Ultrasonics 54 (2014) 1245–1250

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Two-wave behavior under various conditions of transition area from cancellous bone to cortical bone

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ARTICLE INFO

Article history:
Available online 12 November 2013

Keywords:
Cancellous bone
Two-wave phenomenon
FDTD simulation

ABSTRACT

The two-wave phenomenon, the wave separation of a single ultrasonic pulse in cancellous bone, is expected to be a useful tool for the diagnosis of osteoporosis. However, because actual bone has a complicated structure, precise studies on the effect of transition conditions between cortical and cancellous parts are required. This study investigated how the transition condition influenced the two-wave generation using three-dimensional X-ray CT images of an equine radius and a three-dimensional simulation technique. As a result, any changes in the boundary between cortical part and trabecular part, which gives the actual complex structure of bone, did not eliminate the generation of either the primary wave or the secondary wave at least in the condition of clear trabecular alignment. The results led us to the possibility of using the two-wave phenomenon in a diagnostic system for osteoporosis in cases of a complex boundary.

1. Background

In porous media, propagation of two kinds of compressional wave, called the *two-wave phenomenon*, has been reported [1–4]. Since the wave separation behavior of a single ultrasonic pulse in cancellous bone was first reported by Hosokawa and Otani [5], this phenomenon has been considered a useful tool for the diagnosis of osteoporosis. The two waves propagate mainly in solid portion or liquid portion respectively; thus, the received wave contains information of their respective propagation media in addition to that obtained by the conventional speed of sound (SOS)/broadband ultrasound attenuation (BUA) method [5–7]. Because cancellous bone has a complicated porous structure, the detailed behavior of ultrasound in cancellous bone, including the effect of structural anisotropy, has been investigated [8–11]. Supporting these experimental studies, a simulation technique making use of the actual bone structure revealed the mechanism of the two-wave phenomenon [9,12–17].

In the *in vivo* assessment of bone, cancellous bone is always surrounded by cortical bone. Typically, the transition region between cortical part and trabecular part is not sharp [18,19]. Valentinitsch et al. assessed the spatial distribution and connectivity of different regions of human distal radius [19]. Around the transition region, the bone volume fraction gradually decreases from the cortical side to the trabecular side, and it is mostly difficult to decide a clear border line. In previous studies, some simple methods to separate the cortical part and the trabecular part using CT or MR images were proposed [20,21].

Although the influence of the transition region is not negligible for the use *in vivo* measurement because the ultrasonic wave propagation in the transition region is considered to be very complicated, few quantitative evaluations of geometrical properties of the transition region was reported and only a few investigations using the specimen sealed by cortical bone have been performed [22–24]. Some studies have claimed that the two waves were rarely detected in the case of sealed pores. However we have found that the two-wave phenomenon occurs under artificial closed pore conditions in a comparative study of simulation and experimental measurements using a single specimen, suggesting that the sharp transition at the boundary did not cause extinction of the slow wave [25,26]. In addition, Hosokawa et al. showed that the transition condition between the cancellous and cortical bone regions affect both the fast and slow waves [27]. Because Hosokawa et al. investigated the wave propagation using simplified geometrical models of bone, more precise studies on the effect of gradual transition using more realistic bone models are required for a detailed understanding of the two-wave phenomenon. In this study, therefore, using three dimensional X-ray CT images of actual trabecular bone specimen, we investigated the effects of the transition

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0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.10.016

condition between cortical and cancellous parts by simulating the detailed wave propagation in the model.

2. Materials and methods

This study used the same cancellous bone, obtained from the distal part of the left radius of a racehorse, as was used in a recent study [26]. The bone volume fraction (BV/TV) of the equine bone sample was similar with human bone, however, the degree of anisotropy (DA) was higher than that of human bone [7,26]. The high DA values result in clear two wave separation. It helps us to investigate the effects of transition conditions on the two wave behavior. In the simulation part of the study, the boundaries were sealed with cortical bone plates. The size of the ROI (region of interest) of the specimen was $15 \times 15 \times 13\ mm^3$, and the thicknesses of the plate-like cortical bones were set to 2.0 mm [28,29]. The spatial resolution of the 3-D computed tomography (CT) images was 48.0 μm, and the size of simulation field was

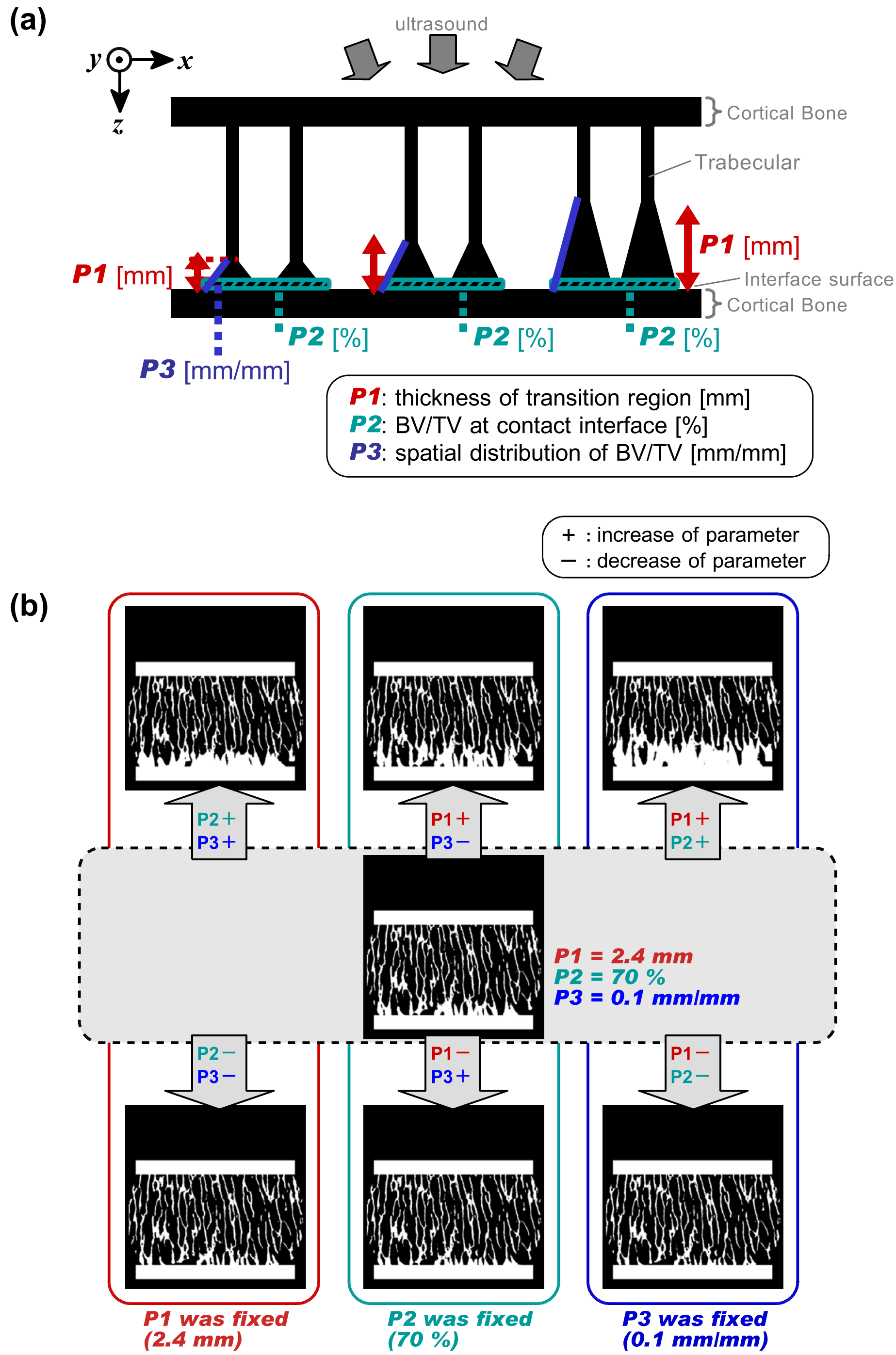

Fig. 1. (a) The three parameters used to define changes in the transition condition between cortical and cancellous parts. The black portion in the figure indicates the trabeculae and cortical parts. The incident wave is transmitted from the top area. (b) Example of the effect of the each parameter P1, P2, and P3. The figures show the cross-section diagrams of the models when P1, P2, and P3 were fixed at certain values, respectively.