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# Bone Ultrasound
超音波と骨，その関わり

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## 1. Introduction

The first step in the evaluation of anisotropic and heterogeneous bone via ultrasound was achieved by Langton et al., who discovered that the transmission of ultrasound through the heel could discriminate between women with versus without osteoporosis[1)]. Since then, various techniques to characterize bone at different sites have been introduced[2)]. Several ultrasound apparatuses have been approved by the FDA, and have provided evidence that ultrasound transmission is a valid, radiation-free, inexpensive method for detecting fractures. Japan is one of the most advanced countries regarding ultrasonic diagnostic technology for bones, referred to as quantitative ultrasound (QUS), and QUS is commonly used to evaluate the heel during annual health checks in Japan. The QUS standardization committee of the Japan Osteoporosis Society has made the first attempt at standardization of QUS results for the heel[3)].

This paper describes the recent developments in QUS and other ultrasonic studies on bone. Bone ultrasound shows similar trends to other ultrasonic clinical studies regarding diagnosis and therapeutic assessment.

## 2. Bone characterization

Bone is composed of two main structures: outer cortical (or compact) bone, and inner cancellous (or trabecular) bone filled with bone marrow; it also has a hierarchical structure that extends over several organization levels. The bone matrix is a composite material containing about 70% mineral (hydroxyapatite), 22% protein (type I collagen), and 8% water by weight. In the midshaft of long bones (such as the radius and tibia), cortical bone shows almost uniaxial elasticity, with the highest elasticity in the direction of the bone axis. The trabeculae in cancellous bone roughly align along the direction of stresses, and decrease rapidly as osteoporosis progresses. Cancellous bone changes are an early indicator of osteoporosis[2)].

Ultrasonic evaluation of bone provides the longitudinal wave velocities and attenuation, which reflect the characteristics of both the bone structure and bone matrices. The wave velocities show strong heterogeneity in the measured areas[2)]. The microscopic elasticity of bone has been evaluated *in vitro* via acoustic microscopy[4, 5)]. In addition, the micro Brillouin scattering technique has been used to determine that the wave velocities in the minute area of cancellous bone depend on the trabecular structure and alignment direction[6)]; this technique has also been applied to evaluate the elasticity of bones in diabetic patients[7)]. Bernard et al. were the first to use resonant ultrasound spectroscopy to evaluate cortical bone in the tibia by using the Bayesian technique to evaluate the anisotropic elasticity[8)].

In addition to osteoporosis, endocrine diseases like diabetes mellitus have detrimental effects on bone. These diseases mostly result in the degradation of collagen, which cannot be checked by the bone mineral measurements in conventional radiography techniques. Thus, ultrasonic bone characterization is expected to be a useful tool with which to evaluate the viscoelasticity of bone in patients with endocrine diseases.

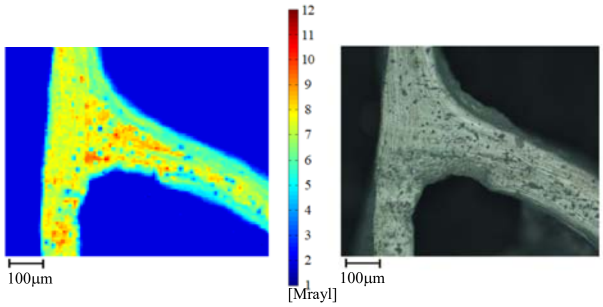


Fig. 1 Acoustic impedance mapping (acoustic microscopy, 200 MHz) and optical image of a bovine trabecula.

Since the initial mechanical study by Fukada and Yasuda in the 1950s[9)], there has been a lot of discussion on the mechanism of the piezoelectricity in bone. Okino et al. used the “bone ultrasound transducer” to prove that the bone can sense ultrasound in the MHz range[10)]. The piezoelectricity of bone is very small and is considered to result from the collagen. Ikushima et al. then successfully observed the acoustically stimulated electromagnetic wave from bone and introduced non-contact bone evaluation[11)]. The piezoelectricity may play an important role in ultrasonic bone fracture healing, where the mechano-sensing system of cells cannot be expected. As Padilla et al. have discussed, ultrasonic bone fracture healing is now a common technique in the area of orthopedics[12)].

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## 3. Novel *in vivo* QUS techniques

Various *in vivo* techniques involving QUS in the MHz range have been developed to evaluate different sites with the help of bone phantoms[13]. The new pass-through airborne ultrasound shows future possibility of non-contact measurement[14]. The present main measurement techniques are focusing the cortical and cancellous parts.

The axial transmission (AT) technique measures the first arriving signal (FAS) or Lamb waves using the time-of-flight techniques with linear array transducers (Fig. 2). Talmant et al. first used this AT technique in the *in vivo* evaluation of cortical bone in the radius, showing the dependence of FAS velocity on age, and a decrease in velocity in postmenopausal women[15]. A unique AT apparatus for tibial measurements has also been reported in Japan[16].

Fig. 2 The axial transmission device (left, France) and the two-wave apparatus LD-100 (right, Japan) for the radius[15, 18].

Recently, a Japanese technique has been developed based on the characteristic wave propagation phenomenon in cancellous bone. In 1997, Hosokawa and Otani first experimentally confirmed two longitudinal wave propagation in bovine cancellous bone[17], which has since been observed in human cancellous bone. The detailed characteristics of these two waves have been thoroughly investigated regarding bone density, trabecular structure, and anisotropy. The studies resulted in the development of a novel ultrasonic apparatus for measurement of the radius (approved as a medical device in Japan), which can estimate the trabecular bone density and cortical thickness, as well as the trabecular elasticity[18] (Figs. 2 and 3). Regarding cancellous bone evaluation, Wear also introduced a back-scattering technique[19].

## 4. In the future

Bone ultrasound studies have been performed by a strong collaboration between clinicians and physicians; however, there is still debate regarding the value of X-ray studies, which are currently considered the mainstay of bone evaluation. In 2017, the International Society of Bone Ultrasound was established, comprising a collaboration of researchers in Europe, Asia, and the USA. We hope for a new stage of bone ultrasound studies with Japanese and international colleagues in the near future.

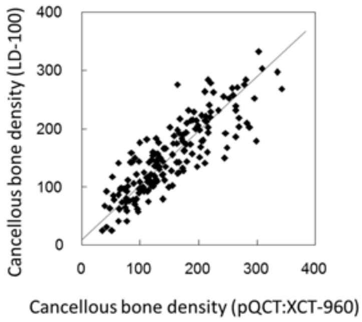


Fig. 3 The site matched cancellous bone density measured by the two-wave apparatus (LD-100) shows a strong correlation with X-ray CT measurement (pQCT).

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