conference attendees at any time during the conference.

Social Program

Monday 20th - Barbeque party at the lakeside terrace of the Hotel Alba

After the scientific sessions on Monday we invite you to enjoy the company of your colleagues and the taste of barbequed dishes. The barbeque party takes place at the terrace of the Hotel Alba, close to the conference venue. All participants are welcome.

Tuesday 21st - Gala dinner at the idyllic farmyard of Savutuvan apaja.

We hope that you will join us on a gala dinner on Tuesday after the scientific program. A bus will transport all the enrolled to a historical country site about 12 km away from the city of Jyväskylä. A finnish dinner will be served and you can enjoy the warm summer evening by the lake Päijänne. The lakeside scenery provides a beautiful setting in which you can follow the midnight sun, which barely sets at all at this time of the year. The bus leaves in front of the Hotel Alba at 7 p.m. and we will return around 11 p.m.

Internet access

A free of charge WLAN access will be available during the whole conference. Detailed instructions and personal password will be given to each conference participant.

Sponsors

Schedule

Time	Sunday 19th	Monday 20th	Tuesday 21st
8:30		8:30 Registration	
9:00		9:00 **Opening and Welcome note** Petro Moilanen 9:15 **Invited lecture:** Prof. Juliet Comspton 9:45 **Session I:** Bone Material and Structure	9:00 **Invited lecture:** Prof. Claus-Christian Glüer 9:30 **Session V:** Clinical Quantitative Ultrasound
9:30			
10:00		10:15 Coffee break	10:15 Coffee break
10:30		10:45 **Session II-a:** Bone Growth 11:00 **Session II-b:** Fractures and Healing	10:45 **Session VI:** Models for Ultrasonic Characterization of Cortical Bone
11:00			
11:30			
12:00		12:00 Lunch break: Restaurant Ylistö	12:15 Lunch break: Restaurant Ylistö
12:30			
13:00			
13:30		13:30 **Session III:** Ultrasonic Propagation Models for Cancellous Bone	13:45 **Session VII:** Guided Waves and Ultrasonic Characterization of Cortical Bone
14:00			
14:30		14:45 **Poster session** / Coffee break	
15:00			
15:30			15:30 Coffee break
16:00	16:00-20:00 Registration	16:15 **Session IV:** Ultrasonic Characterization of Cancellous Bone	16:00 **Session VIII:** New Technologies and Imaging
16:30			
17:00		17:00-17:45 Lab tour: Micro-CT laboratory	17:00-17:45 Lab tour: Micro-CT laboratory
19:00		19:30-21:30 Get-together evening: Barbeque at Hotel Alba	19:00-23:00 Gala dinner: Finnish evening
20:00			

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Session IV: Ultrasonic Characterization of Cancellous Bone
Monday, June 20th 2011, 16:15, Chair: Jukka Jurvelin

Invited lecture
Tuesday, June 21st 2011, 09:00, Chair: Jussi Timonen

Session V: Clinical Quantitative Ultrasound
Tuesday, June 21st 2011, 09:30, Chair: Jussi Timonen

Session VI: Models for Ultrasonic Characterization of Cortical Bone
Tuesday, June 21st 2011, 10:45, Chair: Pascal Laugier

Session VIII: Novel Instrumentation and Imaging
Tuesday, June 21st 2011, 16:00, Chair: Reinhard Barkmann

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Invited Lecture

Monday, June 20th 2011, 09:15

Chair: Sulin Cheng

Bone quality: a clinical perspective

*Juliet Compston

Medicine, University of Cambridge, Cambridge, United Kingdom
*jec1001@cam.ac.uk

Bone strength is determined by a number of inter-related variables which include bone mineral density (BMD), bone geometry and bone quality. Whilst BMD is a strong predictor of bone strength and fracture risk in the untreated state, therapeutically induced changes in BMD explain only a small proportion of the associated reduction in fracture, indicating that changes in bone quality may be more important in this context. The importance of bone quality is also evident from disease states in man, some of which are associated with increased fracture risk despite increased bone density and even bone size.

Assessment of bone quality in vivo can be made using a number of approaches, including biochemical markers of bone turnover, bone histomorphometry and imaging techniques, for example quantitative computed tomography (QCT) and magnetic resonance. In particular, the application of high-resolution QCT techniques to both the axial and appendicular skeleton enables more detailed characterisation of cortical and cancellous bone structure in vivo than has previously been possible and will provide new insights into the mechanisms underlying bone fragility in disease and the effects of therapeutic interventions on bone structure and strength.

*Presenting author

Session I: Bone Material and Structure

Monday, June 20th 2011, 09:45

Chair: Sulin Cheng

Most of variations of cortical bone elasticity at the mesoscale (millimeter scale) are determined by porosity variation in aged women.

*Mathilde Granke[1], Quentin Grimal[1], Amena Saïed[1], Pierre Nauleau[1], Françoise Peyrin[2], Pascal Laugier[1]

[1]UPMC Univ Paris 06, CNRS, UMR 7623, Laboratoire d'Imagerie Paramétrique, France
[2]CREATIS INSERM U1044; CNRS 5220; INSA Lyon; Université de Lyon; ESRF, France
*mathilde.granke@gmail.com

At the mesoscale (i.e. a few millimeters), cortical bone can be described as two-phase material, which consists of pores and a relatively hard mineralized matrix. The cortical porosity is known to influence the mesoscopic elasticity. Our objective was to determine whether the variations of porosity are sufficient to predict the variations of bone mesoscopic anisotropic elasticity or if the bone matrix stiffness is an important factor to consider. Measurements were conducted on human femoral cortical bone (21 specimens taken from 10 women donors). A 50MHz scanning acoustic microscope (SAM) was used to evaluate the bone matrix elasticity (reflected in impedance values) and porosity. Porosity evaluation with SAM was validated against Synchrotron Radiation microCT measurements. A standard contact ultrasonic method was applied to determine the mesoscopic anisotropic stiffness coefficients. The mesoscopic stiffness was found to be highly correlated ($R^2 = [0.72 - 0.84]$) to the cortical porosity. Multivariate analysis including tissue elasticity did not provide a better statistical model of mesoscopic stiffness variations. This work suggests that the cortical porosity accounts for most of the variations of mesoscopic elasticity, at least when the analyzed porosity range is large (3-27 % in this work).

*Presenting author

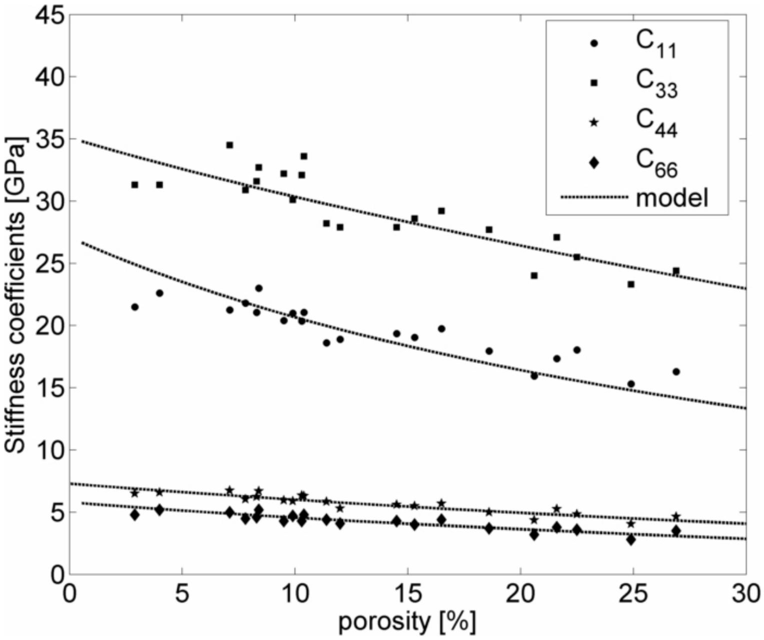

Figure 1: The comparison of our results with the predictions of a micromechanical model indicates that cortical bone can be modeled with fixed matrix properties and a sample-dependent porosity fraction.

Spatial distribution of tissue mineralization and anisotropic tissue elastic constants in human femoral cortical bone

Daniel Rohrbach[1], Sannachi Lakhsmanan[1], Max Langer[2], Francoise Peyrin[2], Alf Gerisch[3], Quentin Grimal[4], Pascal Laugier[4], *Kay Raum[1]

[1]Julius-Wolff-Institut, Charité-Universitätsmedizin Berlin, Berlin, Germany
[2]ESRF, Grenoble, France
[3]TU Darmstadt, Darmstadt, Germany
[4]UPMC, Paris, France
*kay.raum@charite.de

The spatial distribution of micro- and mesoscale anisotropic elastic properties and mineralization within a human femoral cortical bone shaft (female:72years) have been investigated. Cylindrically shaped punch biopsy samples (diameter: 4.4mm,N=56) were analyzed using SAM at 50MHz (Fig.1) and SR-μCT.

For all samples the average cortical porosity (Ct.Po), tissue elastic coefficients (c_{ij}) and the average tissue degree of mineralization (DMB) were derived from SAM and SR-μCT measurements. The volumetric bone mineral density (vBMD) and mesoscale stiffness coefficients (C_{ij}) were derived using a rule of mixtures and an asymptotic homogenization approach, respectively. Variations of these properties were derived with respect to the anatomical location and relations between these properties were analyzed.

Variations of DMB (1.5%) had a minor effect on the variations of mesoscale elastic properties (11-21%). Multivariate regression revealed that the microscale coefficients c_{ii} and Ct.Po contributed approximately equally to the variations of C_{ij}. The correlations of vBMD with C_{ij} were less than 70 %. However, a combined in-vivo assessment of vBMD and C_{ii} may lead to a precise and distinct prediction of variations of Ct.Po and tissue elasticity, e.g. in the course of pathologies or treatment.

*Presenting author

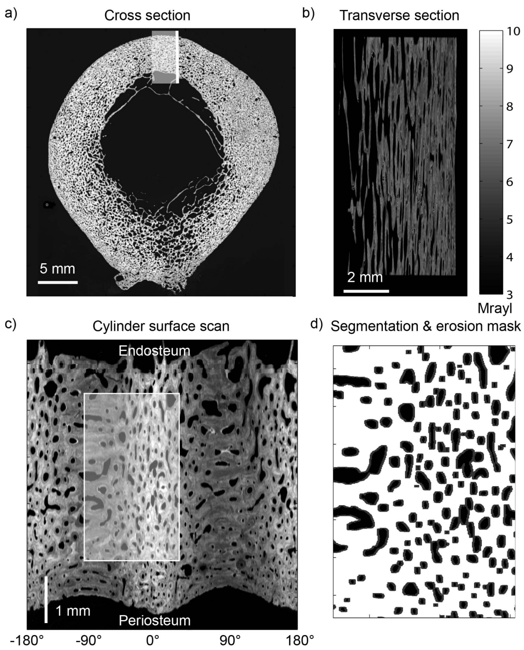

Figure 1: Acoustic impedance image of a cross-section (a). The highlighted rectangle and line indicate the region for the transverse sectional scan (b), and the cylinder measurement (c). For better illustration the cylinder surface was unwrapped. The image segmentation and erosion is shown in (d) for the small region highlighted in (c).

Session II-a: Bone Growth

Monday, June 20th 2011, 10:45

Chair: Kay Raum

Elastic values of fibula children bone autotransplants

*Jean-Philippe Berteau[1], Martine Pithioux[2], Hélène Follet[3], Patrick Chabrand[2], Philippe Lasaygues[1]

[1]UPR 7051, LMA, Marseille, France
[2]UMR 6233, CNRS & Université de la Méditerranée, Marseille, France
[3]U831, INSERM, Lyon, France
*jean-philippe.berteau@univmed.fr

For cortical bone, few studies consider mechanical characteristic of growing process. In the literature, the samples studied are close to cancellers cells (Baleani et al., 2008), or from cadaver (Currey, 1975) and the results are dispersive. We have focused our study to the most used bone for cortical transplantation, the fibula bottom extremity. It is a two step method; first we have evaluate the porosity and the osteonal orientation with histological image; second, we have tested cortical sample in ultrasonic bench with nominal frequency of 7 and 10 MHz. The first step shows a low porosity level and an osteonal orientation similar to an adult fibula, it is leading us to consider it as transversely isotropic and reliable to an ultrasonic transmission scanning. The second step gives an average value of CL (longitudinal velocity) of 13 bone samples (extracted from children from 4 year old to 16) is 2818 m·s^{-1} (± 540) and of CT (transversal velocity) is 1804 m·s^{-1} (± 213). These results are lower than adult, but not depending of children age. This is the first study which provides cortical bone ultrasonic velocity of children population.

*Presenting author

Session II-b: Fractures and Healing

Monday, June 20th 2011, 11:00

Chair: Kay Raum

Noninvasive functional assessment of a rat femur model and phantoms using quantitative focused ultrasound (QUS): A pilot study.

*Daniel Rohrbach[1], Bernhard Hesse[1], Bernd Preininger[2], Kay Raum[1]

[1]JWI, AG Raum, Charite, Berlin, Germany
[2]Charite, Berlin, Germany
*Daniel.Rohrbach@charite.de

It was hypothesized that QUS is suitable for the assessment of the early stages of bone healing. Precise understanding of the interaction of ultrasound (US) with biological tissue has not been achieved yet. Thus the aim of this study was to gain a profound understanding of ultrasound wave propagation. The experiments were conducted using two 5-MHz US transducers (lateral resolution=0.45 mm). Synthetic phantoms mimicking the geometrical properties of small long bones and rat femora were scanned in through-transmission and pulse-echo modes. Different sets of phantoms were prepared: (i) water filled, (ii) air filled, (iii) 1-mm gap region and gap filled with (iv) connective tissue and (v) cartilage.

Structural parameters like wall thickness (1.05±0.05) could be extracted from phantom i and ii. Different wave types, reflected, transmitted-direct and transmitted-guided waves (net time delay 0.19±0.01) could be distinguished and separately analyzed for the rat femora and phantoms. For each region the average broadband ultrasound attenuation (BUA) and time of flight (TOF) were calculated and compared.

These results emphasize on the feasibility of QUS measurements for the investigation of small animal long bones. It could be demonstrated that different waves and parameters are related to different tissue types and ultrasonic pathways.

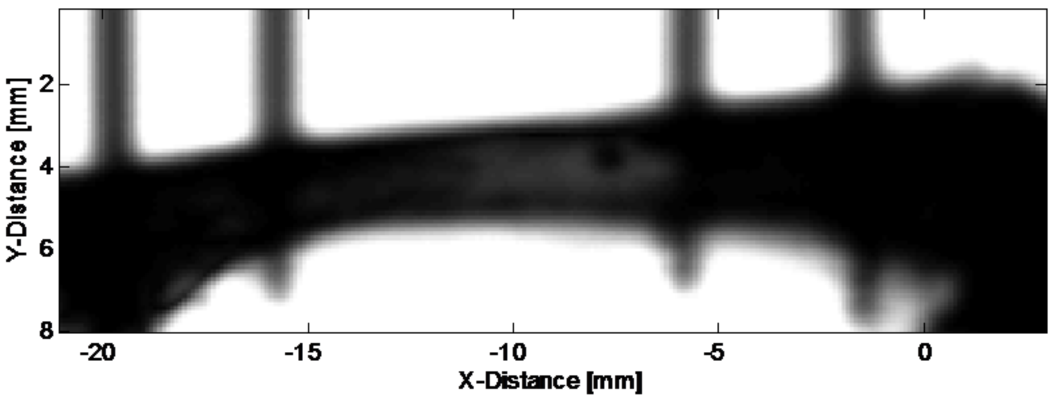

Figure 1: Shows a through transmission QUS amplitude image of intact rat femora fixed at four pins.

*Presenting author

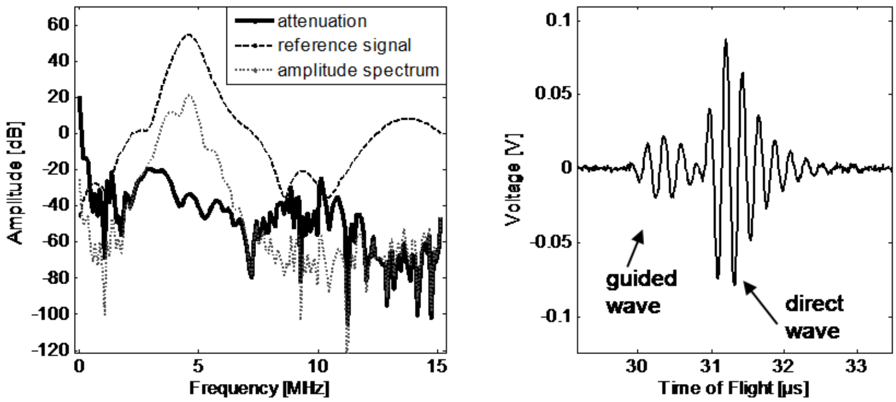

Figure 2: Shows a transmitted time resolved signal (right) and a power spectrum (left) of a phantom. The guided and direct wave are separable. Reference signal is referred to be the power spectrum measured in water and attenuation is the difference spectrum of the reference signal and amplitude spectrum (power spectrum of signal).

Using micro Brillouin scattering technique for the assessment of the elastic properties of newly formed bone in the vicinity of an implant

*Vincent Mathieu[1], Kenji Fukui[2], Mami Matsukawa[2], Masahiko Kawabe[2], Romain Vayron[3], Emmanuel Soffer[1], Fani Anagnostou[1], Guillaume Haïat[3]

[1]Lab. Biomécanique et Bioingénierie Ostéo Articulaire, CNRS, 75010 PARIS, France
[2]Lab. Ultrasonic Electronics, Doshisha University, 610-0321 KYOTO, Japan
[3]Lab. Modélisation et Simulation Multi Echelle, CNRS, 94010 CRETEIL, France
*vincent.mathieu@univ-paris-diderot.fr

The use of titanium implants allowed considerable progress in dental and orthopaedic surgery. However, the reasons for implant failure remain difficult to understand. Remodeling phenomena at the bone-implant interface play a predominant part in the osseointegration of the implant. In this study, the use of micro-Brillouin scattering technique is proposed to assess the elastic properties of newly formed bone in the vicinity of the implant, at the micrometer scale. To do so, an original animal model was used, consisting in securing a coin-shaped titanium implant (see Fig. 1) in contact with a leveled surface of the tibia of a rabbit. This animal model allows the formation of a cavity exclusively filled with newly formed bone after the implantation period. After the sacrifice, micro-Brillouin velocity measurements were performed in mature and newly formed bone regions and an histological analysis was realized. The results show that significantly higher velocities are obtained in mature bone compared to newly formed bone, which is in agreement with the higher mineral content observed in histological slices for mature bone. This multimodality study shows the potentiality of the animal model and of micro-Brillouin scattering for the assessment of newly formed bone elastic properties.

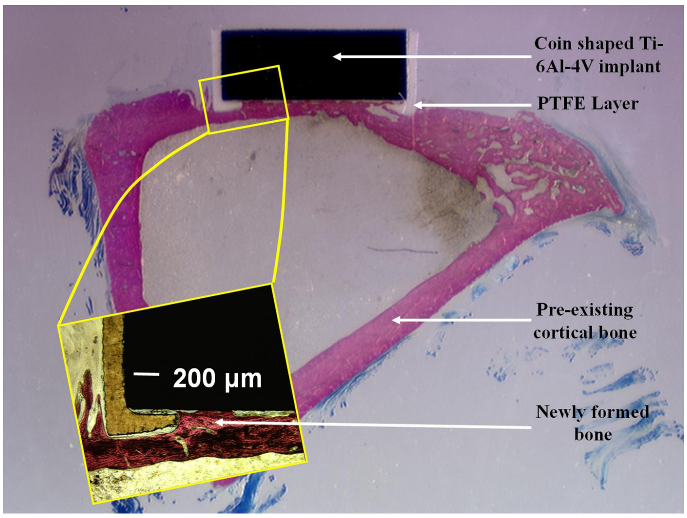

Figure 1: Image of a coin shaped titanium implant after 7 weeks of implantation on the tibia of a New Zealand White rabbit.

*Presenting author

The influence of callus mineralization degree on ultrasound axial transmission measurements: an in vitro approach

Christiano Bittencourt Machado[1], Wagner Coelho de A. Pereira[2], Mathilde Granke[3], Maryline Talmant[3], Frédéric Padilla[4], *Pascal Laugier[3]

[1]Biomechanics Laboratory – Campus Friburgo, Estácio de Sá University, Nova Friburgo – RJ, Brazil
[2]Biomedical Engineering Program, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro – RJ, Brazil
[3]Laboratoire d'Imagerie Paramétrique, Université Pierre et Marie Curie, Paris, France
[4]Department of Radiology, University of Michigan Medical Center, Ann Arbor, USA
*Pascal.Laugier@upmc.fr

This work aims at studying the effect of cortical bone mineralization on ultrasonic axial transmission measurements, using experiments and numerical simulations. A reverse fracture healing approach is proposed, using a cortical bovine femur sample with a 3-mm fracture gap. A 3-mm thick cortical bone slice was extracted and submitted to a progressive chemical demineralization during 12 days. Each day, axial transmission measurements were achieved with the 3-mm thick cortical bone slice placed back inside the gap. Calcium concentrations in chemical solutions were also quantified each day. Axial transmission measurements and FDTD simulations using a 1-MHz probe were performed to estimate the time-of-flight of the first arriving signal (TOFFAS) (Figure 1) in three configurations: (i) bone specimen intact; (ii) bone specimen with the fracture gap; (iii) bone specimen with the 3-mm thick cortical bone slice placed back at each stage of demineralization. A progressive increase in TOFFAS ($p < 0.001$) was observed until day 4 of demineralization (Figure 2), corresponding to the rapid initial loss of calcium. Experimental data were in good agreement with numerical simulations and the results show the potential of axial transmission on the consolidation follow-up, specifically on callus mineralization.

*Presenting author

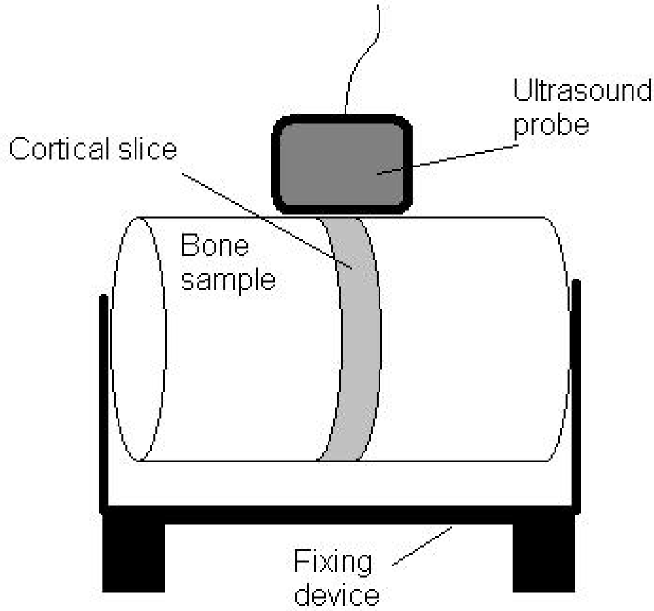

Figure 1: Experimental setup. The cortical slice is put inside the 3-mm fracture gap for ultrasound measurements with a 1-MHz ultrasound probe. A fixing device is used to avoid undesirable movements.

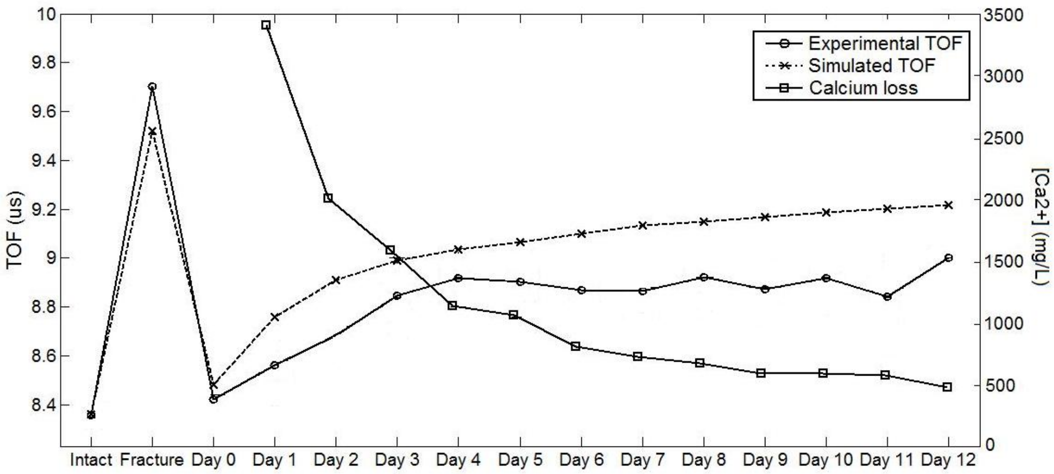

Figure 2: Experimental and simulated TOFFAS for intact, fractured and demineralized bone (from days 0 to 12). It can be also observed the calcium loss curve from the demineralization process.

Nonlinear ultrasound monitoring of four-point bending fatigue induced micro-damage

*Sylvain Haupert[1], Sandra Guerard[2], Paul A. Johnson[3], David Mitton[4], Pascal Laugier[1]

[1]UPMC – CNRS – LIP, Paris, France
[2]Arts et Metiers ParisTech – LBM, Paris, France
[3]Geophysics Group, Los Alamos National Laboratory, Los Alamos, USA
[4]Univ Lyon – Ifsttar – LBMC, Arts et Metiers ParisTech – LBM, Paris, France
*sylvain.haupert@upmc.fr

Accumulation of bone micro-damage is suspected to lead to severe impairment of mechanical properties (toughness and stiffness) with an increase in skeletal fragility and fracture risk. The objective of the study was to evaluate the resonant ultrasound spectroscopy (NRUS) technique for measuring micro-damage accumulation in cortical bone using mechanical fatigue. Sixteen human cortical bone specimens were machined as parallelepiped beams (50*4*2mm) to control damage localization during four-point bending fatigue cycling and to unambiguously identify resonant modes for NRUS measurement. During damage progression, load and displacement curves were recorded to extract secant (Esec), loading (Eload) and linear elastic beam theory (ELEBT) moduli. The latter has been shown previously to reflect micro-damage accumulation during four-point bending mechanical fatigue. Before and between each damage step, nonlinear ultrasonic elastic (af) and dissipative (aQ) coefficients were monitored by NRUS. At the end of fatigue cycling, results showed no significant variation of the linear elastic moduli (Esec and Eload). In contrast, mean values of both af and aQ increased significantly (50% and 20% respectively) while ELEBT mean value decreased significantly (43%). The results of this study suggest that non invasive monitoring fatigue micro-damage accumulation in cortical bone can be achieved using nonlinear ultrasound techniques.

*Presenting author

Session III: Propagation Models for Cancellous Bones

Monday, June 20th 2011, 13:30

Chair: Michal Pakula

Investigation of fast and slow wave attenuation properties of cancellous bone -application of Bayesian techinique to the experimentally observed waveforms-

Amber Nelson[1], Joseph J. Hoffman[1], Christian Anderson[1], Mark Holland[1], Katsunori Mizuno[2], Yoshiki Nagatani[3], James G. Miller[1], *Mami Matsukawa[2]

[1]Department of Physics, Washington University in St. Louis, St. Louis, USA
[2]Laboratory of Ultrasonic Electronics, Doshisha University, Kyotanabe, Japan
[3]Department of Electronics, Kobe City College of Technology, Kobe, Japan
*mmatsuka@mail.doshisha.ac.jp

The goal of this study was to investigate the attenuation behavior of overlapping fast and slow waves in cancellous bone, using Bayesian parameters estimated from experimentally obtained waveforms. Simulated data with Bayesian parameters were generated using a propagation model including both fast and slow waves. Two analysis methods for determining the attenuation as a function of propagation distance were applied to samples of two lengths. The first was a time-domain analysis using amplitudes of the first peak of mixed waveform. The second was a frequency-domain analysis using the separated fast and slow waves. In the time-domain analysis, the apparent attenuation of the fast wave is larger at the beginning and gradually decreases as the wave travels farther into the bone. The frequency-domain analysis gives almost constant attenuation coefficients for each wave mode without dependence on the propagation distance, but different values of samples of different length. The simulated data tell us that the apparent dependence of the attenuation on propagation distance can arise from analyzing the unseparated signal with time domain analysis. Phase cancellation at the face of a phase sensitive receiver can also yield attenuation that appears to vary with propagation distance. Supported in part by NIH R01 AR057433

*Presenting author

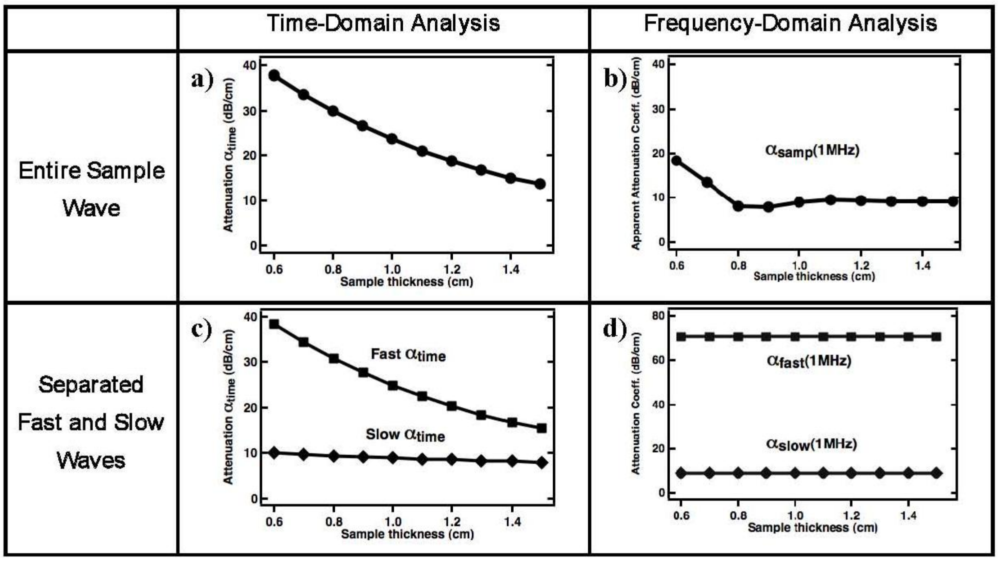

Figure 1: The attenuation behavior as a function of sample thickness results when applying, panel (a): the time-domain method to the unseparated fast wave, panel (b): the log spectral subtraction technique to the entire sample wave, consisting of overlapping wave modes, panel (c): the time-domain method to the individual fast wave and slow wave, and panel (d): the log spectral subtraction technique to the separated fast wave and slow wave.

Role of absorption mechanisms for ultrasound attenuation in cancellous bone: Macroscopic modeling and experiment

*Michal Pakula

Institute of Mechanics and Applied Computer Science, Kazimierz Wileki University, 85-074 Bydgoszcz, Poland
*michalp@ukw.edu.pl

Evaluation of the relative contribution of physical mechanisms responsible for attenuation of ultrasonic wave in cancellous bone is one of the crucial issues from the point of view of modeling elastic wave propagation and related model-based identification of the structural and mechanical properties of bone material. Considering trabecular bone as a porous material filled with fluid, the wave attenuation may stem from: (i) intrinsic absorption in the fluid and solid phase, (ii) friction at the fluid-solid interface as well as (iii) wave scattering by inhomogeneities (pores/trabeculaes). The commonly used for modeling ultrasound propagation in cancellous bone the macroscopic Biot's theory will be discussed in context of its potential applicability for prediction of wave parameters: phase velocity and attenuation coefficient as functions of frequency. Since the model was introduced for long wavelength range, the scattering effects are neglected, and the analysis will be focused on the absorption mechanisms responsible for attenuation of ultrasonic waves in bone material. The suitability of the model will be verified by comparison of results of sensitivity analysis of the model with in vitro experimental ultrasonic data obtained for cancellous bones filled with different fluids.

*Presenting author

Two wave propagation in equine radius cancellous bone

*Keisuke Yamashita[1], Katsunori Mizuno[1], Mami Matsukawa[1], Takahiko Otani[1], Hiroko Aida[2], Hirokazu Tsubone[3]

[1]Laboratory of Ultrasonic Electronics, Doshisha University, Japan
[2]JRA, Equine Research Institute, Japan
[3]Tokyo University, Japan
*dtk0181@mail4.doshisha.ac.jp

The evaluation and diagnosis of bone fracture in race horse is difficult but very important. However, the X-ray measurement is difficult to realize, because of the long horse legs. The compact and safe QUS method is then considered to be a good candidate. For the first step of quantitative evaluation, we investigated the longitudinal wave propagation in equine cancellous bone. The bone sample was obtained from distal part of the left radius of a race horse (thorough bread, 36-month-old, female). The sample was a plate (thickness 13 mm) and defatted. In addition to the ultrasonic measurements using a pulse technique in the MHz range, the sample was measured by X-ray micro CT (Shimadzu, SMX-160CTS) to obtain the 3D structural parameters. The sample had a strong trabecular orientation, and two-wave phenomenon (fast wave and slow wave) was clearly observed in bone axis direction. Two waves completely separated in some parts of the sample. The amplitude and velocity of two waves showed strong correlation with the structural parameters, which were very similar tendency with bovine and human cancellous bones. These results imply the future possibility of a two-wave diagnostic system for the horse.

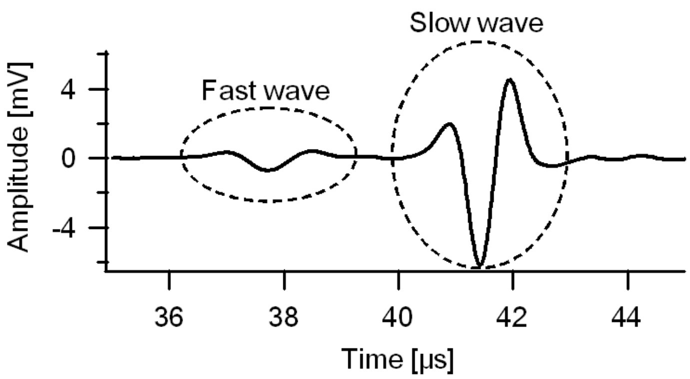

Figure 1: Example of clearly separated two waves.

*Presenting author

In vitro ultrasonic characterization of human bones using focused transducers: a model-based approach

*Roberto Longo[1], Quentin Grimal[2], Josquin Foiret[2], Pascal Laugier[2], Steve Vanlanduit[1], Patrick Guillaume[1]

[1]Mechanical Engineering, Vrije Universiteit Brussel, Belgium
[2]Laboratoire d'Imagerie Paramétrique, Université Pierre et Marie Curie-Paris6, Paris, France
*rlongo@vub.ac.be

Acoustic properties of bone are heterogeneous at the millimeter scale. This heterogeneity can be proved in vitro by mapping the acoustic properties of bone slabs with ultrasound in the MHz range. A problem when measuring human bone samples using ultrasound is to deal with the small surface they offer for ultrasonic investigation. Diffraction effects on the sample borders are a limitation to measurement precision. The use of focused transducers is advantageous because it concentrates the sound beam in a smaller region than plane transducers. A method was previously developed (R. Longo et al. IEEE UFFC, 2010) to measurement simultaneously speed of sound, mass density, thickness and attenuation of bone slabs using plane transducers. The wave propagation model was presented in the frequency domain, for transmission measurements. This method was not applicable to human bone due to their small size. In this paper we show how the method can be adapted to measurements with focused transducers. The alignment of the emitter-receiver transducers (supported also by Laser Doppler Vibrometer wave fronts visualizations), the post-processing technique (based on the impulse response function) and the validation of the method using reference materials (Copper and Perspex) are also shown along this article.

*Presenting author

Ultrasonic monitoring and parameters identification of simulated tissue culture

*Guillermo Rus Carlborg[1], Nicolas Bochud[2], Juan Manuel Melchor[3]

[1]Dpt. Structural Mechanics, University of Granada, 18071, Spain
[2]Dot. Structural Mechnaics, University of Granada, Granada, Spain
[3]Dpt. Structural Mechanics, University of Granada, Granada, Spain
*grus@ugr.es

A monitoring Petri dish is tested for real-time measurement of mechanical properties of thin layers of biomaterials, such as tissue culture or bone. To verify the sensitivity, a gelification process is monitored during approximately an hour, and validated numerically.

A layer of phantom gel is cultured on a Petri dish. The gel suffers consitency changes during a period in the order of magnitude of one hour. The device was excited by high-frequency ultrasonic burst waves at a central frequency of 20 MHz, and the signal was registered during a period of 5 [μs] and a sampling rate of 400 [MHz]. The forward problem simulation of the experimental system is proposed using a semi-analytical model of the ultrasonic wave interactions within the Petri dish and gel based on the transfer matrix formalism. An inverse problem is proposed for determining the sensitivity of the mechanical properties of the gel regarding the time evolution of the gelification process.

This propagation model, combined with an inversion algorithm, allow to determine the time evolution of the mechanical properties of the gel, such as the stiffness and the attenuation coefficent, and thus to interpret the gelification procedure.

*Presenting author

Poster session / Coffee break

Monday, June 20th 2011, 14:45

Chair: Mami Matsukawa

Numerical simulation of cancellous bone remodeling using a finite-difference time domain method

*Atsushi Hosokawa

Department of Electrical and Computer Engineering, Akashi National College of Technology, 674-8501 Akashi, Japan
*hosokawa@akashi.ac.jp

Cancellous bone remodeling, which is a couple of formation and resorption on the trabecular surface, was numerically simulated using a finite-difference time domain (FDTD) method with X-ray microcomputed tomographic models. Assuming that the formation/resorption could be generated on the trabecular surface where the local stress under the mechanical load was larger/smaller than the surrounding stress, the voxel elements in the cancellous bone models were added/removed. An ultrasound wave at 0.5 MHz was applied to bovine cancellous bone as the mechanical load, and the local stress was calculated using the FDTD method. The change in the trabecular structure due to the remodeling was observed, as shown in Figs. 1 and 2. In Fig. 1, the bone volume fraction (BV/TV) decreases with the remodeling step, which means that the resorption rate was larger than the formation rate. In Fig. 2, the degree of the trabecular orientation, that is the ratio of the mean intercept length (MIL) of the trabeculae in the direction parallel to the ultrasound propagation to MIL in the perpendicular direction, increases with the remodeling step. Consequently, the trabecular orientation in the ultrasound direction became strong by the remodeling.

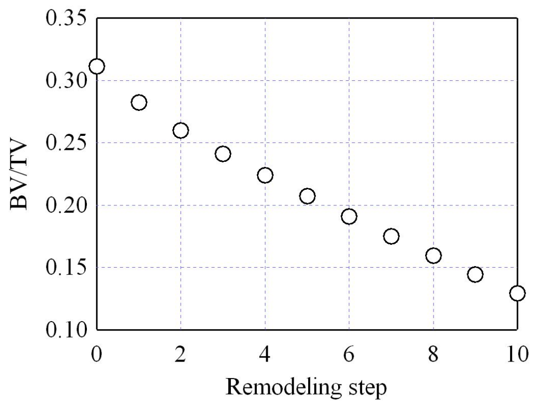

Figure 1: Variation in BV/TV with remodeling step.

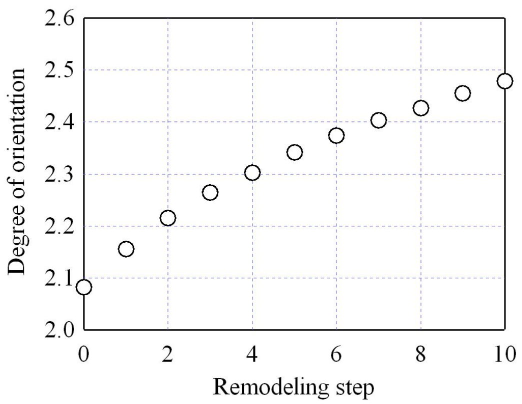

Figure 2: Variation in degree of trabecular orientation with remodeling step.

*Presenting author

Distribution of the longitudinal wave velocity in equine cortical bone – effects of microstructure and HAp orientation

*Kazufumi Yamamoto[1], Daisuke Suga[2], Tomohiro Nakatsuji[2], Mami Matsukawa[2], Takahiko Otani[2], Hirokazu Tsubone[3], Hiroko Aida[4], Hironobu Hoshino[5], Yukihiro Matsuyama[5]

[1]Department of Orthopaedic Surgery, JA Shizuoka Kohseiren Enshu Hospital, 430-0929 Hamamatsu city, Japan
[2]Doshisha University, Japan
[3]The University of Tokyo, Japan
[4]Equine Research Institute Japan Racing Association, Japan
[5]Hamamatsu University School of Medicine, Japan
*kazyama@hama-med.ac.jp

Nowadays, diagnosis techniques to assess racehorse bones are urgently required to discover bone disease (fatigue fracture etc.) early. We have then evaluated the ultrasonic wave properties in equine cortical bone for the future applicability of QUS to the assessment of racehorse bones. In the nanoscopic level, bone consists of hydroxyapatite (HAp) crystal. The preferred orientation of c-axis of HAp crystallites induces anisotropy of elastic properties in bone. The objectives of this study are to investigate the distribution of the longitudinal wave velocity in the axial direction, in relation to HAp crystallites orientation, microstructure, Bone Mineral Density (BMD). Three ring shaped cortical bone samples were made from equine third metacarpal bone. Longitudinal ultrasonic wave propagation was investigated by using a conventional ultrasonic pulse system. HAp orientation was obtained using X-ray diffraction. BMD was measured with DXA method. Microstructure was classified in two types of Haversian structure. Fig. 1 shows velocity distribution. Regardless of microstructure, significant correlation between velocity and HAp orientation was observed (R^2 = 0.74-0.77; Fig. 2). There was no correlation between velocity and BMD. It was thought that velocity could reflect nanoscopic bone quality in the equine bone.

*Presenting author

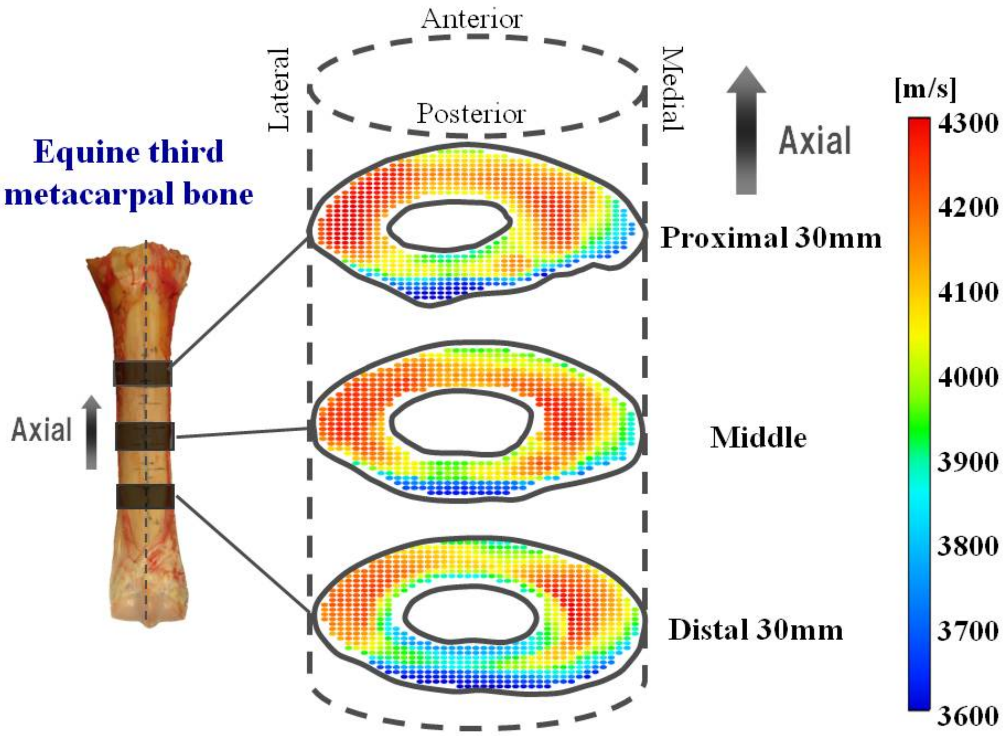

Figure 1: Distribution of longitudinal wave velocity in each three sample..

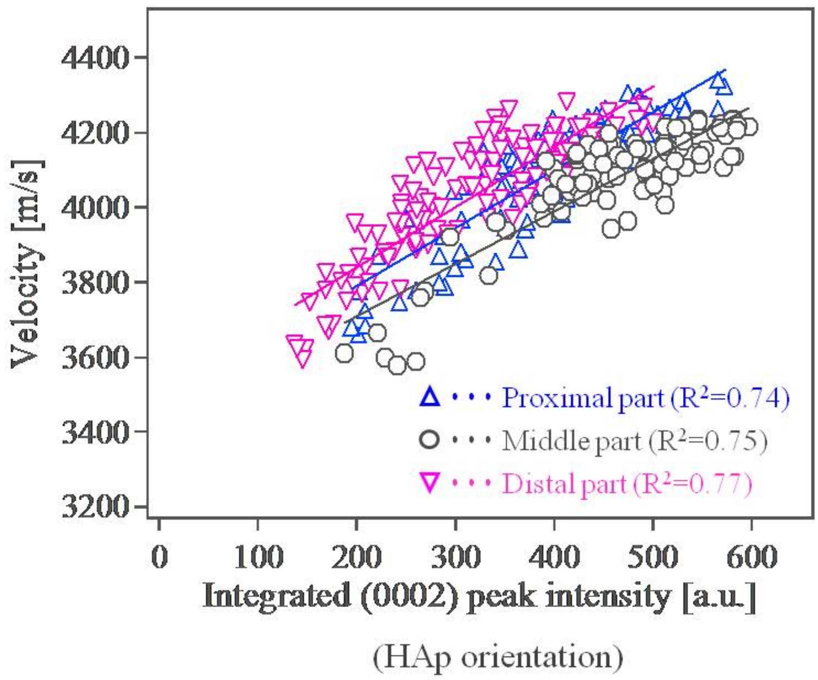

Figure 2: Relationship between wave velocity and HAp orientation..

Ultrasound velocity estimation of cortical bones using axial transmission technique with angle beams

*Rui Zheng[1], Lawrence H Le[2], Edmond Lou[1]

[1]University of Alberta, Canada
[2]University of Alberta, T6G 2V2 / Edmonton, AB, Canada
*ruiz@ualberta.ca

Being able to obtain a reasonable background velocity profile is essential to image internal bone structures when Born Scattering theory is used. The cortical velocity can be estimated by measuring the direct wave (FAS) traveling from the ultrasound source to the receiving transducer. The radiation pattern of a compressional wave transducer has a main lobe with the maximum energy strength perpendicular to the transducer surface. Therefore the ultrasound beam requires tilting to have more energy travelling toward the horizontal direction. Four angle wedges (30o, 45o, 60o, and 70o) were used to acquire twelve data sets for three bone samples. The arrival times of the FAS were measured and linear regression was applied to find the best-fitted line. The velocities thus obtained were compared with the reflection-based measurements. The latter was obtained by dividing the computed tomography determined thickness of the cortical layer by the one-way traveling time between the cortical interfaces. Due to the irregularities of the bone surfaces, we found the 60o wedge provided the least errors. For the three bone samples, the absolute errors are 1.36%, 5.02% and 3.61% for velocity and 1.89%, 4.55% and 3.23% for thickness.

*Presenting author

Relationships between broadband ultrasonic attenuation and microstructure of human trabecular bone

*Michal Pakula[1], Jalmari Pirhonen[2], Petro Moilanen[2], Pascal Laugier[3], Tuomas Turpeinen[2]

[1]Institute of Mechanics and Applied Computer Science, Kazimierz Wielki University in Bydgoszcz, 85-074 Bydgoszcz, Poland
[2]Department of Physics, University of Jyväskylä, Jyväskylä, Finland
[3]Laboratoire d'Imagerie Paramétrique, University Paris 6- CNRS UMR 7623, Paris, France
*michalp@ukw.edu.pl

The study focused on elucidation of the influence of human trabecular bone microstructure on the broadband ultrasonic attenuation (BUA). Ultrasonic assessments where performed on 30 human cancellous bone specimens filled with marrow, water and alcohol, successively by using three pairs of custom made transducers (OPTEL; D = 10 mm; fc = 0.5, 1 and 2 MHz). A 2D ultrasonic scanning method was applied and the BUA was recorded. In addition, bone volume fraction (BV/TV) was determined by x-ray microtomography (SkyScan 1072) at the same volumes as the ultrasonic assessments. BUA showed a strong correlation with BV/TV at 2 MHz for marrow (R^2=0.90, $p<$1e-4) and water (R^2=0.89, $p<$1e-4) saturated specimens. Significant correlations were also found at 1 MHz for specimens with marrow (R^2=0.71, $p<$1e-4), water (R^2=0.87, $p<$1e-4) and alcohol (R^2=0.87, $p<$1e-4). Interestingly, at 0.5 MHz the BUA well correlated with BV/TV for alcohol saturated specimens (R^2=0.81, $p<$1e-4), but not so well with marrow (R^2=0.37, $p<$1e-4) and water (R^2=0.35, $p<$1e-4) saturated ones. Strong correlations between BV/TV and BUA for higher frequencies were thus shown. Poor correlation at 0.5 MHz could be explained by another mechanism of attenuation appearing at lower frequencies or by challenges of signal analysis (Anderson et al. JASA, 2010).

*Presenting author

Numerical simulation reveals how the fast wave is generated in cancellous bone

*Yoshiki Nagatani

Department of Electronic Engineering, Kobe City College of Technology, 651-2194, Japan
*nagatani@ultrasonics.jp

In cancellous bone, longitudinal waves often separate into fast and slow waves depending on the alignment of bone trabeculae in the propagation path. We pointed that fast wave required certain propagation distance for steady propagation [Nagatani et al., Ultrasonics (2008)]. However, the precise mechanism of fast wave propagation is not clarified yet. In this study, the detailed behavior of fast wave generation was investigated using three-dimensional simulation technique. Using the virtual model whose central portion inside the specimen was assumed to be vacuum, relationship between the thickness of the margin and first positive peak amplitude of the fast wave was investigated. As a result, fast wave was mainly originated from the soundwave that goes into trabecular within 1 to 2 times of wavelength after entering the cancellous bone (Fig. 1). In addition, when the acoustic impedance of the liquid part was higher, the degradation of fast wave attenuation was higher caused by the leakage of soundwave from solid portion into liquid portion (Fig. 2). These interesting phenomena may show that the fast wave attenuation is caused by both multi-path effect, leakage, and absorption in media. These investigations help us understand the precise behavior of soundwave inside cancellous bone.

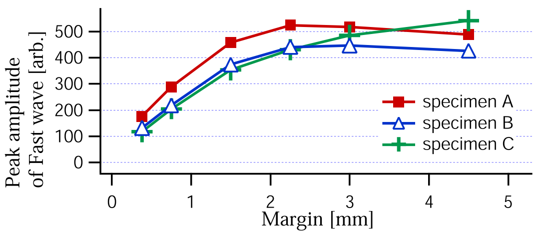

Figure 1: Relationship between the thickness of the margin and first positive peak amplitude of the fast waves. The amplitude of fast wave gradually increases, then plateaus at 1 to 2 times of wavelength.

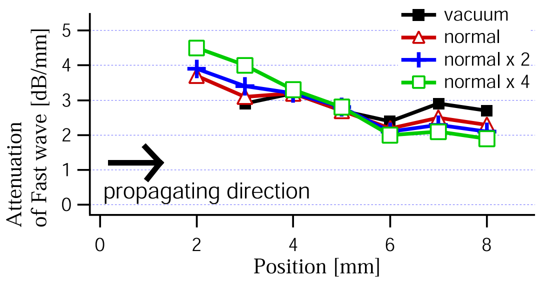

Figure 2: Distribution of fast wave attenuation of specimen when the acoustic impedance of liquid portion was changed. The degradation rate of the attenuation depends on the acoustic impedance of the liquid portion.

*Presenting author

Separation technique for ultrasonic waveform propagated in cancellous bone using wavelet transform analysis

Sho Hasegawa[1], *Yoshiki Nagatani[1], Katsunori Mizuno[2], Mami Matsukawa[2]

[1]Kobe City College of Technology, Japan
[2]Doshisha University, Japan
*nagatani@ultrasonics.jp

Ultrasonic waves targeted on cancellous bone separate into fast and slow waves according to the alignment of bone trabeculae. The characteristics of the specimen, however, can sometimes result in ambiguous wave separation. In this study, we proposed using wavelet transform as a new method of analyzing ultrasonic waveforms. The experimentally observed waveforms were used for the analysis. Using continuous wavelet transform, two components were separated by fitting two-dimensional Gaussian function in scalogram (Fig. 1). Because the residual is distributed mainly in the lower-frequency portion, the component may include a fast wave that passes through the shorter path in the trabecula. The relationship between bone volume fraction and the peak amplitude of the lower- and higher-frequency components showed a clear negative correlation. This result derived from scalogram conflicts with the previous knowledge derived from time domain analysis. Therefore, it is natural to consider that the peak value of the lower-frequency component in the scalogram and the first positive peak of the fast wave in the time domain properly reflect physical phenomena, respectively. We recognized lower-frequency component as the multiple reflections (forward scattering) in cancellous bone.

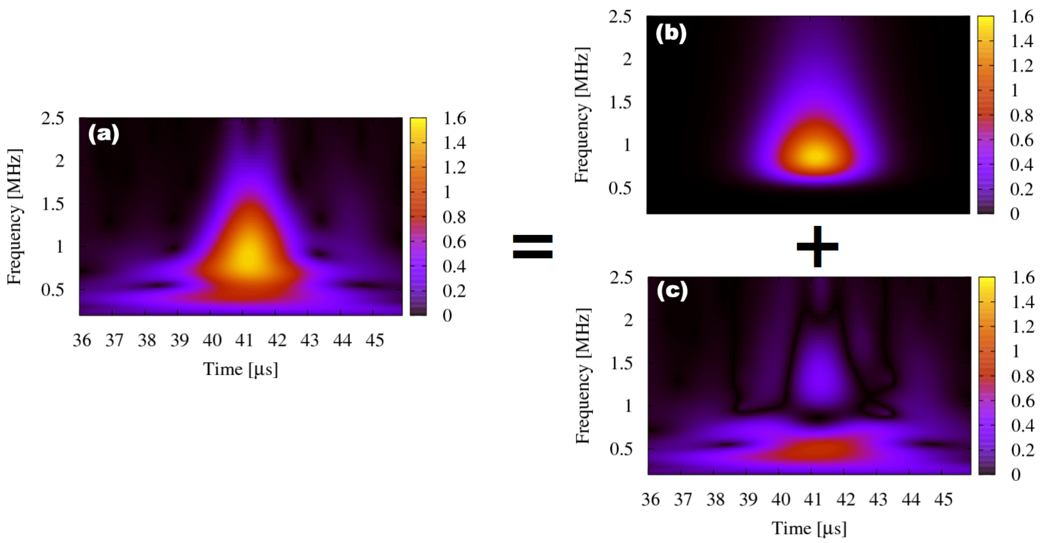

Figure 1: Example of scalogram. Figure (a) is a scalogram of the original waveform that propagated in cancellous bone; (b) is the fitted two-dimensional Gaussian function; (c) is the residual of fitting. The residual may include the "fast wave" that passes through the shorter path in the trabecula.

*Presenting author

A crazy climber method for analyzing fundamental flexural guided wave in ultrasonic axial transmission signals recorded by a low-frequency array transducer

*Vantte Kilappa[1], Kailiang Xu[2], Petro Moilanen[1], Dean Ta[2], Jussi Timonen[1]

[1]Department of Physics, University of Jyväskylä, Jyväskylä, Finland
[2]Department of Electrical Engineering, Fudan University, Shanghai, China
*warma@iki.fi

In a recent study, we have introduced a 6-receiver low-frequency (100-400 kHz) array transducer for ultrasonic axial transmission of the first arriving signal (FAS). Due to the low number of receivers, techniques based on two-dimensional fast Fourier transform (2D-FFT) cannot be used to analyze modes like the fundamental flexural guided wave (Lamb A0) with this array. The purpose of the present work was thus to test the suitability of an alternative approach based on a time-frequency representation (TFR) of the signal. A method of Crazy Climbers (CC) was used to enhance the separation of modal components in TFR. Time of flight of the highest amplitude component was detected and separated from TFR, and these data were used to determine the group velocity by linear regression. The method was tested on acrylic plates and 41 human radius specimens with the soft tissue removed. Velocity measured in the phantoms was in accordance with the group velocity of the Lamb A0 mode (Fig. 1). In the bone samples it was correlated with the cortical thickness ($R=0.71$, $p<0.001$) (Fig. 2) and bone mineral density ($R \approx 0.6$). In conclusion, CC-TFR analysis enabled assessment of the fundamental flexural guided mode with an array transducer.

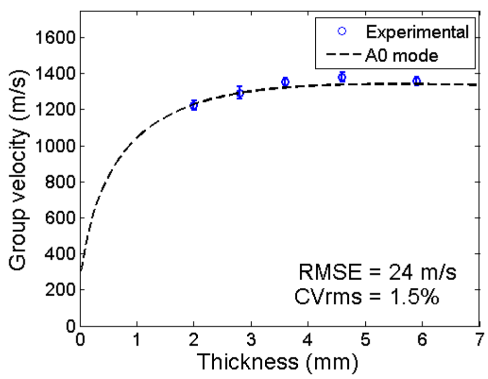

Figure 1: Group velocity of the extracted guided wave mode as a function of thickness, as determined by the CC method at 100 kHz for acrylic-plates (markers). That of the A0 mode is shown by a dashed line.

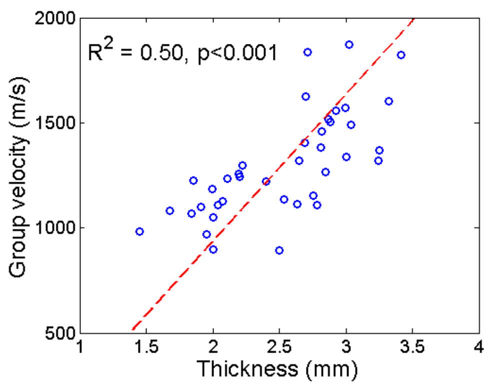

Figure 2: Extracted guided wave velocity as a function of cortical thickness for human radius specimens. Cortical thickness was assessed by pQCT.

*Presenting author

Reproducibility of the new ultrasound technique for osteoporosis diagnostics at primary healthcare level

*Ossi Riekkinen[1], Aleksi Mönkkönen[2], Jarkko Kauppinen[2], Janne Karjalainen[1], Jukka Jurvelin[1]

[1]Applied Physics, University of Eastern Finland, Kuopio, Finland
[2]Savonia University of Applied Sciences, Finland
*ossi.riekkinen@uef.fi

At present, there are no reliable methods to diagnose osteoporosis at the primary healthcare level. Therefore, partially, about 75% of osteoporotic patients are not diagnosed or treated. For optimal treatment decisions, novel diagnostic techniques for primary healthcare level should closely match with the axial DXA and the clinical risk factors (e.g. FRAX). The new in vivo pulse-echo ultrasound (PE-US) technique for the measurement of cortical thickness could fulfil these aims. Changes in cortical thickness are known to indicate sensitively early bone pathology. In this study, we tested whether the PE-US technique is simple, fast and easy to use, as well as independent of the operator.

Fourteen inexperienced operators (healthcare students/professionals) were trained to use the PE-US technique (2,25 MHz) for in vivo measurement of the cortical bone thickness at the tibia of one volunteer.

The reproducibility for the measurements of cortical bone thickness was good (CV 3.6%) between the operators. The operators used 8 ± 2 min for training and 6 ± 3 min for the measurements.

Using the first PE-US prototype reproducibility of the technique was good. However, we believe that the measurement time and usability of the technique will be improved with the second prototype under development.

*Presenting author

Bone phantoms for ultrasonic axial transmission studies

Jalmari Pirhonen[1], *Petro Moilanen[1], Vantte Kilappa[1], Pasi Karppinen[2], Zuomin Zhao[3], Ari Liikkanen[2], Timo Karppinen[2], Edward Hæggström[2], Risto Myllylä[3], Jussi Timonen[1]

[1]Department of Physics, University of Jyväskylä, Jyväskylä, Finland
[2]Department of Physics, University of Helsinki, Helsinki, Finland
[3]Department of Electrical and Information Engineering, University of Oulu, Oulu, Finland
*petro.moilanen@jyu.fi

Ultrasonic axial transmission enables multimodal assessment of human cortical bones such as the radius and tibia. We consider bone, coated by soft tissue and filled with marrow, as an elastic waveguide and model it by a fluid-coated and fluid-filled axisymmetric tube. The purpose of the present study was to develop bone phantoms, i.e. reference waveguides, consistent with this model. The phantoms were made from a homogeneous composite of aluminium oxide (Al_2O_3) and epoxy resin. Their manufacturing included mixing and de-airing of the components, molding and turning the castings on a lathe, and drilling them into tubes. Phantoms were coated and/or filled by gelatin gel to mimic the soft tissue and bone marrow, respectively (Fig.1). Dependence of the first arriving signal velocity (v_{FAS}) on the amount of Al_2O_3, temperature and sample wall thickness (Fig.2) were evaluated by a 400kHz array ultrasonometer. Maximum of 2930m/s was achieved at room temperature for 70% by mass of Al_2O_3, with a temperature dependence of -10 m s^{-1} $°C^{-1}$. In addition, a 200kHz scanning ultrasonometer was used to record the velocity of a fundamental flexural guided wave, showing reasonable agreement with theoretical models. A series of five bone phantoms with individual wall thickness (1-5mm) was developed.

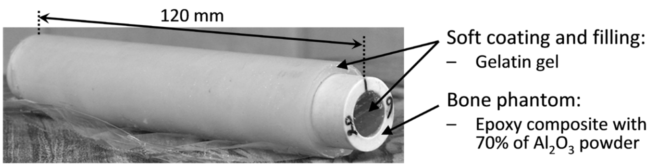

Figure 1: A bone phantom with soft coating and soft filling

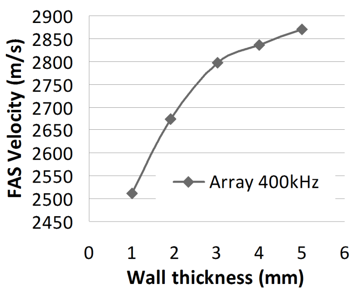

Figure 2: Thickness dependence of FAS velocity in coated and filled phantoms

*Presenting author

Volumetric quantification of repair cartilage and subchondral ossification using ultrasound biomicroscopy

*Nils Männicke[1], Martin Schöne[1], Ronny Schulz[2], Hannes Kuttner[2], Bastian Marquaß[2], Kay Raum[1]

[1]Julius Wolff Institute and Berlin-Brandenburg School for Regenerative Therapies, Charité – Universitätsmedizin Berlin, Berlin, Germany
[2]Translational Centre for Regenerative Medicine Leipzig, Leipzig, Germany
*nils.maennicke@charite.de

A method is presented that enables quantification of repair tissue and subchondral ossification volumes in cartilage repair studies using ultrasound biomicroscopy. Involved is a semi-automatic detection of surface and cartilage bone-boundaries that allow a reliable tracking of subchondral bone growth.

In Merino-sheep, the effect of different treatment approaches for chronic focal osteochondral cartilage 7-mm-diameter-lesions was studied. Treatment groups covered untreated control groups (N=16), collagen-type-I-scaffolds (N=8) and BmMSC-cell-seeded scaffolds (N=8). Convalescence was 12 months. Immediately after explantation, time-resolved C-scans of defect area and surrounding native tissue were recorded using a portable ultrasound biomicroscope equipped with a focussed 40MHz transducer. 3D- surface and cartilage bone interface were approximated using a threshold-based analysis of the Apparent Integrated Backscatter (AIB) and manually refined by physicians. Positions of surface and bone interface outside the defect area served as input for a 2D polynomial. By comparison of the polynomial model and the actual position, subchondral ossification as well as the occurence of bone cysts were quantified volumetrically.

Accurate determination of subchondral bone boundaries and its comparison with native areas allowed quantification of ossification and detection of bone cysts at a high spatial resolution. The presented method will help improving a non-destructive assessment of different treatment strategies.

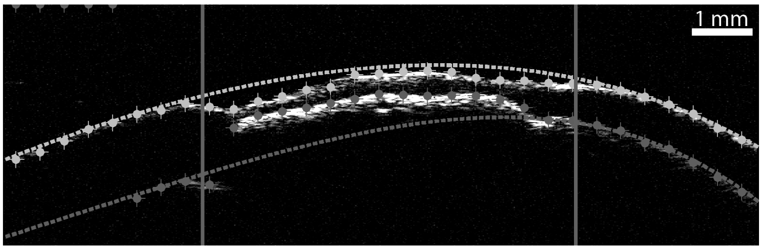

Figure 1: Exemplary B-mode cross section. Displayed are defect borders as vertical lines, surface (light gray) and cartilage-bone interface (dark gray). Cartilage-bone boundary could not be detected on the left side. A 2D polynomial was used for approximation of native boundaries in the defect region, shown as dotted lines.

*Presenting author

Micro Brillouin scattering study on the velocity anisotropy in a trabecula

*Kenji Fukui, Mami Matsukawa

Laboratory of Ultrasonic Electronics, Doshisha University, Kyotanabe, Japan
*dtk0112@mail4.doshisha.ac.jp

Ultrasonic wave properties in bone include various information from different scales, such as microstructure, soft tissues, composition of the bone matrix, etc. It is then very difficult to extract the precise effect of each factor on the obtained properties. As for the cortical bone and trabecula, they are often treated as isotropic without the actual measurement of anisotropic properties. We have then investigated longitudinal wave velocities in a single trabecula using a micro-Brillouin scattering technique. This technique enables velocity measurements in a small area (diameter 8 micron meter) without the effect microstructure in a sliced specimen. In addition, rotation of the specimen can give us in plane wave velocities. Specimens used were obtained from the cancellous bone of a bovine femur (27-month-old). Rod type trabeculae were selected using X-ray CT image of the cancellous bone and carefully polished to thin specimens (thicknesses 50-70 micron meter). In all specimens, measured velocities were in the range of 4.92-5.31e3 m/s, and showed weak uniaxial anisotropy. The maximum wave velocity direction was always similar to the direction of rod. The high velocities seem to come from high frequency range (around 13.7GHz) and few effect of microstructure in a small area.

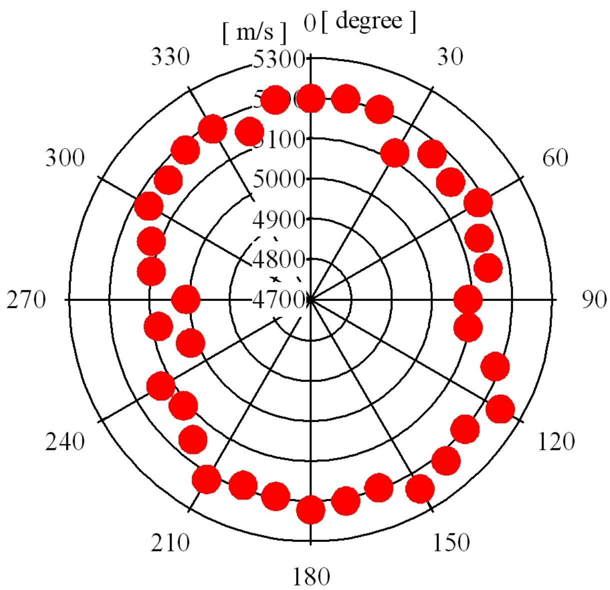

Figure 1: Velocity anisotropy in a trabecula. 0-180 direction indicates the direction of the trabecular rod.

*Presenting author

A nonlinear stratified model to predict ultrasonic wave propagation in trabecular bone

*Nicolas Bochud[1], Quentin Grimal[2], Sylvain Haupert[2], Pascal Laugier[2], Guillermo Rus[1]

[1]University of Granada, Granada, Spain
[2]UPMC-CNRS, Paris, France
*nbochud@ugr.es

Ultrasound is regarded as a promising tool for bone quality assessment. In the past, many linear techniques have been developed to image ultrasonic wave propagation velocity and attenuation in trabecular bone, among them methods based on stratified models or on Biot theory. However, these methods are almost insensitive to progressive induced damages. Recently, a relation between damage accumulation and trabecular bone density was obtained in vitro by nonlinear ultrasound techniques. Models of nonlinear wave propagation in bone are required to analyse the experimental results and to help quantify the in situ level of damage.

In this study, the complex architecture of trabecular bone is modeled as a stratified medium of alternating solid (trabecular material) and liquid (marrow) layers. The volume fraction of solid phase represents bone volume fraction. The model accounts for the transmissions and reflections of the ultrasonic signal describing the nonlinear interactions of primary waves within bone. The acoustic response is simulated with a method which extends the classical transfer matrix formalism to classical nonlinearity.

The effective nonlinearity of trabecular bone is evaluated regarding the local nonlinearity and the volume fraction of trabecular material, and is characterized by the amplitude ratio between the second and first harmonic amplitude.

*Presenting author

Age affects the bone healing kinetics in a rat osteotomy model

Katrein Sauer[1], Daniel Rohrbach[1], Patrick Strube[2], Bernd Preininger[2], *Kay Raum[1]

[1]Julius-Wolff-Institut, Charité-Universitätsmedizin Berlin, Berlin, Germany
[2]Center for Musculoskeletal Surgery, Charité-Universitätsmedizin Berlin, Berlin, Germany
*kay.raum@charite.de

The course of bone healing in animal models is conventionally monitored by μCT or histology approaches. Both techniques do not allow the determination of the material properties of the involved tissues. In this study, quantitative scanning acoustic microscopy was used at 50 MHz to investigate microstructural and elastic alterations of mineralized callus and cortical tissue after transverse femoral osteotomies in young (12 weeks, N = 5) and old (12 months, N= 13) rat. Analyses were performed after 6 weeks of consolidation with stabilization by either a rigid or a semi-rigid external fixator. The mean stiffness values in cortical and callus tissues were 33.05 ± 7.56 GPa and 19.32 ± 5.93 GPa, respectively. The callus stiffness values in the young group were significantly (9.33 %) higher than those in the old group (F = 17.23). Porosity values in cortical and callus tissues were 2.8 ± 1.0 % and 53.9 ± 9.8 %, respectively. The callus porosity in the young group was significantly (13.3 %) lower than that in the old group (F = 11.27). These results indicate that callus healing is considerably delayed in old rat.

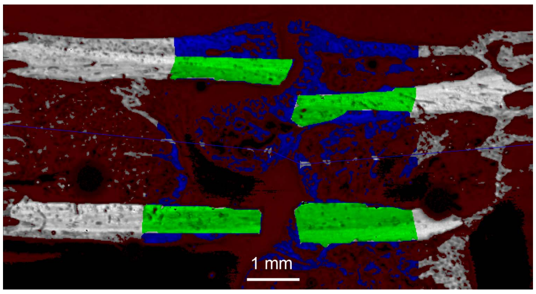

Figure 1: Exemplary grey-scale stiffness map obtained by SAM measurements. The overlaid colors indicate segmented evaluation regions (red = excluded non-mineralized tissue and embedding material; green = cortical tissue; blue = callus tissue).

*Presenting author

Session IV: Ultrasonic Characterization of Cancellous Bone

Monday, June 20th 2011, 16:15

Chair: Jukka Jurvelin

A new perspective on ultrasound assessment of cancellous bone

*Christian Langton

Physics, Queensland University of Technology, Brisbane 4001, Australia
*christian.langton@qut.edu.au

The measurement of broadband ultrasonic attenuation (BUA) in cancellous bone at the calcaneus for assessment of osteoporosis was first described 25 years ago. The technique has been extensively clinically validated and is utilized worldwide. However, there is still no fundamental understanding of the dependence of BUA upon the material and structural properties of cancellous bone as well as the observed 'parabolic' relationship between BUA and bone volume fraction.

It has recently been proposed that the primary BUA mechanism in cancellous bone is phase cancellation due to variations in transit time as detected over the phase-sensitive surface of the receive ultrasound transducer [1]. A combined experimental and computer simulation study has successfully demonstrated that lateral inhomogeneity of transit time has significant potential for phase cancellation to occur; relatively simplistic solid:liquid models exhibited lateral inhomogeneity ranging from minimal, a single transit time, to maximal, a wedge being the ultimate case.

This has led to the development of Ultrasound Transit Time Spectral Analysis, with the potential to quantify both the bone volume fraction and 'structure' of cancellous bone.

1. Langton C M; 2011; 25th Anniversary of BUA for the Assessment of Osteoporosis – Time for a New Paradigm?; Engineering in Medicine; 225 (2),113-125

*Presenting author

In situ ultrasound backscatter measurements of intact human proximal femur

*Markus Malo, Ossi Riekkinen, Viktoria Prantner, Hanna Isaksson, Janne Karjalainen, Juha Töyräs, Jukka Jurvelin

Department of Applied Physics, University of Eastern Finland, Kuopio, Finland
*markus.malo@uef.fi

Ultrasound reflection and backscatter parameters have been shown to relate to mechanical and structural properties of trabecular bone. However, the potential of reflection and backscatter parameters in measurements of intact human proximal femur have not been studied. In this study, human femoral bones of 14 cadavers (3 females and 11 males, 49.4 ± 17.4 years, range: 17 − 78 years) were measured at the neck and at the trochanter in the anterior posterior and lateral medial directions. Ultrasound reflection coefficient (IRC) and apparent integrated backscatter (AIB) were obtained and compared with structural microCT parameters for trabecular bone samples extracted from the same locations. Pearson correlation analysis was used to calculate linear correlation coefficients. The IRC values showed no significant correlations with structural parameters, however, AIB correlated significantly with several structural parameters, e.g. the structure model index ($r = 0.72$, $p < 0.01$). AIB was also correlated significantly with age ($r = 0.82$, $p < 0.01$). The present results encourage further in vivo measurements. However, the overlying soft tissues that distort and attenuate the ultrasound pulse make in vivo pulse-echo measurements from the proximal femur more challenging.

*Presenting author

Estimating mean trabecular bone spacing from ultrasonic backscattering signals based on two fundamental frequency estimation methods

*Dean Ta, Baiding Yang, Weiqi Wang

Department of Electronic Engineering, Fudan University, Shanghai, China
*tda@fudan.edu.cn

The mean trabecular bone spacing(MTBS) estimated from ultrasonic backscattering signals can indicate the change of cancellous bone microstructures. This paper first proposed a MTBS estimation method based on fundamental frequency estimation(SFE). The SFE first utilizes simplified inverse filter to remove the high frequency multiplicative interference of system response, then the combination of event-based instantaneous fundamental frequency estimation and improved autocorrelation algorithm are applied to get the estimated fundamental frequency, from which the MTBS can be obtained. Then the paper proposed Hilbert transform- fundamental frequency estimation(HFE). Two methods were applied to backscattering signals from simulations and in vitro bovine trabeculae experiments. The results shows that the performances of two proposed methods outperform that of the Autoregressive(AR) and simplified inverse filter tracking(SIFT) algorithms. In the in vitro experiments, the results are in agreement with simulation ones, the most of estimates are more precise compared with reference MTBS values from micro-CT than AR and SIFT methods. It can be concluded that SFE algorithm is more robust for MTBS estimation than AR cepstrum and SIFT algorithm with precise estimates and small estimated variance, and HFE proved to be a more robust algorithm than SFE method, especially for varying SNR and MTBS.

*Presenting author

Invited lecture

Tuesday, June 21st 2011, 09:00

Chair: Jussi Timonen

Development strategies for clinical skeletal quantitative ultrasound approaches: challenges and opportunities

*Claus-Christian Glueer

Medical Physics, Diagnostic Radiology, CAU Kiel, Kiel, Germany
*glueer@rad.uni-kiel.de

The history of skeletal applications of Quantitative Ultrasound (QUS) methods has been a roller coaster ride. Starting with cortical elasticity, moving on with attenuation in trabecular bone, large studies confirmed the predictive power of QUS approaches for fracture risk assessment. However, the lack of inclusion in drug studies, real and virtual quality issues hinders widespread acceptance of QUS. The resurgence of technological innovations in skeletal QUS methods in the past few years is quite impressive. What are the topics for successful QUS approaches? In cortical bone wave propagation can be simulated, measured and understood very accurately. More importantly, the field of osteoporosis diagnostics is waiting for methods for in vivo assessment of material properties. Cortical porosity, mineralization, anisotropy are key determinants of bone strength independent of bone density. Elasticity can be measured at the radius or the tibia but it is not clear yet whether bone strength and toughness are accessible by ultrasound as well. Also the correlation with material properties of the main fracture sites needs to be established and thus QUS measurements at the proximal femur are relevant. However, most importantly: establishing the quality of QUS in the assessment of bone qualities is the challenge to face !

*Presenting author

Session V: Clinical Quantitative Ultrasound

Tuesday, June 21st 2011, 09:30

Chair: Jussi Timonen

Multi-site bone ultrasound measurements in elderly women

*Janne Karjalainen[1], Ossi Riekkinen[1], Juha Töyräs[1], Mikko Hakulinen[2], Heikki Kröger[3], Toni Rikkonen[4], Kari Salovaara[4], Jukka Jurvelin[1]

[1]Department of Applied Physics, University of Eastern Finland, Kuopio, Finland
[2]Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital, Kuopio, Finland
[3]Department of Orthopaedics, Traumatology and Hand Surgery, Kuopio University Hospital, Kuopio, Finland
[4]Bone and Cartilage Research Unit, University of Eastern Finland, Kuopio, Finland
*janne.karjalainen@uef.fi

At present, no reliable diagnostic methods for osteoporosis are available at the primary health care level. In this study, multi-site pulse-echo (PE) ultrasound method is proposed.

Thirty elderly women were examined in vivo using PE ultrasound (at 2.25 and 5.0 MHz) measurements in proximal femur, distal radius, proximal and distal tibia. Further, areal bone mineral density (BMD) in the proximal femur was determined by axial DXA. First, we predicted the BMD at femoral neck (BMDneck) by ultrasound measurements in tibia combined with subject characteristics (density index, DI), Second, we tested the ability of ultrasound backscatter measurements at proximal femur to discriminate between individuals with previously fractured hips from those without fractures.

Cortical thickness at distal and proximal tibia combined with age and weight of the subject, provided a good estimate of BMDneck ($r = 0.86$, $p < 0.001$, $n = 30$). When inserted into FRAX (World Health Organization fracture risk assessment tool) the DI indicated the same treatment proposal as the BMDneck with 86% sensitivity and 100% specificity. The ultrasound backscatter parameter combined with patient characteristics discriminated subjects with fracture from the controls.

The results indicate that ultrasound parameters, combined with patient characteristics, may provide means for osteoporosis diagnostics.

*Presenting author

Ability of low-frequency axial transmission ultrasound to discriminate retrospective low-energy fractures

Petro Moilanen[1], *Mikko Määttä[2], Vantte Kilappa[1], Leiting Xu[3], Timo Jämsä[2], Jussi Timonen[1], Sulin Cheng[3]

[1]Department of Physics, University of Jyväskylä, Jyväskylä, Finland
[2]Department of Medical Technology, University of Oulu, Oulu, Finland
[3]Department of Health Sciences, University of Jyväskylä, Jyväskylä, Finland
*mikko.j.maatta@oulu.fi

Low-frequency axial transmission ultrasound (LF-AT; fc=400 kHz) shows good sensitivity to cortical thickness and BMD deep in the endosteum of long cortical bones. Purpose of the present study was to evaluate the ability of this method when assessing bone fragility retrospectively. The fracture group (F) consisted of n=25 females (age 26-80 yrs) with a history of low-energy fractures and the non-fracture group (NF) included n=100 females (age 27-86 yrs). Subjects with medication or disease affecting bone metabolism were excluded. An LF-AT array probe was used to measure the velocity of the first arriving signal (VFAS) in the midshaft radius and tibia. Site-matched pQCT assessments were done by XCT2000 (Stratec Medizintechnik). In addition, areal BMD of the whole body, femoral neck and lumbar spine were assessed by DXA (Prodigy, GE). Odds ratios (OR), adjusted for the age and body mass index, were 1.80 (95% CI: 1.31-2.50) and 1.42 (1.10-1.83) and areas under the receiver operator characteristics curve (AUC) were 0.70 and 0.65 for the VFAS radius and tibia, respectively. The pQCT and DXA measurements yielded similar or weaker results. These results thus show that LF-AT is able to discriminate low-energy fractures with similar or better accuracy than pQCT and DXA.

*Presenting author

In vitro evidence that the circumferential wave guided by the femur cortical shell can be used to predict femur strength

Julien Grondin[1], *Quentin Grimal[1], Sandra Guérard[2], Reinhard Barkmann[3], Claus Glüer[3], Pascal Laugier[1]

[1]Laboratoire d'imagerie paramétrique, UPMC-CNRS, Paris, France
[2]LBM, Arts et Metiers PARISTECH, Paris, France
[3]Medizinische Physik, Klinik für Diagnostische Radiologie, UKSH, Kiel, Germany
*quentin.grimal@upmc.fr

QUS at the proximal femur shows a good performance for hip fracture discrimination (Barkmann et al, Osteoporosis Int. 2010). With the implemented signal processing, the technique essentially measures trabecular bone. However the first arriving signal was shown to be associated with the propagation of a circumferential wave guided in the cortical shell and to be independent from the trabecular compartment. Because cortical bone is a key factor to maintain femur neck mechanical integrity, we hypothesized that the measurement of the propagation time of the first arriving signal (T) could be predictive of femur strength. For nine left femurs of women donors (mean age 83y.) we measured: (1) femur strength in one-legged stance configuration; (2) BMD from DXA; (3) T through the neck with two cylindrically focused transducers (0,5 MHz central frequency) which illumated a 5 mm-thick transverse neck cross-section. Significant relationships were observed between T and mechanical parameters: failure load: R^2=0.79; elastic energy : R^2=0.63; apparent stiffness R^2=0.70. DXA was also well correlated to strength (R^2=0,78 for failure load). In future work, we shall investigate whether a combination of independent ultrasound measurements of the cortical and trabecular compartments at the upper femur enhance fracture risk prediction.

*Presenting author

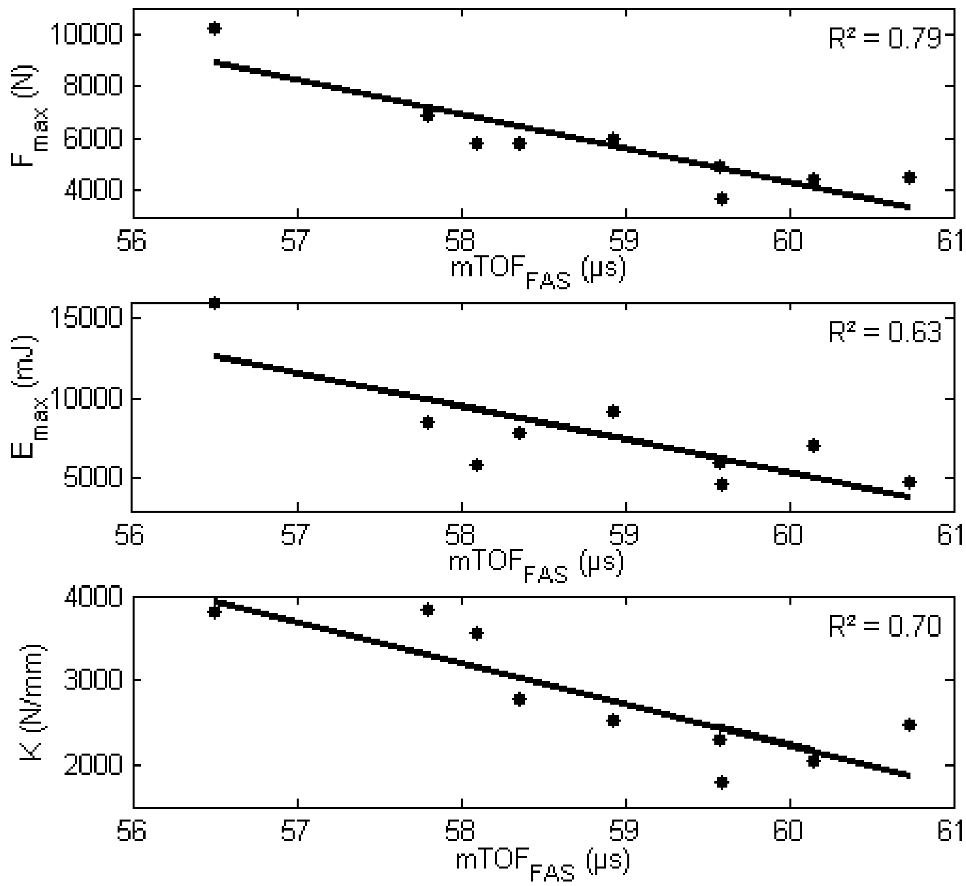

Figure 1: Relationships between measured first arriving signal time-of-flight and proximal femurs mechanical characteristics.

Session VI: Models for Ultrasonic Characterization of Cortical Bone

Tuesday, June 21st 2011, 10:45

Chair: Pascal Laugier

Excitability of axially transmitted guided waves in models of human long bones

*Maryline Talmant[1], Petro Moilanen[2], Josquin Foiret[1], Jean-Gabriel Minonzio[1], Pascal Laugier[1], Jussi Timonen[2]

[1]Laboratoire d'Imagerie Paramétrique, CNRS-UPMC, Paris, France
[2]Department of Physics, University of Jyväskylä, Jyväskylä, Finland
*maryline.talmant@upmc.fr

Previously, the Jyväskylä group has used an empty tube as the reference waveguide for inversion or identification of ultrasound measurements, but the role of the marrow has remained an open issue. The objective of this study was to test several reference waveguides, empty, fluid-filled and fluid-coated tubes, in the modelling of guided waves. Mode excitability in fluid-filled tubes was evaluated using the normal mode expansion method (NME), with normal stress excited by the source while receivers detected the normal displacement. Results are shown in Fig 1 as a gray-scale image in the frequency-wavenumber plane. For cross validation, a corresponding spectrum was obtained by 2D-FFT of signals simulated by SimSonic3D. Related experiments were performed to evaluate the sensitivity properties of real transducers. Finally, the utility of group velocity filtering on mode separation was analyzed. Introduction of absorption in the fluid and/or in the tube material is currently under way, and its relevance will be evaluated by experiments. Tuning of the excitation and detection of ultrasound signals will as well be analyzed so as to optimize the measurement of A0/F11 properties.

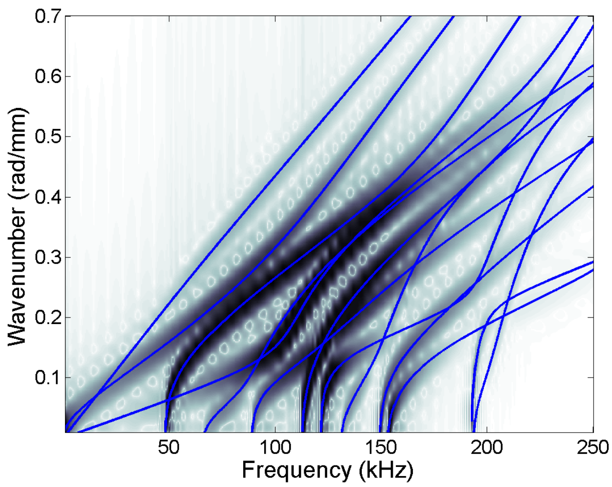

Figure 1: Ultrasound spectrum as determined by the NME method (gray scale image) for a fluid-filled tube. Corresponding dispersion curves are shown by solid lines.

*Presenting author

Characterization of growing bone: curvature and anisotropy

*Cecile Baron

ISM, CNRS/Aix-Marseille University, F-13288 Marseille, France
*cecile.baron@univmed.fr

In ultrasound characterization, long bones can be realistically modeled as tubes with orthorombic crystal structure. Nevertheless, numerous studies on ultrasound propagation in bones represent long bones as transversely isotropic (or even isotropic) waveguides (typically plates). This paper proposes a semi-analytical method to solve the wave equation in orthotropic waveguides. Based on an analytical solution, the matricant, explicitly expressed under the Peano series expansion form, it allows to consider a degree of anisotropy greater than the transverse isotropy with a curved geometry. In this work, we investigate how the curvature of long bone influences the wave propagation and how wave speeds are sensitive to components of the orthotropic stiffness matrix. The results confirm that the plate model may be adequate to study guided waves propagation in tubes with outer radius to thickness ratio lower than 0.5 and beyond a minimal frequency value. Moreover this study gains insight the role of the stiffness coefficients on the propagation of the first – extensional and flexural – guided modes travelling in an orthotropic tube. This model may reveal particularly appropriate to characterize growing bone for which the outer radius to thickness ratio is greater than 0.5 and the material symmetry is considered as orthotropic.

*Presenting author

Characterization of circumferential guided waves in the femur cortical shell – Part II: Sensitivities of phase velocities to variations of porosity and shell thickness

*Mathieu Chekroun[1], Quentin Grimal[2], Jean-Gabriel Minonzio[2], Pascal Laugier[2]

[1]Laboratoire d'Imagerie Paramétrique (LIP), Paris, France
[2]Laboratoire d'Imagerie Paramétrique (LIP), France
*mathieu.chekroun@upmc.fr

Experiments and simulations evidenced that circumferential guided waves are involved in the ultrasonic propagation at the proximal femur (Fig.1) and that their measurement could contribute to improve fracture risk prediction. The frequency-dependent phase velocity of guided waves depends on material properties and geometry (thickness) of the structure in which they propagate. An array signal processing tool derived from time reversal principles (DORT method) can be used to recover the dispersion curves of the circumferential waves. The objective of the work was to asses the sensitivity of phase velocities retrieved with the DORT method to variations of porosity and thickness in a cortical bone shell model. Ultrasound propagation was numerically investigated using a finite difference time-domain numerical code. The bone model consisted of a circular cortical shell whose thickness and porosity could take several values falling in the usual physiological range. Anisotropic effective elastic properties of cortical bone were derived from porosity using a micromechanical homogenization code (BonHom). The DORT signal processing was applied to the synthetic signals to obtain a set of phase velocities for each model.The ability and limitations of the method to discriminate between samples of different properties will be discussed.

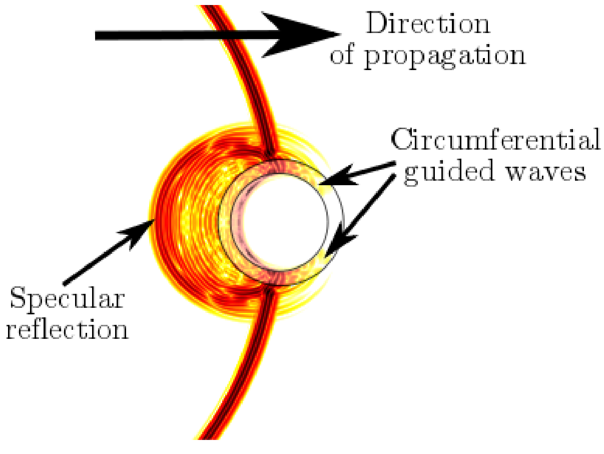

Figure 1: Snapshot of the simulation of the interaction of an incident wave with a circular shell, visualisation of circumferential waves.

*Presenting author

Three-dimensional finite-difference time-domain simulations demonstrate the sensivity of ultrasound measurements at the femoral neck to cortical bone geometry

*Pierre Nauleau[1], Julien Grondin[1], Quentin Grimal[1], Klaus Engelke[2], Pascal Laugier[1]

[1]Laboratoire d'Imagerie Paramétrique, UPMC Paris 6-CNRS UMR7623, Paris, France
[2]Institute of Medical Physics, University of Erlangen-Nürnberg, Erlangen, Germany
*pierre.nauleau@upmc.fr

The ability of QUS to predict fracture risk at the hip has been recently demonstrated. Our group is investigating circumferential propagation of guided waves at the femoral neck as a mean to enhance fracture risk prediction. Two-dimensional numerical simulations have suggested a relationship between mechanical strength and propagation time of circumferential guided waves. This study is an extension of our previous work to the three-dimensional case. The three-dimensional structure of eleven femoral necks was reconstructed from X-ray computed tomography. Three-dimensional simulations of a transverse transmission configuration were performed using a finite-difference time-domain code assuming constant material properties of bone. A transverse cross-section, in the mid-neck axis, was illuminated by the beam (5 mm-width) of a cylindrically focused transducer. The transmitted signal was processed to compute the time-of-flight (TOF) of the first arriving signal. Geometrical parameters, known as relevant indices of bone strength, (volume, V and moment of inertia, MI) were calculated for the probed volume. Strong relationships between the geometry and TOF with R^2-values of 0.78 (TOF vs. MI) and 0.61 (TOF vs. V) were consistent with our previous two-dimensional work. Three-dimensional numerical simulations are a powerful tool to investigate ultrasounds interaction with the complex geometry of the proximal femur.

*Presenting author

2D simulations of the impact of porosity and cortical thickness on the wave propagation at the inferior femoral neck cortex

*Kerstin Rohde[1], Melanie Daugschies[1], Quentin Grimal[2], Pascal Laugier[2], Claus-Christian Glüer[1], Reinhard Barkmann[1]

[1]Medizinische Physik, UK S-H Kiel, Diagnostische Radiologie, Kiel, Germany
[2]Laboratoire d'Imagerie Paramétrique, UPMC, Paris, France
*k.rohde@rad.uni-kiel.de

Cortical ultrasound propagation depends on cortical thickness and porosity. We performed 2D-simulations (SimSonic, LIP Paris) on an Xtreme-CT-Scan of a femoral neck cortex with artificially modified porosity, pore size (PS) and cortical cross-sectional area (CSA).

For the simulation sender and receiver (10 mm diameter, centre frequency 500 kHz) were positioned at both sides of the inferior cortex. PS was varied in 4 steps (diameters 0.08-0.32 mm) at each level of porosity and CSA, CSA in 3 steps (100%-74%) at each level of porosity and pore size, and the porosity in 4 steps (0%-15.8%) at each level of pore size and CSA. Using a multivariate model the impact of all variables and their interaction on the time-of-flight (TOF, at 10% of the signal's first maximum) was calculated.

All variables contributed significantly to the estimation of TOF (13.9micro-sec per % porosity; -2.03micro-sec per mm PS and -4.2micro-sec per % CSA). Only porosity and PS interacted significantly. The slope of the TOF-porosity regression line decreased with increasing PS (17.6 – 11.3micro-sec/%). There was no significant impact of porosity and PS on the slope of the TOF-CSA regression line.

These results have to be checked in measurements on phantoms or specimens and in 3D.

*Presenting author

Advanced stress guided waves simulation to support the non-invasive assessment of human long bones

Giovanni Castellazzi[1], *Alessandro Marzani[1], Luca De Marchi[2], Nicolò Speciale[2], Annapaola Parrilli[3], Matilde Tschon[3], Gianluca Giavaresi[3]

[1]DICAM, University of Bologna, Bologna, Italy
[2]DEIS, University of Bologna, Bologna, Italy
[3]Laboratorio Studi Preclinici e Chirurgici, Istituto Ortopedico Rizzoli, Bologna, Italy
*alessandro.marzani@unibo.it

Bone characterization via axial transmission can be fully exploited only once the complexities of guided wave propagation are unveiled. Generally, plate/cylindrical waveguide models are used to identify the propagating modes.

Here, a numerical strategy for a more rigorous characterization of guided wave propagation in elongated bones is proposed.

First, from a computed tomography image a 3D finite element (FE) mesh of the problem is built by converting voxels into elements. At this level, the soft tissues can be discharged and the mechanical properties of bones obtained converting the Hounsfield units. If necessary, the mesh can be enhanced by smoothing the bone surface. Next, a representative 2D cross-section of the bone is used to set the guided wave equation by means of a Semi-Analytical Finite Element (SAFE) formulation. Via SAFE, the dispersive branches excited by forcing functions generally applied by medical devices are finally obtained.

Such information is validated by passing the 3D mesh to a standard FE code, where waves propagation is simulated, and then by processing the bone time-responses with a time-frequency warped transform suitable for guided waves extraction.

These proposed strategy can support the research on non-invasive techniques based on stress waves for the assessment of long bones.

*Presenting author

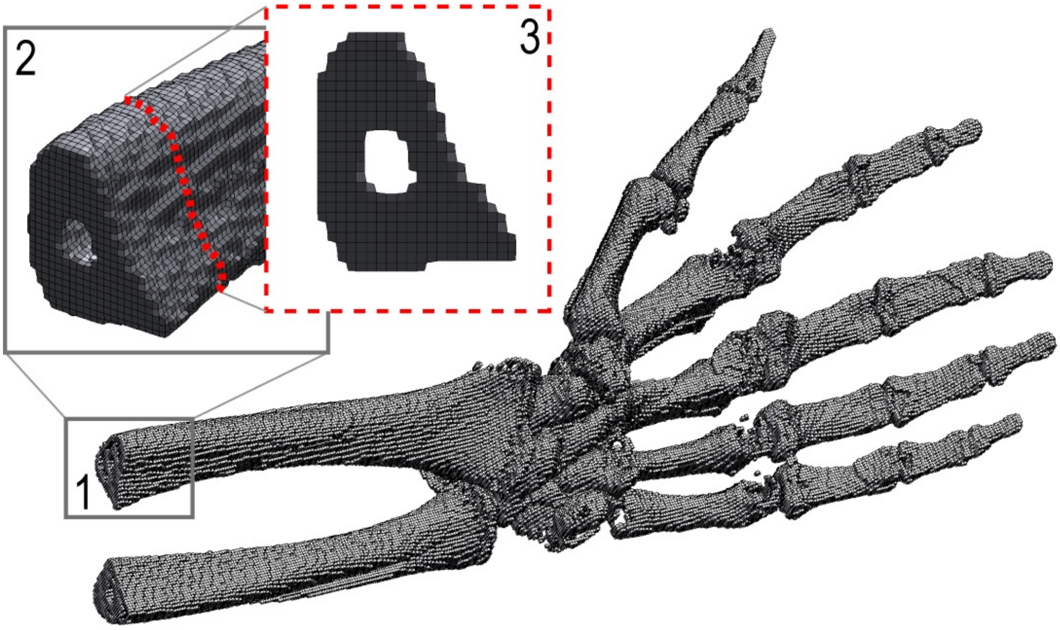

Figure 1: (1) Voxel model of a human hand extracted from a CT image, (2) detail of the FE mesh of a bone segment with surface enhancement, (3) bone cross-section.

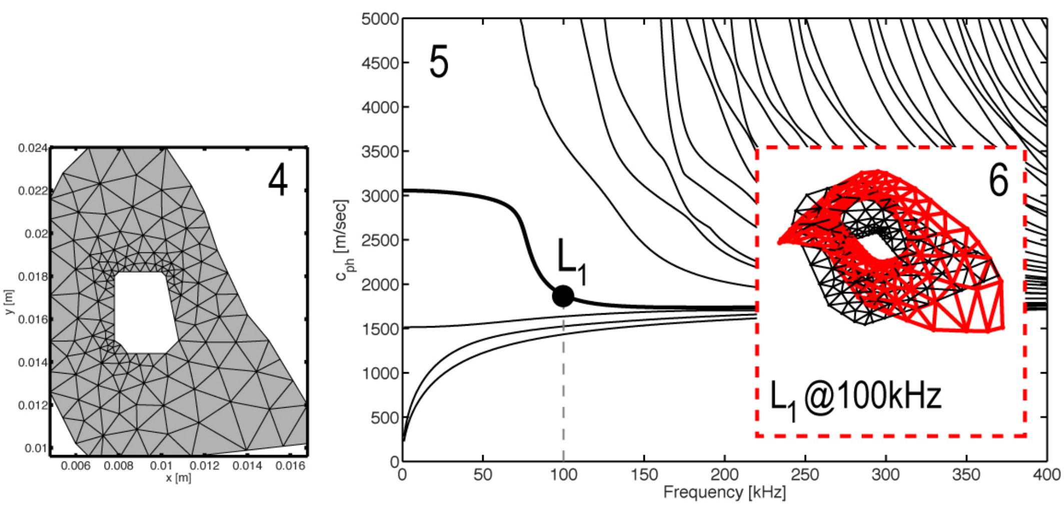

Figure 2: (4) SAFE mesh of constant strain triangles, (5) phase velocity dispersion curves, (6) wavestructure (red color) for the fundamental L1 mode at 100 kHz.

Session VII: Guided waves

Tuesday, June 21st 2011, 13:45

Chair: Patrick Nicholson, Dean Ta

The impact of soft tissue on the propagation of ultrasonic guided waves through a bone plate

*Lauren Stieglitz[1], Lawrence Le[2], Jeff Gu[3], Edmond Lou[4]

[1]Physics. Biomedical Engineering, University of Alberta, Edmonton, Canada
[2]Radiology and Diagnostic Imaging, Physics, Biomedical Engineering, University of Alberta, Edmonton, Canada
[3]Physics, University of Alberta, Edmonton, Canada
[4]Biomedical Engineering, University of Alberta, Edmonton, Canada
*las11@ualberta.ca

Recent studies have shown that guided waves in long bones and bone phantoms can successfully characterize bone properties. This work has great potential in the study of osteoporosis. For clinical applications of guided wave technology to be viable, we need to consider the layer of soft tissue covering bone. Soft tissue is expected to change the dispersion characteristics of guided wave modes, and the impact of this layer has not yet been sufficiently examined. We analyzed the impact of a soft tissue layer on guided wave propagation through experimental work and theoretical modeling. Experimental studies were performed on a cortical bone plate with and without a soft tissue layer using the axial transmission method. The effect of soft tissue was examined using dispersion curves and time-frequency analysis. The experimental studies were validated using numerical modeling. Both the experimental and simulated results were shown to be consistent with the theoretical predictions. Guided wave modes were successfully identified and the modal changes due to the presence of soft tissue were examined. The results showed that the wave propagation through the soft tissue modulated the low frequency guided waves, and higher order guided wave modes were excited.

*Presenting author

Axial transmission guided mode measurement with 1MHz clinical probe on bone mimicking phantom

*Josquin Foiret, Jean Gabriel Minonzio, Maryline Talmant, Pascal Laugier

LIP, UPMC Univ Paris 6, CNRS UMR 7623, Paris, France
*josquin.foiret@upmc.fr

In axial transmission on long cortical bones, Lamb type guided waves are increasingly used with the aim of bone characterization, i.e. determination of relevant properties such as thickness and porosity which are determinants of bone strength. The presence of interfering multimodal responses in recorded signals requires sophisticated signal processing to disentangle individual modes and to evaluate their dispersive properties. Multi-emitters and multi-receivers signals were obtained using a 1 MHz clinical probe with a large frequency bandwidth. Processing was made using an updated version of the singular value decomposition technique to overcome effect of absorption. Plates with uniform thickness and made of transverse isotropic absorbing material were tested. Typical cortical bone stiffness matrix and thicknesses (from 1 to 4 mm) were considered. On the 2.3 mm bone mimicking plate (Fig. 1), five modes were identified after measurement along the fibers direction: S0, A1, S1, S2, and S4. A method of determination of plate properties (elasticity and thickness) from experimental Lamb spectra was developed and extended to phantoms of tube and human radius geometry. In the example shown in Fig. 1, elastic coefficients after best fitting are (in GPa) $c_{11} = 17.1$, $c_{13} = 6.8$, $c_{33} = 21$, $c_{55} = 4.2$.

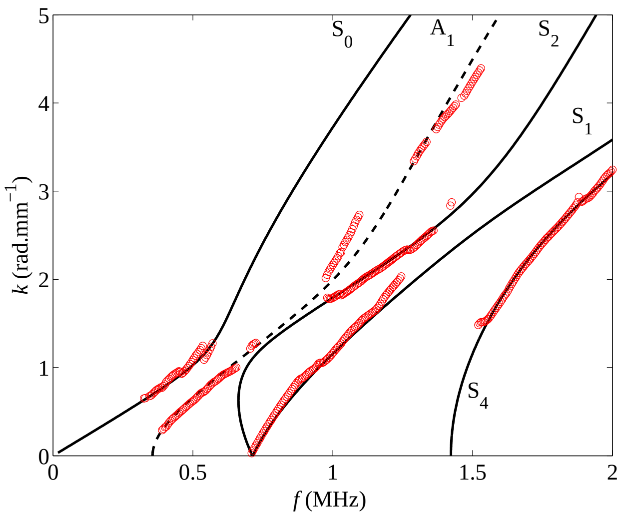

Figure 1: experimental wavenumber k (circle) as a function of frequency f on a 2.3 mm thick bone mimicking plate measured along the fibers direction. Theoretical modes for best fitted model are shown with continuous and dashed lines (respectively symmetric and anti-symmetric modes).

*Presenting author

Signal processing for guided mode measurement in absorbing material

*Jean-Gabriel Minonzio, Josquin Foiret, Maryline Talmant, Pascal Laugier

Laboratoire Imagerie Paramétrique, France
*jean-gabriel.minonzio@upmc.fr

Robust signal processing methods adapted to clinical measurements of guided modes are required to assess bone properties such as cortical thickness and porosity. Recently, an approach based on the singular value decomposition (SVD) of multidimensional signals recorded with an axial transmission array of emitters and receivers has been proposed for materials with negligible absorption. At each frequency f the most energetic singular vectors of the response matrix are interpreted as the signal subspace basis. The so-called Norm-function corresponds to the projection into the signal subspace of non attenuated plane waves (real wavenumber k). Guided modes are associated with Norm maxima in the (f-k) domain. In presence of absorption, the magnitude of the maxima of the Norm-function decreases, which degrades the ability to extract guided mode. The objective of the present study is to extend the method to the case of absorbing media. The Norm-function is extended considering attenuated plane waves (complex wavenumber). The maxima are enhanced and the order of magnitude of the attenuation of the guided mode are estimated. This method is validated on a 2 mm thick PMMA plate (Fig. 1). Results (cL=2690m.s-1;cT=1380m.s-1;e= 1.98mm) are consistent with the values obtained from transmission measurements (cL=2680m.s-1;cT=1320m.s-1;e=1.94mm).

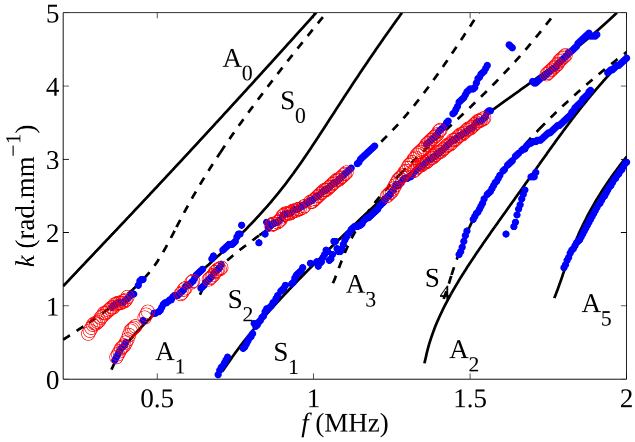

Figure 1: real part of the guided mode wavenumbers for a 2-mm tick PMMA plate. More experimental points are obtained with the extended Norm function (blue dots) than with the former Norm function (red circles). A same threshold equal to 0.75 has been applied in the two cases..

*Presenting author

Characterization of circumeferential guided waves in the femur cortical shell – Part I : Measurements on a bone mimicking tube

*Pierre Nauleau[1], Etienne Cochard[2], Jean-Gabriel Minonzio[1], Quentin Grimal[1], Claire Prada[2], Pascal Laugier[1]

[1]Laboratoire d'Imagerie Paramétrique, UPMC Paris 6-CNRS UMR7623, Paris, France
[2]Laboratoires Ondes et Acoustique, ESPCI Université Paris 7-CNRS UMR7587, Paris, France
*pierre.nauleau@upmc.fr

There is evidence that circumferential guided waves are involved in the ultrasonic propagation at the proximal femur. The frequency-dependent guided waves phase velocities depend on material properties and geometry (thickness) of the structure in which they propagate. The measurement of guided waves at the proximal femur could contribute to improve fracture risk prediction. A method exists (DORT method, Prada and Fink, JASA 1998) to measure circumferential guided waves in hollow cylinder. It involves several signal processing steps which have to be modified in order to measure bone. The objective of the work was to implement the method to measure a tube-like bone phantom (cylindrical cross-section), with the typical material properties (elasticity, attenuation) and dimensions of upper diaphysis and neck. A focused array of 128 tranducers of 1 MHz central frequency (for both emission and reception) and the phantom were immersed in water. The DORT method parameters were optimized in order to retrieve as much information on the phantom as possible. Three branches of guided waves modes were obtained and identified by comparison with theoretical dispersion curves of a plate. This study shows that dispersion curves of some circumferential waves in a bone phantom can be measured with a good precision.

*Presenting author

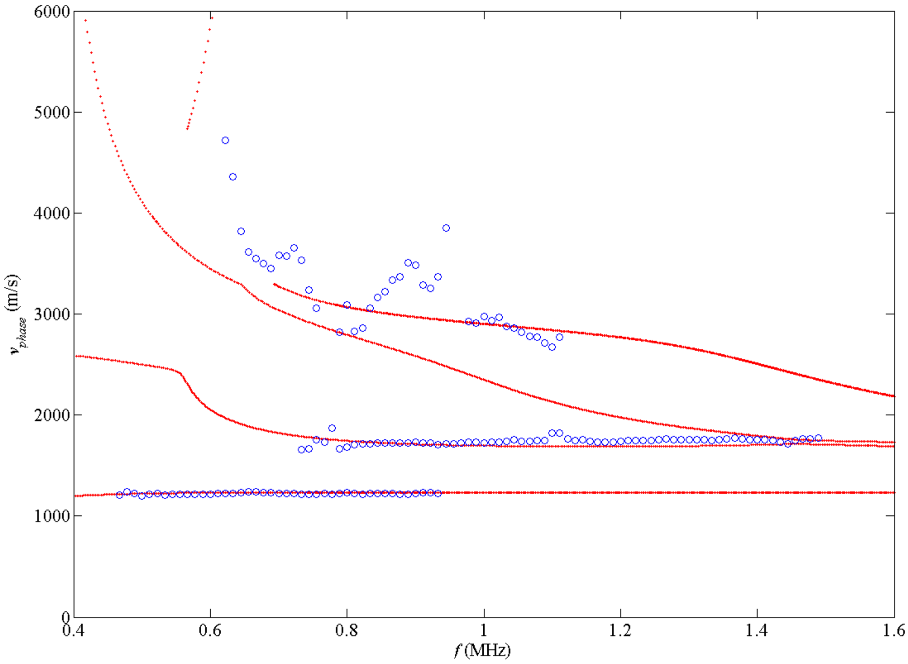

Figure 1: Phase velocity dispersion curves : three branches of guided waves modes are obtained (blue circles). They can be identified using the theoretical curves for a plate (red points).

Measurement of long cortical thickness using ultrasonic guided waves based on two signal processing methods

*Xiaojun Song[1], Dean Ta[2], Weiqi Wang[1]

[1]Department of Electronic Engineering, Fudan University, Shanghai, China
[2]Department of Electronic Engineering, Fudan University, Shanghai, 200433, China
*081021049@fudan.edu.cn

The group velocities and other parameters of ultrasonic guided waves (GWs) are very sensitive to the mechanical characteristic and they have the potential to assess the changes of cortical bone. But due to the mixed multiple modes, it's a challenge to obtain the parameters for a single mode. In this report, two methods are applied to separate the superimposed GWs in the cortical bone. One is blind identification algorithm by joint approximate diagonalization of eigen-matrices (JADE) which can process the data fast, and the other is spatial time-frequency based blind source separation (TFBSS) method which can still work well in the poor SNR situation. In the simulation, a highly agreement was found between the theoretical group velocities and estimated ones by both methods. And in the experiments of bovine bones, the cortical thickness of long bone was measured by the two methods. The results showed the estimated thickness had strong correlation with the real one. It suggests that both JADE algorithm and TFBSS method can be used to get single mode from the superimposed GW and have strong potential to assess long bones. The results also showed TFBSS method performed better than JADE algorithm when the noise was strong.

*Presenting author

A wavelet-based processing method for simultaneously determining broadband ultrasonic velocity and cortical bone thickness

*Philippe LASAYGUES, Matthieu LOOSVELT

Wave & Imaging, Laboratory of Mechanics and Acoustics, UPR CNRS 7051, 13009 Marseille, France
*lasaygues@lma.cnrs-mrs.fr

The aim of the present study was to develop a method of simultaneously determining the ultrasonic wave velocity in a cortical bone sample and the apparent thickness of the bone. The wave propagation in these structures, which involves several processes, generates ultrasonic signals forming packages with different time and frequency signatures. To correlate the complex physical processes involved with the various packets forming the signals, it is advisable to separate the useful information from the parasite information. After testing several possible methods with variable levels of success, it was proposed to investigate a processing method, which can be optimized by simultaneously analyzing the time and frequency parameters. For this purpose, an algorithm based on the wavelet decomposition of the signals was used and suitable transmitted incident wave correlated with the parameters of the experimental device was selected. The mathematical properties of the transmitted signal lend themselves well to this time and frequency based approach. This method, called the "wavelet-based processing" method, can be used to determine the velocity of the ultrasonic wave and the wave path across the thickness of bone sample, independently (e.g., without knowing each other), and also makes it possible to estimate the sub-wavelength size.

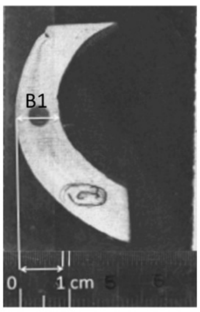

Figure 1: Position of the calipers used to measure the thicknesses of the bone sample

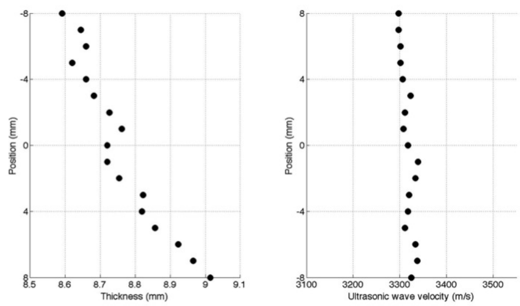

Figure 2: Thicknesses of the bone sample and associate ultrasonic wave velocities

*Presenting author

Multi-frequency approach of the first arriving signal (FAS) on long cortical bones

Thien-Ly PHAM, *Maryline Talmant, Pascal Laugier

Laboratoire d'Imagerie Paramétrique, CNRS-UPMC, Paris, France
*maryline.talmant@upmc.fr

In axial transmission studies on cortical bone, the velocity of the first arriving signal (VFAS) was shown to be able to discriminate osteoporotic patients from healthy subjects.

The study aims at elucidating the physical origin of the first arriving signal. Fifty human radius specimens were measured with a bidirectional wideband axial transmission probe (frequency bandwidth 0.4-1.5 MHz). Individual frequency variations of VFAS were obtained by filtering the response signal using a bank of narrow pass-band filters at intervals of 100 kHz.

Two types of frequency dependence of VFAS were mainly observed. Increasing VFAS with frequency was found consistent with Lamb type guided wave propagation in the samples. Decreasing VFAS with frequency was related to ray propagation of compressional bulk waves in the samples. The cortical thickness which defines the boundary between ray propagation and guided waves propagation depends on the excitation frequency, the distance between emitter and receiver and the elastic properties of the specific sample.

Such sorting of the propagation phenomenon related to FAS in cortical bone is crucial to design a procedure of bone properties determination, aiming at evaluating thickness and porosity from frequency dependent FAS velocity.

*Presenting author

Session VIII: Novel Instrumentation and Imaging

Tuesday, June 21st 2011, 16:00

Chair: Reinhard Barkmann

Experimental assessment of the amount of bone surrounding an implant with quantitative ultrasound

*Vincent Mathieu[1], Fani Anagnostou[1], Emmanuel Soffer[1], Guillaume Haïat[2]

[1]Lab. Biomécanique et Bioingénierie Ostéo Articulaire, CNRS, 75010 PARIS, France
[2]Lab. Modélisation et Simulation Multi Echelle, CNRS, 94010 CRETEIL, France
*vincent.mathieu@univ-paris-diderot.fr

The prediction of the biomechanical stability of titanium implants is of primary importance in oral and maxillofacial surgery. Despite a routine clinical use, implant failures are still observed and may cause painful and expensive additional surgical interventions. The present in vitro study proposes the use of Quantitative Ultrasound for the assessment of the amount and quality of bone surrounding Ti-6Al-4V cylindrical implants. 4 groups of 10 rabbit femurs were considered, each group corresponding to bone specimens prepared to obtain a controlled level of stability. The 10 MHz ultrasonic response of each implant was recorded (see Fig. 1) and a quantitative indicator was calculated, based on the decay of amplitude of the successive echoes. Mean values of the indicator increase from 11.6 to 18.6 (arbitrary units) when the anchorage depth of the implant decreases. A significant dependence of the indicator to the biomechanical stability of the implants was established. An empirical model enabled the understanding of propagation phenomena occurring in the implant by considering mode conversion at the interfaces of the implant. The results demonstrate the potentiality of QUS techniques for the assessment of the biomechanical stability of an implant.

Figure 1: Contact probe positioning during the recording of the ultrasonic response of an implant.

*Presenting author

Impact of the beam incidence angle on Quantitative Ultrasound (QUS) measurements of the calcaneus

*Melanie Daugschies, Kerstin Rohde, Claus-Christian Glüer, Reinhard Barkmann

Medizinische Physik, Diagnostische Radiologie, UK-SH, Kiel, Germany
*m.daugschies@rad.uni-kiel.de

Commercial devices of calcaneus QUS do not consider the irregular anatomical shape of the bone. Especially the direction of the ultrasound transmission is not well standardized. We built a device in which the direction of propagation can be adjusted, and investigated in a small pilot-study the impact of beam angle rotation on QUS variables. The scanner comprises two transducers of 10 cm diameter, an receiver array with cells of 6mm * 6mm sizes and a single emitter, mounted on a c-arm opposite to each other and positioned on both sides of the calcaneus. Contact to the skin was established using oil filled flexible membranes. SOS and signal amplitude were measured in two volunteers with the c-arm mechanically rotated in two angles in a range of resp. ±15 degrees. SOS varied 57 m/s resp. 39 m/s. We could locate a propagation direction where a minimum in SOS and a maximum in signal amplitude appear. This direction was roughly consistent in the subjects and distinctly different from the direction usually used. Future tests will show if the reproducibility of calcaneus QUS measurements can be improved by our approach of tilting the angles of ultrasound penetration.

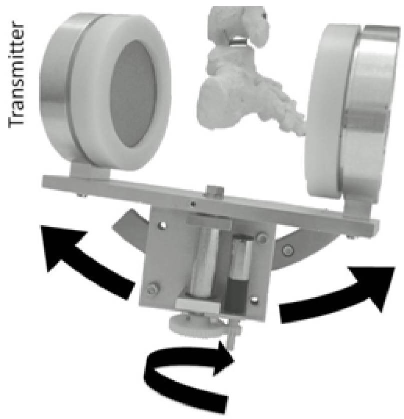

Figure 1: The C-arm can be rotated around a vertical and horizontal axis, see arrows.

*Presenting author

Simultaneous quantitative ultrasound assessment of cartilage and subchondral bone

*Jukka Liukkonen, Antti Aula, Juha Töyräs, Jukka Jurvelin

Department of Applied Physics, University of Eastern Finland, Kuopio, Finland
*jukka.liukkonen@uef.fi

In osteoarthritis, changes in cartilage and subchondral bone appear in parallel. Simultaneous analysis of both tissues might yield diagnostically valuable information. Presently, we test quantitative ultrasound (QUS) to evaluate the cartilage and subchondral bone in situ in a bovine knee as well as during in vivo arthroscopy of human knee joint. In situ the pulse-echo measurements (5MHz) were conducted through the articular cartilage, apparent integrated backscatter (AIB) was calculated for the subchondral bone and compared with mineral density, recorded with a pQCT scanner. During clinical arthroscopy potential of QUS to detect changes in subchondral bone related to osteochondritis dissecans (OCD) was evaluated by using a ultrasound system equipped with an ultrasound catheter (dia=3mm, frequency=9MHz). Ultrasound enabled quantitative live imaging of articular cartilage and subchondral bone. Statistically significant correlation was found between the AIB and mineral density of the subchondral plate. During arthroscopy, cartilage-bone interface and subchondral bone were visualized and OCD changes were diagnosed. In conclusion, QUS has potential to become a quantitative in vivo method for simultaneous assessment of articular cartilage and subchondral bone during arthroscopy. For further improvement, effect of ultrasound attenuation in the overlying cartilage should be determined and eliminated from the bone measurement.

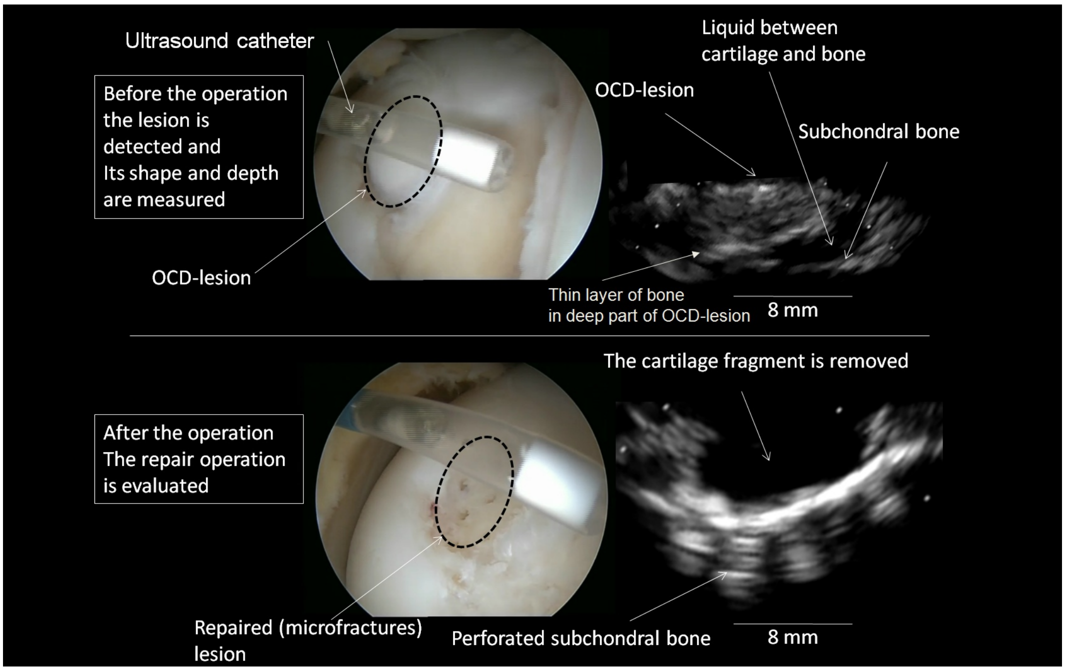

Figure 1: Ultrasound enables quantitative live imaging of articular cartilage and subchondral bone during clinical arthroscopy..

*Presenting author

Ultrasound imaging of long bones using Born scattering theory: in vitro study

*Rui Zheng[1], Lawrence H Le[2], Mauricio D Sacchi[1], Edmond Lou[1]

[1]University of Alberta, Canada
[2]University of Alberta, T6G 2V2 / Edmonton, AB, Canada
*ruiz@ualberta.ca

Osteoporosis will lead to cortical thinning and micro-structural deterioration in bones. Ultrasound imaging has the potential to measure the elasticity and estimate fracture risks. An ultrasound imaging method based on Born scattering theory was implemented to reconstruct the internal structures of long bones. With the source and receiver pairs at the same location, reflection data sets were collected along the axial direction of four long bone samples. The signal processing steps were applied to enhance signal-to-noise ratio and extract major reflections for inversion. The CT image provides the thickness measurements and a reference for comparison. The reconstructed results demonstrate that the major tissue interfaces can be recovered and mostly comparable to the reference. Especially the top cortical/marrow interface is faithfully reconstructed among all interfaces and can be used to estimate the thickness of the cortex. The sectional mean thickness is a reliable indicator for thickness measurement. The absolute errors between the reconstructed thickness and CT-thickness are as low as 1.89%, 4.55% and 3.23% for the three samples with approximate cortical thickness of 5mm, 4mm and 3mm respectively.

*Presenting author

List of Authors