Three-dimensional Bone Shape Sonography System Aided by Fuzzy Logic

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Abstract

This paper describes a sonography system that enables us to recognize three-dimensional (3D) bone shape by using ultrasonic technique. Conventional ultrasonic technique can visualize soft tissue of human body (e.g. heart and liver). However, it cannot apply to hard tissue (i.e. bone) because of the difficulty in inserting the ultrasonic wave to the bone caused by significant attenuation of the ultrasonic wave in it. To overcome this problem, we employ fuzzy logic, which can deal with ambiguous information. This method consists of two stages. First, a degree of bone surface is calculated from knowledge of bone surface. Second, a degree of bone bottom is calculated from knowledge of bone bottom. This method could visualize 3D bone shape by using each degree based on fuzzy logic. It applied to artificial bones. As a result, the error of the determined thickness was less than approximately 1.0 mm.

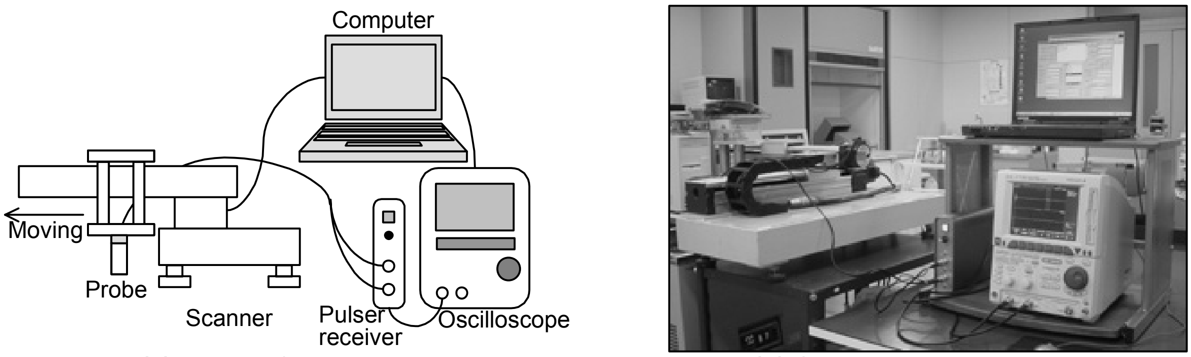
1. Introduction

For diagnosing and curing fracture or osteoarthritis, information of bone shape is essential to check the current state of human bone. X-ray Computed Tomography (CT) scanners are widely used for visualizing bone shape. CT systems cannot visualize bone shape in real time, and it requires high cost and large equipment, in comparison with ultrasonic systems. In addition, bone shape visualizing system in real time is required because physician would like to understand bone shapes on operation table, especially, under orthopedic surgery such as total knee arthroplasty and intramedullary nail locking.

Ultrasonic technique is well known for real time visualizing technique. The ultrasonic technique is used in many fields (e.g. diagnostic technique [1]-[3] and non-destructive evaluation [4]) due to its low cost and non-invasiveness. Moreover, ultrasonic technique helps us to diagnose the human body. However, since a bone is layer structure constructed of the cortical bone, the cancellous bone, and so on, the ultrasonic wave is significantly attenuated in bone tissue. Several researchers studied about visualizing bone tissue using ultrasonic technique [5][6]. However, because of pulse transit-time method or fixed specific region, it was not enough to visualize bone shapes. Development of pulse echo ultrasonic techniques that propagates bone tissue enables us to visualize bone shapes in real time.

Fuzzy logic [7][8] provides a high robustness scheme to control or manipulate ambiguous information. Especially, fuzzy inference technique is employed for various medical fields, such as image processing [9][10] and signal processing [1][3]. This paper therefore employs fuzzy inference technique to develop the sonography system.

The developed ultrasonic system consists of a composite probe whose center frequency is 1 MHz. The ultrasonic wave with frequency of 1 MHz penetrates bone practically. The system acquires several A-scope waves by moving the probe using a scanner. These A-scope waves comprise three-dimensional (3D) ultrasonic data. These waves have characteristics of the ultrasonic wave such as amplitude and frequency. This paper aims to determine surface and bottom points of a bone. We realize the bone sonography system that consists of two stages by considering these characteristics on fuzzy logic. First, we determine bone surface from the degrees of the surface echo. Second, we determine bone bottom from degrees of the bottom echo. We applied our method to artificial bones. As a result, the error of the determined thickness was less than 1.0 mm.



(a) Model of our method **(b) Our development system**

Figure 1. Ultrasonic data acquisition system.

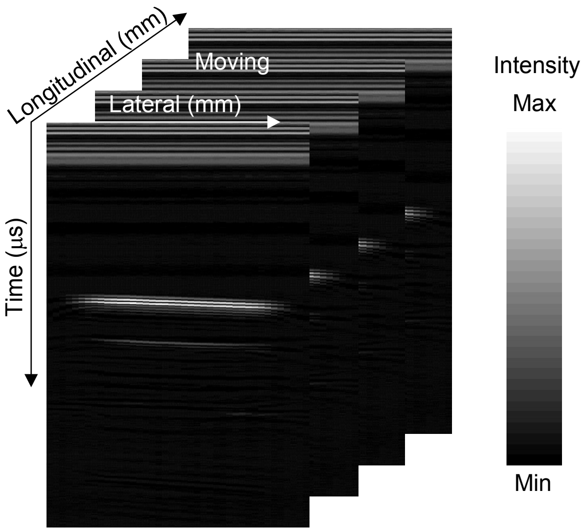


Figure 2. Ultrasonic data.

2. Preliminaries

2.1 Ultrasonic data acquisition system

Figure 1 shows an overview of the developed ultrasonic data acquisition system. We use a low frequency probe (KGK, 1K14I/6I-F20) whose center frequency is 1 MHz. This probe is a doughnut-type probe that means to be arranged (a transmit probe and a receive probe) in concentric circle shape. In this experiment, the outside probe transmits ultrasonic waves, and the inside probe receives it. The ultrasonic pulser receiver (New Sensor Inc., NSI-PR2000L) transmits and receives ultrasonic waves via this probe. The oscilloscope (Yokogawa Electric Corp., DL1720) obtains A-scope waves that are displayed as amplitude value vs. propagation time. By moving the probe using a scanner, A-scope waves at several lateral and longitudinal locations are obtained. These waves convert into 3D ultrasonic data (shown in Figure 2). The scanner and the oscilloscope are handled using a personal computer. The sampling interval of data is 10 ns. In our experiment, the ultrasonic data is obtained in a thermostat water bath (Thomas Kagaku Co. Ltd., T-22L) that keeps the target at a fixed temperature of 20 degrees Celsius.

2.2 Characteristics used in our method

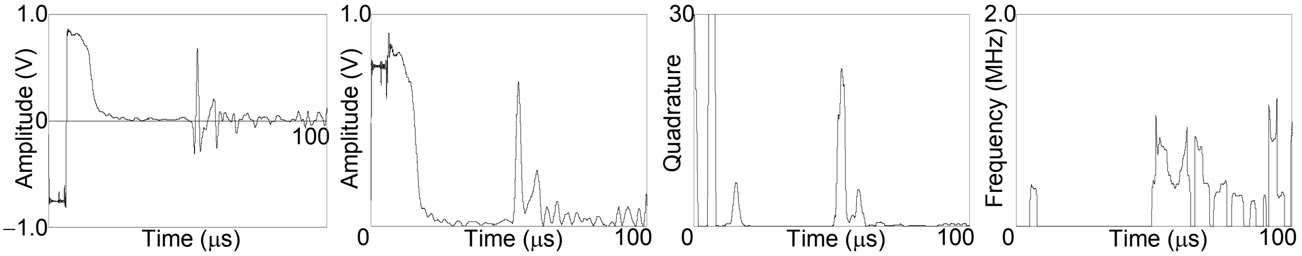
We focus on four characteristics (i.e. *Amplitude*, *Quadrature*, *Frequency*, and *Distance* between bone surface and bottom) with respect to the ultrasonic wave in our method.

First, *Amplitude* indicates ultrasonic wave power. In general, ultrasonic wave oscillates between a positive value and a negative value. Since, we need to deal with ultrasonic wave power, we do rectifying ultrasonic waves and smoothing them.

Second, *Quadrature* indicates ultrasonic wave spectrum for a frequency. When $y(t) = A\sin(\omega t + \theta)$ is given as a wave, *Quadrature* is calculated by following equation. The sine component of the wave S is calculated by Equation (6).

$$\begin{aligned} S &= \int_0^T y(t)\sin(\omega t)dt \\ &= \int_0^T A\sin(\omega t+\theta)\sin(\omega t)dt \\ &= A\int_0^T \{\sin(\omega t)\cos\theta + \cos(\omega t)\sin\theta\}\sin(\omega t)dt \\ &= A\cos\theta\int_0^T \sin^2(\omega t)dt + A\sin\theta\int_0^T \sin(\omega t)\cos(\omega t)dt \\ &= \frac{A}{2}\cos\theta \end{aligned} \tag{6}$$

The cosine component of the wave C is calculated by Equation (7).



(a) Raw wave **(b) *Amplitude*** **(c) *Quadrature*** **(d) *Frequency***

Figure 3. Characteristics of ultrasonic wave.

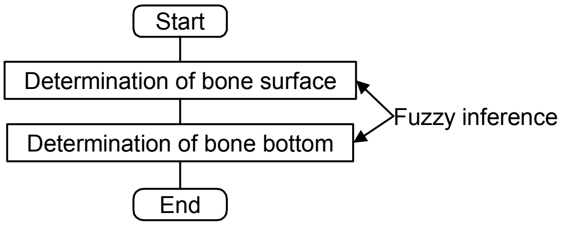


Figure 4. Procedure of our method.

$$\begin{aligned} C &= \int_0^T y(t)\cos(\omega t)dt \\ &= \frac{A}{2}\sin\theta \end{aligned} \tag{7}$$

Consequently, *Quadrature* is calculated by Equation (8).

$$A = 4(S^2 + C^2) \tag{8}$$

Third, generally, the ultrasonic wave has fixed frequency range. The fixed frequency is calculated from spectrum of the echo. Peak spectrum indicates the highest power for a frequency. In this paper, frequency with the highest peak magnitude is called by *Frequency*.

Finally, all materials have distance between surface and bottom. The ultrasonic wave is reflected from surface and bottom of the material. *Distance* is calculated from both acoustic velocity in the material and time lag between surface and bottom echoes.

Example of raw wave data is shown in Figure 3(a). These *Amplitude*, *Quadrature*, and *Frequency* are shown in Figures 3(b), (c), and (d), respectively.

3. Bone shape visualization

3.1 Bone shape visualization method

We employ fuzzy logic technique to determine bone surface and bottom. Fuzzy logic proposed by Zadeh facilitates us to handle uncertain and imprecise information. Our method employs fuzzy knowledge derived from characteristics of echoes. Figure 4 shows the procedure of this method. This method consists of two stages. First stage determines bone surface from the degrees of the surface echo at each measured point. Second stage determines bone bottom from degrees of the bottom echo at the each point. On the basis of determined bone surface and bottom, the 3D bone shape is visualized. The detail of each process is described in the following section.

3.2 Bone surface determination

First, bone surface is determined. Bone has high acoustic impedance compared with other region of body. The echo from the bone is higher amplitude value than other echoes, i.e. higher amplitude value is the echo from the bone. Moreover, because no region of body has high attenuation except for bone, peak frequency of the echo from the bone is close to center frequency of the probe. From these facts, we can obtain three knowledge as follows,

Knowledge 1: Higher amplitude implies the higher degree of bone surface,

Knowledge 2: Higher quadrature implies the higher degree of bone surface, and

Knowledge 3: The peak frequency of bone surface is close to center frequency of the probe.

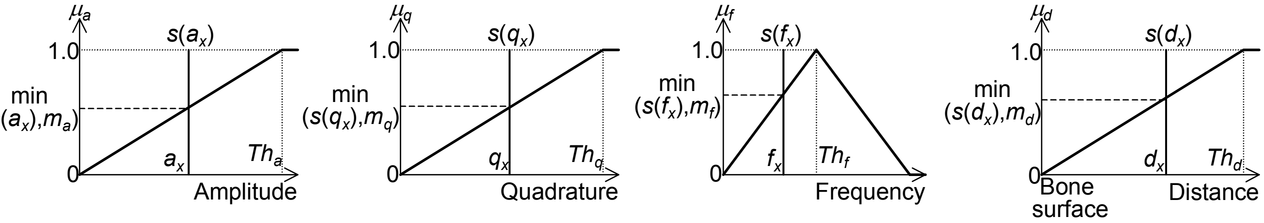
The following fuzzy if-then rules are derived from these knowledge,

Rule 1: IF *Amplitude* is high, THEN degree of bone surface is *High*,

Rule 2: IF *Quadrature* is high, THEN degree of bone surface is *High*, and

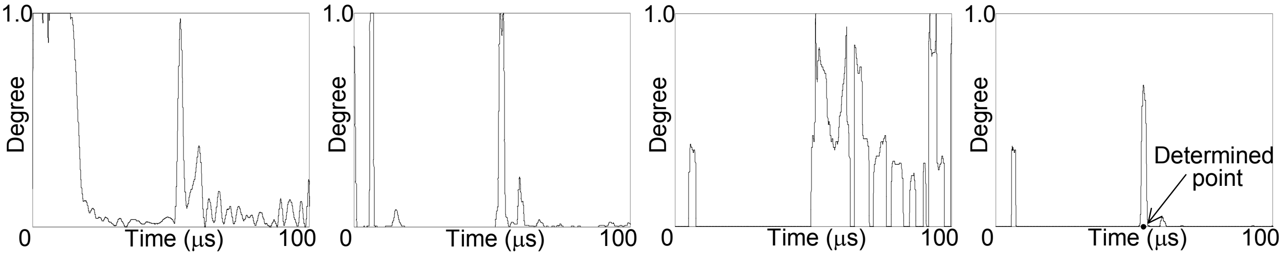
Rule 3: IF *Frequency* is close to center frequency of the probe, THEN degree of bone surface is *High*.

These knowledge can be usually translated to a fuzzy inference mechanism by min-max-center-of-gravity method. However, in this case, simple fuzzy calculation using membership functions is enough to manipulate it. The membership functions are shown in Figure 5, where Th_a and Th_q, are thresholds of *Amplitude* and *Quadrature*, respectively. They are determined by target region,



(a) ***Amplitude*** (b) ***Quadrature*** (c) ***Frequency*** (d) ***Distance***

Figure 5. Membership functions.



(a) ***Amplitude*** (b) ***Quadrature*** (c) ***Frequency*** (d) **Total**

Figure 6. Fuzzy degrees of surface.

ultrasonic wave power, and so on. Th_p is a threshold of *Frequency*, which is determined by center frequency of the probe. The total degree $\mu_s(x)$ of a point x (= a_x, q_x, f_x) is calculated by arithmetic product of three degrees as follows,

$$\mu_s(x) = \min(s(a_x),\mu_a) \times \min(s(q_x),\mu_q) \times \min(s(f_x),\mu_f) \quad (9)$$

where $s(a)$ is a singleton function: $s(a)=1$ if $x=a$; $s(a)=0$ otherwise. The $\mu_s(x)$ expresses the fuzzy membership degree of bone surface The point with the highest degree is determined as bone surface.

[Example 1] Bone Surface Determination: Consider the raw wave data in Figure 3(a). Three fuzzy degrees, *Amplitude*, *Quadrature*, and *Frequency* are calculated and are shown in Figures 6(a), (b), and (c), respectively. Here, in *Quadrature* and *Frequency* parameter, we use center frequency of the probe for ω and Th_f. In *Amplitude* and *Quadrature* parameter, Th_a and Th_q are determined the probe characteristics. From these three degrees, the total degree of bone surface $\mu_s(x)$ is calculated by Equation (6). This result is shown in Figure 6(d).

[End of example]

3.3 Bone bottom determination

In case of heterogeneous materials such as bone, the ultrasonic wave is almost attenuated in regard of amplitude and frequency. The echo from bone bottom is low amplitude and low frequency in comparison with the echo from bone surface. A bone has almost fixed distance between bone surface and bottom at several regions. From these facts, we can obtain knowledge 4,

Knowledge 4: Bone bottom is not close to bone surface.

The following fuzzy if-then rules are derived from this knowledge,

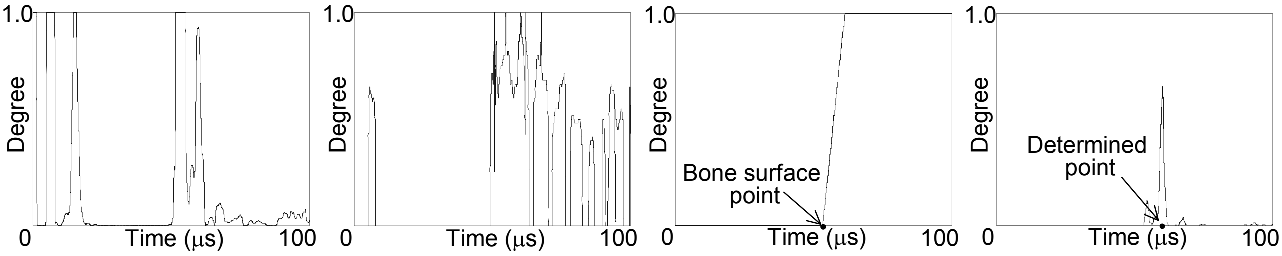
Rule 4: IF *Distance* between bone surface and bottom is not small, THEN degree of bone bottom is *High*.

In the similar way in bone surface determination, the membership functions are shown in Figure 5, where Th_d is a threshold of *Distance*. Rule 4 plays a role to divide the region into bone surface and bone bottom regions. Therefore, Th_d satisfies μ_t = 0 before the bone surface point determined. The total degree $\mu_b(x)$ of a point x (= a_x, q_x, f_x, d_x) is calculated by arithmetic product of four degrees.

$$\mu_b(x) = \min(s(a_x),\mu_a) \times \min(s(q_x),\mu_q) \times \min(s(f_x),\mu_f) \times \min(s(d_x),\mu_d) \quad (10)$$

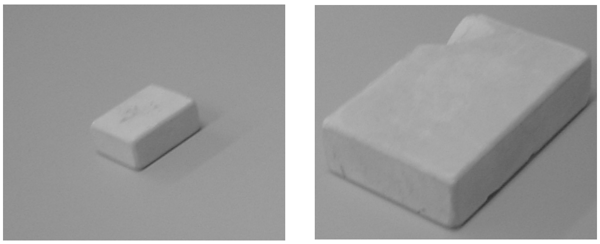
The $\mu_b(x)$ expresses the fuzzy membership degree of bone bottom. The point with the highest degree is determined as the bone bottom.

[Example 2] Bone Bottom Determination: Consider the raw wave data in Figure 3. Four fuzzy degrees, *Amplitude*, *Quadrature*, *Frequency* and *Distance* are calculated shown in Figures 6(a), 7(a), (b), and (c),



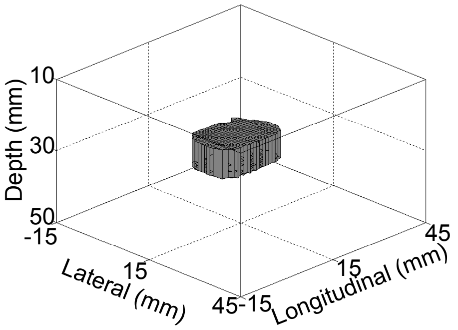
(a) ***Quadrature*** **(b)** ***Frequency*** **(c)** ***Distance*** **(d) Total**

Figure 7. Fuzzy degrees of bottom.

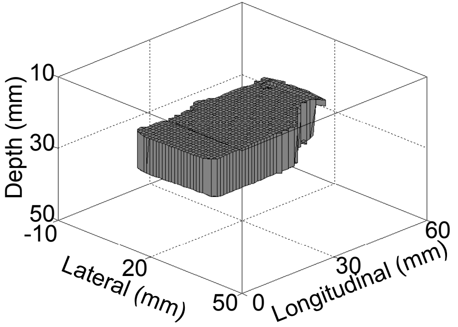


(a) Specimen A (b) Specimen B.

Figure 8. Bone specimens.



(a) Specimen A



(b) Specimen B

Figure 9. 3D images of our results.

respectively. Here, in *Amplitude* and *Quadrature* parameter, we use thresholds of Example 1. In *Quadrature* and *Frequency* parameter, we use lower frequency compared with ω and Th_f of Example 1. Th_d is determined as the surface point calculated in Example 1.

From these four degrees, the total degree of bone bottom $\mu_b(x)$ is calculated by Equation (10). This result is shown in Figure 7(d).

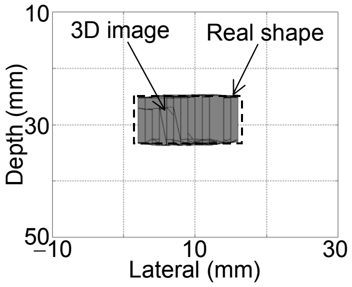
[End of Example]

4. Results

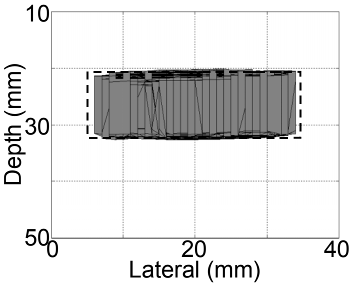
We prepared two specimens (the artificial bone made by hydroxyapatite) shown in Figure 8. These specimens are cuboid shape: Specimen A has 8.20 mm of thickness, 15.20 mm of lateral length, and 20.15 mm of longitudinal length. Specimen B has 12.30 mm of thickness, 30.25 mm of lateral length, and 45.25 mm of longitudinal length. Here, we set that acoustic velocities in water and an artificial bone are 1500 m/s and 3300 m/s, respectively. The value 3300 m/s can be known experimentally. We applied our method to these specimens. These 3D images are shown in Figure 9. Because specimens are cuboid shape, the determined thickness should be of same in several lateral and longitudinal locations. Figure 10 visualized the overlapped image (lateral view) of 3D shapes by our method and real shapes. The dotted line represents the real shape. In this method, the lateral error is higher than the depth error because lateral resolution is coarser than depth resolution. We compare the real bone shape with our shape. The result is tabulated in Table 1. In it, the mean ± SD (standard deviation) for thickness of the bone at each lateral and longitudinal location is shown. The mean ± SD is shown for the error (= |real value – our method|). Our method provides that the mean error of bone thickness was less than 1 mm in both cases. The small specimen A (the mean error of thickness: 0.27 mm) was determined more precisely than big specimen B (0.67 mm).

5. Conclusions

This paper has proposed a sonography system for visualizing 3D bone shape using ultrasonic wave. Our method has visualized 3D bone shape aided by fuzzy



(a) Specimen A



(b) Specimen B

Figure 10. Overlapped image of our method shape and real shape.

Table 1. Comparison of thickness between our method and real value

	(a) Specimen A	(b) Specimen B
Our method (Mean ± SD)	8.30 ± 0.31	11.63 ± 0.23
Real value	8.20	12.30
Error (Mean ± SD)	0.27 ± 0.19	0.67 ± 0.22

(unit: mm)

logic from ultrasonic data acquired by pulse-echo method. Bone surface and bottom were correctly identified from knowledge of surface and bottom echo of bone based on fuzzy logic. As the result of applying our method to two artificial bones, the error of thickness between determined value and real value was less than 1 mm in both cases. We cannot compare our method with other method because there is no works to provide 3D bone shape using ultrasonic wave. It remains as future works to improve visualizing accuracy by adding new knowledge and to apply our method to human bone.

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