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A Fat-Tissue Mimic Phantom for Therapeutic Ultrasound

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** Regular Paper*

***Abstract*:** As the number of treatments in the therapeutic ultrasound field targeted at fat tissue increase, the performance of the equipment should be evaluated for safety using a fat phantom. In this study, a fat phantom was fabricated using olive oil and a tissue-mimicking material (TMM) phantom. To evaluate the acoustic properties of the TMM phantom according to the changes in the olive oil, the composition ratio of a liquid mixture of olive oil with a surfactant was adjusted from 5–20% in 5% steps. The acoustic properties of the phantom were evaluated using the sound velocity, attenuation coefficient, density, and acoustic impedance. The experimental results showed that the sound velocity decreased with increasing amount of olive oil but the other acoustic properties did not change. In addition, the phantom using an olive-oil mixture with a 15% composition ratio was most similar to the acoustic characteristics of fat tissue with a sound velocity of 1477.35 m/s, an attenuation coefficient of 0.514 dB/MHz-cm, a density of 1.07 g/cm^3, and an acoustic impedance of 1.575 MRayl. These experimental results are expected contribute to the accuracy of the results using a TMM phantom and will be useful for the therapeutic ultrasound field targeted at subcutaneous fat tissue.

***Keywords*:** Fat phantom, TMM phantom, Olive oil, Acoustic property, Fat tissue

1. Introduction

The increasing interest in the treatment of obesity in recent years has led to the increased interest in lipoplasty using ultrasound. Lipoplasty is a technique that destroys fat cells from the cavitation phenomenon within the cell as the mechanical vibration energy passes through the fat tissue [1]. The process has the advantages of no damage and bleeding in the other tissues owing to the selective destruction of unwanted tissue. On the other hand, burns in the surrounding tissues caused by the heat generated during treatment have been reported [2]. To reduce these side effects, the safety of the treatment equipment should be examined thoroughly by evaluating the performance. In addition, proficient practitioners are needed. The performance of the diagnostic equipment and training practitioners are currently evaluated using tissue-mimicking material (TMM) phantoms with similar acoustic properties to those of human soft tissue [3]. On the other hand, it is difficult to obtain accurate results caused by the differences in the acoustic properties between the TMM phantom and fat tissue. Accordingly, it is essential to develop a usable therapeutic ultrasound fat phantom by replacing human fat tissue in the therapeutic ultrasound field.

Early fat phantoms were fabricated using the fat tissue of an animal. Until the early 1990s, porcine fat tissue and its oil had been used to confirm the fat-tissue characteristics during an examination of diagnostic ultrasound [4, 5]. Despite this, the fabricated fat phantoms using the animal fat tissue were difficult to process and store, and inaccurate results were obtained because the speed of sound in this tissue is lower than that in human fat tissue. Hence, fat phantoms were developed to mimic the acoustic properties of human fat tissue using an oil component with similar fat characteristics to overcome these disadvantages. These developed fat phantoms were used in in vitro studies to evaluate the performance of diagnostic and therapeutic ultrasound machines [6]. Kondo et al. developed an oil-gel phantom using propylene glycol and oil [7]. Ortega et al. fabricated a similar fat phantom by considering the speed of sound and attenuation coefficient of fat tissue using mineral oil [8]. These phantoms, however, had a tendency to be inflexible or broken easily owing to the poor toughness. Therefore, they were difficult to use as a replacement for fat tissue. Thereafter, a fat phantom was fabricated by Cannon et al. using olive oil with similar characteristics to the animal-fat component for the purpose of breast phantom development [9]. Unfortunately, phantoms of this type are limited to therapeutic ultrasound targeted at the subcutaneous fat tissue because they are set to the acoustic properties of breast tissue for breast phantom fabrication.

In this study, a fat phantom was fabricated using olive oil and glycerol based on the phantom specified in the IEC standard as a TMM phantom. To determine the composition ratio of the fat phantom most similar to the acoustic properties of fat tissue, its acoustic properties were evaluated according to changes in the olive-oil composition ratio. Furthermore, this study examined whether the fabricated fat-tissue-mimicking phantom would be applicable to the therapeutic ultrasound field targeted at subcutaneous fat tissue.

2. Materials and Methods

2.1 Preparation of fat phantom

The olive oil containing a vegetable-fat component and a standardized glycerol-based TMM phantom were used to produce a fat phantom. The glycerol-based TMM phantom was mixed with glycerol, distilled water, benzalkonium chloride, silicon carbide, aluminum oxide (3.0 μm, 0.3 μm), and agar according to the IEC standard [11]. The sound velocity of the phantom was adjusted by the amount of glycerol, and silicon carbide and aluminum oxide were used to adjust the attenuation coefficient. A systematic increase of the particulate concentration such as silicon carbide and aluminum oxide was found to result in a corresponding increase in attenuation coefficient [9]. Olive oil was used to mimic the acoustic properties of fat tissue, which consisted of unsaturated fatty acids as the main ingredient; a surfactant was added to produce a uniform distribution of oil. After the surfactant was diluted in distilled water to a concentration of 10%, olive oil and the surfactant solution were mixed at a ratio of 9:1. The olive oil and surfactant solution were heated to 96 °C and then poured into a mixture of the glycerol-based phantom at 90 °C. To harden the mixture of the fat phantom, the temperature was reduced to 50 °C at room temperature and then poured into the produced mold. To determine the appropriate composition ratio of the fat phantom, the composition ratio of the liquid mixture of olive oil with the surfactant was adjusted from 5–20% in 5% steps for the TMM phantom. Table 1 lists the composition of the fat phantom according to the changes in the composition of olive oil. The fat phantoms, P1, P2, P3, and P4, were the fat phantoms in which the ratios of the olive-oil composition in the olive oil and surfactant mixture were 5, 10, 15, and 20%, respectively.

Table 1. Composition of fat phantom(%).

Component	Composition ratios (%)			
	P1	P2	P3	P4
Olive oil	4.5	9	13.5	18
Surfactant	0.05	0.1	0.15	0.02
Glycerol	10.65	10.09	9.53	8.97
Distilled water	79.25	75.55	71.85	68.16
Benzalkonium chloride	0.45	0.42	0.4	0.38
Silicon carbide	0.5	0.48	0.45	0.42
Aluminum oxide (3.0 μm)	0.89	0.85	0.8	0.75
Aluminum oxide (0.3 μm)	0.84	0.79	0.75	0.7
Agar	2.87	2.72	2.57	2.42
Total	100	100	100	100

2.2 Measurements of acoustic properties

To evaluate the acoustic properties of the phantoms according to the changes in the olive-oil composition ratio, the sound velocity, attenuation coefficient, density, and acoustic impedance were measured for each phantom. Fig. 1 shows the experimental setup used to evaluate the acoustic properties of the fat phantoms. To simulate the environment in the human body, the temperature of the tank was maintained at 37 °C. The inside of the tank consisted of the phantom, reflector, and sound-absorbing material in sequence, and an ultrasonic signal was generated using an ultrasonic pulse–receiver (MKPR-1030, MKC, Korea). The transmission and reception of ultrasound was realized using a single transducer with a frequency centered at 3.5 MHz. The received signal was stored in a digital oscilloscope (Waverunner 6100A, Lecroy), which was then analyzed by Acqknowledge.

Fig. 2 shows the A-mode signals measured in the phantom and water at 37 °C. The occurrence of the first reflected signal at the phantom surface and the second reflected signal from the reflector were confirmed from the upper signal measured at the phantom.

To measure the sound velocity of the phantom, the software measured the time difference in the peaks (time shift, Δt) of the two reflected signals. The sound velocity was calculated using the following equation:

$$c = \frac{2d}{\Delta t}, \quad (1)$$

where c is the sound velocity in the phantom, Δt is the measured time shift, and d is the phantom thickness in the axial direction in the transducer as the moved path of the transmitted ultrasonic pulse; it was measured using digital Vernier calipers.

To measure the attenuation coefficient of the phantom, the reflected signals were measured from the reflector with and without the phantom in place. The attenuation coefficient of the phantom according to the measured

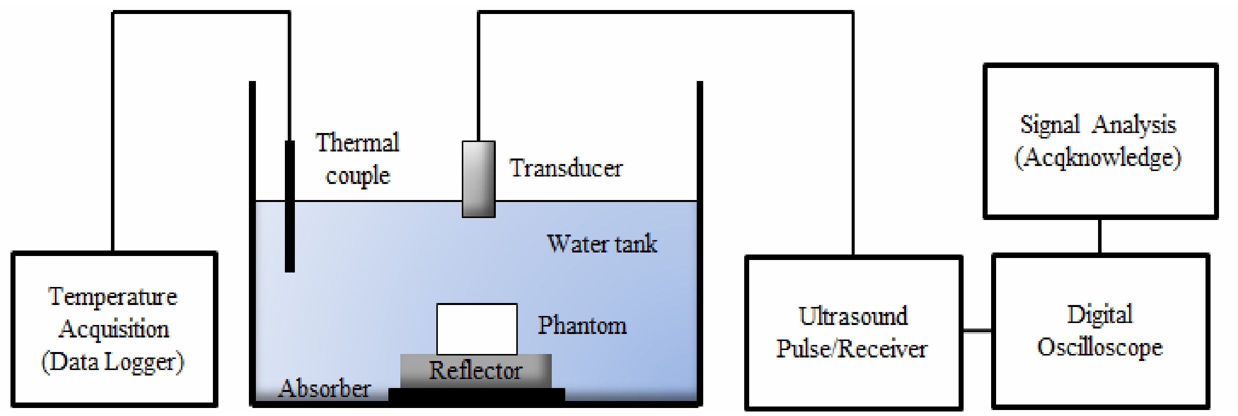

Fig. 1. Experimental setup for evaluating the acoustic property of a fat phantom.

signals was calculated by

$$\alpha(f) = -\frac{20}{2d}\log_{10}\frac{A(f)}{A_0(f)}, \quad (2)$$

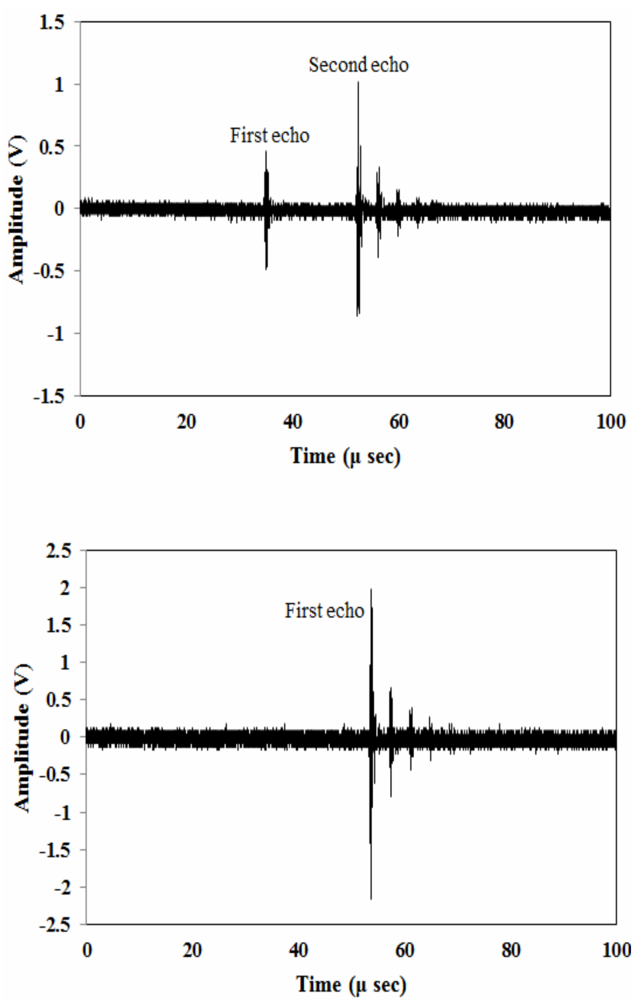

Fig. 2. The reflected signal for the measurement of sound velocity and attenuation coefficient in the phantom: (upper) reflected signal at the phantom, (lower) reflected signal at the water.

where α is the attenuation coefficient of the phantom, A(f) is the amplitude of the reflected signal with the phantom at a frequency f, and $A_0(f)$ is the amplitude of the reflected signal without the phantom at a frequency f. The density of the phantom was determined by the standard Archimedes immersion technique, dividing the weight of the phantom (measured by the electronic balance) by the volume of the phantom. The acoustic impedance was calculated from the product of the sound velocity and the density of each phantom. The acoustic impedance was calculated using the following equation:

$$z = \rho c, \quad (3)$$

where ρ is the density of the phantom.

3. Results

Fig. 3 shows the fat phantom with an olive-oil composition ratio of 15% in the mixture. The measurements of the acoustic properties in each phantom showed that the sound velocity decreased with increasing olive-oil composition ratio, whereas the attenuation

Fig. 3. Fabricated fat phantom.

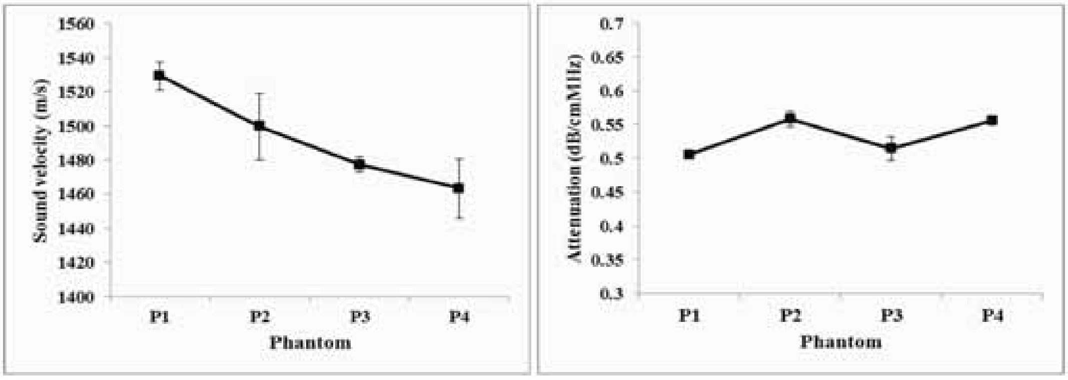

Fig. 4. Change in the sound velocity and attenuation coefficient by increasing the olive oil composition ratio: (left) the sound velocity, (right) attenuation coefficient.

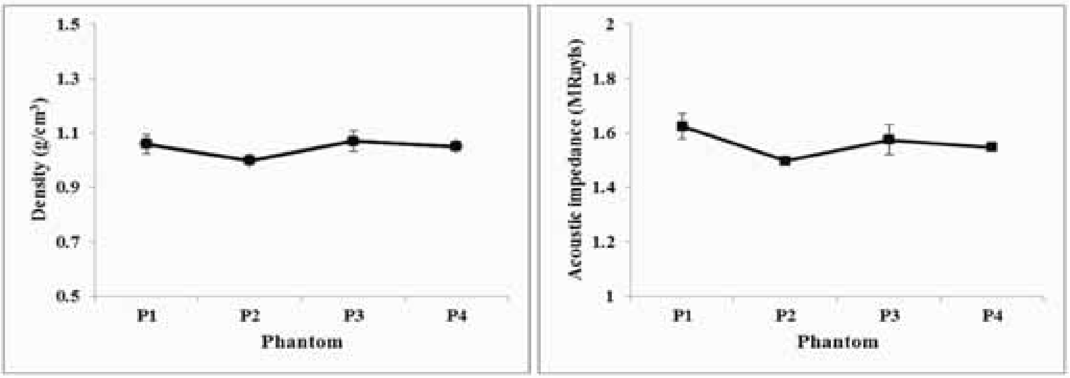

Fig. 5. Change in the density and acoustic impedance by increasing the olive oil composition ratio: (left) the density, (right) acoustic impedance.

Table 2. Comparison of the acoustic properties in the fabricated fat phantom and fat tissues.

Acoustic Property	Fat phantom	Breast fat tissue[1)]	Subcutaneous fat tissue
Sound velocity (m/s)	1,477.35 ± 4.66	1,436	1,479 ± 32[2)]
Attenuation coefficient (dB/MHz cm)	0.514 ± 0.017	-	0.6 ± 0.1[3)]
Density (g/cm^3)	1.07 ± 0.037	0.911	0.95[4)]
Acoustic impedance (MRayls)	1.5 ± 0.054	1.3	1.4[4)]

1) Yongchen et al. 1986, 2) Scherzing et al. 1988, 3) D'Astous and Foster 1986, 4) Mast 2000.

coefficient remained the same at 0.50–0.55 dB/cm-MHz.

Fig. 4 shows the change in the sound velocity and attenuation coefficient of the fabricated fat phantom. By increasing the olive-oil composition ratio, the density and acoustic impedance exhibited values of 1.00–1.07 g/cm^3 and 1.50–1.62 MRayl, respectively. These values were similar in tendency to the attenuation coefficient. Fig. 5 shows the change in the density and acoustic impedance according to the olive-oil composition ratio.

Table 2 compares the acoustic properties of the fabricated fat phantom in this study, subcutaneous fat tissue [12-14], and fat tissue of the breast area [10] as typical fat tissue. From a comparison of the subcutaneous fat tissue and the fat tissue of the breast area, the sound velocity of the subcutaneous fat tissue was 40 m/s higher than the fat tissue of the breast area. When the acoustic properties of each of the fabricated phantoms were compared according to the olive-oil composition ratio, the acoustic properties of the phantom containing 15% olive oil were most similar to the subcutaneous fat tissue because the sound velocity, attenuation coefficient, density, and acoustic impedance of the phantom had values of 1,477.35 m/s, 0.514 dB/cm-MHz, 1.07 g/cm^3, and 1.575 MRayl, respectively. Therefore, a phantom containing 15% olive oil was adopted as a suitable fat phantom. On the other hand, the sound velocity of the phantom containing 20% olive oil was closest to the fat tissue of the breast area with a value of 1463 m/s, showing a difference of 20 m/s.

Table 3 lists the acoustic properties in the previously existing fat phantoms. Porcine fat tissue and its oil component had been used for a long time, and its sound velocity was relatively low. The attenuation coefficient of fat tissue showed a difference of 0.2 dB/MHz-cm [11]. The

Table 3. Comparison of the acoustic properties in the existing fat phantoms.

Acoustic Property	Porcine fat[1)]	Porcine oil[1)]	Oil gel phantom[2)]	Mineral oil phantom[3)]	Breast phantom[4)]
Sound velocity (m/s)	1,466	1,455	1,480	1,449	1,482 ± 10
Attenuation coefficient (dB/MHz cm)	0.4	0.5	0.4	0.8	0.5
Density (g/cm^3)	-	-	1.04	-	0.7 - 0.8
Acoustic impedance (MRayls)	-	-	-	-	2.1 – 2.2

1) Yongchen et al. 1986, 2) Kondo et al. 2005, 3) Ortega 2009, 4) Cannon 2011.

sound velocity of the oil-gel phantom was similar to that of subcutaneous fat tissue, whereas there was a difference in attenuation coefficient [6]. Although the sound velocity of the fat phantom containing mineral oil was most similar to the sound velocity of the breast phantom, the attenuation coefficient was high [8]. For the breast phantom using olive oil, the density and acoustic impedance exhibited large differences from both the subcutaneous fat tissue and fat tissue of the breast area. On the other hand, its sound velocity was more similar to the subcutaneous fat tissue than the fat tissue of the breast area [9]. Overall, these results show that the fat phantom fabricated in this study had the most outstanding similarity in acoustic properties to subcutaneous fat tissue.

4. Discussion and Conclusion

A fat phantom was fabricated by evaluating the acoustic properties according to changes in the olive-oil composition ratio. The sound velocity of the fabricated phantom is in the range of 1,529.3–1,463.2 m/s; the sound velocity decreased with increasing composition ratio of olive oil. According to Louise's study, the sound velocity of a glycerol-based phantom was affected by glycerol, and it was confirmed that its sound velocity increased linearly with increasing composition ratio of glycerol [9]. On the other hand, the sound velocity of the fabricated fat phantom in this study exhibited a decreasing trend of the form of a logarithm as the olive-oil composition was increased (R^2 = 0.9966). Accordingly, we decided that the change in sound velocity of the fabricated fat phantom is affected by the reduction ratio of glycerol as well as the increase in olive oil. In contrast to the sound velocity, the attenuation coefficient, density, and acoustic impedance showed no significant changes because each of the values remained relatively constant at 0.5–0.55 dB/cm-MHz, 1.00–1.07 g/cm^3, and 1.50–1.62 MRayl, respectively. This shows that the increase in olive oil does not affect significantly the attenuation coefficient, density, and acoustic impedance. This tendency can be confirmed via the acoustic properties of the glycerol-based phantom. When the acoustic properties of the specified glycerol-based phantom were confirmed in the IEC standard, they correspond to a phantom with a 0% composition ratio because the sound velocity, attenuation coefficient, density, and acoustic impedance of the phantom were 1540 m/s, 0.5 dB/cm-MHz, 1.05 g/cm^3, and 1.6 MRayl, respectively [11]. When the acoustic properties of this phantom and the fat phantom fabricated in this study were compared, the sound velocity of the glycerol-based phantom was relatively higher than the sound velocity of the fat phantom, whereas the attenuation coefficient, density, and acoustic impedance were quite similar.

As a result of a comparison of the subcutaneous fat tissue, the fat tissue of the breast area, and fat phantoms fabricated in this study, the acoustic properties of the fat phantom containing olive oil with a composition of 15% were most similar to the acoustic properties of the subcutaneous fat tissue. On the other hand, it was decided that the composition of the olive oil should be increased further to mimic the acoustic properties of the fat component in breast tissue. In addition, a fat phantom will be developed through further experiments, where the acoustic properties are similar to the fat component in breast tissue. When the acoustic properties in previously existing fat phantoms and the fat phantom in this study were compared, the fat phantom in this study was most similar to subcutaneous fat tissue, and its usefulness as a fat phantom was confirmed by these results.

In this study, a fat phantom that mimics more accurately the acoustic properties of subcutaneous fat tissue was fabricated, and its acoustic properties were evaluated according to changes in the olive-oil composition ratio. The experimental results are expected to contribute to greater accuracy in the results of in vitro studies using a TMM phantom and help improve the usefulness of therapeutic ultrasound targeted at subcutaneous fat tissue.

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