

Manufacturing of a Gelatin Phantom With Lymphedema for Ultrasonic Imaging Measurement

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For diagnosis of secondary lymphedema, amplitude mode (A-mode) examination using a single ultrasound probe has been suggested as one of the possible diagnostic modalities due to its relatively low cost, ease of usage, and mobility. However, A-mode ultrasound waves with respect to time have lots of noise and are complicated to analyze and achieve well-correlated information related to change in volume of each layer of skin and subcutaneous tissues. Thus, the development of an adequate ultrasound calibration phantom is needed. For this, a fundamental study on proper phantom materials which show acoustic characteristics of skin and subcutaneous tissues is needed. In this research, the fabrication method for ultrasonic phantom using gelatin material is presented in a wide range of acoustic impedance and their acoustic characteristics and usability were discussed.
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Introduction

Clinical ultrasound-guided imaging tests are harmless to the human body and quick to obtain results. Most of them examine the liver, gallbladder, pancreas, spleen, kidney, and edema [1]. Ultrasonic imaging diagnosis is difficult to achieve superior results due to the complex interactions of tissues, and it is also very important to produce elastic substance-based phantom-like tissues to evaluate the precise examination effect.

For phantom production, ultrasonic measurements require reference results of sound waves (1540 m/s), transmission speeds (0.5 dB/cm/MHz), and attenuation coefficients (0.5–0.9 dB) similar to the electrical properties (soft tissue) of the human body [2–4]. And each tissue has its sound wave, transmission speed, and attenuation factor [5].

Therefore, the phantom material is used for usually agar, polyurethane gel, polymer, silicon, and arc polymer [6–8]. Then, agar is easy to adjust the attenuation coefficient, but the acoustic characteristics are not accurate, and the polyurethane gel is impact-resistant but has a lot of damping [6,7]. The polymer, silicon, and arc polymer have a large difference in speed of sound and severe attenuation [8].

Gelatin is similar to the electrical properties of human tissue and can produce desired shapes and electrical properties [9]. Gelatin also has high elasticity (soft material), low unit cost, and biocompatible properties [10,11]. Also, gelatin is easy to control the speed of sound and damping coefficient [6]. The ultrasound phantom has to similar sound speed and attenuation factor to the human body. To make a phantom, shape and electrical characteristics must be relaxed, and a phantom with sound speed and attenuation coefficient like the human body should be made.

In this paper produces an ultrasound imaging diagnostic phantom using gelatinous materials. The phantom manufactured has similar electrical properties to the human body through a mixture of gelatin, salt, and water. This phantom is easy to control shape and electrical characteristics. To obtain the electrical properties of the phantom, an ultrasound-based on the A-mode single probe was used in the laboratory.

Analysis of the Wave Propagation

The acoustic impedance (Z) of medium is the product of the density (ρ) of the medium and the speed of sound (c) in the medium as given in Eq. (1). Also, the k is compressibility [12]

$$Z = \rho \cdot c = \sqrt{\frac{\rho}{k}} \quad (1)$$

The speed of sound (c) is given by Eq. (2) which density (ρ) and Young's modulus (E) are 1050 kg/m^3 and 2.259 kPa (2.259×10^3), respectively. Thus, the average speed of sound for human tissue (water and soft tissue) is 1540 m/s , and the ultrasonic electrical property for human tissue is shown in Fig. 1 and Table 1 [5,12–17]

$$c = \sqrt{\frac{E}{\rho}} \quad (2)$$

Skin Phantom Using Gelatin Powder

Skin features have both physical and biological functions. Conditions for producing a skin-shaped phantom using gelatin must have flexibility, elasticity, and absorption as given in Table 2 [15].

Figure 2 shows the manufacturing for skin phantom with gelatin material. For gelatin phantoms, 10–50 g (10 g interval) of gelatin powder was dissolved in 200 ml boiling water and solidified in acrylic cases ($4.5 \text{ cm} \times 4.5 \text{ cm} \times 10 \text{ cm}$) as many as 8 cm in height. Additionally, to fabricate phantoms with high speed of sound and acoustic impedance, 10–50 g (with 10 g interval) of salt was

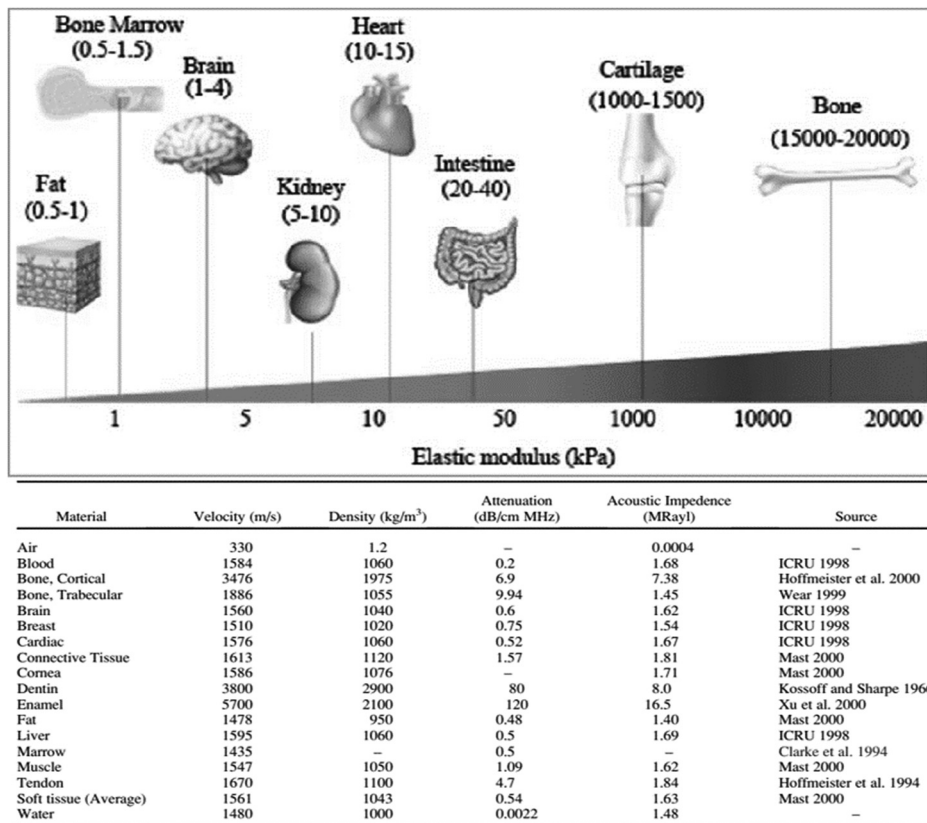


Fig. 1 Difference of electrical property with human tissue for ultrasound [5,17]

Table 1 Ultrasonic electrical property of human tissue [5,12,13]

Tissue	Water	Muscle	Blood	Liver	Bone	Fat	Skin
Density (kg/m ³)	1.48	1.71	1.65	1.65	7.80	950	1200
Acoustic impedance (MRayl)	0.004 (20 °C)	1.70	1.61	1.65	7.80	1.38	1.450
Acoustic velocity (m/sec)	1.48	1.59	1.57	1.549	4.08	1478	1558

Table 2 Characteristic of ultrasonic electrical property of tissue

Physicochemical properties	Biological properties
Controls evaporative water loss	Controlled rate of biodegradation
Impermeability of bacteria	Nontoxic metabolites
Adherence	Nonantigenicity
Water absorption	Absent inflammatory or foreign body reaction
Handling and suturing characteristics	Synthesis of neoepidermal tissue
Availability-easy to store	Tissue
	Modulate contracture and scar formation

dissolved in gel–water mixture (water 200 ml + gelatin 50 g) as many as 8 cm in height.

Fabricated phantoms were stored at room temperature until bubbles disappear. And then, they were stored in refrigerator. After keeping them refrigerated for 2–3 h for proper solidification.

Experimental Results. Ultrasonic waves have different characteristics depending on the tissue (see Fig. 1), and the acoustic velocity has difference soft tissue, normal tissue, and abnormal tissue (e.g., Lymphedema) as shown in Fig. 3. Epically, the lymphedema of ultrasonic waves and imaging has different with normal tissue. Because this equipment calculates phantom's depth with fixed speed, it has error depending on characteristics of the

measuring medium. Calibration is important for ultrasound for diagnosis. Then, the wave propagation can be analyzed by three-dimensional wave formation which is given by Eq. (3) [16]

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) p(x, y, z, t) = \frac{1}{c^2} \frac{\partial^2 p(x, y, z, t)}{\partial t^2} \quad (3)$$

Then, the plane wave traveling in the z -direction is expressed by Eq. (4). Therefore, the cyclic frequency domain is described by Eq. (5)

$$\frac{\partial^2 p(z, t)}{\partial z^2} = \frac{1}{c^2} \frac{\partial^2 p(z, t)}{\partial t^2} \quad (4)$$

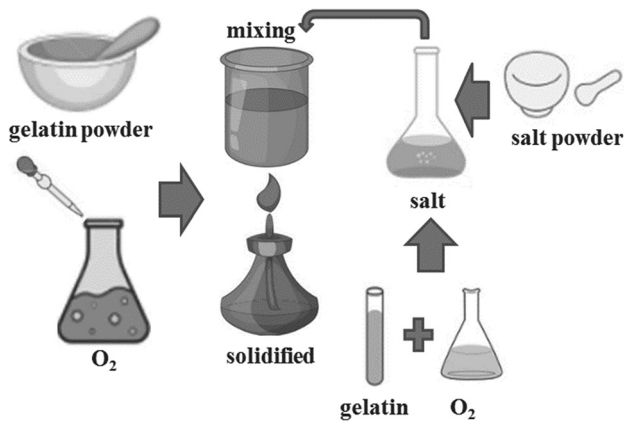


Fig. 2 Manufacturing for gelatin phantom

$$f = \frac{kc}{2\pi} = \frac{c}{\lambda} \quad (5)$$

In this work, time was calculated until the signal was generated by the sound waves hit the case floor as dividing a depth that appear in the program by a fixed speed of equipment (1540 m/s). And then, real speed of sound of phantom was calculated by dividing real depth (8 cm) by the calculated time.

To measure the elastic modulus of a gelatin phantom, the experimental system is composed as shown in Fig. 4(a). From the picture, apply a constant external shock to the phantom. And the elasticity value can be obtained through the elasticity meter.

To measure the impedance of the gelatin phantom, experimental instruments and systems are constructed as shown in Fig. 4(b). Fill a plastic container with water from the figure. Then, the gelatin is placed in a container and electrical properties are measured using a transducer. At this point, the transducer attempts to connect the ultrasonic monitoring system, oscilloscope, and impedance analyzer, respectively. Upon completion of the impedance

measurement, the sound velocity value of the ultrasound can be obtained by Eq. (2).

In Fig. 4(c), the phantom is measured using by single probe ultrasound pulser (with receiver board) and transducer, and the single probe ultrasound pulser and transducer are used for Sono-Lab Echo I (BioSono Inc., Fremont, CA) and Blatek, respectively. Then, the measured frequency and dimension of transducer are 2.25 MHz and 12.5 mm, respectively.

Also, to obtain data about the impedance change of the phantoms with the passage of time, after all phantoms were solidified, changes of acoustic impedance and shape were measured for 3 days. The measurement and realization of the gelatin phantom can be observed by Fig. 5.

In the case of gelatin phantom, speed of sound was measured about 1540 m/s similar to average value of human tissues. The real speed of sound of phantom was calculated as dividing real depth (8 cm) by the calculated time. As Table 3, Table 4, and Fig. 5, the gelatin content was increased, density, speed of sound, and acoustic impedance was linearly increased with respect to an increase in gelatin mass [5,12,13]. For the salt-gelatin mixed phantoms, they were measured they have higher speed of sound and acoustic impedance than only gelatin phantoms.

From the results, it could be concluded that a wide range of acoustic impedance from about 1.5–2.1 can be achieved from gelatin and salt-gelatin mixture phantoms.

As time passed, a mass of the phantom was decreased, and its surface was hardened as shown in Fig. 6. The shape of the surface was deformed, so the volume of the phantom was also changed. The density of the gelatin phantom decreased but the density of the gelatin-salt phantom was almost constant as shown in Fig. 7. Thus, the acoustic impedance of the gelatin phantom decreased slightly, and the acoustic impedance of the phantom was almost constant with the passage of time as shown in Fig. 8.

Discussion

On the other hand, Lymphedema is a disease in which lymph fluid accumulates in the subcutaneous fat layer due to circulatory disorders in the lymphatic system. Lymphedema can cause

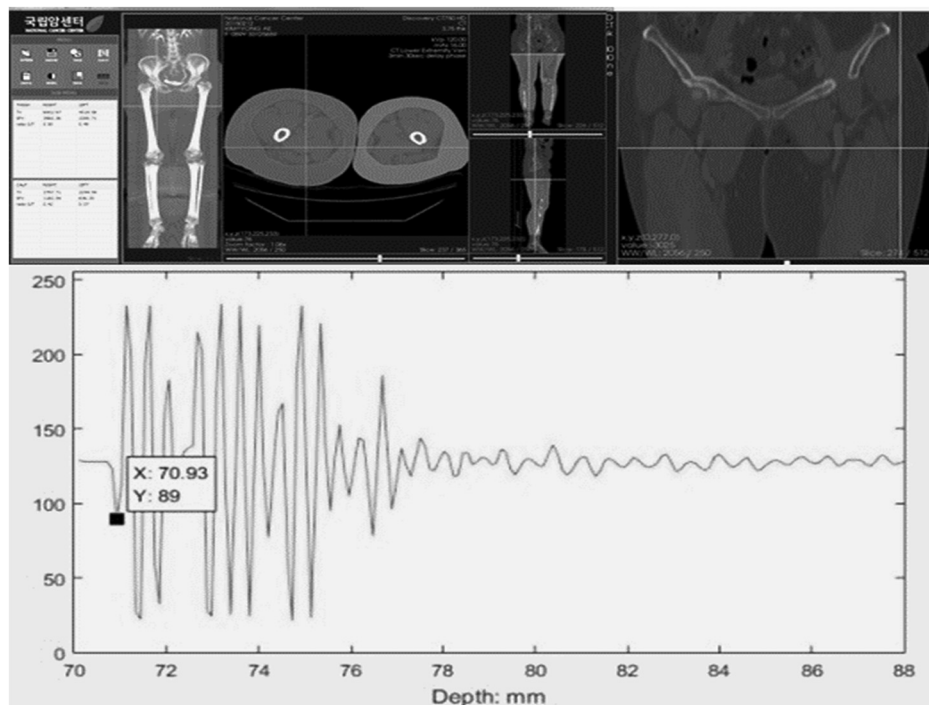


Fig. 3 Difference of lymphedema imaging with diagnosis ultrasound and A-mode waveform using single probe

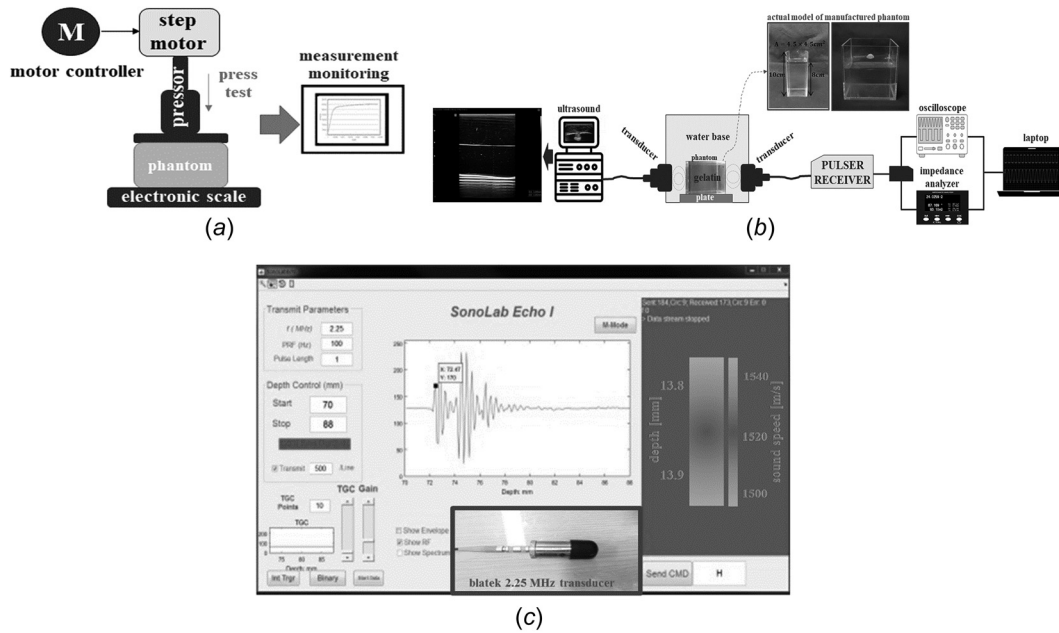


Fig. 4 Environment for experimental configuration: (a) elasticity factor measurement, (b) impedance measurement, and (c) test result for transducer of Blatek (2.25 MHz)

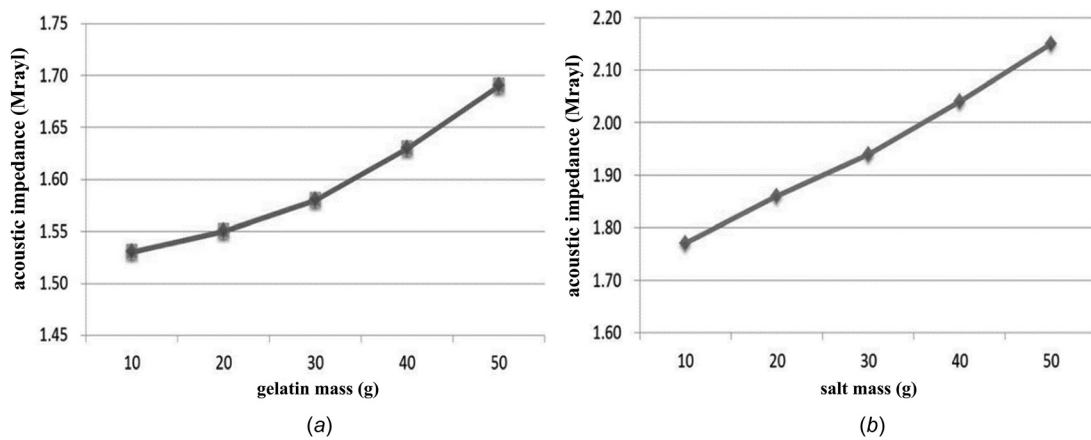


Fig. 5 Measurement result for acoustic impedance: (a) gel-salt phantoms and (b) gelatin phantoms

Table 3 Ultrasonic electrical property and density of gelatin phantoms [5,12,13]

Gelatin (g)	Density (kg/m ³)	Speed of sound (m/s)	Acoustic impedance (Mrayl)
10	1019.48	1511.29	1.53
20	1031.27	1495.10	1.55
30	1042.49	1520.37	1.58
40	1054.90	1543.67	1.63
50	1059.33	1595.36	1.69

Table 4 Ultrasonic electrical property and density of gelatin-salt phantoms [5,12,13]

Salt (g)	Density (kg/m ³)	Speed of sound (m/s)	Acoustic impedance (Mrayl)
10	1099.09	1612.13	1.77
20	1119.10	1661.18	1.86
30	1144.91	1694.45	1.94
40	1176.33	1734.33	2.04
50	1190.04	1805.12	2.15

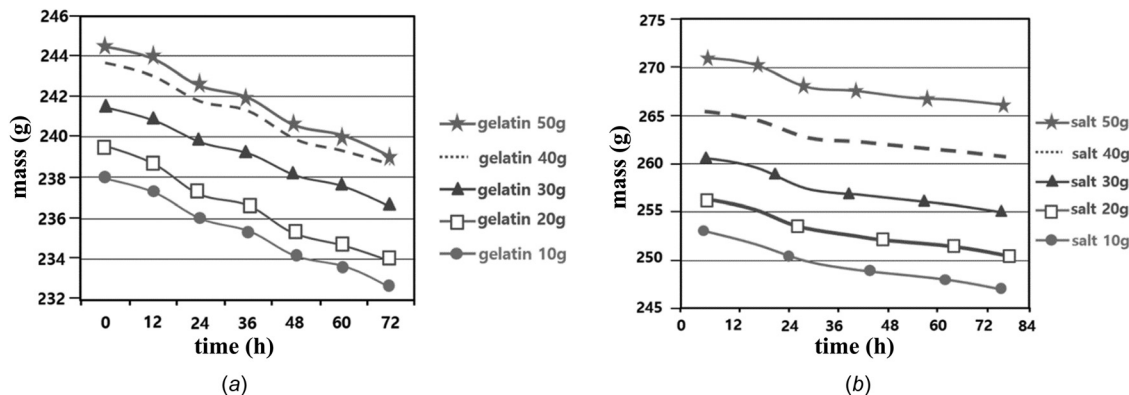


Fig. 6 Measurement result for variation of phantoms mass: (a) gelatin and (b) salt

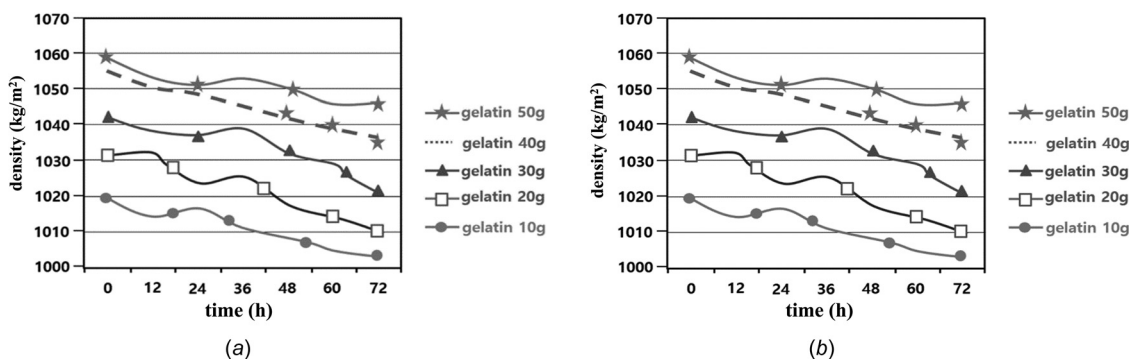


Fig. 7 Measurement result for variation of phantoms density: (a) gelatin and (b) salt

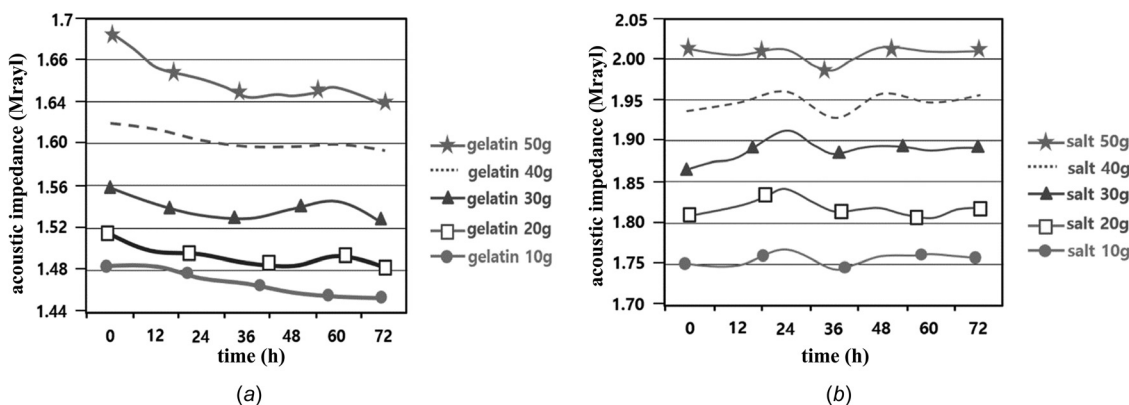


Fig. 8 Measurement result for variation of acoustic impedance with phantoms: (a) gelatin and (b) salt

cosmetic problems, psychological problems such as anxiety and depression, physical discomfort, and functional loss such as limited range of motion in cancer patients. Therefore, severe symptoms cause immune dysfunction, which can lead to emergencies [18,19]. Therefore, there is a growing demand for an ultrasound diagnostic method for diagnosing lymphedema at an early stage by tracking changes before and after surgery or during the recovery period.

The most commonly used method for measuring the volume of lymphedema is the tape phantom measurement method. The measurement method is calculated by measuring the circumference of the arm and leg and approximating it to a cylinder. This measurement method has the principal problem of calculating an oversimplified approximation. In addition, there is a problem in that it largely depends on the skill of the person making the measurement and the posture of the patient. To improve this, Pero-System

GmbH, Wuppertal, Germany were introduced in 1997, but the error problem could not be solved because it still uses the approximate calculation method [20,21]. Then, in order to diagnose the occurrence of lymphedema, there is a phantom measurement method that measures and predicts changes in bioresistance or dielectric constant [22–24]. However, they have the disadvantage that it is difficult to determine the direct relationship with the lymphedema progression.

Therefore, the ultrasonic phantom is continuously being developed. As mentioned in the introduction, phantom materials are commonly used for agars, polyurethane gels, polymers, silicones, and arc polymers [6–8]. Then, the agar is easy to control the damping coefficient, but the acoustic properties are not accurate, and the polyurethane gel is strong in impact but has a lot of damping [6,7]. Polymers, silicones, and arc polymers have large differences in the speed of sound and severe attenuation [8].

Gelatin has similar electrical properties to lymphedema. In addition, gelatin is an eco-friendly material for the human body, has elasticity, and has the advantages of low unit cost [6,9–11]. At this time, when the impedance of lymphedema is 1.69 Mrayl, the impedance of the prepared gelatin phantom is 1.69 (50 g) Mrayl [25]. Therefore, it is analyzed that it can be used as a phantom of lymphedema.

In the future, these phantom studies will be utilized in the measurement of clinical organization.

Conclusion

In this work, gelatin-based ultrasound phantoms were fabricated in a wide range of acoustic impedance and their acoustic characteristics and usability were discussed.

The phantom was dried to obtain the value of the phantom's impedance change over time. And after 3 days, the acoustic impedance and shape changes of the phantom were measured using ultrasonic waves.

The average sound velocity value of the gelatin phantom was 1540 m/s similar to that of human tissue. In addition, the measured sound velocity of the phantom was analyzed as 8 cm. Density, sound velocity, and acoustic impedance linearly increase with increasing gelatin content and mass.

The sound velocity and acoustic impedance of the salt-gelatin mixture phantom were analyzed to be faster and higher than that of the general gelatin phantom. Therefore, mixed gelatin phantoms can measure a wide range of acoustic impedance values from about 1.5–2.1.

When the time is exceeded for a certain amount of time, the manufactured phantom loses mass and the surface becomes hard, meaning that the density of gelatin has decreased. The produced gelatin phantom is expected to be of great help in future nonclinical experiments.

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Nomenclature

c = speed of sound in the medium
 E = Young's modulus
 Z = acoustic impedance
 ρ = density of the medium

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