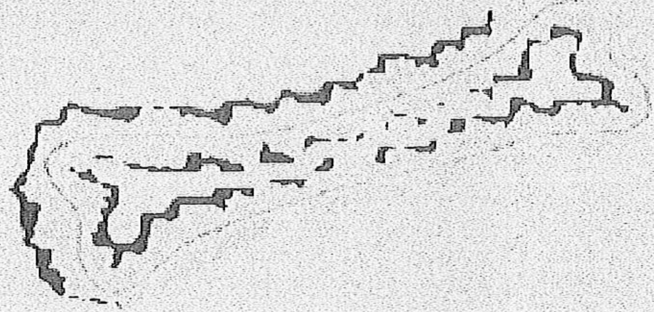
Abstracts Book

1st European Symposium on Ultrasonic Characterization of Bone



Centre des Cordeliers
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6 & 7 March 2006

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Mon 9:15 Pavillon 1

Keynote Lecture 1

Numerical simulation of ultrasound propagation in bone: a powerful tool to elucidate relationships between quantitative ultrasound measurements and bone properties

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Quantitative ultrasound (QUS) techniques applied to bone have played in recent years an increasing role in the assessment of bone status. Although these techniques have been studied for more than 20 years providing the clinicians with a diversity of technical developments and clinically useful parameters, the physics underlying the interaction between ultrasound and bone is not fully understood yet. While analytical approaches that would take into account a large number of parameters (complex 3D anisotropic structure, fluid/solid interaction, material properties, etc) quickly become intractable, numerical simulation offers a powerful alternative. The presentation will first discuss the advantages and limitations of simulation approaches in the context of ultrasonic bone characterization, and review the work published to date. In a second part, we will illustrate the use of FDTD (finite-difference in time-domain) simulations in two different cases, both involving 3D maps of real bone structures measured by means of X-ray 3D tomography: the case of axial transmission through the cortical bone, for which obstacles to analytical approaches arise from the geometry of bone and the type of wave involved, and the case of propagation through trabecular bone, for which the difficulty in modelling arises from the complexity of the medium itself (complex 3D microarchitecture, fluid/solid interaction, etc.) relatively to ultrasound propagation.

Mon 9:45 Pavillon 1

Characterization of cancellous bone : simulation studies

Numerical simulation of the sensitivity of ultrasonic properties to bone microarchitectural and material properties

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The aim of this work was to study the dependence of quantitative ultrasonic (QUS) parameters on bone properties. Simulations of ultrasonic wave propagation were performed using 3-D elastic finite-difference computations coupled with real trabecular microstructures. Thirty cancellous bone volumes (human femur) of 5x5x8 mm3 were reconstructed from synchrotron radiation μCT acquisitions. In the computations, a plane wave was propagated through these bone volumes. The model assumed the bone material to be isotropic and the porous trabecular structure to be filled with a non viscous fluid. QUS variables, namely broadband ultrasonic attenuation (BUA) and speed of sound (SOS) were computed. To study the impact of microstructure on QUS parameters, the initial 3-D structures were altered using a dedicated image processing iterative algorithm leading to structures with gradually increasing or decreasing bone volume fraction (BVTV). Computations were performed at each step of the process, while keeping material properties unchanged. Sensitivity of QUS parameters to material properties was also tested for the thirty initial bone structures by successively modifying a single material property, i.e., (i) compression wave velocity of bone, (ii) transverse wave velocity of bone and (iii) bone density. Our results suggest that the main influence on QUS parameters is due to BVTV (BUA (resp. SOS) varies at a rate of 2 dB/MHz/cm (resp. 10 m/s) per % of BVTV), immediately followed by the influence of microstructure. The impact of changes in material properties remains lower than the variability caused by structural variations: BUA (resp. SOS) increases at a maximum rate of 0.25 dB/MHz/cm (resp. 2.5 m/s) per % of variation of any material property. This study emphasizes the potential of numerical computations tools coupled to realistic 3-D structures to assess the sensitivity of ultrasound variables to different bone properties and the usefulness of these computational models to progress towards a solution of the inverse problem.

Mon 10:00 Pavillon 1

Characterization of cancellous bone : simulation studies

Simulation and Experimental Study on the Wave Propagation in the Cancellous Bone

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Longitudinal wave propagating in the cancellous bone separates into fast and slow waves depending on the alignment of bone trabecula. In order to understand the phenomenon, we have tried to simulate the wave propagation with Finite Difference Time Domain (FDTD) method. The elastic FDTD method is suitable, because it can treat both normal and shear stresses and particle velocities in the elastic medium.
Wave propagation was calculated using a 3-dimensional X-ray CT model of the actual bovine cancellous bone. Here we have assumed a single sinusoidal longitudinal wave transmitted from a concave transmitter, which focuses on the front surface of the bone. As the acoustic constants of cancellous bone, the experimentally observed values of the cortical bone were adopted. As a result, generation of fast and slow waves was confirmed. We have also experimentally measured the waves, which propagate the identical sample under the same condition. The simulated arrival time of fast wave and peak amplitude of slow wave had good correlations with the experimental results.
From the comparison of calculated and experimental results, we have also investigated the effect of wave attenuation in the trabecula and the precision of CT model.

Mon 10:45 Pavillon 1

Characterization of cancellous bone : experimental studies & models

In vitro studies of cancellous bones ; Comparison of the prediction of Biot's model, experiments and computer simulations

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Quantitative ultrasound (QUS) techniques have received considerable attention during the last decade for non-invasive assessment of bone quality. However, poorly understood mechanisms implied in ultrasound wave propagation through bone require clarification, in order to improve QUS diagnostic capability and relate bone characteristics to ultrasound parameters. This paper is focused on ultrasonic propagation through cancellous bone. The aim is to compare experimental results with predictions from Biot's model and from numerical simulations based on a finite difference time domain (FDTD) algorithm for elastic wave propagation in non absorbing materials.. Ultrasonic (0.4-0.9MHz) tests for 35 dry and water saturated specimens of trabecular bones (human femur) were performed.Then the microarchitecture of the specimens was assessed by synchrotron microtomography (SR-μCT). The reconstructed 3D microarchitectural models were used as an input structure for FDTD simulations. Finally, parameters like tortuosity, permeability, porosity and density of solid phase were measured using techniques dedicated to characterization of porous materials. The so called Biot-Willis porous material constants were derived based on these experimental data and formulas available for example in [Biot, J. Acoust. Soc. Am., 1962]. Experimental phase velocity (SOS) and attenuation coefficient (BUA) were then compared to FDTD and Biot's model predictions. Whereas a strong relationship was observed between measurements and FDTD simulations r^2_{SOS}=0.74 and r^2_{nBUA}=0.81, no correlation was found between SOS and nBUA predicted by Biot's model and experimental or FDTD data. In conclusion, our data suggest that Biot's model is inappropriate, even when using individually measured values of parameters such as tortuosity and permeability. In contrast, FDTD simulations using real 3D models of micro architecture provided accurate predictions of SOS and BUA, suggesting an important role of ultrasound scattering by the trabecular network in the interaction mechanism.

Mon 11:00 Pavillon 1

Characterization of cancellous bone : experimental studies & models

Direct and inverse scattering problem in cancellous bone: Application of Biot theory

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The ultrasonic wave propagation in human cancellous bone is considered using Biot theory. The direct problem is solved by calculting analytically the reflection and transmission coefficient of a slab of porous material having an elastic frame. The sensitivity analysis of each physical parameter is studied on the waveform of the transmitted wave. The inverse problem is solved using experimental transmitted data and an estimation of the porosity, tortuosity, viscous characteristic length, Poisson ratio and the Young modulus of the skeletal frame is given. Experimental results for slow and fast waves transmitted through human cancellous bone samples are given and compared with theoretical predictions.

Mon 11:15 Pavillon 1

Characterization of cancellous bone : experimental studies & models

Scattered waves in trabecular bones in the light of two-phase macroscopic model with complex elastic moduli

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Due to the non-invasive nature and cost-effectiveness, ultrasound is the diagnostic tool which is continuously developed for assessment of bone quality. Since the fact except the demand for more advanced experimental techniques there is also a great role for accurate model to have a chance to extract as much information from the experiments as possible. Trabecular bones are high porosity materials saturated with fluid (marrow) and number of two-phase approaches for modelling of wave propagation phenomena, based on Biot's theory, were used for interpretation of experimental ultrasonic data. The models have taken into account elastic volumetric interaction of phases, viscous and dynamic interaction being result of relative motion of phases, macroscopic anisotropy of skeleton, inhomogeneity of microscopic velocity in fluid, macroscopic viscosity of fluid phase. Although the number of considered effects and complexity of these models increase, there are still not able to describe consistently the experimental results for velocity and attenuation of ultrasound in bones that are obtained systematically by different laboratories. In particular there is a poor quantitative agreement between the experimental data and theoretical predictions for wave velocity and attenuation as well as the role of viscosity of pore fluid. This, together with the fact that wavelength is comparable with characteristic size of elements of microstructure (pores or trabeculae), may indicate that the main physical factor causing the specific dispersion and frequency dependence of attenuation of longitudinal waves is strong scattering. This phenomenon, however has not been well described within the two-phase model, because the available proposals concerns only the weak range of scattering. The purpose of this paper is to study the strongly scattered waves in high porosity medium using model with complex elastic moduli. The predictions and applicability of the considered macroscopic model are discussed for trabecular bones and used to illustrate the peculiarities of ultrasound in the materials.

Mon 11:30 Pavillon 1

Characterization of cancellous bone : experimental studies & models

Ultrasound characterisation of trabecular thickness in cancellous bone

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We present a method to estimate trabecular thickness (Tb.Th) in trabecular bones from ultrasound backscatter measurements. The estimation scheme is based on a non-linear adjustment of predictions from a model to experimental data. The model assumes weak scattering from bone, where scattering is assumed to arise from the elastic solid trabeculae. The fluctuations of acoustical properties between bone tissue and the saturating fluid are assumed to be random and are described by the 3-D spatial autocorrelation function of the medium. In this paper, a Gaussian autocorrelation function is used. The inversion procedure is applied to a set of data measured on 33 femoral bone specimens. Results show that the model can predict both the magnitude and the frequency-dependence of the backscatter coefficient (root mean square error RMSE=1 dB). The estimated trabecular thickness values are compared to the true trabecular thickness measured on high resolution m-CT 3-D reconstruction of bones micro-architecture. A close agreement is obtained on average over the group of specimens between predictions and the reference values: true Tb.Th is 132 $\pm$ 12 μm and estimated Tb.Th is 134 $\pm$ 15 μm. However, a moderate correlation between actual and estimated Tb.Th values is found (R^2 =0,44, p<10^{-4}, RMSE = 8,7 μm). Sources for the variability are speckle noise and the measurement errors. Using synthetic rf signals, we demonstrate the total uncertainty on Tb.Th estimates is of the order of 7μm. The influence of the attenuation compensation function used to derive the backscatter coefficient is studied, and we demonstrate the necessity of compensating for the effect of the gating time window.
The results are discussed with respect to their meaningful clinical value. Two different strategies are examined.
First, to characterize trabecular thickness without consideration of bone quantity (or bone mineral density). A comparison between precision of our estimator and biological variability leads us to the conclusion that our estimator should only permit to distinguish between micro-architectures characterized by extreme values of trabecular thickness. In this respect, it would be interesting to test wether the estimator is able to discriminate between rod-like (thin) and plate-like (thick) structures that are known to influence differently bone strength.
Second, to estimate of trabecular thickness after adjustment for BMD. This strategy is more demanding in terms of technique performance, and our estimator is not able yet to catch small differences in Tb.Th values expected after adjustment to bone density.
Progress in the field will require a significant reduction in speckle noise and measurement errors and/or the development of other and more efficient microstructural estimators.

Mon 11:45 Pavillon 1

Characterization of cancellous bone : experimental studies & models

A new material for modelling sound propagation in trabecular bone

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Studies of the propagation of ultrasound in trabecular bone have been progressing for several decades and a considerable volume of empirical data has now been assembled. However the corresponding theoretical model is still not fully developed and this is hampered by the existence of a large number of inter-related variables. Bone mimicking materials have been identified as useful tools in this area since they allow some control on variables such as porosity, density and isotropy. However none of these materials described to date has found widespread acceptance for a variety of reasons. We have been experimenting with steel wool as a potential bone mimic. Its advantages are ready availability, low cost and wide range of sizes. The steel wires used can be found in sizes which cover most of the range of trabecular widths and the space between the filaments can be filled with water or any selected oil or fatty liquid. Compression of the samples of steel wool allows the porosity to be changed while keeping the simulated 'trabecular' sizes constant. Equally it is possible to vary the 'trabecular' dimensions while maintaining either the mass of steel or the sample thickness. Thus most scattering models can be investigated in a systematic way.

Limitations of the material include the somewhat higher than desired speed of sound and the difficulty in achieving low porosities. Nonetheless we have found this useful already and can present some early data on its scattering characteristics.

Mon 14:00 Amphithéâtre Portier

New devices for bone status assessment : technological developments and in vivo studies

Risk of fracture assessed by 1 MHz-ultrasound bidirectional axial transmission

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The objective was to assess a new quantitative ultrasound device suitable for the measurement of speed of sound in radius. Ultrasound measurements were performed using bidirectional axial transmission as previously described [Bossy & al., IEEE Trans on UFFC, 51(1), 71-79, 2004]. An accurate estimation of velocity was based on a compensation for soft tissue effects implemented directly inside the probe, consisting in a combination of the time delays on a unique central set of receivers of the first arriving signal coming from direct and opposite directions. Velocity measurements of the first arriving signal were performed at the one third distal radius. Intra-operator in vivo RMS coefficient of variation (assessed from three repeated measurements with intermediate repositioning on 14 subjects, 23-55 years of age) was 0.4% (RMS SD = 15 m/s). The interoperator precision was 0.5% (RMS SD = 20 m/s). It was deduced from measurements performed by two different operators in 9 subjects age 23-45. For the age-stratified velocity values, only 125 control women of the 362 enrolled women (34%) were included, following exclusion criteria such as use of bone-affecting drugs and previous fracture following low trauma. The average velocity by age decade increases to a peak velocity of 4033 m/s (±45 m/s) in the class 30-39 years (N=16) and decreases thereafter. The curve patterns of the 'eligible' and the 'non-eligible' women were similar, showing a rate of decline of 4.7 m/s per year between 60 and 90 years in the total population. The annual loss divided by the young population SD is then 0.10. Fracture discrimination. The study group consisted of 133 postmenauposal women without history of fracture (group NF) and 49 postmenopausal patients (group F) with osteoporotic fractures (hip, spine, Colles). Women using bone affecting drugs were included in this study. The odds ratio for fracture prediction by ultrasound velocity, was 1.77 [1.19-2.64] when adjusted for age and BMI. The area under the receiver operating characteristic curve (AUC) was 0.72. In a second study, women using drugs were excluded (NF = 49, F = 25), the odds ratio adjusted for age (BMI was not anymore a significant factor) was 2.14 [1.06 ; 4.31] with an associated AUC of 0.76. In this study a clinical evaluation of bidirectional axial transmission technique was performed, assessing the in vivo precision, age related changes and fracture discrimination. Despite the small population and the variety of fractures in the fracture group, our data indicate that the velocity of the first arriving signal measured by bidirectional technique discriminates patients with osteoporotic fracture.

Mon 14:15 Amphithéâtre Portier

New devices for bone status assessment : technological developments and in vivo studies

Dual-Frequency Bone Ultrasonometer for Long Bones with Axial Scanning

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The dual-frequency method and device have been proposed as a new modality in axial bone quantitative ultrasonometry (QUS). The knowledge of changes in elastic properties and the cortical thickness are of equal diagnostic value for different kinds of bone pathology. Measurement of propagation parameters of ultrasonic signals in long bones at different ratios of the wavelength to the bone thickness and taking into account both bulk and guided waves allows assessment of changes in both the material properties related to porosity and mineralization as well as the cortical thickness. Topographical changes assessed by axial scanning can be considered as a new diagnostic indicator of spatial processes developing from epiphyses of the long bones towards the diaphysis, such as gradual thinning of the cortex by progressing resorption in osteoporosis and the porosity onset. Ultrasound propagation parameters are evaluated for the consecutive pulses with carrier frequency of 0.1 and 1 MHz. Data acquisition is realized by a 100 MPIS 8051 core microprocessor managed unit. Model studies conducted on tubular and layered phantoms of different materials mimicking the progressing porosity and variations of the cortical thickness confirmed feasibility of the proposed approach. Limited clinical trials included examinations of proximal tibiae in groups of healthy subjects of both genders and patients with osteopenia and osteoporosis. Statistical analysis of ultrasound propagation parameters axial profiles allowed discerning consequent steps of bone atrophy and grading the groups according to their general bone health status. Comparison of symmetrical tibiae in patients with one-side injuries of the lower extremities during immobilization period revealed the same trends as in osteoporosis. Acknowledgement: This work was supported in part by the NIH grant 2R44AG17400 and NASA grant NAS3 02167

Mon 14:30 Amphithéâtre Portier

New devices for bone status assessment : technological developments and in vivo studies

A Novel Ultrasonic Bone Densitometer Based on Acoustic Parameters of Cancellous Bone for Fast and Slow Waves

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A novel ultrasonic bone densitometer, prototype LD-100, has been developed to obtain the bone mass density in the unit of [mg/cm3] and the elasticity in the unit of [GPa] with a comparable space resolution and a comparable accuracy to the pQCT system. The ultrasonic wave propagation path through cancellous bone is modeled to specify the causality between ultrasonic wave parameters and bone density. The bone mass density and the bone elasticity are evaluated by ultrasonic parameters based on the fast and slow waves. The measurement site of the developed system, LD-100, is selected at the distal radius, at the same measurement site as pQCT system, in order to realize a direct comparison of measured bone densities between the developed ultrasonic system and the pQCT system. The site to be measured is set between a pair of broadband focused transducers through water-filled bags. The transmitter is driven by single sinusoidal pulse voltage at a frequency of 1 MHz. The ultrasound beam scans in a raster pattern through the measurement site by means of a 2-axis scanning mechanism. The ultrasonic measurement consists of two scanning processes, the first and the second scanning. During the first scanning, transmitted ultrasonic signals are taken and recorded every 2 mm over a scanning area in both X-Y directions 28×28 mm. Overall amplitudes of the transmitted signals including both the fast and slow waves are analyzed to obtain a local attenuation distribution of the measurement site. Measured attenuation levels are converted into a color variation and the local attenuation distribution is displayed as a pseudo-bone density image of the measurement site (a mapping of the distal radius, the distal ulna and some parts of palm). The pseudo-bone density image obtained by the first scanning is used to confirm the bone geometry of measurement site and to discriminate the measurement site for the second scanning. The second scanning area (4×4 mm) is automatically selected by specially developed measurement algorithm at the same measurement site as pQCT system. During the second scanning, the measurements are executed every 1 mm both in transmission and echo modes. Transmitted and echo signals are analyzed to obtain the mass density and the elasticity of cancellous bone. Measured values are given with a real unit of density [mg/cm3] and of elasticity [GPa]. Measured in vivo density agrees well with that obtained by pQCT system and the correlation coefficient between both systems attains to 0.87.

Mon 14:45 Amphithéâtre Portier

New devices for bone status assessment : technological developments and in vivo studies

Ultrasonic measurement of human cancellous bone utilizing Biot's theory and its clinical application

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AIM) To assess bone mass with quantitative ultrasound (QUS) utilizing the Biot's theory and compare that measured by the current bone mineral density measurement instruments.
METHODS) Ex vivo study: Human femoral head was sectioned to 10 mm-thick slices perpendicularly to the femoral cervical axis. The samples were subjected to the measurement using PVDF transducers, and the bone mass and elastic constant of cancellous bone were calculated form the slow and fast waves. The bone volume ratio was measured in the same sample by micro CT, and structural parameters were calculated from the micro CT data. In vivo study: In adult subjects aged 20-80 years, the left distal radial bone mineral density (RBMD) was measured using LD100, QDR4500 (DXA), and XCT960 (pQCT) (the lumbar vertebral bone mineral density (LBMD) was also measured using QDR4500).
RESULTS) Ex vivo study: The bone volume ratio measured by micro CT and attenuation of transmitted slow waves was negatively correlated (r=0.88). The bone volume ratio measured by micro CT was positively correlated with the sound velocity of fast waves (r=0.73), and with Mean Intercept Length (0,0) (r=0.80). A similar tendency was noted in the elastic constant of cancellous bone. In vivo study: The correlation coefficients of RBMD measured by LD100 and other instruments are shown below. (Table 1) Concerning the presence or absence of vertebral insufficiency fracture (50 years of age or older), the RBMD was significantly lower in patients with fracture than in those without fracture in all measurements using LD100, XCT960, and QDR4500. The cancellous bone elastic constant was also lower in the fracture group, but no significant difference was noted in LBMD.
CONCLUSION) QUS utilizing the Biot's theory is useful for evaluation of fracture risk.

LD100	XCT960 r=0.744	QDR4500-UD r=0.832	QDR4500-L r=0.549
p value	p<0.01	p<0.01	p<0.01

Mon 15:00 Amphithéâtre Portier

New devices for bone status assessment : technological developments and in vivo studies

A 60 days Bedrest Study: Quantitative Ultrasound Bone Calcaneus Assessment

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In the context of manned-space flights, we have developed for ESA, a dry QUS device dedicated to heel bone parametric imaging: Beam Scanner. To that aim, a pair of 2D arrays US probes including 576 elements, at 5OO KHz central frequency (Vermon, Tours, France) and a beam forming and scanning electronic bay (Ultrasons Technologies, Tours, France) have been manufactured. This device calculates and displays two parametric images of BUA (Broadband Ultrasonic Attenuation, dB/MHz) and SOS (Speed of Sound, m/s). The Beam Scanner has been fully validated and has provided non standardised coefficients of variation of 2% and 0.3%, for BUA and SOS respectively. A 60 days bed rest study has been organised in the Benjamin Franklin Universitätklinikum in Berlin by the Professor Felsenberg and Dr Rittweger, under ESA requirements. It consists in simulating O gravity effects on body physiology, by lying horizontally in bed for a while. We have participated to that study in order to evaluate the bone changes at the heel site using the Beam Scanner device. 16 young, healthy males (volunteers), aged from 20 to 40 years old, have been including in the QUS protocol. Three QUS acquisitions were performed on each foot with interim repositioning. Measurement sessions were planned before bed rest, every 15 days during the Bedrest, and after 1 month, 3 months, 6 months and 12 months. The subjects were divided in two groups: a control group and an exercise group. The exercise training session was essentially concerning the lower limbs and feet. We clearly have a difference in bone loss between these two groups. The control group bone loss has been estimated superior to 6% for the BUA parameter and is statistically highly significant. The bone loss difference between groups is also statistically significant. Similar results have been obtained with the SOS parameter. In conclusion it was the first time that a QUS device was used in the context of such a longitudinal bone changes study. Two months bedrest are long enough to provide changes at the lower limbs and it has been demonstrated that QUS measurements are well adapted to follow bone changes over such a period.

Mon 15:15 Amphithéâtre Portier

New devices for bone status assessment : technological developments and in vivo studies

A Portable Real-Time Ultrasonic Bone Assessment Device

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The objectives of this study were to develop a novel ultrasound device to estimate BMD at the calcaneus. The new device, known as the QRT® 2000 - for Quantitative Real-Time - is entirely self-contained, portable (<1kg), handheld, and permits real-time evaluation of the ultrasound parameters. The device computes a parameter known as net time delay (NTD) which is defined as the difference between the transit time through the heel of an ultrasound signal and the transit time through a hypothetical object of equal thickness (to the heel) but containing soft tissue only. This parameter is sensitive primarily to the total amount (i.e., the average total thickness) of bone contained in the propagation path, and thus is equivalent to the bone mineral content estimated by DXA scanners, and to the (areal) BMD when normalized by transducer area. In this study, we used computer simulations of ultrasound propagation to study the relationship between NTD and BMD. The simulations used micro-CT images of a set of ten calcaneal bone cores, which were further processed by morphological image processing to obtain a set of thirty-six 'samples' with BMD's ranging from 0.25 - 1.83 g/cm2. The NTD and BMD were found to be very highly correlated (r = 0.99), demonstrating the sensitivity of the NTD to bone mass. In a clinical IRB-approved study the QRTô 2000 was used to measure 85 adult women at the heel. BMD was measured at the same time using DXA. A multivariate linear regression - using the NTD, age and weight produced an R-squared value of 0.78, equivalent to a linear correlation coefficient of 0.88, which represents a significant improvement over present ultrasound bone densitometers, but not nearly as good as the simulation results. Reasons for this have been identified (viz., errors in distance measurement and lack of coincidence between the DXA and ultrasound regions of interest), and a new device (QRT® 2510) and experimental protocol to deal with these sources of error has been developed and is currently under clinical trials. It is expected that this should improve the correlation between NTD and BMD even further (> 0.9), effectively making the former parameter a proxy for the latter. In conclusion, although x-ray methods are effective in bone mass assessment, osteoporosis remains one of the largest undiagnosed and under-diagnosed diseases in the world today. The research described here, in conjunction with the fact that the QRT® devices are designed to be manufactured at very low cost ($400 USD), should enable the significant expansion of diagnosis and monitoring of osteoporosis throughout the world.

Mon 15:30

Poster Session & Coffee Break

Simulation of Ultrasonic Pulse Waves Propagating through Cancellous Bone Using Three-Dimensional Trabecular Models

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Ultrasonic pulse waves propagating through cancellous bone were numerically simulated using a three-dimensional finite-difference time-domain (FDTD) method. Various simplified trabecular structures, which were oriented in the direction of ultrasonic waves, were modeled in 3D to analyze the propagations of the Biot's fast and slow longitudinal waves. The trabecular models used in the numerical simulations were classified into two types: the model made of numerous trabecular elements in bone marrow and the model of the solid bone with numerous pore spaces (filled with bone marrow). The simulations were performed using a viscoelastic FDTD method considering the absorptive loss in a medium. The simulated results of the pulsed waveforms propagating through various trabecular structures were compared to investigate the contribution of the trabecular structure to the fast and slow wave propagations.

Mon 15:30

Poster Session & Coffee Break

Model based Segmentation of High Resolution Acoustic Cortical Bone Images

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Macroscopic mechanical bone properties are predominantly determined by the elastic properties of the mineralised collagen matrix and by the micro-architecture composed of bone matrix and voids, e.g. Haversian canals or resorption lacunae. Scanning acoustic microscopy (SAM) provides non-invasive quantification of structure and matrix elasticity and thereby comprehensive information for the prediction of the mechanical integrity of the tissue. However, practical preconditions, e.g. usable frequency, scan parameter and acceptable scan duration often limit the achievable spatial resolution. The aim of this study was therefore to validate segmentation concepts taking into account the system transfer function of the microscope. We have developed academic structural models and a virtual SAM using the 'Field II' program. In particular we evaluated the segmentation of Haversian canals with a diameter range from 40 to 90 μm. Measurements and simulations were performed using a broadband 50-MHz transducer that has a beam width of 23 μm in the focal plane. Canal area and diameter were estimated from the segmented images and compared with the object parameters. This simulation allowed a systematic survey of the factors affecting the threshold for correct object segmentation. Rules were then derived to refine an object-based threshold. With this table-lookup threshold selection a reliable segmentation was possible for all investigated canal shapes and diameters. The establishment of a virtual SAM allows to validate the results of image processing and segmentation strategies. The artefacts caused by the incremental scanning with low frequencies are decreased by locally adapted thresholds and the accuracy of the segmentation was improved for the investigated biological structures.

Mon 15:30

Poster Session & Coffee Break

Ultrasonic transmission device based on crossed beam forming

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The currently devices for quantitative assessment of bone status, using mechanical scanning to perform an image, present several limitations such as a long duration of examination, and a coupling by water bath which requires a particular management. A new technology had been adopted by LUSSI (Laboratoire UltraSon Signaux et Instrumentation) in collaboration with the LIP (Laboratoire d'Imagerie Parametrique) by the development of an osteodensitometer based on a technology of 2D multi-elements transducer which allows an electronic displacement of the ultrasonic beam [1]. Consequently, the examination time is reduced. However, the electronics managing the elements of each matrix is very complex. In order to reduce these disadvantages, we developed a new ultrasonic osteodensitometer less demanding in terms of technology, based on one-dimensional matrix transducers and cylindrical crossed beam forming [2]. This technique has been validated by two methods. First in LUSSI, the crossed beams were obtained using 2D matrix transducers and the BUA (Broadband Ultrasonic Attenuation) values were obtained in vivo with this technique[3]. Second, in LIP; measurements were performed in vitro for 22 samples of human cancellous bone with two cylindrical focusing mono-element transducers in a crossed configuration with an active surface of 80x29mm2, focal length of 50mm and central frequency of 500 kHz. In both cases, the values of BUA were strongly correlated with those obtained with the reference technique, i.e. spherical focusing.
A new imaging device had been developed by LUSSI (Tours) and LIP (Paris) based on a technology of one-dimensional matrix transducers for cylindrical crossed beam forming. Compared to two-dimensional matrix transducers previously developed in LUSSI, the number of elementary transducers of each matrix is considerably reduced (72 elements for the 1-D matrix compared to 576 elements for the 2-D matrix) as well as the complexity of driving electronics and fabrication cost. The crossed beam arrays consist of fully connected 72 elements with a length of 92mm, a pitch of 1.25mm (active surface area: 1x92mm2), center frequency of 0.5 MHz positioned confocally. Both transducers are immersed in a water balloon (silicon). Beam forming is performed either electronically (by driving the emitters with appropriate delays) either synthetically (by reconstructing the signals after emission-reception). The geometry of the device allows cylindrical focusing. The orientation of both arrays is orthogonal, so that the signal in reception arises from the intercept of the two focusing lines. Preliminary testing has been performed on phantoms of known attenuation coefficient and speed of sound. Here we report on the performance of the matrix transducers and of the electronics tested several beam forming solutions (electronic or synthetic focusing with or without apodization) and several apertures (12 or 24 elements). We will present the first images of BUA and SOS obtained with the prototype, after measurements of a Teflon phantom with cylindrical inclusions, and we will compare them with values obtained with the reference technique.

[1] Defontaine & Al. "1999 IEEE Ultrasonic Symposium"
[2] Ermert & al. "2000 IEEE Ultrasonic Symposium".
[3] Defontaine & al. "2003 Medical Ultrasonic Imaging".

Mon 15:30

Poster Session & Coffee Break

Calcaneal Ultrasound measurements in children and adults male tennis players

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Introduction

Bone ultrasound measurements as Broadband Ultrasonic Attenuation (BUA, dB/mHz) and Speed Of Sound (SOS, m/s) have been demonstrated of interest for in vivo bone exploration; but potential relations with lean mass and fat mass were less investigated. Most of studies compared athletes and sedentary people but none of them observed effect of maturity on people participating in sports with loading impacts. The aim of this study was to compare bone ultrasound measurement between boys and male adult tennis players.

Methods

A group of 22 boys (11.5±1.4 years) and a group of 31 male adults (25.7±6.2 years) playing tennis at a regional or national level were enrolled in this study. BUA and SOS at the non dominant calcaneus were measured using an UBIS 3000 (DMS®). Total whole body Bone Mineral Density (BMD) and body composition (lean mass (g) and fat mass (g)) were also determined using DXA (Hologic, 4500 W).

Results

BUA and SOS were significatly higher in adults compared to children.

BUA (dB/MHz)		n	Mean±std (median)	p	Ajusted to lean mass	p
	Adults	31	71.6±4.7(70.8)	$< 10^{-4}$	68.80±0.79	NS
	Boys	2	64.1±4.4 (64.1)		68.11±0.93	
SOS (m/s)						
	Adults	31	1583.13±41.6 (1583.7)	0.03	1575.00±5.8	NS
	Boys	22	1565.14±21.58 (1560.5)		1570.00±6.77	

BUA (dB/MHz)			Adjusted to fat mass	p	Adjusted to BMD	p
	Adults	31	71.41±0.82	<5.10-4	67.07±0.75	NS
	Boys	22	64.42±0.98		70.52±0.89	
SOS (m/s)						
	Adults	31	1585.71±6.1	0.02	1567.00±6.18	NS
	Boys	22	1561.49±7.2		1587.00±7.34	

When BUA and SOS were adjusted to lean mass and whole body BMD, differences between adults and children did not appear; when adjsuted to fat mass, no variation was noted on the mean values.

Conclusion

There is no difference in BUA and SOS between boys and adults involved in impact loading sports. The difference between groups is only related with differences of BMD status and lean mass.

Mon 15:30

Poster Session & Coffee Break

Temperature dependence of speed of sound in bone marrow

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There is substantial literature on the ultrasonic properties of bone but continuing debate about mechanisms of propagation. Many of the relevant theories rely on a knowledge on bone constituents including marrow. However data about the properties of marrow are difficult to find and there seems to be no information about the temperature dependency. We have measured the speed of sound in 10 samples of bovine bone marrow extracted from 5 animals using a time-of-flight method at temperatures from 17 to 44C. The results show a very linear response with SOS changing from 1457 m s-1 at 17°C to 1345 m s-1 at 44°C. The mean value at 37C was 1380 m s-1. The temperature coefficient of the SOS was found to be -4.18 m s -1 °C-1. This was well fitted to a least squares model with R2 = 0.99. However a significant variation between samples was found. At any given temperature, this could amount to ± 20 m s-1.

Mon 15:30

Poster Session & Coffee Break

On the vibratory response of a human tibia: Comparison of 1D Timoshenko model, 3D FEM and experiment

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The most cited contributors to bone strength are bone density and bone quality. Moreover precise definition of bone quality remains elusive and unfortunately, tools for directly measuring bone strength in patients are not available. However, it is apparent that the tremendous loss of bone strength in elderly persons results from changes in the geometry of the structure as well as changes in the material properties. In this study the vibroacoustic response of a bone to a vibrational input is used to infer its material and structural properties. We compare the flexural vibratory response of a human tibia clamped at one of its ends, obtained from a one dimension(1D) Timoshenko beam model, three dimensional finite element model(FEM) and experimental data. The 1D model is based on the resolution of the Timoshenko beam model equation, which incorporates shear and rotation inertia into the Euler-Bernoulli beam model, by employing a fourth order finite difference scheme. The simplified 3D vibration model is computed using the finite element method. Experimentally the resonance frequencies and their attenuations are recovered from the impulse response using Prony's method. The real bone cross section geometry is often too complex for the analytic computation of the shear correction factor for the 1D model. The 3D modeling solves this problem if the exact geometry is known. Consequently, we have developed a simple laboratory system using a turntable and a theodolite to scan the exterior geometry of bones.

Mon 15:30

Poster Session & Coffee Break

In vitro studies of cancellous bones. Determination of macroscopic structural and mechanical properties of cancellous bone

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Cancellous bone in its natural environment is at least two phase material composed of solid rod-like or plate-like skeleton and fluid. If the ultrasonic wave propagation in trabecular bone is considered the internal structure of the material strongly influences wave parameters such as attenuation and dispersion. The two-phase theory of dynamics of fluid saturated porous materials proposed by Biot, [Biot, J. Acoust. Soc. Am. 1957], and extended by other authors, [Bourbie et al, Acoustics of Porous Media, 1987], is mostly used as theoretical basis in number of studies of cancellous bone, [Hosokawa & Otani, J. Acoust.Soc. Am. 1997, 1998, Langton & Haire, Bone, 1999, Fellah et al J Acoust Soc Am 2004; Kaczmarek et al Poromechanics III 2005]. However, appropriate interpretation of the experimental ultrasonic data in terms of Biot's model demands evaluation of macroscopic structural parameters and mechanical properties of cancellous bone. The model includes three macroscopic pore structure parameters: porosity, permeability and tortuosity, physical and mechanical properties of solid and fluid as well as so called Biot-Willis elastic constants, [Biot &Willis, J. Appl. Mech. 1957].

The aim of the studies performed within the paper is focused on experimental evaluation the mechanical properties of cancellous bone specimens treated as saturated porous material and their macroscopic structural parameters such as porosity, permeability and tortuosity. In the studies experiments were performed on 35 human cancellous bone cylindrical samples of diameter about 7 mm and thickness varying form 8 to 12 mm.

The structural parameters were evaluated techniques devoted to the characterization of porous materials: gas picnometry (porosity measurements), electrical spectroscopy (tortuosity investigations) and water permeametry (permeability test). The mechanical properties of the cancellous bone were derived based on the micromechanical models and results of ultrasonic studies for unsaturated cancellous bones.

Mon 16:30 Amphithéâtre Portier

Characterization of cortical bone : simulation studies & models

Acoustical Identification of a Cortical Bone-like Cylindrical Tube

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It has become fairly common to acoustically identify some mechanical properties of bone tissue, supposed strongly linked to some bone pathology, in particular osteoporosis. We consider a 2D long bone configuration (typically a human radius or femur in its appendicular part) which we treat as an infinitely-long cylindrical object. A rigorous model of such a bone should take account of its complicated shape and porous nature (essentially in the cortical component). Both of these properties are sources of difficulties, especially in connection with the resolution of the inverse problem consisting of the identification of the mechanical constitutive properties of the cortical component from the scattered acoustical field. The porosity requires the Biot model for the description of the way the cortical component responds to the acoustical solicitation, but the repeated resolution of the two coupled partial differential wave equations of this model, as is required during the inversion process, constitutes a formidable numerical task that should be avoided, if possible. Another option is to treat the cortical component as a viscoelastic solid and solve the wave equation by a finite element time domain method, but even this may not be enough to enable the resolution of the inverse problem in a reasonable amount of time. A further simplification is obtained by approximating the inner and outer boundaries of the bone (in its cross-section plane) by concentric circles. Thus, the bone is reduced to a circular cylindrical tube. The medullar core is filled with marrow which is another viscoelastic solid, whereas the soft tissue surrounding the bone is yet another viscoelastic solid. Both of these, as well as the cortical tissue, are treated as homogeneous (homogenized) materials. Since the shear velocities in the outer and inner soft tissues are small, a further simplification is to treat these tissues as fluids. A final aspect of the inversion strategy is to employ a low frequency approximation of the solution of the inverse problem as the initial trial solution in the iterative inversion scheme (at higher frequencies). This procedure is employed to retrieve the mechanical constitutive parameters of the cortical component of a long bone from simulated scattered field data generated by means of the finite element time domain method.
This research was supported by Action CNRS/Etats-Unis 2005 no. 3321

Mon 16:45 Amphithéâtre Portier

Characterization of cortical bone : simulation studies & models

Ultrasonically determined thickness of long cortical bones: simulation study

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Recent experimental studies have shown that an ultrasonically determined thickness (UTh), based on a fit between measured and theoretical velocity of fundamental flexural guided wave, correlated significantly with the cortical thickness (CTh) of human radius bones [1]. These results were, however, subjects to errors, such as variations in material and geometrical properties, which were not properly explained by the theoretical model used. The purpose of this study was to start investigating the gap between the theoretical and experimental results for real bone. Numerical model, based on 3D X-ray reconstructions of human radii in vitro (n=29), was developed, and wave propagation was simulated using the finite-difference method [2]. In spite of variations in cortical thickness along the propagation path (44 ± 17 %), a wave mode consistent with the fundamental flexural guided wave was identified, and UTh was indeed strongly correlated ($r^2 = 0.90$, $p < 0.001$; RMSE = 0.45 mm, 15%) with the CTh. These were initial results based on simulations in two dimensions, three-dimensional simulations are in the progress of being made. A good accordance between the previous in vitro experiments and new simulation results thereby validated the numerical bone model developed. It was observed, that slight variation in geometry of bone did not affect too strongly the dispersion of the measured guided wave and simple analytical theory can, in fact, be used as a satisfactory model for the average geometrical properties of cortical bone. The numerical bone simulation model will further be used to establish connections between ultrasonically measurable quantities and bone material properties, such as Young's modulus and microporosity. This is expected to yield essential enhancements on assessing particular properties of long bones by ultrasound.

References:

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[2.] E Bossy, M Talmant, P Laugier. Three-dimensional simulations of axial transmission velocity measurement on cortical bone models. J Acoust Soc Am 115 (5): 2314-2324, 2004.

Mon 17:00 Amphithéâtre Portier

Characterization of cortical bone : simulation studies & models

Three-Dimensional Finite Element Modelling of Guided Ultrasound Wave Propagation in Intact and Healing Long Bones

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Introduction: The ultrasonic axial-transmission technique has been used for the evaluation of metabolic disorders and the monitoring of bone healing. Two-dimensional models have shown that the propagation of guided waves can supplement traditional velocity measurements. A recent three-dimensional (3D) study demonstrated the influence of bone geometry, anisotropy and porosity on velocity measurements. In this work, we present a 3D Finite Element (FE) model for the investigation of guided wave propagation in intact and healing bones.
Materials & Methods: The bone was modelled as a homogeneous and linear elastic solid. In a first approach (Series I), the bone was assumed to be isotropic, whereas in Series II the bone was modelled as transversely isotropic. The 3D bone geometry was reconstructed from CT scans obtained from a midshaft bone segment. The fracture callus was modelled as an inhomogeneous material consisting of six different ossification regions. The healing process was simulated by a 3-stage process. At each stage, each region was assigned the properties that correspond to the different tissue types involved in the healing process. We used a transmitter-receiver configuration in which the emitted ultrasound wave was simulated by a vertical transient loading (central frequency 1-MHz), whereas the received signal waveform was the time history of the vertical displacements recorded at a 35 mm distance. The bone was assumed to be in vacuum and thus the influence of the surrounding tissues was not taken into account. Solution to the elastic wave problem was performed with the use of the FE method (ABAQUS, explicit). The FE mesh of the model consisted of about 1.3 million hexahedral elements (mean inter-nodal distance was 0.18 mm). In each waveform, the first-arriving signal (FAS) was detected using a threshold-based technique. The propagating guided waves were represented in the time-frequency signal domain by superimposing velocity dispersion curves. The dispersion curves were computed for a tube with circular cross section (inner radius 4.5 mm, outer radius 8.5 mm) that fits to the bone's cross-section in the least square sense.
Results & Conclusions: The velocity of the FAS in the long axis direction was the same in Series I and II. The dispersion of guided modes was described by the theoretical tube modes, but was greatly affected by the anisotropy of bone. During the simulated healing process, the guided waves were gradually reconstructed. In conclusion, the anisotropy and the tubular bone geometry have a significant effect on guided wave propagation.

Mon 17:15 Amphithéâtre Portier

Characterization of cortical bone : simulation studies & models

Quantitative ultrasound simulation studies in compact bone

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Today, drugs are available with the potential of reducing osteoporotic fracture risk substantially. Usually, the increase in bone mineral density is too small to explain the increase in bone strength and it is not clear whether changes in mineralization or structure contribute to this effect. A method is warranted which can be used to separately measure changes in bone properties, which cannot be assessed using radiological methods alone.
Ultrasound transmission through compact bone is affected by a variety of bone properties. Using simulation methods of ultrasound wave propagation we tested whether a combination of different modes of ultrasonic propagation has the potential to separately assess changes in geometry, porosity and mineralization of compact bone.

Tue 9:00 Pavillon 1

Keynote Lecture 2

Assessment of microstructure and tissue elastic stiffness by site-matched acoustic microscopy and synchrotron radiation-μCT

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200-MHz scanning acoustic microscopy (SAM) and synchrotron radiation μCT (SR-μCT) were used to assess microstructural parameters and tissue properties in cortical bone. Structural parameters, including diameter and number of Haversian canals per cortical area and porosity were assessed with both methods using a custom developed image fusion and analysis software. Acoustic impedance Z and degree of mineralization of bone DMB were extracted separately for osteonal and interstitial tissue from the fused images. A model was developed that relates the DMB accessible with SR-μCT to mass density ($R^2 = 0.999$). The formulation incorporates the volume fractions and densities of the major bone tissue components (collagen, mineral and water), and accounts for tissue porosity. With this model it was possible to derive the elastic coefficient c33 from site-matched measures of Z and DMB. Structural parameter estimations obtained from radiographic and acoustic images were almost identical. DMB and impedance values were in the range between 0.77 and 1.28 g cm^{-3} and 5.13 and 12.1 Mrayl, respectively. The regression between DMB and Z follows a second order polynomial ($R^2 = 0.39$, $p < 10\text{-}4$). The derived elastic coefficients c33 were in the range between 14.8 and 75.4 GPa. c33 correlated more strongly with the acoustic impedance ($R^2 = 0.996$) than with mass density ($R^2 = 0.310$). Both modalities fulfill the requirement for a simultaneous evaluation of cortical bone microstructure and material properties at the tissue level. While SAM inspection is limited to the evaluation of carefully prepared sample surfaces, SR-μCT provides volumetric information of the tissue without substantial preparation requirements. However, SAM provides a quantitative estimate of elastic properties at the tissue level that cannot be captured by SR-μCT.

Tue 9:30 Pavillon 1

Scanning acoustic microscopy

A Comparison of Acoustic Impedance, Mineral Density and Structure Assessed in Femur of Different Mice Models of Bone

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Scanning acoustic microscopy (SAM) permits to study through the measurement of acoustic impedance, the elastic properties of a material at a micrometric level of resolution. We assessed acoustic impedance (Z), degree of mineralization (DMB) and structure of femoral bone taken from genetically different mouse strains (C3H, BL6,BSP deficient wild type and their wild type controls). C3H and BL6 strains have previously been shown to differ in bone mineral content and density. BSP deficient mice do not express bone sialoprotein (BSP) that has been shown to be involved in the biomineralization of collagen matrix. However, the precise function of BSP is unknown and its relationship to bone composition, strength, and structure is unclear. This study sought first to investigate the relationship between the acoustic impedance of bone on the tissue level and its degree of mineralization by comparing both cortical and cancellous bone in C3H and BL6. Z and DMB site-matched regions were analyzed on Z and DMB images obtained using a 200 MHz SAM and SR-μCT (8 and 10 μm spatial resolution respectively). Bone tissue elasticity c11 was extracted from the combination of Z and DMB images. Our findings indicate that DMB was not correlated with c11 ($R^2 = 0.13$) In a second step, Z, DMB (both evaluated in different sites of the femur) and bone geometry (femur diameter and cortical width) were compared among the four strains. Within each mice group, cortical diaphysis showed greatest material properties as compared to cancellous bone and epiphysis. Cortical and cancellous bone material properties varied among the four mouse strains. All tissue properties were lower in the BL6 mice than in the C3H mice. BSP mice exhibited lower cortical width and lower degree of mineralization than their wild controls. Z also decreased in BSP mice but the difference in acoustic impedance was not significant because the important variability of Z values found in wild type mice. We found similar changes in total DMB between control (C3H, wild) and hypomineralized mice (BL6, BSP) but wild strains displayed greater values of acoustic impedance than inbred mice. Acoustic microscope data indicate that acoustic impedance reflects phenotype of bone material properties that are not reflected by mineral content but might be related to changes in mineralized collagen fiber anisotropy. The current findings do not, however, show a relationship between BSP and the microstructural mechanical properties of bone.

Tue 9:45 Pavillon 1

Scanning acoustic microscopy

Effects of Leptin Deficiency on the Elastic Bone Phenotype of the C57/BL6 Mouse

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Several studies have been conducted to understand the effects of leptin on bone phenotype. Nevertheless, data on this adipocytokine are still controverse and not yet fully understood. The aim of this study was to further elucidate the bone pathology in the leptin deficient ob/ob mouse, using a 200 MHz high resolution imaging technique SAM. It has been shown in previous studies of mice femur, that the acoustic impedance measured by SAM correlates very well (R^2=0.99) with the elastic coefficient in the probing direction. The high spatial resolution allows localized estimation of the elastic tissue state, e.g. new bone formation and indirectly the degree of tissue mineralization. 64 femurs from 3, 6, 9 and 12 months old male and female C57/BL6 wild type and ob/ob mice were prepared and embedded in a modified methylmethacrylate (MMA). The acoustic impedance (Z), bone diameter B.Dm, cortical width Ct.Wi, and cancellous diameter Cn.Dm were evaluated within a 2-mm region of the mid-diaphysis, as well as the acoustic impedance of the epiphysis. Our results show that adult leptin deficient mice have a lower cortical width but a higher mean acoustic impedance compared to lean mice. We hypothesize that reduced osteoblast and osteoclast activity and differentiation leads to a reduction of bone turnover with an increased secondary mineralization of the bone matrix.

Tue 10:00 Pavillon 1

Scanning acoustic microscopy

Prediction of Biomechanical Stability After Callus Distraction by High Resolution Scanning Acoustic Microscopy

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Accurate clinical prediction of the resistance to fracture after callus distraction requires a detailed understanding of structural and elastic properties of the newly formed bone. Scanning acoustic microscopy (SAM) provides high resolution maps of the tissue acoustic impedance, a parameter that has been shown to be highly correlated with the elastic stiffness of the tissue. We investigated 28 sheep that underwent mid-diaphyseal callus distraction at a rate of 0.5 mm every 12 hours for 30 days using a standard unilateral fixator system. The sample included four groups undergoing different treatments to improve bone healing, including bone grafting and local application of growth factors. All animals were sacrificed 8 weeks after the end of distraction. The lengthened tibia from each animal were evaluated by histological, biomechanical (three-point bending) testing, and by 50-MHz SAM. The impedance and structural parameters were assessed from acoustic scans of transverse and cross sections. All parameters were evaluated separately for callus and adjacent cortical tissue in manually selected regions of interest. Both the absolute impedance values and the anisotropy ratios (defined as the ratio of the impedance values measured in the cross and transverses sections) were significantly lower in the newly formed callus tissue than in the adjacent cortical tissue. The relationships between resistance to fracture, structural and material properties of the newly formed callus tissue and adjacent cortical tissue were investigated. A significant linear multivariate regression model was developed that predicts the fracture force with a high accuracy (RMSE = 248 N, $R^2 = 0.86$, $p < 0.0001$). The results suggest that high resolution SAM is capable of identifying the impact of microscopic tissue structure and elasticity on macroscopic bone strength in animal models. Thereby SAM is a promising research tool to gain new insight in the mechanics of fracture healing.

Tue 10:15 Pavillon 1

Scanning acoustic microscopy

Determination of the Elasticity Coefficient for a Single Trabecula of a Cancellous Bone: Scanning Acoustic Microscopy Approach .

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Scanning acoustic microscopy (SAM) techniques enable to determine mechanical properties of small samples. These techniques can be applied to a single trabecula of the cancellous bone. The paper describes nondestructive methods for assessing the bone tissue elasticity for the samples accessible from one side only. Two methods are applied in the same area of a trabecula. The first one allows to determine the tissue impedance based on the correlation between the gray levels of the SAM images and of the reference material of a known impedance. The second newly-developed technique enables to measure the velocity of surface waves with a spatial resolution less than 100 μm using theoretical and experimental analysis of the position of the first interference of V(z) curve. These two experimentally-derived parameters are used to calculate the density and elasticity coefficient for trabecular bone samples of patients who suffer from metabolic bone diseases, such as osteoporosis, osteomalacia and osteoidosis. Medical description of these diseases explains the differences in mechanical properties of a trabecular bone tissue found experimentally.

Tue 11:00 Pavillon 1

Signal processing

Introduction of a Wavelet-based Method for the Reduction of Failures in Quantitative Ultrasound (QUS) Signal Processing at the Proximal Femur

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Quantitative Ultrasound measurements at peripheral sites can be used for the assessment of osteoporotic fracture risk. However, prediction of fractures at the human femur, one of the main fracture sites, can be done best by direct measurements at this site. Best method today is bone mineral density (BMD) measurement using dual energy x-ray attenuation (DXA). In an European collaboration we are developing an ultrasound device for the measurement of human femoral bone strength. First ultrasound measurements, however, showed that the conventional signal processing failed for a considerable large amount of data in a scanning area at the proximal femur. To overcome these limitations we tested the performance of wavelet approaches for the signal analysis.

In two in-vitro test sets excised human femurs (test set 1: 6 specimens, test set 2: 34 specimens) were measured in transmission with a pair of focused 0.5 MHz center frequency transducers. On the radio frequency signals of the two-dimensional scans a new algorithm based on the Continuous Wavelet Transform was investigated. Applying standard wavelets the standard variable Speed-of-Sound (SOS) was computed.

SOS and BMD correlated significantly (test set 1: $p < 0.007$, test set 2: $p < 0.0001$) in both data sets (test set 1: $r^2 = 0.87$ to 0.92, test set 2: $r^2 = 0.68$ to 0.79, depending on the applied wavelet). Residual errors ranged from 61 mg/cm2 to 79 mg/cm2 in test set 1 and 96 mg/cm2 to 119 mg/cm2 in test set 2. Results are similar to conventional approaches. However, this algorithm failed for only 0-6 % of the measurement data in test set 1 and for 2-12 % in test set 2 compared to 29% and approximately 40 %, respectively, using conventional algorithms. These results demonstrate a superior performance of wavelet based methods for the prediction of BMD using ultrasound transmission methods. Future potential lies in a separate assessment of cortical and trabecular bone parts using more specific wavelets.

Tue 11:15 Pavillon 1

Signal processing

How Does Frequency-dependent Attenuation and Velocity Dispersion Affect the Prediction of Bone Mineral Density with Ultrasonic Measurements in Excised Human Femur ?

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Bone Mineral Density (BMD) measured with DXA techniques is the current gold standard for osteoporotic fracture risk prediction. Quantitative ultrasound techniques (QUS) in transmission measurements have been accepted as an alternative approach. Broadband ultrasonic attenuation (BUA) and ultrasonic velocity (UV) measured on the proximal part of the human femur have been shown to be both significantly correlated with BMD. However, a lack of standardization of signal processing techniques used to compute UV complicates the comparison between data obtained with different commercial devices. In this study, 38 excised human femurs were measured in transmission with a pair of focused 0.5-MHz central frequency transducers. Two dimensional scans were performed and RF signals were digitally recorded at each scan position. BUA was estimated and 8 different signal processing techniques were performed to estimate UV. The resulting difference in measured UV was determined as a function of frequency-dependent attenuation and velocity dispersion. A numerical simulation was employed to explain how attenuation and dispersion impact these different UV measurements. A new method aimed at compensating for the effect of attenuation was devised and led to a significant reduction in the difference between UV values obtained with the various signal processing approaches. A comparison between different UV and BMD measurements indicated that the best correlation (r^2=0.86; RMSE=0.08 g/cm^2; p<10-4) was reached for UV calculated using a marker located in the early part of the signal. Moreover, we show that a linear multiple regression using both BUA and UV and applied to site matched regions of interest improved the accuracy of BMD predictions (r2BMD-UV/BUA = 0.95, RMSE=0.05g/cm^2). The conclusion is that velocity measurements considering early part of the signal should be preferred for ultrasonic assessment of BMD at this potential fracture site and that highly accurate estimate of BMD are possible using a combination of BUA and UV.

Tue 11:30 Pavillon 1
Signal processing

Spatial and Temporal Contribution for Real Time Quantitative Imaging of Cortical Long Bone

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We are concerned by qualitative (size and shape) and quantitative (mechanical properties) imaging of cortical long bone cross-sections by broadband ultrasonic pulse. For such methods, one of the main difficulties is the high contrast of material properties between the bone and the surrounding medium. This introduce a strong deviation of the acoustical beam and weak information from the inner part of the bone. The inversion is based on the minimization of a cost function accounting for the discrepancy between measured and estimated data. The measured data provides from simulation or from experiments with bones phantoms. To enhance the speed of computations, we use the Intercepting Canonical Body Approximation (ICBA) as forward solver during the inversion. This consists in approximating the scattered field along the measurement direction of the real almost circular bone (femur or phalanx) by the scattering due to a centred circular cylinder. Our inversion algorithm is therefore computationally efficient as it uses an analytic expression for computing the scattered field. This model is suitable for high contrast object because it take into account the deviation of the beam at the interfaces. In a first step, the inversion algorithm is validated when the model is exact (i.e. with synthetic simulation for circular bone). The contribution of each frequency content is highlighted showing an increasing of local minima of the cost-function when the frequency increase. For a temporal inversion, the difference of between the full wave-form inversion and typical pulse inversion (first arrival pulse or others) is presented. Particularly, the analysis of the cost-function show that the information contained in each scattered pulse is different according to the measurement angle and the temporal content. A new iterative inversion process is then proposed reconstructing only the most robust parameter for a specific temporal window and angle of diffusion. This method increases also the speed of reconstruction by reducing at each step the amount of unknowns. When the model is no more exact (synthetic or real phantoms) the algorithm is validated. The shape and mechanical properties are well reconstructed except the densities. The reconstruction are obtained in few minutes.

Tue 11:45 Pavillon 1

Signal processing

Development of a wavefront removal algorithm for cortical bone characterization with an axial transmission device: in vivo application

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In the context of bone status assessment, the axial transmission technique allows ultrasonic measurements of the elastic properties of cortical bone using a multi-element transducer. The axial transmission set up generates a diversity of propagating modes or wave types in the cortical shell. The current processing only evaluates the velocity of the first arriving signal, commonly referred to as the speed-of-sound. Later contributions are potentially valuable in respect to the mechanical characterization of the cortical bone and are not yet analysed. The issue is that all the later contributions interfere which disrupt the various mode analysis. A novel ultrasonic wave extraction algorithm using a singular value decomposition method is proposed. This algorithm aims at characterizing a given energetic low frequency contribution observed in vivo around 1 MHz. The performance of the proposed algorithm is evaluated by estimating the wave velocity of the considered wave front and is tested on 100 simulated signals. For a signal to noise ratio of 10 dB, the mean error associated with this method is of 5.2%, to be compared with 34% with a classical signal analysis. The algorithm is also tested on real in vivo measurements and is shown to be effective for wave extraction. The results show that it is possible to accurately determine and possibly remove the contribution of this wave front in this experimental configuration.

Tue 12:00 Amphithéâtre Portier

New developments : Non linear ultrasound techniques

Development of nonlinear ultrasound approaches to fatigue damage diagnostics in bone

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It has recently been demonstrated that bone micro-damage has a strong influence on bone quality and fracture risk (1). However, in vivo micro-damage has remained relatively poorly documented due to the lack of non-invasive techniques for its assessment. The aim of this work is to develop a damage assessment technique that could be used in vivo. The presence of damage in solids can induce significant elastic wave distortion. Monitoring the distortion level shows that it increases with increasing damage quantity, as well as with dynamic wave amplitude. Simultaneously, the material experiences a nonlinear induced softening due to the interaction of the waves with the damaged regions. We are attempting to apply nonlinear dynamics to monitor and ultimately characterize bone damage in vivo. Toward that goal we have conducted a suite of experiments whereby we induce progressive damage in bone and study the simultaneous material softening that takes place, using the Nonlinear Resonant Ultrasound Spectroscopy (NRUS) technique (2). In our experiments, damage accumulation was progressively induced in samples of human femoral diaphysis by compressional fatigue cycling in a mechanical testing device. At various damage steps, a nonlinear elastic parameter that measures the material softening as a function of wave amplitude was extracted applying resonance methods. The nonlinear elastic parameter was compared to mechanical parameters such as the slope of the load/displacement curve and the amount of hysteresis exhibited by this curve, known as a good marker of damage. As the quantity of damage accumulation increased in bone, a good agreement was found between the nonlinear acoustic parameter and the amount of hysteresis, suggesting the ability of NRUS to characterize fatigue damage in human bone.
(1) Zioupos, P., Accumulation of in-vivo fatigue microdamage and its relation to biomechanical properties in ageing human cortical bone. J Microsc, 2001. 201(Pt 2): p. 270-8. (2) Muller, et al., Nonlinear resonant ultrasound spectroscopy (NRUS) applied to damage assessment in bone. J. Acoust. Soc. Am., 2005. 118(6): p. 3946.

Tue 12:15 Amphithéâtre Portier

New developments : Non linear ultrasound techniques

Characterization of trabecular bone with nonlinear techniques: preliminary results

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In the area of ultrasound osteodensitometry, we propose to use non linear acoustic waves coupling to characterize the trabecular bone. We present results obtained with two different techniques which use nonlinear effects. The first one is the so-called "vibroacoustography" method. In this method, we use an amplitude-modulated US beam (obtained with the simultaneous generation of two beams with slightly different frequencies) which induces an alternative second order radiation pressure in the focal zone of the transducer. In reaction to this vibrating stress, the bone structure generates a low frequency wave proportional to its rigidity, recorded by a sensible hydrophone. We present results on phosphocalcic ceramic samples (bone substitute of calcium hydroxyapatite) with different porosities and show that the vibroacoustography signal amplitude decreases with porosity (identical pore diameter). On calcaneus bone samples, we have scanned the same 1D line with different modulation frequencies, and we show resonances, i.e. a strong dependence of the vibroacoustography amplitude with frequency. Finally, we present images obtained with a 2D scan of the calcaneus bone for a fixed frequency and we compare our image with a classical BUA transmission image. For the second method, we use a technique called "parametric receiver" or phase modulation. It consists in spatially mixing two acoustic waves with very different frequencies, and perpendicularly. The higher one (the pump wave) is in the order of the Megahertz and the lower one (vibrator) is in the order of few hundreds of Hertz. The nonlinear interaction in the bone can be interpreted like a phase modulation of the pump wave with a modulation amplitude proportional to the nonlinear coefficient B/A, to the pump wave frequency, to the two waves interaction length and to the low frequency pressure amplitude. After verification in water, we present results obtained in ceramic samples. We confirm the dependence of the amplitude modulation with the pump wave frequency and with the amplitude of the low frequency pressure. Finally, we show the increase of the modulation amplitude with porosity.

Tue 14:00 Pavillon 1

Multiscale analysis of bone elasticity

The Relationship Between Acoustic Anisotropy and Crystal Orientation in Bovine Cortical Bone

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It is well known that bone tissue is composed of hydroxyapatite (HAp) like mineral particles and collagen matrix. We have tried to make clear the complicate anisotropy and elasticity distribution of cortical bone and their effects on velocity, considering microstructure and crystalline orientation. The objective of this presentation is to investigate the influence of crystallites orientation on acoustic anisotropy. In order to achieve the objective, we measured the distribution of ultrasonic velocity and X-ray diffraction profile in bovine cortical bone along three axes. 40 cube specimens of cortical bone were obtained from a whole cylindrical part of three bovine femurs. The longitudinal wave properties of the cortical bone were determined by a conventional pulse system, using self-made wide-band transducers. The measurement of ultrasonic velocity was achieved along three axes, axial, radial and tangential. The density of specimens was determined by Archimedes' principle. The obtained ultrasonic wave properties were discussed with the microscopic structure of the measured area. X-ray diffraction (XRD) measurements were performed using X-ray diffractometer (Rigaku, RINT2000). XRD patterns were obtained from three different sides of samples and powder of cortical bone as reference. In order to evaluate preference of c-axis of HAp crystals, the preference ratio was calculated by dividing the integral strength of (002) peak by that of (310) peak. Velocity was found to vary significantly due to the direction of propagation and the location of the measured specimens. The preference ratio of HAp c-axis was correlated with velocity in axial direction (plexiform: $R2 = 0.664$, $p< 0.001$, haversian: $R2 = 0.800$, $p<0.001$). The degree of preference ratio varied according to microstructure of the specimen. In some parts with plexiform structure, clear variation in velocity anisotropy was found, despite no significant difference in density and microstructure. The preference ratios of crystallites in the specimens were significantly varied and showed agreement with the velocity anisotropy in the tangential direction. As a result, acoustic anisotropy was influenced by not only microstructure but also crystallites orientation.

Tue 14:15 Pavillon 1

Multiscale analysis of bone elasticity

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Correlation between the Elastic Anisotropy of Human Cortical Bone Tissue and its Microstructure

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Thorough understanding of bone structure-property relationships is a key need to aid in orthopaedic implant design and in the development of new materials that can be used in the future as biomechanical analogs of bone. Work by previous researchers described bone as either transversely isotropic or orthotropic. Previous studies have also shown anatomic variation in elastic constants and elastic symmetry. The magnitudes of elastic constants have been compared to parameters such as apparent tissue density, BMD and porosity, with the strongest correlation occurring with apparent density. However, these relationships cannot account for the elastic anisotropy because apparent density is a scalar quantity. Therefore, the objective of this study was to measure anatomic variation in the elastic anisotropy of human cortical bone, demonstrate the limitations of apparent density correlations, and to establish a relationship between the elastic anisotropy of cortical bone tissue and its microstructure.
Ultrasonic wave propagation was used to measure stiffness coefficients for specimens sectioned along the length of five human femurs from donors that were 73 to 99 years old. The elastic constants were orthotropic and varied with anatomical location. Stiffness coefficients were generally largest at the diaphysis and stiffness anisotropy ratios were largest at the ephiphyses. Stiffness coefficients were shown to be correlated as a power law relation to apparent density, but anisotropy ratios were not.
X-Ray Diffraction (XRD) was employed as a texture analysis tool to measure the orientation distribution of the bone mineral crystals. Inverse pole figures showed that bone mineral crystals had a preferred crystallographic orientation, coincident with the long axis of the femur, which is its principal loading direction. The degree of preferred orientation was represented in Multiples of a Random Distribution (MRD), and found to be correlated to the anisotropy ratios. From this data, variation in elastic anisotropy was shown to be primarily due to the bone mineral orientation. The results found in this work can be used to incorporate anisotropy into structural analysis for bone as a material, and shows that bone mineral orientation is an important factor in the elastic anisotropy of human cortical bone. Our ongoing work includes more detailed XRD measurements of bone samples and improved correlations with anisotropy parameters.

Bone isotropic only in the middle shaft

Tue 14:30 Pavillon 1

Multiscale analysis of bone elasticity

Incomplete Ultrasound Measurements can Benefit from a Multiscale Model of Bone Elasticity to Retrieve the Elastic Stiffness Tensor

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Quantitative ultrasound QUS techniques around 1MHz are sensitive to bone elastic properties at the millimeter scale. If bone, at this scale, is assumed to be orthotropic or hexagonal, nine or five independent elastic coefficients, respectively, are required for a full characterization of material elasticity. Because of the limitations of in vivo measurements, QUS techniques cannot provide all of these coefficients. Hence the data available from experiments is incomplete. A model of bone tissue could be used to relate the measured data to the unknown coefficients, in order to obtain the full elastic description of a given bone. Explicit models based on the bone physical organization as well as phenomenological models are eligible for this purpose.
The presentation will detail a multiscale modeling strategy based on microscopic data and micromechanical equations. The procedure provides the linear anisotropic elastic parameters of bone at a scale of 1mm using a quantitative mapping of structural and elastic data at the microscopic level. The model capabilities will be illustrated for a set of cortical bone samples. Quantitative acoustic impedance images of eight transverse sections of radii obtained with 50-MHz scanning acoustic microscopy (SAM), were used. The resolution of the images is 23 μm. The measured acoustic impedance data were converted into elastic data at each point of the image. Between 50 and 60 square 1mm2 regions (virtual samples) were randomly selected and extracted from the impedance images of each cortical shell. A program was developed to compute the effective stiffness tensor of each virtual sample. The mechanical homogenization problems were solved using the finite element method. Assuming hexagonal symmetry, five engineering elastic constants of an equivalent homogeneous material were derived upon post-treatment of the effective computed stiffness tensors.
The model yields meaningful phenomenological laws between certain elastic coefficients. For instance, $G_{12} = 0.38E_1 - 0.014$ GPa ($R^2 = 0.99$); $G_{23} = 1.17G_{12} - 1.8$ Gpa($R^2 = 0.95$). In addition, the model provides laws for the dependence of the elastic coefficients on porosity and mean elastic value around the pores. Possible strategies for the validation of the model will also be discussed.

Tue 14:45 Pavillon 1

Multiscale analysis of bone elasticity

Multi-scale characterization and modelling of human cortical bone

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The objectives of the present study were 1) to investigate the influence of multiscale structural characteristics of the bone tissue on its mechanical behavior and 2) to perform a micro-macro numerical modelling based on the experimental data. This knowledge is of importance for the assessment of the impact of bone pathologies and their treatments on skeletal functionality. The study was based on mechanical, morphological and physico-chemical measurements on cortical bone samples exhibiting significant alteration of structural properties. The following technical protocol has been investigated on samples obtained from three human femurs (F1, F2, F3) with respective mean density 1892±29 kg/m3, 1608±275 kg/m3, 1221±161 kg/m3. At the organ level: Morphological and mechanical properties data were assessed using CT scans (GE, ZXi) and acoustic imaging transmission technique. At the tissue level : Elastic properties of the haversian system and osteon lamellae were investigated respectively by an ultrasonic transmission technique and nanoindentation technique. In parallel, morphological parameters such as microporosity of the samples were calculated from ESEM images and a custom made software. At the molecular level, physico-chemical analyses allowed to quantify the mineral and organic components of the samples of the three femurs. In order to correlate the mechanical and morphological properties assessed in different levels, a micro-macro model based on a variational approach and bounds methods was developed. At the organ level, CT and acoustic images provides similar heterogeneous distribution. The local variations exhibited by both data are related to cortical bone microporosity. The elastic moduli measured at the macroscopic level was respectively were 20±5 GPa (N=6). At the microstructural level of the same samples, axial elastic moduli of the interstitial lamella was found to be equal to 22±3. Axial elastic modulus for the white (N=61), grey (N=17) and dark osteons (N=39) were found to be statistically different ($p<0.05$) with respective values of 21.30 ± 3.00 GPa, 19.27 ± 1.78 GPa and 12.95 ± 2.66 GPa. The range of variation of elastic properties within the same osteon lamella is 0.2GPa to 8GPa (mean value of 2.6 ± 1.7). These data allowed the micro-macro model to be validated. It should be noted that variations of the elastic properties are higher (40%) at the microstructural level than those found at the macroscopic level (about 15%) for measurements performed in the same anatomical direction. Physico-chemical analyses found that organic components were found to be higher for femurs exhibiting lower mechanical properties. There is a consistency between changes observed at the different levels. These results contribute to a basic understanding of the multiscale mechanical behavior of human cortical bone.

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Multiscale analysis of bone elasticity

Macroscopic and Microscopic Mechanical Properties of Wistar Cortical Bone by Ultrasound and Nanoindentation Technique

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The mechanical properties of cortical bone are dependent on its complex multiscale structure and on the intrinsic properties of the collagen and apatite composite matrix. Our objective is to investigate the correlation between the macroscopic and the microscopic properties in cortical bone of Wistar rats. Femurs of six age class of Wistar rat (1, 4, 9, 12, 18 and 24 months-old) were harvested, cut transversally with a diamond saw and cleaned in saline solution. Bone densities were measured using a precision density measurement kit (Mettler Toledo GmbH, Greifensee, Switzerland) based on the Archimedes' principle. Bar velocities (Vbar) through samples were calculated in the longitudinal direction using ultrasound transducers at low frequency (100 Khz). Along with the bone density, ultrasound velocities were used to calculate the longitudinal Young's modulus (E3) of samples. After a polishing step of the upper transversal section, microscopic properties were investigated with a Nano indenter® XP (MTS System Corp., MN, USA) using a pyramidal Berckovich tip and the Continuous Stiffness Measurement (CSM) method. This method consist in performing a quasi-static loading/unloading with a constant displacement oscillation of the indenter (oscillation frequency: 45 Hz, oscillation amplitude 2 nm) along the indentation test and to calculate Young's modulus (E) and hardness (H) at every data point acquired during the indentation. Data were collected from 2000 nm to 3000 nm depth at a constant strain rate of 0.05 s-1. Macroscopic Young's modulus values vary with age from 8 to 19.8 GPa and are found to be lower than the microscopic values which vary from 20.2 to 29.5 GPa. Ratio between macroscopic and microscopic Young's modulus are found to be constant for 4, 9, 12 months old (about 1.5), and greater for 1, 18 and 24 months old rats (2.5, 1.7 and 2 respectively). It is interesting to observe that adult rat values for mechanical properties are similar to those found for human cortical bone (about 20 GPa and 27 GPa for macroscopic and microscopic Young's modulus respectively).

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Multiscale analysis of bone elasticity

Distribution Of Elasticity Tensor Of Human Cortical Bone Derived From Multimodal Imaging

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Mechanical and ultrasonic techniques allow to characterize the mechanical and acoustic properties of in vitro cortical bone, respectively. Imaging methods (micro CT, pQCT) provide structural information of bone. Multimodal fusions of different imaging technique are used for medical application. The aim of this study is to assess elasticity tensor distribution of human cortical bone sections from the fusion of acoustic and computed tomography imaging.
A cadaveric femur (male 70 years of age) was obtained from the anatomical laboratory of Hospital University of Amiens. The femur has been sectioned transversely with a low-speed diamond saw. Four cross sections were obtained with an average thickness of 2.09mm  0.27mm. Transmission ultrasonic technique have been used with immersion focused transducer at 5MHz. The cross sections have been laid down into a water container (T=20°C) and the transducer scans the surface of the sample. On each point of acquisition two acoustic echoes have been recorded. Then, with the time delay between the two different echoes and the thickness of the material, the longitudinal bulk velocities (V33(x,y)) on each point of acquisition have been calculated. All images have a pixel size of 0.5x0.5 mm^2 and a size of 71x71 pixels for cross section 4 and a size of 81x81 pixels for cross sections 1, 2 and 3. Spatial distribution of bone mineral density BMD(x,y) were computed from CT images obtained with a LightSpeed Ultra unit at 120 Kvp. All images are coded on 12 bits with a size of 512x512 pixels and a field of view of 96x96 mm^2.
To obtain elasticity tensor distribution (C33(x,y)) of cross femoral section, a data fusion was performed between acoustic velocity and BMD images. This method involves a prior registration step between images. A fully automatic two step registration process is proposed using principal axes transformation and spatial domain cross-correlation. The registration step was applied on segmented acoustic and BMD images. Hence, data fusion is performed.
Four elasticity tensor maps were obtained. Tensor elasticity values are more important in the periosteal compared to the endosteal region. Posterior area showed lowers values than in the anterior, medial and lateral area. A strong correlation (R2 = 0.95) between the elastic and structural properties was found for the 4 sections. Moreover, the linear correlation found between C33 and BMD showed the influence of the structural properties on the mechanical ones.

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Multiscale analysis of bone elasticity

Determination of Transverse Isotropic Stiffness Coefficients from High Resolution Angular Acoustic Impedance Measurements

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Assessment of anisotropic elastic properties at the tissue level is still one of the major challenges in bone research. In previous studies bone sections were cut in different directions relative to a principle axis of symmetry. This causes a high preparation and measurement effort. We have developed a new acoustic scanning procedure, that allows to measure the angular dependence of the acoustic impedance of cylindrically shaped samples (diameter: 4 mm) with a single measurement. Therefore our scanning acoustic microscope (SAM200EX, Q-BAM, Halle) was equipped with a rotational stage and a scanning procedure was developed that measures the surface reflection of the rotating cylinder. It has been shown in a previous study that the acoustic impedance derived from the reflection coefficient is highly correlated with the elastic coefficient in the probing direction (Raum et al., 2006). This correlation was used to convert $Z(\theta)$ to $c(\theta)$. c11, c33, and c* = c13 + 2c44 were determined by fitting c() to an orthotropic material model. A continuum micro-mechanical open foam model (Hellmich and Ulm, 2002) finally reveals the remaining elastic constants. This method was applied to the inspection of one human femur. The shaft was divided into 16 sections. From each section 4 cylinders were prepared from the anterior, posterior, medial and lateral regions. The long axis of the cylinder was always in the radial direction. The measurements were performed with a 50 MHz transducer, providing a lateral resolution of 23 μm. N - way ANOVA of the acoustic impedance with anatomical (A, P, M, L) and shaft positions as categorical factors showed that both factors contribute significantly to the variance of Z. The means and standard deviations of the derived elastic coefficients are: c33 = 32.6 ± 4.18 GPa, c11 = 28.5 ± 13.8 GPa, c12 = 6.03 ± 0.78 GPa, c13 = 7.57 ± 1.24 GPa, c44 = 10.56 ± 1.32 GPa, and c66 = 10.36 ± 1.29 GPa. The correlation coefficients between the coefficients range from R^2 = 0.7 - 0.9.

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Multiscale analysis of bone elasticity

Cancellous fracture toughness and compressive properties at the head of the femur vs peripheral quantitative ultrasound measurements

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Peripheral quantitative ultrasound (QUS) has been used to predict the risk of fracture and to non-invasively assess the biomechanical properties of human bone. The best invasive vs. non-invasive correlations are obtained when mechanical tests are compared vs. contact QUS on excised samples in-vitro. A few studies attempted to relate non-invasive peripheral QUS values on cadavers against excised material of the same donors at the scan site, but not to the material of a remote site and for scanning performed in-vivo. The aim of this study was to correlate QUS values taken in-vivo at various peripheral sites to the biomechanical properties of the cancellous bone of the femoral head of the same individuals. It was also hypothesised that the abilities of QUS may extend to the prediction of both the fracture mechanics (FM) and compressive properties of the axial skeleton. Twenty individuals who suffered a fractured neck of femur, were scanned in the radius, the phalanx, the tibia and the calcaneus by using two commercially available QUS systems: the Sunlight Omnisence (Sunlight, Rehovot, Israel) and the CUBA Clinical (McCue, Soton, UK). All clinical measurements were taken by one experienced operator and within 48 hours of the fracture incident. After the operation cancellous tissue was analysed for its mechanical properties by compression testing of cylindrical specimens (elastic modulus, compressive strength, yield properties, energy to failure), fracture mechanics tests (KC, GC, J-integral) and structural properties (apparent density, porosity). A number of significant correlations existed between the QUS data and biomechanical properties. BUA and VOS by the CUBA Clinical, for instance, gave R^2 values ranging between 0.44 and 0.56 for the compressive properties and R^2 in the range of 0.77-0.89 for the FM parameters. For FM data the correlations were stronger for samples tested across the trabecular structure than along it. The correlations between QUS and apparent density had R^2 values in the range of 0.47 and 0.63. The K, G and J-integral of cancellous bone depended on 'direction', but also primarily on the apparent density of the sample to a power function of between 1 and 2, with an average value of 1.5 in accordance with models for cellular solids. These promising results show that scanning remote sites (radius, tibia, phalanx, calcaneus) to the mechanically tested site (head of femur) still provides meaningful data for the biomechanical competence of the cancellous bone material. In addition to QUS being able to reflect density changes, the present tests provided documented evidence on its ability to predict not simply the compressive but also the FM properties of the tissue.

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