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Original Article

Temperature changes caused by the difference in the distance between the ultrasound transducer and bone during 1 MHz and 3 MHz continuous ultrasound: a phantom study

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Abstract. [Purpose] This study aimed to use a thermograph to observe temperature changes caused by different distances between an ultrasound transducer and bone during 1 MHz and 3 MHz continuous ultrasound emission on a phantom. [Materials and Methods] We observed the distribution of temperature elevations on a phantom consisting of pig ribs and tissue-mimicking material. One megahertz and 3 MHz ultrasound were delivered at 2.0 W/cm^2 for 5 minutes. To record the temperature changes on the phantom, we took a screenshot of the thermograph with a digital camera every 20 seconds. [Results] With 1 MHz ultrasound at the distances of 2 and 3 cm, the temperature elevation near the bone was higher than that near the transducer. However, with 3 MHz ultrasound, the temperature elevation was higher near the transducer rather than near the bone. At this point, we consider that there is a possibility of heat injury to internal organs in spite of there being no elevation of skin temperature. [Conclusion] When performing ultrasonic therapy, not only should the frequency be taken into consideration, but also the influence of the absorption coefficient and the reflection of the tissue. We visually confirmed the thermal ultrasound effect by thermography. Special attention to the temperature elevation of the internal organs is necessary to avoid injuries.
Key words: Ultrasound, Thermal effect, Thermography

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INTRODUCTION

Therapeutic ultrasound is reported to have several applications for patient rehabilitation, such as knee osteoarthritis[1)], chronic rhinosinusitis[2)], wounds[3)], subacromial impingement syndrome[4)], and bone repair[5)]. Generally, the effects of ultrasound may be divided into thermal and nonthermal effects. The thermal ultrasound effect has been evaluated on phantom[6–8)], human[9–13)], and animal tissues[14, 15)]. However, the majority of studies have measured temperature changes using thermistor needles; still, a few studies[16, 17)] have observed the temperature distribution by means of a thermograph. In general, the thermal effect of ultrasound cannot be visibly confirmed. The temperature distribution depends on the irradiation strength and the coefficient of absorption. Bone has a higher coefficient of absorption and reflection than other tissue. So the difference in the position of the bone complicates the temperature distribution. To understand the properties of ultrasound, it is worthwhile to visually confirm the thermal effect. The purpose of this study was to use a thermograph to observe temperature changes caused by different distances between an ultrasound transducer and bone during 1 MHz and 3 MHz continuous ultrasound emission on a phantom.

MATERIALS AND METHODS

The acoustic characteristics that can influence the propagation of ultrasound include the sound velocity, attenuation, reflection, scattering, and acoustic impedance. The amount of heat generated depends on the irradiation strength and the coefficient of absorption. Therefore, attenuation and

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scattering related to absorption are especially important in the thermal effect of ultrasound. It is difficult to distinguish between attenuation and scattering, so both are usually regarded as attenuation. Further, absorption can also be regarded as attenuation, and thus, we used a tissue-mimicking phantom to adjust the level of attenuation. A previous study[18] reported that the attenuation value increased linearly, as the mixture ratio of the graphite powder. Additionally, another study[19] reported attenuation values of tissue at 1 MHz. On the basis of these results, a phantom with attenuation similar to that of muscular tissue was created. To make a 3.3% agar solution, we dissolved agar in tap water, which was sufficiently deaerated, and mixed it with 0.016 g/cm^3 graphite powder (99% purity). Afterwards, the agar solution was cooled, and a parallelepiped rectangle was created with a length, width, and height of 10 cm, 15 cm, and 8 cm, respectively. The created phantoms were examined by ultrasound to confirm they had been mixed properly. Phantoms with deformations in temperature distribution was excluded from the experiment.

Pig ribs that were 2.2 cm wide, 3 cm long, and about 7 mm thick were inserted into each created phantom so that the bone was facing the transducer side. Three distances between the transducer and bone were evaluated: 2 cm, 3 cm, and 5 cm. All phantoms were irradiated with 1 MHz and 3 MHz continuous ultrasound for 5 minutes at doses of 2.0 W/cm^2. The ultrasound device used was a Sonopuls 590 (Enraf-Nonius B.V., Rotterdam, The Netherlands). The transducer surface area was 5.8 cm^2, effective irradiation area was 5.0 cm^2, and beam nonuniformity ratio was under 5.0. Thermopure JIG 3310 (JEOL Ltd., Tokyo, Japan) was used for thermometry, and a screenshot was taken of the thermograph with a digital camera every 20 seconds. Calibration of the infrared camera was carried out with liquid nitrogen. The transducer was fixed in place so that half of the plane was in contact with the phantom, and the camera of the thermograph was installed so that photographs could be taken of the upper surface of the phantom (Fig. 1). The transducer was fixed in place to clarify the thermal effect of ultrasound. We performed a preliminary experiment to confirm the pattern of the temperature distribution. We first measured the temperature distribution with an infrared camera after ultrasound irradiation with the entire transducer in contact with a horizontal section. Then we compared the surface temperature distribution with different contact areas of the transducer with the temperature distribution of the horizontal section. The half of entire transducer in contact with a horizontal section was most definitely in the temperature distribution. We conducted the same experiments several times to confirm the reproducibility of the data of the experiment. The room temperature was adjusted to within the range of 27.5–28.0 °C in all experiments.

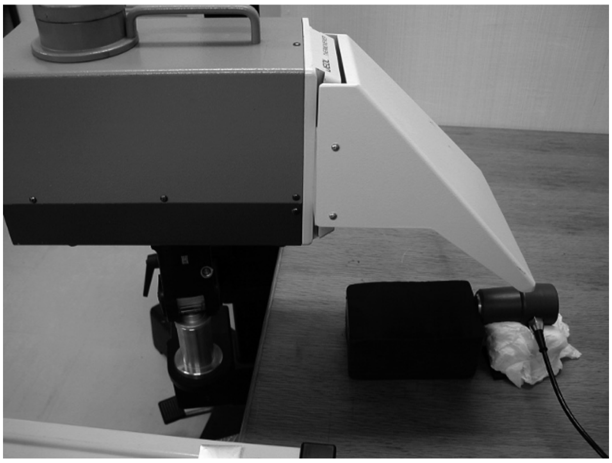

Fig. 1. Setting for thermometry
The phantom was positioned at the center, the ultrasound transducer was positioned to the right, and the camera for thermography was set above them. The transducer was fixed in place so that half of the plane could make contact with the phantom.

RESULTS

We recorded the distribution of temperature elevations on a phantom, which consisted of ribs from a pig and tissue-mimicking material, resulting from 1 MHz and 3 MHz ultrasound. The temperature in the center of the upper surface of an upside down triangular area was the highest, exceeding 40 °C. The temperature then decreased with distance from the point of transducer contact. The highest temperature shown in Fig. 2B is larger than that Fig. 2A, but the ultrasound energy reached relatively deeper in Fig. 2A. The temperature distribution in Fig. 2D did not appear to be influenced as much by the bone, as the results in Figs. 2B and 2D are similar. Figure 2C depicts the temperature distribution for 1 MHz ultrasound at a distance of 5 cm for 5 minutes. The position of the bone is shown by the arrow, and the portion with the highest temperature, which exceeded 40 °C, was observed near the transducer and near the bone. Figures 2E and 2G depict the temperature distribution for 1 and 3 MHz ultrasound at the distances of 3 and 2 cm for 5 minutes. The temperature elevation near the bone was higher than the temperature elevation near the transducer. Figures 2F and 2H depict the temperature distribution for 3 MHz ultrasound at the distances of 3 and 2 cm for 5 minutes. Both the areas near the transducer and the bone are included in the areas exceeding 40 °C. Figure 3 shows the temperature changes around the bone and transducer under all conditions. With the 1 MHz ultrasound, earlier temperature elevation was observed near the bone at the distances of 2 and 3 cm than near the transducer (Figs. 3A and 3B). However, with 3 MHz ultrasound, earlier temperature elevation was observed near the transducer than near the bone (Figs. 3C and 3D).

DISCUSSION

Using a thermograph, we showed the temperature changes in a phantom caused by different distances between the ultrasound transducer and bone during 1 MHz and 3 MHz continuous ultrasound.

The temperature elevations seen in the present study were substantially larger compared with the results of in

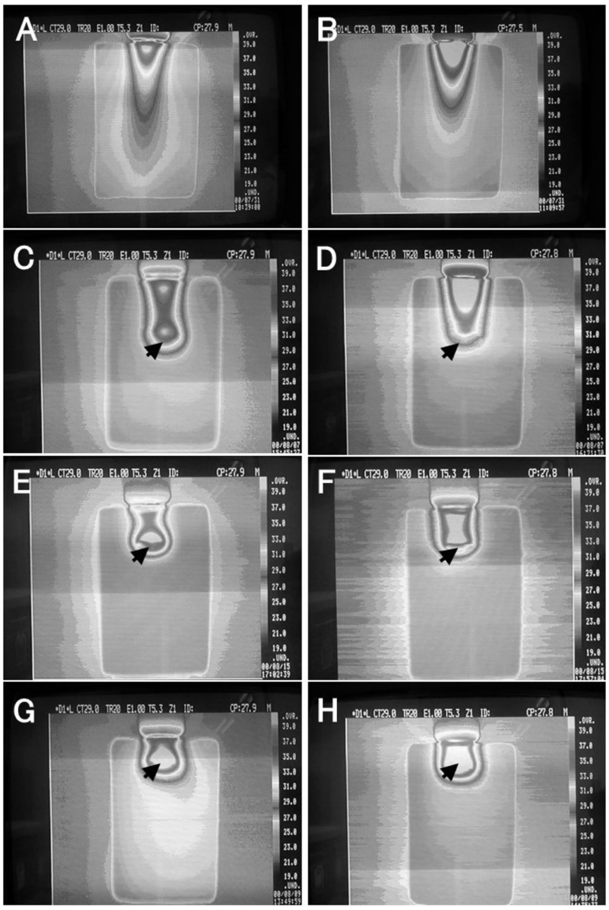

Fig. 2. The temperature distribution of the phantom irradiated with 1 MHz (A, C, E, G) and 3 MHz (B, D, F, H) continuous ultrasound for 5 minutes at 2.0 W/cm^2 at distances between the bone and transducer of 5 cm (C, D), 3 cm (E, F), and 2 cm (G, H). The arrow shows the position of the bone (C–H)

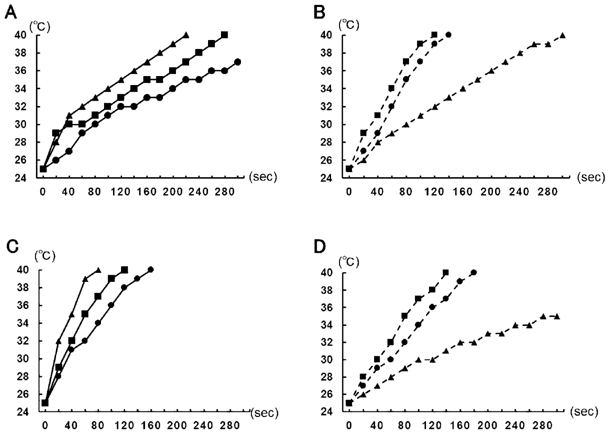

Fig. 3. The temperature around the bone and transducer Graphs A and B show the temperature of the phantom irradiated by 1 MHz continuous ultrasound, and graphs C and D show the temperature for 3 MHz continuous ultrasound. The solid lines represent the temperature around the transducer (A, C). The dashed lines represent the temperature around the bone (B, D). The squares, circles, and triangles represent temperature at distances between the bone and transducer of 2 cm, 3 cm, and 5 cm.

vivo studies[9–13]. Temperature changes in a living organism are influenced by heat conduction, amount of heat generated, and blood flow. Blood flow greatly influences the variation in temperature, and it decreases the temperature in the tissue in vivo. Furthermore, the transducer was fixed in the present study. Indeed, our results indicated higher temperatures compared with those reported in in vivo studies[9–13].

A previous study[20] reported a temperature distribution with a shape similar to the one presented in Figs. 2A and 2B. It was easy to increase the temperature near the ultrasound transducer or ultrasound transducer's center axis. Thus, the thermal effect of ultrasound could be visibly confirmed in the present study. The validity of the experiment and the difference between 1 MHz and 3 MHz ultrasound have been reported in a previous paper[21].

The area in which temperature changes were observed narrowed significantly as the distance between the bone and transducer shortened. We hypothesized that the area narrowed because the bone that was inserted absorbed and reflected the ultrasound. A previous study[8] measured the temperature on the surface of a bone and the back of a phantom, which consisted of a human temporal bone and tissue-mimicking material. The authors of that study reported that the temperature in the remote part of the back of the bone did not increase, which is similar to our observations in the present study. Moreover, they reported that the temperature elevation at the surface of the bone was higher than that at the back of the bone. Likewise, in the present study, the high temperature areas in Figs. 2E and 2F, indicated by a semicircle, show that the temperature elevation in the bone was mainly superficial .

The most important observation in this study was that the temperature elevation that occurred near the transducer was lowered by insertion of a bone. Figures 2E and 2G indicate these changes. When Fig. 3A is compared with Fig. 3B, the temperature elevation at the distances of 2 and 3 cm in Fig. 3B is higher than that in Fig. 3A. The temperature near the bone appeared to increase as the distance between the bone and transducer shortened, and the temperature near the transducer did not increase by as much. Intriguingly, the temperature near the bone increased at the distances of 2 cm, 3 cm, and 5 cm, but the temperature near the transducer increased first at 5 cm, then at 2 cm, and finally at 3 cm. It is thought that the reason why the temperature at the 5-cm distance rose first was that the temperature near the bone did not increase by as much; thus, the total ultrasound energy loss was low. Accordingly, the ultrasound energy density near the transducer became high. Further, it is thought that the reason why the temperatures at the 2-cm distance rose second was that the temperature near the bone was very high, so the total ultrasound energy loss was high; however, it is thought that the bone reflected the ultrasound, causing a reduction of the influence area as the distance between the bone and transducer shortened. Accordingly, the ultrasound energy density near the transducer became high. Moreover, the reason why the temperature at the 3-cm distance finally increased was that the ultrasound energy loss was intermediate; thus, the ultrasound energy density near the transducer was intermediate. A previous study[22] reported overprediction of the temperature rise at the bone surface using high-intensity focused ultrasound. It seems that these results were similar to those for the area around the bone in the present study. In addition to the allocation of the total ultrasound energy, interference actions and oscillations in the boundary area might also influence the temperature distribution. Consequently, we demonstrated a variety of temperature changes by changing the frequency and distance between the bone and transducer.

When applying ultrasonic therapy, the frequency and the influence of the absorption coefficient and reflection of the organs should both be considered. In this study, we visually confirmed the thermal ultrasound effect by thermography. Special attention to the temperature elevation of the internal organs is necessary to avoid injuries.

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