Microwave Ablation Efficacy Evaluation of Bone Tissue Based on Near Infrared Spectrum

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Abstract

Background:

Microwave hyperthermic tumor ablation has played an important role in the treatment of bone tumors because of its obvious curative effect, less side effects and fewer complications. The real-time evaluation of the curative effect in microwave ablation of bone tumors is a research tissue. In this paper, it proposes to study the ablation effect of bone tissue by near-infrared spectroscopy and optical parameters. First, bone tissue heating experiment was used to verify the difference in bone tissue near-infrared spectrum before and after heating.

Results:

In bone tissue microwave ablation experiment, it studied the changes of tissue near-infrared spectrum and optical parameters (reduced scattering coefficient, slope factor, area factor) during specific microwave ablation conditions. It was found that some factors (area(500-550), slope(524-532) and slope(565-570)) changed significantly, correlated with microwave ablation time, which could be used as evaluation factors of microwave ablation.

Conclusions:

The results lay a foundation for the development of a new method for real-time evaluation of ablation efficacy.

Background

Bone metastasis is one of the most common malignant bone tumors, accounting for 15–20% of the metastatic tumors¹. About 36% of the patients who died of malignant tumors had spinal metastases, who suffer from intolerable pain². Therefore, for patients with intractable bone pain, rapid pain relief has become an urgent task. Conventional treatment mainly includes analgesics, chemotherapy, hormone therapy, radiotherapy, and surgery^{3,4}. Among them, the application of ablation technology in local interventional treatment of bone tumors has been paid more and more attention in clinical application. Microwave ablation (MWA) has the advantages of significant curative effect, less trauma, less side effects and fewer complications, which has played a huge role in clinical cancer treatment, including liver cancer^{5,6}, lung cancer⁷, thyroid cancer⁸, colon cancer⁹ and other common tumors^{10,11}.

Liver cancer is the first cancer type to be used by MWA, and it has gradually become one of the reliable methods to treat and cure liver cancer since the 1990s¹². Studies have shown that the thermal damage of liver tissue under MWA is a dynamic process related to temperature and time^{13,14}. Some researchers have confirmed that thermal injury significantly affects the optical properties of liver tissue^{15,16}. However, there are few studies on the application of MWA in the treatment of bone and soft tissue tumors. The purpose of this study was to evaluate the feasibility, safety, and effectiveness of MWA for bone tissue.

As a special organization, bone tissue may have different characteristics from liver tissue. The inorganic content (calcium salt) of bone accounts for about 70%, and organic matter accounts for 30%, including the protein in blood and bone tissue¹⁷. Inorganic and organic compounds have different optical properties, which are complex in microwave ablation. Studies on dynamic changes reflectance spectrum with thermal damage in bone tissue are sparse and no evaluation factors or standards are available. In this paper, we establishment of bone model for the study of tissue parameter change in MWA. The research results can be used to develop a new real-time evaluation method of ablation efficacy.

Specifically, these bone models were chosen from porcine shank and built. First, bone tissue heating experiment was done to analyze the difference of near-infrared spectrum between the heated and fresh tissue. The purpose of the experiment is to verify the influence of inorganic/organic content on optical properties of bone tissue. Second, during MWA reflectance spectrum of bone tissue (cancellous bone) was measured by an optical parameter measurement system which was previously reported^{18,19}. Finally, different factors were calculated through the spectrum based on previous studies^{20,21}. All factors were compared from different aspects, such as sensitivity, accuracy and correlation. It was found the specific slope factor had a better performance in assessment of MWA efficacy. The experimental results could highlight a new method to assist in the bone tissue MWA therapy.

Results

1. Bone tissue heating experimental results

The results are shown in Fig. 1. In Group 1, there are more blood and water on the samples surface due to no drying. In Group 2, there are less blood and water than those in Group 1 because the blood on the surface had been cleaned. In Group 3, after the samples were heated, the protein would be destroyed and the inorganic substance remained. Meanwhile, after drying there are less water on the samples surface.

As shown in Fig. 1, the near-infrared spectra of samples in Group 1 and Group 2 are very similar. There are two distinct peaks on the left side of the spectrum, while the two peaks in Group 3 almost do not exist. These two peaks may be related to protein content. In addition, there are obvious differences between the two peaks in Group 1 and Group 2. The difference of peak value may be due to the difference of blood content on the surface of samples.

2. Bone tissue MWA experimental results

In spectrum measurement experiment, the near-infrared spectra of samples were measured after bone tissue ablation. In Fig.2(a), the bone tissue was sawn along the channel, and the tissue morphology after ablation could be observed. Figure 2(b) shows three spectra after ablation and three zones can be distinguished based on the results. The spectra from 300-700 nm are selected and normalized.

3. Optical parameter monitoring experimental results

In Fig. 3, it shows the change of 7 factors (three types of factors: reduced scattering coefficient, area factor, slope factor) during optical parameter monitoring experiment. The MWA experiment was carried out for 600 s. It is found that the factors between 360 s and 420 s has obvious changes. Before 360 s and after 420 s, the changes of all factors are consistent. Moreover, the factor changes are more obvious before 360 seconds. Before and after ablation, the reduced scattering coefficient is discriminative. But between 360 s and 420 s, it had no obvious change rule. Comparing the two area factors, between 360 s and 420 s the change of area(500-550) is more obvious than that of area(550-600). Comparing the five slope factors, it is found that there is no significant change in slope(500-520) curve and slope(575-590) curve. Before and after ablation, the changes of slope(524-532) and slope(565-570) are most obvious, and the values before ablation are negative, but positive after ablation. Slope(524-532) and slope(565-570) can be used as the evaluation factors of ablation effect.

Discussion

Thermal ablation therapy has been widely used in many benign and malignant solid tumors such as uterine fibroids, liver cancer, pancreatic cancer, osteoid osteoma^{22,23}. The technique is effective and safe, but there are still many scientific and technical problems to be solved in the application of microwave thermal ablation in bone tumor surgery. For example, it is not real-time and accurate to obtain the information of tissue thermal damage and thermal distribution during the operation. The real-time temperature cannot accurately reflect the ablation degree of tumor tissue. In addition, there is a lack of accurate and effective evaluation factor in microwave thermal ablation. The final ablation effect depends on the thermal ablation dose (power and time), but the dose still cannot describe the real-time thermal injury of tissues, so it is difficult to achieve accurate real-time intraoperative efficacy evaluation.

Near infrared spectroscopy technology has the advantages of high analysis speed, high analysis efficiency and low cost^{24,25}. It can realize non-destructive analysis and in vivo real-time monitoring, which can be used for non-destructive or minimally invasive detection of bone tumors. In previous studies, Li et al. carried out a real-time minimally invasive study of the vertebral tissue scattering characteristics based on near-infrared technology²⁶. In this paper, based on the pre-developed near-infrared detection equipment, the curative effect evaluation factors of bone tissue before and after microwave ablation were studied, and the changes of different factors were compared, which laid the foundation for quantitative evaluation of tissue thermal damage in microwave ablation.

It was found that the near infrared spectra of bone tissue before and after heating were different in Fig. 2. The bone tissue in Group 1 and Group 2 belongs to fresh tissue and contains fresh blood components, while that in Group 3 is boiled, the blood and other proteins contained in the tissue are denatured. It is possible that the presence of protein affects these two peaks, mainly the effect of hemoglobin. In addition, the blood content of bone tissue in Group 1 is fresh, while that in Group 2 is significantly reduced after soaking and drying, which means that the difference of peak value may be due to the difference of blood content on bone surface. Before and after microwave ablation, the changes of protein content in bone tissue can be studied by judging the near infrared spectrum of bone tissue.

Figures 3 and 4 show the changes of near infrared spectra and optical parameters during microwave ablation. Because the distance between the microwave ablation probe and the optical fiber probe is 1 cm, the optical fiber probe begins to detect the tissue changes after 360 s, and the tissue optical parameters begin to stabilize after 420 s. And before 360 s, the factors change more obviously, which may be due to the complexity of fresh tissue components. Comparing the two face factors, it can see that the change of area(500–550) is more obvious than that of area(550–600) between 360 s and 420 s. Comparing the five slope factors, it found that slope(500–520) and slope(575–590) do not change significantly. The changes of slope(524–532) and slope(565–570) were obvious, and the value was negative before ablation and positive after ablation. They can be used as evaluation factors of ablation effect

In this paper, various possible factors have been proposed for the evaluation of tissue efficacy, but it is still a long way to use these factors directly in the evaluation of intraoperative efficacy. First, due to the special structure of bone tissue, the detection distance of optical fiber probe is limited. It is difficult to predict the effect of microwave ablation in time. In the future research, the probe can be studied and improved to increase the detection distance. Moreover, we can combine with other technologies to realize the multimodal detection of microwave ablation effect. Second, the detection samples are limited. Porcine bone is like human bone in composition and structure [31], but many human bones are needed as samples to build the model. There are a lot of studies on the establishment of human liver tissue model, but the related research of human bone is still less and a lot of research are needed.

Conclusions

This paper presents a method to evaluate the microwave ablation effect of bone tissue based on near infrared spectroscopy. First, the difference of near infrared spectra of bone tissue before and after heating were verified. Then, the spectral changes of bone tissue before and after microwave ablation were studied and different factors were calculated according to the spectrum. After comparison, it was found that some factors could be used as evaluation factors of bone tissue microwave ablation effect. This study laid a foundation for the evaluation of microwave ablation effect of bone tissue.

Methods

1. MWA system

MWA includes microwave ablation instrument and ablation needle, which are commonly used in clinical treatment, shown in Fig. 4. The microwave ablation instrument (KY-2000, Nanjing kangyou Medical Technology Co., Ltd.) has a microwave emission frequency of 2450 MHz, which has two working modes: continuous wave and pulse wave. The microwave power is continuously adjustable in the range of 5-100 W, and the microwave action time is continuously adjustable in the range of 0-100 min. The maximum temperature is 99 °C and the resolution is 0.2 °C. The length of microwave ablation needle is 15 cm, and the outer diameter is 1.9 mm. It has the function of water circulation cooling by the peristaltic pump.

2. NIRS measurement system

The NIRS measurement system for bone tissue has been completed in the early study^{18,19}, shown in Fig. 4. It consists of a light source (HL-2000, Ocean optics), a fiber spectrometer (USB2000, Ocean optics), a dual optical fiber probe and a computer. The basic principle is that the near-infrared light emitted by the light source is incident to the tissue through optical fiber, and the light is transmitted to the receiving optical fiber after tissue absorption and scattering, and then converted by the optical fiber spectrometer and transmitted to the computer to obtain the near-infrared parameters of bone tissue. A computer program is used for spectral storage (300 to 1120nm) and optical parameter calculation in real time.

3. Bone tissue heating experiment

Fresh porcine bones were selected from mature pigs (38-45 kg). Before the experiment, the muscles and soft tissues on the surface of vertebrae were removed with a medical scalpel, and the bone (cancellous bone and cortical bones) was separated. A total of 30 bones were obtained and the cortical bones was removed with a medical scalpel.

Group 1: 10 cancellous bone (fresh bone tissue) were randomly divided into Group 1.

Group 2: The remaining 20 cancellous bone were first cleaned and soaked in deionized water for several hours, then dried at room temperature. 10 vertebrae (dry bone tissue) were taken as Group 2.

Group 3: The remaining 10 cancellous bone were boiled in deionized water until all the bone changes from red to brown. After that, the heated bones were washed and then immersed in deionized water. After several hours, the 10 bones were taken out and dried at room temperature (dry and cooked bone tissue), which used as Group 3.

In the experiment, the probe should be vertically and tightly contacted with the surface of cancellous bone, and the near infrared spectra were obtained. In order to reduce the experimental error, each point collects 10 data. For each bone, 15 points were selected along the midline. After all data were collected, t-test was performed on the data. It showed that there was significant difference in the spectra between the two groups if $P < 0.05$. In data processing, the 10 data at each point were averaged, and then 150 average values of 10 bone sparsely were statistically analyzed.

4. Bone tissue MWA experiment

Fresh porcine bones were selected from mature pigs (38-45 kg) and 40 bones were tested. Before the experiment, the bone tissue was sawed to expose the cross-section.

Spectrum measurement experiment: 20 bones were tested. On the cross-section, an electric drill with a diameter of 2 mm was used to drill a cylindrical bone channel with a diameter of 2 mm and a length of 1.5 cm parallel to the long axis of bone. After that, the bone was put into a water basin with constant temperature of 37 °C. During the experiment, the microwave power is about 70 W until 600 s. After the

experiment, the probe should be vertically and tightly contacted with the surface of cancellous bone, and the near infrared spectra were obtained. After all data were collected, t-test was performed on the data.

Optical parameter monitoring experiment: 20 bones were tested. Similarly, a cylindrical bone channel with a length of 2 cm was drilled. Then, drill the second channel in the same way and the distance between the two channels is 1cm. After that, the bone was put into a water basin with constant temperature of 37 °C. Microwave antenna and probe were both inserted into bone tissue according to the two channels, show in Fig. 1. During the experiment, the microwave power is about 70 W and the transmitting time is 600 s. After the real-time near infrared spectra were obtained and different factors were calculated, t-test was performed on the data.

5. Calculation of different factors

Reduced scattering coefficient: The details in calculation of reduced scattering coefficient were given in the previous research^{27,28}. This slope (700-850) of the spectrum was relevant to reduced scattering coefficient in some wavelength (e.g. 690 nm)²⁹. The empirical formula for calculating reduced scattering coefficient of diffuse reflectance spectrum in 700 nm ~ 850 nm band is as follows.

$$\mu'_s(690) = A \cdot \exp(B \cdot \text{slope}(700-850)) \quad (1)$$

where, slope(700-850) represents the slope of the linear fitting of diffuse reflectance spectrum in the band of 700 nm ~ 850 nm, $\mu'_s(690)$ represents the reduced scattering coefficient at 690 nm. A and B are the coefficients obtained through experiments (A is 4.52 and B is -0.32). This formula is used for real-time calculation.

Slope factor and area factor: Previous studies have found that the original spectra of cancellous bone and cortical bones are obviously different during 500-600nm³⁰. The slope factor $(\text{slope}(\lambda_1 - \lambda_2))$ is defined as the difference mode between the two peaks, as shown in formula (2). Different slope factors (slope(500-520), slope(524-532), slope(540-560), slope(565-570) slope(575-590)) were calculated respectively. Different area factors (area(500-550), area(550-600)) were calculated respectively. All factors were compared from sensitivity and accuracy. The factor with the largest difference can be used as the intraoperative evaluation factor

$$\text{slope}(\lambda_1 - \lambda_2) = \frac{\text{intensity}(\lambda_2) - \text{intensity}(\lambda_1)}{\lambda_2 - \lambda_1} \quad (2)$$

List Of Abbreviations

MWA Microwave ablation

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All authors were the contributor in writing the manuscript, they all read and approved the final manuscript.

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Figures

Figure 1

Near infrared spectra obtained from three groups

(a)

(b)

Figure 2

Spectrum measurement experimental results (a) bone tissue abated after 600 s (b) three spectra in different zones after ablation

(a)

(b)

(c)

(d)

Figure 3

The time dependents of optical parameter during ablation (a)Reduced scattering coefficient (b)Area (c)Slope (d)Slope

Figure 4

The MWA system and NIRS measurement system (1. Computer; 2. Light source; 3. fiber spectrometer; 4. Microwave ablation needle; 5. Optical fiber probe; 6. Vertebral model)