Quantitative scanning acoustic microscopy: methods and applications in medicine

Kay Raum[1], Jörg Brandt[2], Silke Gudziol[3], Albrecht Klemenz[1], Ludger Smitmans[2], Christian Schwinger[4], Klaus-Vitold Jenderka[1]
[1]Institute of Medical Physics and Biophysics, [2]Orthopeadical Clinic, [3]Department of Otolaryngology, Head and Neck Surgery, [4]Institute of Bioengineering, Martin Luther University of Halle, Germany

Abstract - The capabilities of quantitative acoustic microscopy will be demonstrated by a number of different applications. Results show: the determination of elastic constants from acoustic quantities at a mesoscopic scale, the correlation between acoustic and elastic quantities in bone; the anisotropy, age and gender dependence of the acoustic impedance in human cortical bone at the microscopic scale; high resolution patchwork impedance maps of auditory ossicles and microscopic 3D reconstructions of the topography and reflectivity of cortical bone and alginate spheres.

I. Introduction

Pulse-echo scanning acoustic microscopy (SAM) is referred to systems, were very high frequency acoustic waves are focused on a material and images are generated from the reflected signals. In order to achieve a high spatial resolution, usually spherically focused acoustic lenses with high apertures are applied. However, the spatial and temporal characteristics of curved wave fronts have to be considered, when a quantitative evaluation is desired. Refraction and mode conversions result in complex reflection and transmission characteristics (Figure 1). Only in the focal plane all parts of the incident wave front are in phase and the assumption of plane wave propagation is valid. In this case the reflection of the incident wave front is described by:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \qquad (1)$$

where R is the reflection coefficient, Z_1 is the acoustic impedance of the coupling fluid and Z_2 is the acoustic impedance of the solid, respectively. The impedance is defined as the product of mass density ρ and longitudinal wave velocity v_l. In isotropic materials the elastic constants c_{11} and c_{44} are related to the longitudinal and transverse sound velocities:

$$c_{11} = \rho v_l^2 = Z_l v_l, \qquad (2)$$

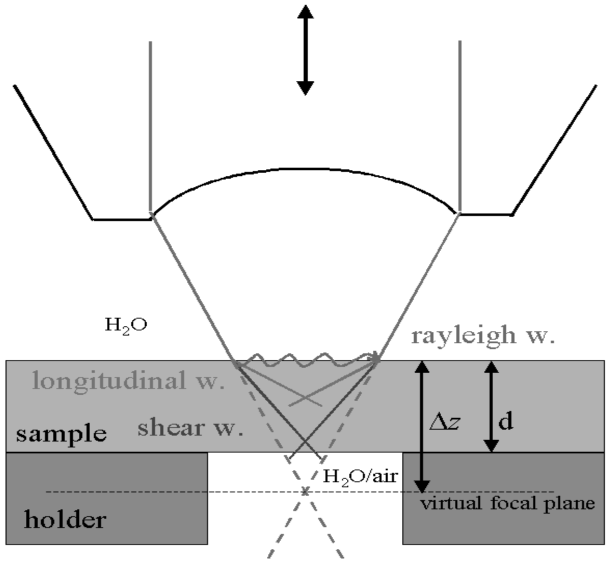

Figure 1: Transmission and reflection at a fluid -solid interface at oblique incidence.

$$c_{44} = \rho v_s^2. \qquad (3)$$

If the material is anisotropic, the longitudinal velocities depend on the propagation direction relative to the axes of symmetry, as described elsewhere [1].

II. Hardware

Two scanning acoustic microscopes were used: The first one is custom made and works the frequency range up to 250 MHz for time-resolved analysis of acoustic impedance, longitudinal and shear wave velocities. The second microscope is a KSI SAM 2000 (Krämer Scientific Instruments, Herborn, Germany), which covers the frequency range from 100 MHz up to 2 GHz and is used for very high resolution topography and acoustic impedance mapping. Custom hardware and software (ELIPS) was developed, which provides full access to RF-circuit settings and controls the mechanical scanner together with precise z-stage positioning. Special software, based on Matlab, was developed for the data analysis.

III. DETERMINATION OF ELASTIC CONSTANTS

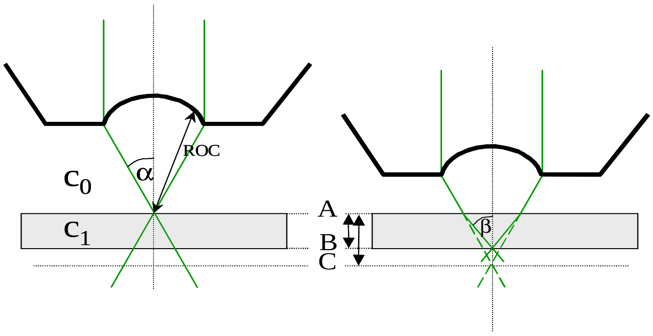

Figure 2: The transducer is moved towards the sample in order to focus on the front or on the back surface.

For the determination of the elastic constants the longitudinal and transverse sound velocities have to be measured. This can be done in thin samples by recording the pulse echo signal, while the transducer is moved towards the sample. From the amplitudes of the echoes of the front and back surfaces their focal positions and the corresponding times of flight are obtained. A special data analysis procedure was developed, which takes into account the transducer aperture, spherical aberration and the effects caused by the angular dependent transmission of energy into the sample, when the speed of sound in the sample is much higher than the sound velocity in the coupling fluid. No additional parameters are required for the determination of the elastic constants, since the thickness of the sample is directly obtained from the measurement and the density is derived from via equation (2). The method was verified using materials with known elastic properties. The accuracy is better than 1 percent for all parameters. A significant correlation between the acoustic impedance and the elastic constant c_{11} was found in cortical bone.

IV. V(Z)-BASED IMAGING

Very high frequency microscopes work with narrow band or burst pulses and amplitude detection. The lateral resolution is comparable to that of light microscopy (e.g. 0.5 µm at 2 GHz). However, since the depth of focus also decreases at higher frequencies, imperfections in the flatness of the sample surface have a dominant influence on the image contrast. A *Multi Layer Analysis* [2] technique was developed, which precisely separates topographical from acoustical influences on the image contrast. Therefore a quantitative

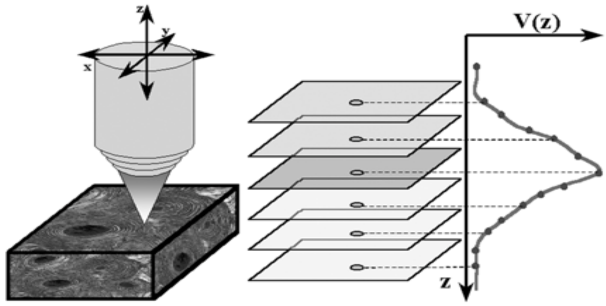

Figure 3: A set of C-scan images is acquired for a MLA. From the 3D data set the focus position and amplitude can be reconstructed for each scanned surface point.

evaluation of biological hard materials, such as bone, cartilage or auditory ossicles is possible [3-5]. Figure 4 shows an example of a measurement of an osteon.

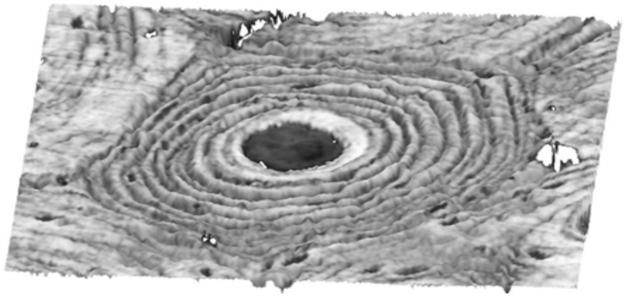

Figure 4: 3D reconstruction of the reflectivity of an osteon.

REFERENCES

[1] J.-Y. Rho, "An ultrasonic method for measuring the elastic properties of human tibial cortical and cancellous bone," *Ultrasonics*, vol. 34, pp. 777-783, 1996.

[2] K. Raum, J. Brandt, A. Klemenz, and U. Cobet , "Quantitative Ultraschallrastermikroskopie zur Bestimmung der akustischen Impedanz von kortikalem Knochengewebe," *Z. f. Med. Physik*, vol. 9, pp. 246-253, 1999.

[3] S. Gudziol, E. J. Haberland, J. Brandt, A. Klemenz, K. Raum, and A. Berghaus, "Scanning acoustic microscopy of the human auditory ossicles," *Laryngo-Rhino-Otology*, vol. Suppl. 1, pp. 96, 2000.

[4] E. J. Haberland, S. Gudziol, A. Klemenz, K. Raum, J. Brandt, and P. Mir-Salim, "High-frequency scanning acoustic microscopy in middle ear research," *Laryngo-Rhino-Otology*, vol. 79, pp. 98, 2000.

[5] L. Smitmans, K. Raum, J. Brandt, and A. Klemenz, "Variations in the microstructural acousto-mechanical properties of cortical bone revealed by a quantitative acoustic microscopy study," in *Proc. IEEE Ultrason. Symp.*, 2001, pp. 1379-1382.