Institute of Environmental Mechanics and Applied Computer Science
National Centre of Excelence POROCENT
Kazimierz Wielki University

3^{rd} International Conference

Esucb 2009

Bydgoszcz/Poland, September 17-18, 2009

Scientific Committee

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International Scientific Committee:
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Scientific Program Information

Oral Presentations
Contributed oral presentations have a gross duration **15 minutes**. Due to very tight schedule the presenting authors are asked to strictly stay within 15 min presentation time. You should plan to speak for **12 minutes** and leave **3 minutes** for questions. Invited speakers have twice this time (**30 minutes**), that break down to **25 min** for presentation and **5 min** for discussion. The conference room will be equipped with a video projector and a computer that is connected to the projector. Normal audio equipment, such as microphones, will be provided.

Poster Presentations
Poster session is scheduled during the Thursday afternoon coffee break (1 hour). The required poster size is **A0** (**vertically oriented**). All posters can be mounted during entire time of conference (from Thursday morning until Friday afternoon). The presenting authors are requested to discuss their work during their scheduled presentation time, but the discussion can be continued any other time.

Social Program

Thursday - Restaurant ”Ogniem i Mieczem”
After the scientific sessions on Thursday we invite you to meet with your friends and colleagues in the restaurant ”Ogniem i Mieczem”. We hope that you will enjoy a traditional polish dinner.
Address: ul. Oginskiego 22, 85-092 Bydgoszcz tel: +48523414126

Friday - Restaurant ”Palacowa”, Lubostron
We encourage you to stay with us after the scientific sessions on Friday. We hope that unique atmosphere of the Lubostron palace will provide new ideas and will help to establish new collaborations. The bus will take the guest from the University at 18:45. The trip will last about 30 minutes. The return of the bus to Bydgoszcz is expected about 24:00 and it will transfer the guests to the hotels directly.
Address: Palac Lubostron, Lubostron, 89-210 Labiszyn,

Internet access

A WLAN access will be available in the lecture room and on the whole University area. The access is free from your own laptops. If you do not bring your own WLAN laptop, you can use one of our PC’s.

Scientific Program

Thursday, September 17th, 2009

8:30	**REGISTRATION**
9:00	**OPENING** Michal Pakula
9:15	**WELCOME NOTE** prof. Jozef Kubik - Rector of Kazimerz Wielki University in Bydgoszcz
9:30	**SESSION I - Ultrasound Propagation Models for Cancellous Bones** chair: Jim Miller
9:30	**INVITED LECTURE: Ultrasound scattering from cancellous bone** Keith Wear
10:00	**COFFEE BREAK**
10:30	**Structure and anisotropy of fast wave in bovine cancellous bone** H. Somiya, K. Mizuno, M. Matsukawa, T. Otani, I. Mano, T. Tsujimoto
10:45	**Bayesian parameter estimation of the ultrasonic properties of cancellous bone** C. Anderson, M. Pakula, M. Holland, G. Bretthorst, P. Laugier, J.G. Miller
11:00	**Biot constants recovery from ultrasound through trabecular bone** G. Rus, M. Pakula, Q. Grimal, P. Laugier
11:15	**Correlations between ultrasonic backscatter parameters and cancellous bone microstructure** D. Ta, K. Huang, W. Wang
11:30	**Multiple scattering contribution to trabecular bone backscatter** J. Wójcik, J. Litniewski, A. Nowicki
11:45	**Influence of the filling fluid on frequency-dependent velocity and attenuation in cancellous bones between 0.35 and 2.5 MHz** M. Pakula, F. Padilla, P. Laugier
12:00	**LUNCH BREAK - Restaurant "Ogniem i Mieczem"**
14:00	**SESSION II - Ultrasonic Characterization of Cortical Bones** chair: Pascal Laugier
14:00	**INVITED LECTURE: Ultrasonic guided waves in bone** Petro Moilanen
14:30	**Axial transmission measurements and compact bone heterogeneity** J. Foiret, Q. Grimal, M. Talmant, R. Longo, S. Naili, Ch. Desceliers, Ch. Soize , G. Haiat, P. Laugier
14:45	**2D ultrasound axial transmission simulations on 40-day fracture healing models** Ch. B. Machado, W. Pereira, M. Talmant, F. Padilla, P. Laugier
15:00	**Low-frequency axial ultrasound velocity predicts bone strength in the radius and tibia** V. Kilappa, P. Moilanen, L. Xu, S. Cheng, J. Timonen
15:15	**Investigating the impact of bone marrow on axial transmission of a low-frequency flexural wave: Three-dimensional simulations of in vitro experiments on human radius** P. Moilanen, M. Talmant, S. Cheng, P. Laugier, J. Timonen
15:30	**Measurement of guided mode phase velocities using multi-emitters and multi-receivers arrays in contact using transfer matrix analysis.** J-G. Minonzio, M. Talmant, P Laugier

Thursday, September 17th, 2009

16:00	**COFFEE BREAK / POSTER SESSION**

P1 **First arriving signal in axial transmission: a multi-frequency approach**
T-L. Pham, G. Costa, M. Talmant, P. Laugier

P2 **Numerical analysis of uncertainties in dual frequency ultrasound technique**
M. Malo, J. Karjalainen, O. Riekkinen, J.Toyras, H.Isaksson, J. S. Jurvelin

P3 **Towards a realistic model sound propagation through the femoral neck: Impact of structural and elastic variations on the distribution of time of flight of the first arriving signal**
Q. Grimal, J. Grondin, D. RohrBach, R.Barkmann, P. Laugier, K. Raum

P4 **Heterogeneity of velocity and attenuation of ultrasound in partially demineralized cortical bone tissue**
H. Trebacz, R. Drelich, M. Pakula

P5 **Fast and slow waves propagating through cancellous bone with porosity distribution in a propagation direction**
A. Hosokawa

P6 **Relationships between anisotropy of longitudinal wave velocity and HAp orientation in bovine cortical bone**
K.Yamamoto, T.Nakatsuji, Y.Yaoi, Y.Yamato, T.Yanagitani, M.Matsukawa K.Yamazaki

P7 **Application of Biot theory for modelling of wave propagation in cancellous bone**
M. Pakula, F. Padilla, M. Kaczmarek, P. Laugier

P8 **Scattering of ultrasonic waves in randomly layered materials**
M. Cieszko, M. Pakula, J. Kubik

P9 **Dynamic behavior of the bone-implant systems**
B. Nowak, M. Kaczmarek

P10 **Waves interaction with a layer of macroscopically inhomogeneous material**
M. Cieszko, W. Kreise

P11 **Determination of bone volume porosity based on histograms of the μCT scans**
M. Cieszko, Z. Szczepanski, G. Zych

P12 **Application of Minkowski metric space to description of anisotropic pore space structure and fluid dynamics in porous materials**
M. Cieszko

19:00	**DINNER - Restaurant "Ogniem i Mieczem"**

Friday, September 18th, 2009

9:00	**SESSION III - Scanning Acoustic Microscopy** chair: Reinhard Barkmann
9:00	**INVITED LECTURE: Multiscale structure-functional modeling of lamellar bone** Kay Raum, Quentin Grimal, Alf Gerisch
9:30	**Variations of nanostructural characteristics of mineral platelets across a human osteon are determined by acoustic impedance modulation** M. Mouchet, A. Gourrier, F. Rupin, K.Raum, F. Peyrin, A. Saied, P.Laugier
9:45	**Spatial distribution of tissue mineralization and anisotropic tissue elastic constants in human femoral cortical bone** S. Lakshmanan, D. Rohrbach, F. Peyrin, K. Raum
10:00	**Cortical bone mechanical properties at the microscopic scale: does the acoustic impedance heterogeneity affect the local strain as determined by microextensometry?** M. Mouchet, Q. Grimal, J-M Allain, D. Caldemaison, J. Crepin, A. Saied, P. Laugier
10:15	**Towards a realistic model of sound propagation through the femoral neck: I - Experimental assessment of microstructure and matrix elasticity by 50-MHz scanning acoustic microscopy** D. Rohrbach, R. Barkmann, J. Grondin, Q. Grimal, P. Laugier, K. Raum
10:30	**COFFEE BREAK**
11:00	**SESSION IV - Applications - Part I** chair: Keith Wear
11:00	**Probing long bones with ultrasonic body waves** L. Le, J. Gu, Y. Li, Ch. Zhang
11:15	**Towards a realistic model of sound propagation through the femoral neck: II 0.5 MHz sound propagation simulations based on microelastic input data** J. Grondin, D. Rohrbach, K. Raum, R. Barkmann, Q. Grimal, P. Laugier
11:30	**Discrimination of cervical and trochanteric fractures by femur QUS (FemUS)** R. Barkmann, C-C. Gluer
11:45	**Ultrasonic method to characterize children bone elastic properties** J-P. Bertau, P.Lasaygues, M. Pithioux, P. Chabrand
12:00	**Improvements in measurements of BUA and SOS in human calcaneus** K. Wear
12:15	**Comparative evaluation of condition of human proximal tibiae 'in vitro' by ultrasonic guided waves and pQCT** A. Tatarinov, V. Egorov, A. Sarvazyan, G. Beller, D. Felsenberg
12:30	**LUNCH BREAK - Restaurant "Ogniem i Mieczem"**

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14:30	**SESSION IV - Applications - Part II** chair: Kay Raum
14:30	**INVITED LECTURE: Bone tissue and implant surface interactions** Krzysztof Scigala , Romuald Bedzinski, Celina Pezowicz
15:00	**Dynamic acoustoelastic testing for non invasive detection of microdamage in cortical tissue of long bones** G. Renaud, M. Defontaine, S. Calle, M. Talmant, P. Laugier
15:15	**Non-optimal focusing of ultrasound does not affect dual frequency ultrasound measurement of bone** M. Malo, O. Riekkinen, J. Karjalainen, H. Isaksson, J. Jurvelin, J. Toyras
15:30	**Ultrasonic imaging of long bones** R. Zheng, M. Sacchi, L. Le, E. Lou
15:45	**Time-filtering and modeling of compressed multisine waves for simultaneous determination of acoustic velocity and mass density of a cortical bone slab** R. Longo, Q. Grimal, J. Foiret, P. Laugier, S. Vanlanduit, P. Guillaume
19:00	**GALA DINNER - Palac Lubostron**

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Session I

Ultrasound Propagation Models for Cancellous Bones

9:30-12:00 - Thursday, September 17th, 2009

Ultrasound Scattering from Cancellous Bone

Keith A. Wear

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Backscatter from cancellous bone samples in vitro shows high correlation with bone mineral density (BMD) and moderate correlations with trabecular thickness and mechanical properties. Backscatter from human calcaneus is very anisotropic in that it is 50% lower when the beam propagates in the antero-posterior orientation compared to when the beam propagates in the medio-lateral orientation. Measurements of attenuation and scattering from cancellous-bone-mimicking phantoms suggest that 1) shear mode conversion of incident longitudinal waves is a significant source of scattering loss at diagnostic frequencies, and that 2) longitudinal scattering becomes significant at frequencies above the diagnostic range. Three theoretical models for scattering will be discussed: (1) Faran Cylinder Model, (2) Weak Scattering Model, and (3) Thin Cylinder model. Data from 23 human cancellous femur samples in vitro suggest that the Faran Cylinder Model and the Weak Scattering Model accurately predict frequency dependence of backscatter coefficient. Ultrasound backscatter has been shown to be useful for characterization of bone in vivo. The correlation coefficient squared for backscatter vs. BMD in vivo is $r^2 = 0.76$. In addition, backscatter has been shown to be useful for predicting fracture risk in a clinical study involving 210 women.

Structure and anisotropy of fast wave in bovine cancellous bone

Hiroki Somiya[1], Katsunori Mizuno[1], Mami Matsukawa[1], Takahiko Otani[1], Isao Mano[2], Toshiyuki Tsujimoto[3]

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Cancellous bone is composed of the trabecular frame and soft tissue, and anisotropic due to the complex structure. It is known that the longitudinal wave which passed through the cancellous bone is separated into two waves, the fast and the slow waves. The fast wave properties mainly reflect the characteristics of trabecular frame. Most in vivo clinical techniques involve propagation of the ultrasonic waves perpendicular to the bone axis. The aim of this study is to investigate the wave propagation perpendicular to the bone axis and know the fast wave behavior. Cylindrical specimens (40B B90 mm in length and 11 mm in diameter) were obtained from distal end of 2 bovine left femora. A PVDF focus transmitter and a receiver were used to measure longitudinal waves.The direction of the incident wave was perpendicular to the central axis of the cylindrical specimen. By rotating the cylindrical specimen, changes in the fast wave speed due to the rotation angle were then observed. The measurements were done at each rotation angle of 10 degrees. We also performed the X-ray CT measurements (Shimadzu) of the specimens and obtained the structural parameters (mean intercept length (MIL)) by the 3D-Bon software (Ratoc). The maximum and minimum values of fast wave speed and MIL changed due to the measured positions and angles. The maximum values of the fast wave speed and MIL were observed from anterior to posterior direction. Considering the MIL, trabecular aligns perpendicular to the bone axis. This is in good agreement with the expected movable direction of the joint near the distal end. These results indicate that we can observe fast waves in the direction perpendicular to the bone axis, showing the usefulness of fast wave for in vivo assessment.

Bayesian parameter estimation of the ultrasonic properties of cancellous bone

Christian C. Anderson[1], Michal Pakula[2,3], Mark R. Holland[1], G. Larry Bretthorst[1], Pascal Laugier[2], James G. Miller[1]

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[2] *Laboratoire d'Imagerie Parametrique, CNRS UMR7623, UPMC-Paris 6, France,*
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Ultrasonic investigations of cancellous bone can be complicated by the interference of fast and slow waves in the ultrasonic field and phase cancellation at the face of a piezoelectric receiver. Such effects may contribute to anomalous phase velocity dispersions. The goal of the present work is to recover the phase velocities and the frequency dependences of the attenuation coefficient for the individual fast and slow waves that are presumed to underlie the observed composite rf signals. Waves were transmitted through a bovine femur condyle and through plastic phantoms designed to yield two waves of differing velocities using broadband 500 kHz center frequency transducers. The data were analyzed using Bayesian probability theory to recover the individual properties of the fast and slow waves. In the Bayesian calculation, ultrasonic wave propagation was modeled as the superposition of two plane waves characterized by a linear-with-frequency attenuation coefficient and a logarithmic-with-frequency increasing phase velocity. Markov chain Monte Carlo (MCMC) was used to obtain estimates of the joint posterior probability for all parameters in the model. The Bayesian models were in moderately good agreement with the acquired data, even in the presence of complicating experimental factors such as phase cancellation and diffraction.

NIH R01 AR057433-01

Biot constants recovery from ultrasound through trabecular bone

Guillermo Rus Carlborg[1], Michal Pakula[2,3], Quentin Grimal[3],Pascal Laugier[3]

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Reliable quantification of mechanical constants of bone tissue is an open issue with relevance for the treatment of bone quality disorders, such as osteoporosis. The reconstruction of such parameters from nondestructive testing based on ultrasonic transmission of pulses and model-based solution of the identification inverse problem is proposed as a novel technique with high potential not only due to the reduced cost and its non-ionizing nature, but for the direct relationship and sensitivity of the propagation of those mechanical waves to the mechanical strength of bone, which defines the ultimate criterion for diagnosis.

This work is aimed at (i) evaluating the feasibility of the model-based inverse problem to reconstruct the mechanical constants that govern Biot theory, and quantify its accuracy and error for trabecular bone specimens. A second goal is (ii) to validate to which extent the Biot theory assumed in the model of wave propagation is valid, and if any corrections can empirically be suggested to overcome inconsistencies. Finally, (iii) the obtained Biot constants are cross-correlated and a parametric study is carried out to extract practical parameters for final bone quality assessment.

As a conclusion, some of Biot constants can be clearly reconstructed by inversion based on matching the time-frequency domain signals, other constants appear to be coupled together, while others cannot be identified. A second conclusion is that the outcome from inversion may reflect relationships between Biot's constants, some of which have been observed independently by other laboratory measurements.

Correlations between ultrasonic backscatter parameters and cancellous bone microstructure

Dean Ta, Kai Huang, Weiqi Wang

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Osteoporosis is a bone disease characterized by bone mass loss, deterioration of bone microstructure. Ultrasonic backscatter signal can provide more cancellous bone microstructure information than ultrasonic transmission signal. The aims of this work are to investigate the correlations among three ultrasonic backscatter parameters (including apparent backscatter coefficient (BC), apparent integrated backscatter coefficient (AIB) and spectrum centroid shift (SCS)) and cancellous bone microstructure parameters. Twenty-six bovine cancellous bones in vitro were measured in this work. Correlations were studied among the three parameters within a ROI (14.2 mm x 14.2mm) and bone microstructural parameters obtained from a μ-CT 3-D reconstruction, which are mean trabecular thickness (Tb.Th), mean trabecular spacing (Tb.Sp), bone volume/total volume ratio (BV/TV), bone surface/volume ratio (BS/BV) and bone material density (BD). Results demonstrated that BC, AIB and SCS have mediate and significant correlations (all $p<0.01$) with the bone parameters. BC and AIB have negative correlations with Tb.Sp (r=-0.513∼-0.596) and increase with Tb.Th (r=0.265∼0.339). SCS has significant correlations with Tb.Th (r=-0.699), Tb.Sp (r=0.477), BV/TV (r=-0.675), BS/BV (r=0.663) and BD (r=0.663). The standard deviation (SD) of BC and AIB values were mediately correlated with Tb.Th (r=-0.550∼-0.645), Tb.Sp (r=0.405 0.627), BV/TV (r=-0.572∼-0.668) and BS/BV (r=0.513∼0.640). The SD of SCS has the significant correlations with Tb.Th (r=-0.720), Tb.Sp (r=0.771), BV/TV (r=-0.754) and BS/BV (r=0.802). The results suggest that the parameters BC, AIB and SCS may helpful characterize bone quality and diagnosis osteoporosis.

European Symposium on Ultrasonic Characterization of Bone
Esucb 2009 Bydgoszcz, 17-18 September 2009

Multiple scattering contribution to trabecular bone backscatter

Janusz Wójcik, Jerzy Litniewski, Andrzej Nowicki

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Trabecular bone consists of trabeculae which mechanical properties differ significantly from the surrounding marrow and therefore the ultrasonic wave is strongly scattered within the bone structure. The aim of the presented paper was the evaluation of the contribution of the first, second and higher order scattering (multiple scattering) into total scattering of ultrasound in the trabecular bone. The scattering due to interconnections between thick trabeculae, usually neglected in trabecular bone models, has been also studied. The basic element in our model of trabecular bone was an elastic cylinder with finite-length and varying diameter and orientation. The applied model was taking into account variation of elements size and spatial configuration. The field scattered on the bone model was evaluated by solving numerically the integral form of the Sturm-Liouville equation that describes scalar wave in inhomogeneous media. For the calculated scattered fields the effective cross-sections as well as the Broadband Ultrasonic Backscatter (BUB) were determined. The results allowed to conclude that within the frequency range from 0.5 to 1.5 MHz the contribution of the second order scattering to the effective backscattering cross-section is at least 500 times lower than the one due to the first order scattering. BUB, calculated under the same assumptions, is 20 times lower. Above the 1.5 MHz the fast growth of the BUB, calculated for the second order scattering, occurs.

Influence of the filling fluid on frequency-dependent velocity and attenuation in cancellous bones between 0.35 and 2.5 MHz

Michal Pakula[1,2], Frederic Padilla[2], Pascal Laugier[2]

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The paper is focused on experiments on human cancellous bones filled with different fluids with the goal of evaluating their contribution to velocity dispersion, absorption and scattering mechanisms. Measurements were performed in transmission between 0.35 and 2.5 MHz. The specimens were measured first filled with marrow and subsequently with water and alcohol filling the pores after marrow removal. No significant influence of the fluids was evidenced on the attenuation coefficient. Given the absence of impact of viscosity of the saturating fluid (marrow vs. water), we hypothesized that the source of attenuation is associated with viscoelastic absorption in the solid trabeculae and with scattering. Alteration of scattering obtained by changing the acoustic impedance mismatch between the fluid (alcohol vs. water) and the trabeculae was reflected neither in the attenuation nor in its slope. This led us to suggest that longitudinal-to-shear scattering together with absorption in the solid phase are candidates as main sources for the attenuation. In contrast, the elastic properties of the fluid are main determinants of the phase velocity. This finding is particularly significant in the context of *in vivo* measurements, because it demonstrate that the subject-dependent properties of marrow may partly explain the inter-subject variability of SOS values.

Session II

Ultrasonic Characterization of Cortical Bones

14:00-15:45 - Thursday, September 17th, 2009

Ultrasonic guided waves in bone

Petro Moilanen

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Recent progress in quantitative ultrasound (QUS) has shown increasing interest towards measuring long bones by ultrasonic guided waves. This technology is widely used in the field of non-destructive testing and evaluation of different waveguide structures. Cortical bone provides such an elastic waveguide and its ability to sustain loading and resist fractures is known to relate to its mechanical properties at different length scales. As guided waves could yield diverse characterization of bones mechanical properties at the macroscopic level, the method of guided waves has a strong potential over the standardized bone densitometry as a tool for bone assessment. Despite this, development of guided wave methods is challenging, e.g., due to interferences and multiparametric inversion problem. This paper discusses the promises and challenges related to bones characterization by ultrasonic guided waves.

Axial transmission measurements and compact bone heterogeneity

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Based on simulation and measurements on calibrated materials, it was previously established that axial transmission (AT) can probe longitudinal wave velocity with a reproducibility of less $\pm 30\ m.s^{-1}$. Compact bone is heterogeneous both in the radial and circumferential directions. Probing heterogeneity may yield valuable information for the analysis of bone quality and the formulation of inverse problem in a stochastic framework. A measurement session with an AT device provides a large number of velocity values. When the probe is moved perpendicular to the bone axis, the dispersion on the velocity values can be of the order of $100 - 200\ m^{-1}$. This range of values reflects both the heterogeneity of the bone volume probed and possible probe alignment discrepancies for different acquisitions. The objective of the present work is to test if bone heterogeneity can be probed with the AT technique. One bovine femur sample was subjected to an AT measurement protocol in order to obtain a large set of velocity values for various positions of the probe. Six slices of $2 - 3\ mm$ thickness each were cut in the probed area. A novel technique developed in parallel to this work was used to measure simultaneously density and velocity at each point of the bone slices with a resolution of about $1\ mm$. We will present the analysis of the velocity and density maps of the bone slices and they relationship to the dispersion of AT velocity values.

2D ultrasound axial transmission simulations on 40-day fracture healing models

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Ultrasound axial transmission (UAT) has been explored for non fractured and healing bone assessment. It has been evaluated so far in simple fracture healing models. This work aims at developing 2D UAT simulations on 40-day fracture healing models. Two finite-element models, presented by Isaksson et al. [2006] were applied, consisting of daily-changing tissue structures. Using a software (SimSonic2D [Bossy et al. 2007]) to simulate US wave propagation, a 1-MHz transducer was placed at 20 mm of fracture center, and a receiver at 40 mm from the emitter. Two protocols were studied: (1) transducers in contact with bone plate, perfect matched layers as boundary conditions; (2) transducers at 0.5 mm from callus top, free boundary conditions. Estimated output parameters weretime-of-flight (TOF) ofthe first-arriving signal and the signal maximum amplitude. A stepwise regression was applied to evaluate the relation between callus composition and TOF prediction. After fracture, TOF decreased during the healing process. The greatest signal attenuation (-45 dB) was observed in the first days of regeneration, mainly because of reflection on the fracture gap. Depending on the model, TOF was found to have from moderate (R-square = 0.63, std. error = 0.25) to strong (R-square = 0.91, std. error = 0.11) relationships with the quantity of bone tissue. UAT is to be better explored, as it should give important information about callus regeneration status.

Low-frequency axial ultrasound velocity predicts bone strength in the radius and tibia

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A low-frequency (LF; 400 kHz) axial transmission approach, based on the first arriving signal, has long enough wavelength ($\lambda = 10$ mm) to probe bone traits such as cortical thickness and subcortical BMD, which exhibit osteoporotic bone resorption substantially better than cortical BMD. In comparison, a 1.25 MHz HF ultrasonometer (Omnisense; $\lambda = 3$ mm) possesses a limited sensitivity being only significantly characterized by cortical BMD. The present study aims to evaluate if LF velocity (V_{LF}) predicts bone strength better than HF velocity (V_{HF}). Midshaft radius and tibia were measured by the LF device in 393 females and 140 males, aged 10-88 yrs, and by the HF device in 121 females and 35 males. Bone strength index (BSI) was estimated at the same bone sites from pQCT scans. V_{LF} correlated significantly better with BSI than V_{HF} at the radius for females (r=0.77 vs. r=0.43, Fisher's Z-transformed coefficients) and males ($r = 0.604$ vs. $r = 0.386$). At the tibia, only V_{LF} correlated with BSI (females $r = 0.34$, males $r = 0.46$), not V_{HF}. In conclusion, LF assessment provided an improved prediction of bone strength over the HF method.

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Investigating the impact of bone marrow on axial transmission of a low-frequency flexural wave: Three-dimensional simulations of in vitro experiments on human radius

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In our previous simulation studies a digital bone model with an empty inner cavity provided good agreement between simulation and in vitro results for the velocity of a slow flexural guided wave. Also, a semi-analytical model for an empty hollow tube fitted well the measured velocity, yielding an accurate estimate for cortical thickness. In the present study the impact of bone marrow is discussed. Semi-analytical theory predicts that introduction of a liquid core inside a cylindrical shell noticeably affects the dispersion and the displacement amplitudes of guided modes. Thus, to evaluate the influence of bone marrow on recorded signals, 3D FDTD simulations were performed on a collection of digitized radius bone samples ($n = 29$) with and without liquid filling in the cavity. The centre frequency of excitation ($120 kHz$) was tuned as close as possible to that of realistic in vitro frequencies, because the impact of filling depends on frequency and wall thickness. It was observed that the results simulated for filled bone models described better the real in vitro signals than those simulated for empty bone models. Introduction of filling decreased slightly the ultrasound velocities. However, the filling did not significantly improve the precision in predicting real in vitro data. Thereby, using a simple semi-analytical model for an empty cylindrical shell is, in this case, sufficient for getting a good estimate of cortical bone thickness.

Measurement of guided mode phase velocities using multi-emitters and multi-receivers arrays in contact using transfer matrix analysis.

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Structural and material properties of elastic waveguides can be characterized by fitting measured to theoretical guided waves phase velocities. Here emitters and receivers are placed in contact on the same side of the waveguide (i.e. axial transmission geometry). Multi-receivers arrays allow the determination of phase velocities using two dimensional spatial-temporal Fourier Transform, which requires a large distance probed by the receivers. Practical constraints, as in clinical inspection of cortical bones, may reduce the inspected spatial length and therefore the efficiency of this technique. A technique taking benefit of using both multiple emitters and multiple receivers, is proposed. The guided mode phase velocities are obtained using a projection in a the singular vectors basis, obtained by the singular values decomposition of the transmission matrix between the two arrays at different frequencies. First experiments, carried out on different metallic plates are shown. Experimental velocities are in good agreement with calculated Lamb waves dispersion curves. A better agreement was found when experimental velocities are determined using the transfer matrix analysis compared to the spatial-temporal Fourier Transform. As a direct application, the thickness and the transverse and longitudinal bulk waves velocities were estimated from experimental dispersion curves and compared well with expected values. The technique was applied on signals recorded on human radius samples and preliminary analysis will be shown

Poster Session

16:00-17:00 - Thursday, September 17th, 2009

First arriving signal in axial transmission: a multi-frequency approach

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QUS axial transmission techniques are based on the analysis of ultrasound waves propagating along the axis of long bones. Clinical studies have shown that velocity of the first arriving signal (FAS) is an indicator of bone status. The FAS velocity is commonly determined after measurement of time-of-flight at amplitude extrema of the earliest contribution of the ultrasound signal recorded at successive receiving positions. Most of the experimental devices use transient excitation pulse with a large frequency bandwidth. According to FDTD simulations [Bossy et al, JASA 2002], FAS velocity was found to vary as a function of cortical thickness-to-wavelength ratio and to become sensitive to cortical thickness lower than half the wavelength. Therefore, evaluating FAS velocity for the same patient at different frequencies may be a tool for ultrasound bone characterization and further improve the accuracy of the diagnosis. We tested the feasibility of a multi-frequency bidirectional ultrasonic axial transmission device. Dedicated probe and electronics were developed respectively by Vermon and Althais Technologies (Tours, France). Using excitation signals constituted of bursts with several cycles, variation of FAS velocity as function of frequency was measured and compared to predicted variations using FDTD simulations. Controlled phantoms and human radius samples were investigated. The issue of the potential of multi-frequency FAS velocity for bone characterization will be addressed.

Numerical Analysis of Uncertainties in Dual Frequency Ultrasound Technique

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The variation in thickness and composition of the overlying soft tissue may cause significant error on the quantitative ultrasound (QUS) parameters of bone [*Kotzki et al., Calcif Tissue Int, 1994, Chappard et al., Clin Densitom, 2000, Riekkinen et al., Ultrasound Med Biol, 2006*] and diminish the reliability of the technique in vivo. Recently, a dual frequency ultrasound (DFUS) technique was introduced to minimize these errors [*Riekkinen et al. Ultrasound Med Biol 2008, Karjalainen et al. Acta Radiol 2008*]. In this study, the significance of soft tissue induced error and its minimization with the DFUS technique was simulated using the finite difference time domain technique. We investigated the potential of the DFUS corrected integrated reflection coefficient (IRC) at cortical bone interface to detect chances in the cortical bone density. Alterations in the thickness of fat and lean tissue layers and the inclination between the layers were simulated. Inclinations greater than 20 degrees at the fat-lean tissue interface increased the relative error in the determination of the soft tissue composition and impaired the correction of the IRC (13%) with the DFUS technique. When the inclination between the layers was zero, the DFUS calculated soft tissue composition correlated highly linearly with the true composition (r^2=0.99, p<0.001). The significant soft tissue induced error on the IRC (> 300 %) could be effectively eliminated (< 10 %) by means of the DFUS correction. Importantly, after the DFUS correction variation (50 kg/m^3) in the cortical bone density could be detected (p< 0.05). The current study suggests that the DFUS technique can be applied to enhance the reliability of QUS measurements.

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Towards a realistic model sound propagation through the femoral neck: III - Impact of structural and elastic variations on the distribution of time of flight of the first arriving signal

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The time of flight of the first arriving signal TOFFAS measured with the FEMUS device at the femoral neck originates from a guided wave travelling along the cortical shell. TOFFAS and amplitude of this signal depend upon various experimental conditions, as well as upon variations of structural and elastic properties of the cortical tissue matrix. The aim of this study was to distinguish the relative impacts of intrinsic bone alterations on TOFFAS from those caused by systemic measurement alterations. Femoral neck disks (N = 11) with a thickness of approximately 10 mm have been excised from human donors, who received a hip implant (age: 60 ± 9 years). The fresh samples were measured in-vitro with the FEMUS scanner. Macro- and microstructure and microelastic tissue properties were assessed by CT and 50-MHz scanning acoustic microscopy (SAM). From these data numerical Finite-Difference Time-Domain (FDTD) simulations of the propagation of plane ultrasonic waves at 0.5 MHz have been performed. Experimental variables, i.e. sample rotation and translation, structural variables, i.e. cortical thickness and cortical porosity, and elastic matrix variables, i.e. absolute stiffness and degree of anisotropy were investigated with respect to their relative impact on TOFFAS. Within one sample TOFFAS did not vary significantly between adjacent sections from the central part of the femoral neck, but increased significantly towards the femoral head. Increased matrix elasticity led to a decrease of TOFFAS (∼ 0.58 % per GPa), while cortical porosity was inversely related to TOFFAS (∼0.08 % per % porosity). Simulated translation of the transducer pair perpendicular to the femoral long axis led to similar amplitude and arrival time variations as measured in-vitro.

Heterogeneity of velocity and attenuation of ultrasound in partially demineralized cortical bone tissue

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Knowledge of the material properties of bone collagen is necessary for understanding the age- and disease-related reductions in elasticity and strength of bone as well as for modeling of number of physiological processes observed in bone tissue. The overall goal of this study was to investigate the impact of collagen organization on heterogeneity of the mechanical properties of cortical bone. Heterogeneously mineralized cortical bone samples were obtained from bovine femur by partial demineralization of parallelepiped samples (n=12) from antrio-medial and posterio-lateral sites in the midshaft of a bovine femur. Samples were demineralized by submerging in 0.5M ethylene-diaminetetraacetic acid (EDTA) for 30 days. The influence of gradual demineralization on material properties and anisotropy of cortical bone tissue was examined using an ultrasonic method. An ultrasonic scanner with 1mm spatial step was applied to measure velocity and attenuation of ultrasound in the specimens in three perpendicular directions (along the long bone axis and in radial as well as in circumferencial directions). A transmission method was applied with a 1 MHz custom made transducer (ϕ= 10 mm in diameter) as a transmitter, while as a signal receiver the nidlle hydrophone (active diameter ϕ= 1 mm) was used. Within the assumed experimental procedure the ultrasonic parameters (wave velocity and attenuation) for intact specimens were compared with the results obtained for the demineralized samples.

The intact samples were anisotropic both in terms of velocity and attenuation of ultrasound with the highest velocity and the lowest attenuation in the longitudinal direction.

The gradual demineralization was followed by a decrease of velocity in all directions and an increase of attenuation in longitudinal direction. Moreover, the intensity of changes was both, direction and site dependent.

Fast and slow waves propagating through cancellous bone with porosity distribution in a propagation direction

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Cancellous bone is a porous material forming by numerous trabecular elements and its porosity changes with position in the bone. Ultrasound propagation through cancellous bone can be affected by the porosity. In this study, the effect of the porosity distribution in the propagation direction on the fast and slow waves, which can propagate in the direction parallel to the trabecular orientation, has been numerically investigated using finite-difference time-domain (FDTD) simulations. Numerical models of bovine cancellous bone were reconstructed from 3-D microcomputed tomographic images. To generate the trabecular structures with distinct porosity distributions, two erosion procedures, in which the trabecular elements in the cancellous bone model were eroded using an image processing technique, were prepared. In one procedure, the erosions were uniformly distributed in the whole region and, in the other procedure, the distribution of the erosions was changed in the direction of the trabecular orientation. For ultrasound propagation in the trabecular-oriented direction, pulse waveforms through the cancellous bone models eroded by each procedure were simulated by the FDTD method. From the simulated waveforms, the amplitudes and propagation speeds of the fast and slow waves were measured in each case of two erosion procedures and their variations caused by the porosity distribution were investigated with the trabecular microstructure.

Relationships between anisotropy of longitudinal wave velocity and HAp orientation in bovine cortical bone

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Quantitative ultrasound (QUS) is a good method for measuring elastic properties of bone in vivo, because the obtained ultrasound wave properties directly reflect the longitudinal elasticity. Bone tissue is composed of minerals like hydroxyapatite (HAp) and collagen matrix. HAp crystallites orientation is thus one parameter of bone quality. In this study, we experimentally investigate the anisotropy of ultrasonic wave velocity and the HAp crystallites orientation in axial-radial and axial-tangential planes in detail, using cylindrical specimens obtained from the cortical bone of three bovine femurs. Longitudinal ultrasonic wave propagation was investigated by using a conventional ultrasonic pulse system. First, we experimentally investigated anisotropy of longitudinal wave velocity. We measured the anisotropy of velocity in two planes using cylindrical specimens obtained from identical parts. The wave velocity changed due to the rotation angle. The direction of the fastest wave velocity was a little inclined from the bone axis. Moreover, X-ray pole figure measurement indicated that there were small tilts of the HAp crystallites orientation. The tilts were similar with the tilts of fastest velocity direction. There were actually good correlation between velocity and HAp crystallites orientation. However, a comparatively low correlation was found in posterior parts, which shows the effects of microstructure.

Application of Biot theory for modelling of wave propagation in cancellous bone

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The paper is focused on comparative theoretical and experimental studies of ultrasonic wave propagation in cancellous bones. The main objective is to verify if the commonly used for modeling of elastic wave propagation in cancellous bone (macroscopic Biot's model) is adequate for mathematical description of the phenomenon in the material.

In the isotropic case, the model requires dozen macroscopic input mechanical and structural parameters, which mostly were measured individually for 31 pure human femoral trabecular bone specimens. Then, frequency dependent wave parameters (phase velocity and attenuation coefficient) predicted by the model were compared with the results of ultrasonic tests performed on the same specimens. In order to simulate real experimental conditions, modelling was complemented by the theoretical solution of the boundary problem of interaction of plane harmonic wave with the slice of cancellous bone treated as a porous material saturated with fluid.

Ultrasonic measurements were performed in immersion following the insertion method. The wave parameters (phase velocity and attenuation coefficient as a function of frequency) were computed from the ratio of the spectrum of the broadband pulse transmitted through the specimen to the spectrum of the reference pulse recorded when there is no specimen between the transducer and receiver.

The sensitivity analysis of the model (studies of the influence of the variability of input parameters on the phase velocity and wave attenuation), shows that the accordance between experiment and the model can be achieved only in the case when porosity is very high and the tortuosity reach its lower limit (around 1). It was established significant contribution of the fluid/bone and bone/fluid boundaries on the global attenuation loss. The corrected values of attenuation coefficient (including the effect of boundaries) are of the same order of magnitude compared to measured values, but the frequency dependence of the parameter was not well predicted by the model. Moreover, the theoretical results exhibit, observed in experiments, higher attenuation of fast wave compared to that of the slow wave.

Scattering of ultrasonic waves in randomly layered materials

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The goal of the paper is the proposal of a new macroscopic description of scattering of elastic waves at internal inhomogeneities of the material. Within the studies the microscopic inhomogeneity of the medium is modeled as the alternately arranged two kinds of elastic layers of random thicknesses and different mechanical properties. Calculations of the acoustical characteristics of such medium (reflection and transmission coefficients) are performed in two stages: (i) first the problem of interaction of plane harmonic wave with the half space of the randomly layered medium for the case of normal wave incidence is analyzed; (ii) then the interaction of the harmonic wave with the slice composed of randomly layered structure is considered. Such approach allowed to derive analytical relations for the phase velocity of wave propagation and attenuation as the explicit functions of frequency, stochastic structural parameters of the medium and material properties of layers. The obtained formulas are helpful for interpretation of experimental ultrasonic data and may serve for identification of the characteristic size of material inhomogeneity based on the measured wave parameters like frequency dependent phase velocity, attenuation as well as backscattering coefficient.

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Dynamic behavior of the bone-implant systems

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Destructive diseases or accidents call for prostheses, which in many fields have achieved a certain degree of perfection, yielding pain-free functionality and longevity. However, gradual loosening of the implant-bone attachment integrity due to wear, bone regress (related to ageing or diseases) and micro-mechanical damage lead eventually to the failure of the replacement and thus to painful consequences: a repetition of the implanting surgery takes place under unfavourable conditions. On the other hand, the total costs of the healing are multiplied.

The existing methods of quality monitoring of implants are based either on the X-ray imaging or ultrasonic inspection. They are therefore impaired by shielding effects when complicated shapes of the prostheses are needed. All the methods mentioned above do not reveal sufficient sensitivity and specificity when needed. Moreover, too frequent X-ray irradiation may lead to other serious injures.

An alternative method of diagnosis is considered, based on the monitoring the integrity of the implant and bone by checking the changes of its vibrational characteristics. Unlike the ultrasonic inspection the proposed method would rely on monitoring of the shifts of the frequency spectrum caused by the changes in the mechanical properties due to the deteriorating state of the system. A feasibility study for this relatively new method begins with the modelling of attachment integrity. This constitutes a starting point for both FE simulations using numerical modal analysis and experimental study based on vibrational techniques.

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Waves interaction with a layer of macroscopically inhomogeneous material

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The problem of ultrasonic wave interaction with continuous inhomogeneity of material is of great importance for theory and applications. On the one hand such materials are commonly present in living systems, nature, building engineering and industry. The macroscopic inhomogeneity is often a result of their formation, production or processes taking place during their life (e.g. osteoporosis), exploitation (e.g. sedimentation of pollution on filters) or interactions with environment (e.g. degradation of concrete surface). On the other hand the ultrasonic research of such materials, due to their non-invasive character, are more commonly applied in diagnostics and determination of pore structure parameters and material constants. In the paper we consider a one dimensional problem of wave interaction with material inhomogeneity caused by a layer of pores. It concerns interaction of waves in the air incident on a porous surface layer of an undeformable material with continuously changeable pore structure parameters, and waves in an elastic solid with a layer of pores in that medium. We assume that the local acoustical properties of the material are characterized by the impedance Z and the wave number k. These parameters, in general, are dependent on the spatial coordinate x and the wave frequency . Due to interaction with material inhomogeneity each wave propagating in such material generates the coupled backward wave. Therefore, the acoustical field in inhomogeneous material is defined by amplitudes T and R of the forward and backward waves, respectively. The analysis was based on the system of coupled differential equations for T and R derived in the other paper. We analyzed elementary situations where the incident wave propagates from the material with lower impedance through a layer with continuous inhomogeneity to the material with higher impedance and also for opposite direction of wave propagation. Other analyzed cases are complex compositions of the elementary ones. This allows to analyze the influence of inhomogeneity parameters on the characteristics of wave interaction with continuous inhomogeneity of the material.

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Determination of bone volume porosity based on histograms of the μCT scans

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The new method is proposed in the paper for determination of volume porosity of bone tissue based on histograms of 3D μCT scans. In this method the normed histogram is considered as a probability distribution of relative mass density in the bone sample. It is a linear combination of two distributions characterizing frequency of occurrence of pore and skeleton types of voxels with different densities in the scan of sample. Such approach makes possible determination of volume porosity directly from the scan of bone sample without necessity of earlier reconstruction of its microscopic pore geometry. It allows also precise definition of the threshold value of relative density preserving calculated volume porosity during the reconstruction of the binary image of sample. The method was applied to the analysis of two samples of human bone tissue with different porosities separated from μCT scan of femur condyle. It was shown that the normed histograms of increasing 3D sample are convergent to the limit curve which can be interpreted as a representative histogram of given sample. The limit histograms have been used to determine: the distributions of relative densities in the sets of voxels of pore and skeleton type and their characteristics, the volume porosities of both samples and thresholds values of their binarisation. The obtained values of parameters were compared with results of other methods.

Application of Minkowski metric space to description of anisotropic pore space structure and fluid dynamics in porous materials

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The paper concerns modelling of mechanical behaviour of fluid in porous materials with anisotropic pore space structure. A new macroscopic description is proposed in which motion of fluid in anisotropic pore space is considered as a motion of material continuum in the Minkowski (anisotropic) metric space. The applied model of pore space enabled obtaining extended and consistent description of anisotropic pore space structure and precise definition of its basic parameters: the pore tortuosity, the volume and surface porosities, and also their tensorial characteristics directly related to the metric tensor of the anisotropic space. These parameters are of great importance for the modelling of mechanical behaviour of fluid in anisotropic porous materials. The balance equations and constitutive relations for stress tensor in fluid and interaction force with skeleton are formulated. The Brinkman and Darcy equations describing flow of fluid through anisotropic pore space as well as the wave equations are derived with explicit tensorial characteristics of pore structure. The proposed description allow formulation and analysis of various problems of fluid flow and wave propagation in porous materials with extended characteristics of pore structure anisotropy and also in materials with nonsymmetric dynamical and filtration properties.

Session III

Scanning Acoustic Microscopy

9:00-10:30 - Friday, September 18th, 2009

Multiscale structure-functional modeling of lamellar bone

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Bone is a natural example of achieving a unique combination and variability of stiffness and strength. One of the striking features bone tissue is the ability to adapt to variable loading conditions by multiple but well organized structural arrangements of mineralized collagen fibrils at several levels of hierarchical organization. A profound understanding of the structure-function relations in bone requires both experimental assessment of heterogeneous elastic and structural parameters and theoretical modeling of the elastic deformation behavior. A bottom-up approach for experimental assessment and numerical modeling of the hierarchical structure from the nanoscale to the macroscale will be presented. Experimental data are obtained by scanning acoustic microscopy between 50 MHz and 1.2 GHz and provide anisotropic elastic and structural information at the lamellar (nanoscale) and at the tissue matrix (microscale) level. These data are directly translated into a Finite Element (FE) mesh. By numerical deformation analyses the homogenized elastic stiffness tensor of the next hierarchical levels (microscale to macroscale) are derived. At each level the numerical results are cross-validated by experimental data. Our results indicate that only an asymmetric twisted plywood structure at the lamellar level (nanoscale) can explain the elastic anisotropy that has been reported at the higher levelas of organization. However, the elastic anisotropy ratio (i.e. AR = c_{33}/c_{11}) of collagen fibrils is considerably higher (AR_{fibril} 2.2) than that of osteonal or interstitial tissue (AR_{osteon} 1.3, AR_{osteon} 1.5). Moreover, it will shown that local variations of elastic anisotropy within the femoral shaft is related to an inhomogeneous strain distribution resulting from external stresses by weight and muscle forces.

Variations of nanostructural characteristics of mineral platelets across a human osteon are determined by acoustic impedance modulation

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Scanning acoustic microscopy derived impedance (Z) of cortical bone osteons shows a bimodal lamellar pattern of alternating high and low Z values. The goal of this study was to assess the relationship of osteon level impedance variation to the orientation and size of mineral (hydroxyapatite) platelet at one micron resolution. Data were acquired on a human femoral cross-section using 900-MHz SAM, synchrotron radiation micro-computed tomography (SR-μCT to measure the local variation of HA content) and small angle X-ray scattering (SAXS). SAXS provides the relative variation of HA platelet orientation and changes in mean thickness from the analysis of the integrated SAXS intensity and pattern, respectively. While SR-μCT images showed a constant level of mineral, both SAM and SAXS images displayed the lamellar level modulation related to the modulation of microelasticity, orientation and thickness of the platelets. Z was strongly correlated with the SAXS intensity (R2=0.91, p<0.0001) but much lower correlated with the platelets thickness (R2=0.35, p<0.0001). Our study is the first one that combines SAXS, SR-μCT and SAM to elucidate the impact of mineral platelets orientation and mean thickness on microelasticity. Our results suggest that the main factor contributing to Z variations is the platelet orientation reflected in modulations of the integrated SAXS intensity.

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

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In this study the spatial distribution of anisotropic elastic properties and tissue mineralization within a human femoral cortical bone shaft (female: 72 years) were investigated. Cylindrically shaped punch biopsy samples (diameter: 4.4 mm) were analyzed using high resolution ultrasonic cylindrical scanning microscopy (SAM, $N = 56$) at 50 MHz and synchrotron radiation μCT (SR-μCT, voxel size: 10 μm, $N = 27$). For all samples the average tissue elastic coefficients and the average tissue mineralization were derived from SAM and SR-μCT measurements, respectively. The impact of tissue mineralization on the five independent elastic coefficients was analyzed with respect to the anatomical location of the femoral shaft. The average values of the elastic coefficients were: c_{33}: 31.0 ± 3.0 GPa: c_{11}: 22.0 ± 1.8 GPa; c_{12}: 9.5 ± 1.2 GPa, c_{13}: 10.0 ± 1.3 GPa, c_{44}: 6.6 ± 3.0 GPa. The average tissue degree of mineralization in the cylinders was 1.10 ± 0.02 g/cm^3. Weak, but significant correlations with DMB were found for c_{33} (R^2=0.11, p $< 10^{-4}$) and c_{44} ($R^2 = 0.008$, p < 0.031). The R^2 between the individual elastic coefficients were between 0.04 and 0.99. Two-factor ANOVA revealed that the axial and radial anatomical locations had significant influences on DMB and the elastic constants. However, these variations were not consistent for DMB and the elastic coefficients. These findings confirm that tissue mineralization is only a minor predictor for tissue elasticity in cortical bone.

Cortical bone mechanical properties at the microscopic scale: does the acoustic impedance heterogeneity affect the local strain as determined by microextensometry?

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This study aimed at investigating the relationships between the local longitudinal acoustic impedance (Z) and local strain fields of cortical bone tissue subjected to a uniform compression. One cubic sample 3x5x7mm^3 was obtained from a human femur and stored in alcohol. Scanning acoustic microscopy (200 MHz, 8 μm spatial resolution) provided Z on the surface perpendicular to the long bone axis (transverse plane). A microextensometry device placed in a scanning electron microscope was used to measure the in-situ strain fields (15 μm resolution) under uniform compression (-2% macroscopic strain) along one direction of the transverse plane. Maps of longitudinal strains and Z were fused, the pores were segmented and only the pixels of the matrix were considered for the analysis. Z and strain fields displayed a strong heterogeneity with a ratio between the maximum and mean values of 1.3 and 2 respectively. No correlation was found between the distribution of the local strains and Z. These results obtained for one sample suggest that tissue heterogeneities have a very limited impact on the distribution of the strain fields at the microscale, supporting that the latter are mainly governed by the deformation of large pores.

Towards a realistic model of sound propagation through the femoral neck: I - Experimental assessment of microstructure and matrix elasticity by 50-MHz scanning acoustic microscopy

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The most frequent site of osteoporotic fractures is the femoral neck. Therefore, ultrasound measurements at this location with the recently developed FEMUS scanner are hypothesized to have a high potential to improve the prediction of individual fracture risk. The aim of this in-vitro study was to assess precise geometrical and elastic properties of the femoral neck and to build a data base for numerical sound propagation analyses. Femoral neck disks (N = 10) with a thickness of approximately 10 mm were excised from human donors, who received a hip implant (age: 60±9 years) The fresh samples were measured in-vitro with the FEMUS scanner and the 3D microstructure was assessed by CT. Afterwards, the samples were embedded in PMMA. High-resolution (23 μm) calibrated acoustic impedance maps were acquired from cross and transverse sections 50-MHz by scanning acoustic microscopy (SAM). From these images the mean elastic coefficients in the directions perpendicular and parallel to long axis of the femoral neck, i.e. $c_{11} = 28.3 \pm 3.7$ GPa and $c_{33} = 38.6 \pm 3.2$ GPa where derived. Furthermore we used MATLAB image analysis tools to obtain descriptive geometrical parameters, like cortical porosity (18.1 % ± 3.5 %) , cortical thickness (2.5 mm ± 0.7 mm), moments of inertia (5099 ± 1639) and section modulus (1308 ± 296).The variation of these parameters was analyzed with respect to the anatomical location. The elastic stiffness in trabecular tissue was significantly lower than in cortical tissue (F = 161, $p < 10^{-4}$) and varied between the individuals (F = 7.5, $p < 10^{-4}$).

Session IV

Applications- Part I

11:00-12:30 - Friday, September 18th, 2009

Probing Long Bones with Ultrasonic Body Waves

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Quantitative ultrasound uses mechanical wave to probe the internal bone structure and is sensitive to bone tissue elasticity and architectural structure relevant to bone strength. However, our knowledge of wave interaction with cortical bone tissue is far from complete and the wave types of propagation have not been fully elucidated. In particular, while it is generally assumed that the interaction between ultrasonic wave and the internal structures of a bone sample leads to reflections and conversions, the actual reflected and converted ultrasound waves from the cortical bone and marrow layers have not been identified or utilized to date. Here we use the methods of seismology including waveform simulations and travel time calculation to reveal the nature of ultrasound wave propagation in bovine long bone. The experiments prove the existence of reflected and converted body waves originating from wave interaction at the internal interfaces of a bone structure. Most unexpectedly, ultrasound wave can be successfully and unambiguously simulated with a simple, horizontally layered one-dimensional approximation. These results indicate that the use of body waves in conjunction with guided waves should provide a complete framework to study bone tissue via mechanical waves.

Towards a realistic model of sound propagation through the femoral neck: II 0.5 MHz sound propagation simulations based on microelastic input data

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Numerical simulation of ultrasound propagation offers the ability to test several configurations representing realistic cases. The objective of the present work is to test whether a complex model of Femoral Neck Cross-Section (FNCS) is relevant for the simulation of low-frequency QUS at the femoral neck. 2D-models of FNCS computed from impedance images obtained from 50-MHz Scanning Acoustic Microscopy (SAM) and accounting for presence of trabecular bone, porosity and heterogeneous anisotropic matrix elasticity were used for Finite-Difference Time-Domain (FDTD) simulations of the propagation of a plane ultrasonic wave at 0.5MHz. The effects of various steps of model simplification, e.g. exclusion of trabecular tissue, filling of cortical pores, and homogenization of cortical tissue elasticity based on previously established models were compared. The removal of porosity decreased significantly the time of flight of the first arriving signal TOF_{FAS} compared to the TOF_{FAS} for the full model. However, homogenisation of elastic coefficients with the Mori-Tanaka method yielded a mean TOF_{FAS} which is not significantly different from TOF_{FAS} for the full model. Multiple regression analysis revealed that 87% of TOF_{FAS} was explained with a linear combination of porosity, impedance and minimum moment of inertia. These results indicate that porosity has a significant influence on the propagation time of the wave through a FNCS.

Discrimination of cervical and trochanteric fractures by femur QUS (FemUS)

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Hip fractures can be separated into cervical and trochanteric fractures. In the EPIDOS study [*Schott et al., Bone 37 (2005)*] BMD and calcaneus QUS were worse predictors of cervical than trochanteric fractures. We tested the power of QUS at the femur to discriminate between both types of fractures and non fractured controls. We measured 9 patients with cervical fractures and 9 patients with trochanteric fractures (both age 69 $\pm$ 5 years) in comparison with 22 controls (age 62 $\pm$ 5 years). Measurements were done using DXA and the Femur Ultrasound Scanner (FemUS). Two QUS variables were measured at the femur, SOS through the trochanter (SOStrab) and through the shaft below the minor trochanter (SOScort). SOStrab and SOScort were combined to predict total femur BMD (BMDest). T-tests were performed between each of the fracture groups and the control group. T-values were 3.7 (5.6) for total BMD, 3.0 (5.2) for neck BMD, 2.5 (7.0) for trochanteric BMD and 3.9 (4.8) for intertrochanteric BMD (values for trochanteric fractures in brackets). Results for the FemUS scanner were 3.7 (5.0) for SOStrab, 4.4 (5.6) for SOScort and 5.3 (5.9) for BMDest. In concordance with EPIDOS data BMD discriminated worse in the cervical fracture group than in the trochanteric fracture group. For the combination of trabecular and cortical SOS results were similar for both fracture types. Our data indicate that QUS at the femur might be a better predictor as BMD for cervical fractures.

Ultrasonic method to characterize children bone elastic properties

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In ageing bone, there is modification in the elastic properties of the material [*Zoupios et Currey, 1998*]. But these changes in childhood are not clearly shown. For example, certain studies compare bone density (Bone Mineral Density: BMD) of children, like in Chron disease [*Edisio et al, 1999*], but not the stiffness, strength or elastic modulus. Few studies consider mechanical characteristic of this process. Some have chosen specific bone, close to cancellers cells [*Baleani et al., 2008*], or cadaver fragments [*Currey, 1975*]. In our study, we have used surgery waste (bone transplantation) from long bone (fibula) composed of cortical bone. After size fitting, frames were suspended to a mechanical stage which is able to process very small sample. Nominal frequency can increase from 3 to 10 MHz. We have evaluated bone velocity using the difference of sound path duration and Snell Descartes law, which led us to an expression of its value. We used the same method as used for isotropic transverse bovine bone frame [*Lasaygues et Pithioux, 2002*], in the case of orthotropic we can right 12 elements of rigidity matrix. This study is the first step of a more general work. Comparisons were made between juvenile specimens and mature specimens, and the first result is that the wave velocities, and the associated elastic modulus, are then lower in children than adult.

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Improvements in measurements of BUA and SOS in human calcaneus

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Although calcaneal broadband ultrasound attenuation (BUA) and speed of sound (SOS) are good predictors of osteoporotic fracture risk, BUA and SOS measurements exhibit substantial inter-system variability. The objectives of this work were to 1) compare phase insensitive (PI) detection, which suppresses phase cancellation, and conventional phase sensitive (PS) detection for measurement of BUA, and 2) test a compensation formula for reducing variability in SOS measurements. Data from 16 human calcaneus samples in vitro and 73 women in vivo were acquired using a GE Lunar Achilles Insight bone sonometer. Radio frequency data were processed off-line using both PI and PS algorithms. BUA measurements (mean $\pm$ sd) were 22.1 $\pm$ 15.8 dB/MHz (PS) and 17.6 $\pm$ 7.2 (PI) in vitro and 81.4 $\pm$ 21.4 dB/MHz (PS) and 67.2 $\pm$ 9.7 dB/MHz (PI) in vivo. Compensation of SOS measurements reduced 1) average transit-time-marker-related SOS variability by 75% in 73 women and 2) bandwidth-related SOS variability by 80% in a bone-mimicking phantom. These new methods may enable a substantial improvement in consistency in bone sonometry. The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health and Human Services.

Comparative evaluation of condition of human proximal tibiae 'in vitro' by ultrasonic guided waves and pQCT

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Ultrasonic slow type guided waves in long bones demonstrate expressed dependence of the velocity on the cortical thickness - one of the main determinants of bone strength. Purpose of this work was to compare estimations of bone conditions by ultrasonic approach applying the guided waves and peripheral Quantiataive Computed Tomography (pQCT). The applied of ultrasonic approach is based on analysis of a wider population of data presented in the form of 2D axial profiles formed by processed entire ultrasound signals, in contrast to the known methods where the sound velocity is determined by the arrival of one point of a signal. Informative area of a signal formed by a slow propagating flexural wave at low frequency stretches to several tens of microseconds. Six fragments of the proximal tibiae 'in vitro' taken from senile females that were examined ultrasonically and by pQCT in parallel. 2D spatial-temporal waveform profiles obtained by stepped measurements along the bones and processed by wavelets at 100 kHz ranged the examined bones similarly as the pQCT measures: cortical thickness CTh and cortical bone mineral density C-BMD. Close correlations between the ultrasonic guided wave velocity and CTh (r=0.94) and C-BMD (r=0.92) determined by pQCT in ultrasonic ROI of total 18 cross-sectional slices were obtained. The study confirmed sensitivity of guided waves implemented in experimental devices of Artann Laboratories for diagnostics of compact bone deterioration.

Session V

Applications- Part II

14:30-16:00 - Friday, September 18th, 2009

European Symposium on Ultrasonic Characterization of Bone
Esucb 2009 Bydgoszcz, 17-18 September 2009

Bone tissue and implant surface interactions

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Dynamic Acoustoelastic Testing for non invasive detection of microdamage in cortical tissue of long bones

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Firstly developed for trabecular bone, Dynamic Acoustoelastic Testing (DAT) is based on the measurement of UltraSound (US) pulses Time Of Flight and Energy Modulations (TOFM and EM) induced by a low-frequency (LF) acoustic wave, synchronously injected in the probed medium. The technique needs the LF wave to be quasi-uniform in space and quasi-static in time (compared with the US TOF). US TOFM and EM are related to elastic and dissipative nonlinearities, respectively, allowing the extraction of nonlinear elastic and dissipative parameters. Here is presented the application of the technique to cortical tissue of long bones. The method is first validated in a cylindrical aluminium samples. A LF vibration is generated along the axis of the sample whose frequency corresponds to the first compressional resonance mode in the fixed-free boundary conditions. In the same time, US pulses are emitted and received by a dedicated probe, after propagation along the surface of the sample. The US probe is placed so that the head wave arrives first in time. US TOFM and EM are thus computed using the head wave. In undamaged samples, dissipative nonlinearity is not measured and only weak classical quadratic elastic nonlinearity is observed, whereas damaged materials are expected to create dissipative effects and more complex nonlinear elasticity. Experimental results obtained on a highly nonlinear rock sample, a hollow aluminium cylinder and cortical femoral bone are presented.

Non-Optimal Focusing of Ultrasound Does Not Affect Dual Frequency Ultrasound Measurement of Bone

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In pulse-echo (PE) ultrasound measurements, the use of focused transducers is essential for quantitative assessment of bones because of the strong attenuation in soft tissues and bone. Furthermore, if the ultrasonic field has a large spatial focal area (e.g. non-focused fields), the natural curvature of the cortical bone surface can distort the measurements. Variable thickness and composition of soft tissues overlying the bone affect the focal depth and may mislead the selection depth in reference measurement from a known reflector. A dual frequency technique (DFUS) was recently introduced for compensation of soft tissue derived errors in the ultrasound measurements [*Riekkinen et al., Ultrasound Med Biol, 2008, Karjalainen et al., Acta Radiol, 2008*]. The aim of this study was to numerically simulate the effect of non optimal focal depth of the ultrasound beam on the integrated reflection coefficient (IRC) of bone as well as on the DFUS based correction of the IRC. When the soft tissuebone surface was out of focus, the errors in the determination of the soft tissue composition increased dramatically (2% - 100%) due to over- and underestimation of lean and fat tissue contents. Attenuation compensation with correct composition of soft tissue resulted average relative error of 28.7% in the IRC values. Interestingly, the attenuation compensation with the DFUS technique was successful, and only a minor bias error (average relative error 8.9%) was observed in the corrected IRC values.

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Ultrasonic Imaging of Long Bones

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When ultrasound travels through bone sample, it will be reflected by scatterers and the echoes are affected by ultrasound parameters such as velocity and attenuation of the medium through which the wave travels. Using wave-imaging principles, it is possible to image the bone's internal structures using a combination of Born scattering and inversion theories. We developed an imaging algorithm based on zero-offset mode, i.e., the transmitting and receiving transducers are at the same spot. A bone model was developed using X-ray CT image as guidance. With this model, we simulated two data sets: one based on a simple convolution method and the other by finite-difference algorithm (Wave 2000). The latter data set is more challenging as it mimics the real bone data and contains all wave phenomena such as multiple reflections. Using these two data sets, we examined the effects of different cost functions, aperture angles, pixel sizes, reverberations, and acquisition spatial intervals upon the inverted images. Finally, the accuracy of the inversion results was addressed by comparing the CT-measured thickness and US-measured thickness. The results of this investigation are very important to guide future study of real bone data because they show that the major tissue interfaces can be reconstructed and correspond favorably to the CT image. Therefore, the algorithm has the potential to predict the inner structures of long bones.

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Time-filtering and modeling of compressed multisine waves for simultaneous determination of acoustic velocity and mass density of a cortical bone slab.

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Pulse signals are widely use for several ultrasonic testing. They indeed allow an easy estimation of the delays occurring in echo and transmission measurements and give the possibility to filter the noise (i.e undesired reflections occurring in the surface of the transducers) applying a window in the time domain. In this paper the use of compressed multisines waves for ultrasonic characterization of a bone slab is presented, in order to offer a good alternative to pulses. These harmonically related sine waves present a strong compactness thanks to the optimization of the phase of each harmonic resulting in a small crest factor (1.4 instead of 10 offered by impulse signals). The reached high signal-to-noise ratio makes these signals suitable to test highly attenuating materials such as bone. However they are more difficult to interpret, indeed because they are always present during the test, they don't allow to understand if undesired reflections are present in the output signal. In this article a filtering procedure in the time domain is proposed; with this approach (referring to the Cepstrum analysis) continuous waves can be used for ultrasonic characterization of materials in an easy way. Moreover, starting from the filtered data, a wave propagation model in the frequency domain has been implemented for simultaneous determination of acoustic velocity, mass density, damping and thickness of the bone slab under test, during transmission experiments.