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Original Article

Deep heat therapy system with resonant cavity applicator for articular cartilage in knee osteoarthritis

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Abstract. [Purpose] Heat can prevent cartilage degeneration when applied to articular cartilage, but the size of the human knee joint makes it difficult to target cartilage during heat treatment. In this study, we aimed to establish a heat therapy method capable of safely applying heat to deep intra-articular tissues utilizing a resonant cavity applicator and to confirm the extent of cartilage heating in the human knee when using this system. [Participants and Methods] Heating experiments were carried out on the knees of healthy three volunteers using a resonant cavity applicator and a microwave diathermy system. After heat application, temperature distributions inside the knee were measured noninvasively using our measurement method based on ultrasound imaging techniques. [Results] We observed an increase in the temperature around the cartilage tissue in the knees of the volunteers using an ultrasonic thermometer; there was no increase in temperature in the overlying layers. During heating with up to 20 W of power, none of the volunteers experienced adverse reactions. [Conclusion] This study indicates the potential safety and effectiveness of the resonant cavity heat therapy system for knee osteoarthritis in a clinical setting.

Key words: Heat therapy, Osteoarthritis, Cartilage

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INTRODUCTION

Osteoarthritis (OA) is steadily becoming more prevalent with the aging of society. The progressive joint destruction and deformity must be treated surgically in many cases. Currently, definitive therapy for knee OA has not been established, and thus treatment strategies need to be developed by combining physical therapy, exercise, and medication[1)].

Heat has been used clinically in physical therapy for motor disorders[2)]. Heat therapy is also recommended in many guidelines for the management of OA of the knee as a single physical therapy or in combination with exercise therapy[3, 4)]. However, there are few studies with a high level of evidence on heat therapy for knee OA. Recent animal studies have shown that heat treatment prevents cartilage degeneration when applied to articular cartilage[5, 6)]. Those studies were in rats and guinea pigs, and heat treatment can easily be applied to the joints of such small animals. However, the size of the human

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knee joint poses challenges for heat treatment. Warm baths, heat packs, and paraffin treatment are examples of superficial heat therapy in which the increase in temperature is limited to the skin and subcutaneous regions and heat does not reach the deeper parts of the joint[7]. The application of heat deep in a joint is also difficult with microwave diathermy systems due to the absorption of electromagnetic energy by the superficial layers[8]. Large skin-contact bipolar applicators can encompass the entire knee and heat tissues deep within the joint[9]; however, their use in the clinical setting is impractical due to their large size and high cost. Furthermore, the dissipation of electromagnetic waves into the surrounding tissue raises safety concerns. These issues associated with this treatment modality may largely explain the near total lack of studies demonstrating beneficial effects of heat therapy for knee OA to date.

We aimed to establish a method for safely applying heat to the deep intra-articular tissues that would avoid the problems outlined above. The development of a deep tissue heat therapy system utilizing a resonant cavity applicator is ongoing. Previously, the in vivo temperature distribution was analyzed by a finite element method, and comparison with a clinically applied microwave diathermy system quantitatively demonstrated that this system could heat deep tissue[10]. This capability was further demonstrated experimentally through heating experiments with muscle-equivalent agar phantoms using a prototype device[11–13].

The aim of this study was to confirm heating of the deep tissue in the human knee with the developed heat therapy system and to investigate its safety with a view toward clinical application.

PARTICIPANTS AND METHODS

The prototype heat therapy system developed for this study is presented in Fig. 1. This system is composed of a high-frequency amplifier and a resonant cavity applicator. Resonance-frequency electromagnetic waves are supplied to the loop-type antenna installed in the applicator, which establishes an electromagnetic resonant mode inside the resonant cavity[14, 15]. With the system in this state, the knee is placed in the gap between the inner electrodes of the resonator, thereby enabling contact-free delivery of heat focused on the knee alone. The applicator is equipped with shield plates at the two openings on its surface to prevent misdirection of heat to the femoral region, lower leg, or other non-target regions[16].

A non-invasive ultrasound thermometer was used to measure the temperature inside the knee. Generally, the speed of sound is dependent on the temperature of the transmission medium[17]. However, commercially available ultrasound medical imaging systems reconstruct images assuming a constant speed of sound[18]. Accordingly, the resulting images will be slightly altered as the temperature changes. On this basis, a non-invasive, ultrasonic thermometer can detect microscopic image displacement by utilizing imaging technology to compare pre- and post-heating, thereby allowing the distribution to temperature increase to be estimated[10]. In our method, temperature increase distribution is estimated from image displacement by using Equations (1) and (2):

$$\Delta T(x) = k_{tissue} \bullet \frac{\partial(\Delta d)}{\partial x}, \quad (1)$$

$$k_{tissue} = \frac{1}{\alpha - \beta}. \quad (2)$$

Here, ΔT is the tissue temperature increase, Δd is the displacement between the ultrasound images taken before and after heating, k_{tissue} is the heat coefficient of each tissue, α is the coefficient of thermal expansion in each tissue, and β is the ultrasound speed factor, which changes depending on the tissue temperature. It is necessary to measure these thermal properties of each tissue for calculating the physical temperature. In this research, we estimated normalized temperature increase (ΔT) distribution inside the knee from displacement (Δd). In future work, we are measuring these parameters and estimating the physical temperature.

First, an ultrasound image was acquired before heating of the target region. After heating was completed, the image was

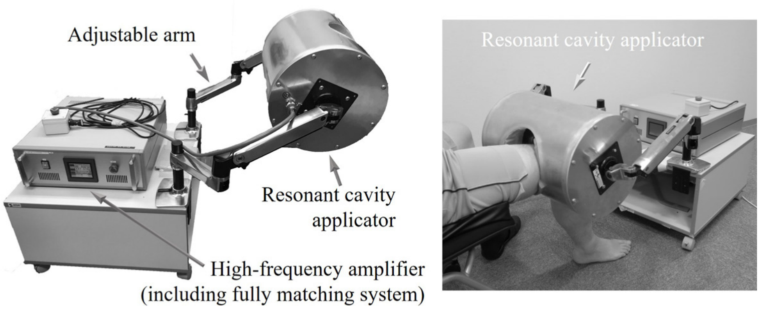

Fig. 1. The high-frequency amplifier is equipped with a fully automated matching system and is capable of automated resonance frequency adjustment and impedance matching. The aluminum-type resonant cavity is equipped with an adjustable arm.

used as a reference to obtain a second ultrasound image in the same position. The amount of image displacement (Δd in equation (1)) was calculated by an image-processing program[10] for each obtained image. Finally, the distribution of temperature increase was calculated by differentiating with respect to position in the depth direction for the ultrasound image, applying equation (1) to the measured displacement. In this study, we used ARIETTA Prologue™ (Hitachi, Ltd, Tokyo, Japan) as an ultrasound imaging device. We captured multiple ultrasound images before and after the experiment, using the pattern matching method to confirm that the images were taken at the same position. Validation and verification of this measurement system was carried out in our previous study[19].

A clinical study of heating was performed with 3 healthy male volunteers (aged 32, 52, and 60 years) with no knee pain or restricted range of motion. This study was approved by the International University of Health and Welfare Hospital Ethics Committee (13-B-248). All participants provided written informed consent prior to participation.

In a basic study using an agar phantom, the heating experimental conditions were verified. From the results, the experimental conditions were determined to be safe for the human body under 20 W for 20 minutes. Therefore, the heating experiment in this study was performed using 20 W of power for 20 min. The resonance frequency was manually adjusted as needed according to the size of the volunteer's knee and the target location; however, it could also be automatically adjusted to the corresponding frequency within the predetermined range by the automated tuning system fitted on the prototype, thereby enabling safe heating. The frequency range for the heating experiment was set at 420–470 MHz. After heating, an ultrasound image was taken around the femoral joint cartilage of the volunteers and compared with that taken before heating. The distribution of temperature increase within the joint was determined based on this comparison. To compare resonant cavity heating with conventional microwave diathermy, a non-contact microwave device was used to emit microwaves at a frequency of 2.45 GHz (MT-SDi Microtizer; Minato Medical Co., Ltd., Osaka, Japan). The MT-SDi probe (circular, 150 mm diameter) was placed approximately 10 cm in front of the patella and set to 100 W for 10 min while the participant sat in a chair with the knees at 90°. After the experiment, the normalized temperature increase was calculated because the temperature of the object to be heated changes according to the heating power. The formula shown below was applied to normalize the distributed temperature increases obtained with our ultrasonic thermometer.

$$\Delta T_N = \frac{(\Delta T - \Delta T_{\min})}{(\Delta T_{\max} - \Delta T_{\min})}$$

Here, ΔT_N is the normalized temperature increase, ΔT_{min} is the minimum temperature increase in the heating object, ΔT_{max} is the maximum temperature increase, and ΔT is the variable temperature increase inside the knee of the participant.

RESULTS

Representative normalized post-heating distributions of temperature increase in the knee joints of a volunteer are shown in Fig. 2. The infrapatellar fat pad region was heated using microwave diathermy; however, the cartilage region was not heated (Fig. 2A). The temperature was then raised in the proximity of the intra-articular cartilage, but not in the overlying skin or subcutaneous tissue, by using the resonant cavity applicator (Fig. 2B). Similar results were obtained in the other volunteers. Figure 3 shows the temperature depth profile along the center of the resulting images of Fig. 2. The infrapatellar fat pad region was successfully heated by both methods but the resonant cavity applicator heated the cartilage region more deeply compared with the microwave diathermy system. These results revealed an increase in temperature around the cartilage tissue with no increase in temperature in the overlying layers. During heating up to 20 W of power, all volunteers experienced almost no sensation of heat in the knee and showed no burns or other adverse reactions. To prove the safety, their progress monitored continually. Electromagnetic field strength external to the resonant cavity applicator was measured during heating

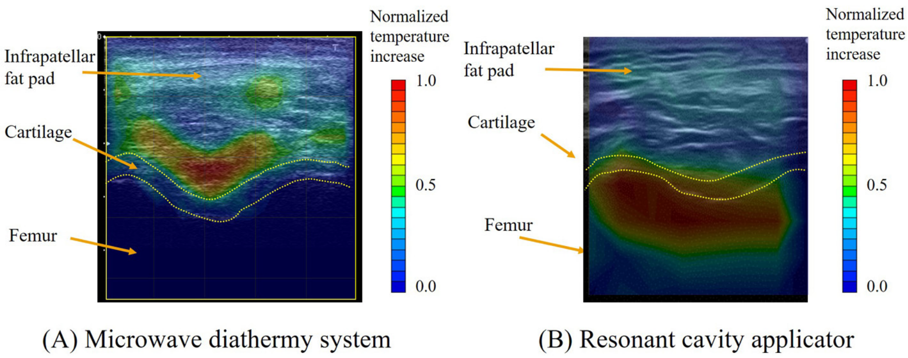

Fig. 2. Distributions of normalized temperature increase in a human knee. (A) A knee heated with the microwave diathermy system for 10 min at 100 W. (B) The same knee heated with the resonant cavity applicator for 20 min at 20 W.

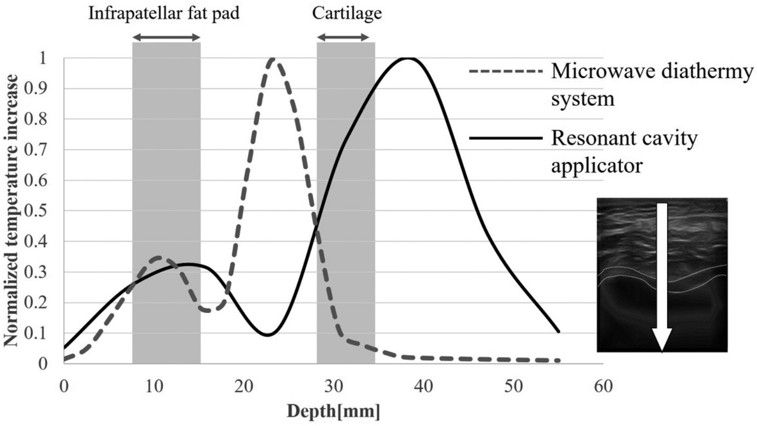

Fig. 3. Normalized temperature increase profiles of a human knee. Dotted line: heated with the microwave diathermy system. Solid line: heated with the resonant cavity applicator.

and the results met the safety standards of the International Commission on Non-Ionizing Radiation Protection, with values not exceeding 25 V/m for the lower limbs, hip, and inguinal regions, which were outside the cylindrical applicator.

DISCUSSION

When using microwave diathermy devices in the clinical setting, the temperature of the skin rises due to the shallow penetration of the electromagnetic waves produced by these machines. To raise the temperature deep tissue intra-articular cartilage in the human knee by 5–6 °C requires long-term high-temperature heating of the skin, subcutaneous tissue, ligaments, and bone surface adjacent to the region. Heating intra-articular cartilage with existing methods is difficult. The developed heat therapy system involves contact heating of the entire knee within a bipolar applicator that emits radiofrequency waves while the contact surface is cooled. A previous study reported that the application of heat in this manner markedly improved symptoms and joint function in cases of knee OA. In that report, the temperature of the inner parts of the knee joint was raised by 5–6 °C[9]. This radiofrequency diathermy using a bipolar applicator was compared with microwave diathermy, which is commonly used in Japan and one of several widely used deep heating modalities in outpatient physical medicine and rehabilitation clinics. Significantly, greater amelioration of knee OA symptoms was noted with radiofrequency diathermy[20]. However, the bipolar applicator has some disadvantages that make it impractical in the clinical setting: it is a large apparatus, limiting the number of locations it can be used; it is expensive; and frequent high-energy heating at 200 W without shielding from the applicator's electromagnetic waves could induce adverse reactions in other organs and tissues. The resonant cavity system developed in this study enables contactless heat therapy concentrated only on the deep tissue in the knee without any sensation of heat in the overlying layers through its low output of just 20 W. The results of this study confirmed that the normalized temperature increase value in cartilage is about 0.1 (10% of the maximum) when using the microwave diathermy system, whereas the same value when using the resonant cavity applicator is 0.8 (80% of the maximum) or more. Assuming a maximum temperature increase of 5 °C, the microwave diathermy system can raise the temperature of cartilage by only 0.5 °C, whereas cartilage can be heated by 4.0 °C or higher when using a resonant cavity applicator. The aluminum cavity shields prevent any emission of electromagnetic waves to areas other than the knee. This heat therapy system breaks new ground by enabling the heating of articular cartilage in a way that is safe for both the patient and therapist[10, 19, 20].

This study has some limitations. The first is that the measurement system used in this study could measure the distribution of temperature increase but not the physical temperature inside the knee tissue. Several studies using small animals reported that the expression of proteoglycan and type II collagen were upregulated when the knee joint was heated to approximately 40 °C and that the progression of OA was suppressed[5, 21]. In our previous study, the accuracy of this measurement system was verified by comparing the physical temperature of agar phantoms taken using a fiber optic thermometer with those taken using this measurement system[19]. To measure the physical temperature in a knee, it is necessary to measure the thermal properties of each tissue. In this research, physical temperatures in biological tissues were not measured, so there is a possibility that the temperature may not have reached the target temperature or that overheating occurred. However, there are no previous reports on non-invasive temperature measurements, and our method is considered a safe and simple way to obtain the temperature distribution inside the knee tissue. We are presently working to improve the measurement system to enable the measurement of the physical temperature in a knee. The second limitation is that the participants were healthy volunteers, so the effect on the OA knee is unknown. Therefore, we are planning to conduct a clinical study to investigate the safety and therapeutic effect in OA patients.

In conclusion, we confirmed that our deep tissue heat therapy system could be used to safely heat the deep tissue in a healthy knee joint. In the near future, we will investigate the effectiveness of this system for knee OA. If the system proves to be more effective than conventional heat therapy, it will open up new possibilities for the treatment of knee OA.

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Conflict of interest

One of the authors (KK) has a patent for the heat therapy system used in this study.

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