Study of applied tissue power in microwave ablation

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Abstract

Objective: Causing the different ablation results at the same power output or net power output, but the same applied tissue power can create the same ablation results. Calculating this value is the focus of research, which could provide accurate reference basis.

Methods: We took two methods (water specific heat capacity measurement and bio-heat transfer equation solution) to calculate the applied tissue power when power outputs were 40W, 60W and 80W. The first one is through measuring the raising temperature of water to calculate at thermal isolation environment. The other one is to calculate by bio-heat transfer equation according to the transient variation of temperature.

Results: When power outputs were 40W, 60W and 80W, the net power outputs were 39.4W, 57.5W and 74.7W by power instrument. The applied tissue powers were 32.2W, 46.6W and 58.5W by the method of specific heat capacity; by the other method, the applied tissue powers were 29.2W, 41.3W and 47.7W. Thus, we built the numerical relationship between the net power output and the applied tissue power to calculate applied tissue power efficiently. Meanwhile, this fitting equations are true by comparing applied tissue power through fitting equation with that calculated by the two methods at 70W power output.

Conclusion: Compared two fitting equations, the one by the method of bio-heat transfer equation is more suitable and has less error to calculate. And applied tissue power is an important reasonable reference to assist clinical guidance, which avoids the loss power to cause different and error results.

Keywords: The applied tissue power; Net power output; Water specific heat capacity; Bio-heat transfer equation;

Introduction

The tumor is one of the most dangerous diseases to human health and survival. According to previous studies and results, surgical resection is not the only method, and hyperthermia plays an important role in the treatment of tumor.

With the development of medical science, hyperthermia has two kinds of method, the local and whole body. And in the treatment of local body, microwave ablation(MWA) is the most great development in the field of tumor ablation. The mechanism of microwave ablation therapy takes advantage of specific conduction heating device and body's blood circulation to make the tumor internal temperature of 52℃[1] or above 60 ℃[2], and does not damage the normal tissue. This treatment aims to destroy the whole tumor and not to damage the surrounding healthy tissue. Sometimes, to make sure destruction the tumor completely, we need to have a 5mm margin of surrounding healthy tissue along the whole boundary of the tumor[3-4]. Compared with existing ablation technologies, microwave ablation will have better results consistently, larger coagulation, higher intratumoral temperatures, faster ablation times[5].

Due to the first success of treatment of small liver cancer through ultrasonic-guided percutaneous MWA[6], researchers have studied the material or structures[7] of antenna to achieve lager coagulation. In fact, they always consider the core wire material and exposed length of the radiation antenna[8], instead of ignoring the waste power of the antenna itself.

Unlike radiofrequency ablation, microwave energy is not an electrical current but rather a propagating electromagnetic field[9]. Thus, the longer time we spare to ablate the tumor, the more waste power antenna produces. In one word, the applied tissue power is the key to cause the ablation results. In the previous studies, looking for better antenna structures and materials to achieve the purpose of larger ablation zone blindly is our main object, which leads us to neglect the major factor. In addition, ignoring the applied tissue power makes confusion of the experiment data. Under the same initial conditions, the results of ablation zone are different. This could misunderstand the truth of experimental data and even influence clinical ablation effect. Therefore, grasping the applied tissue power is essential, which can consummate standardization and unification data of microwave ablation, as well as be benefit for clinical guidance and applications.

In this study, we adopt two methods to achieve our aim. Fist one is relate to water specific heat capacity, and another one is about bio-heat transfer equation. Moreover, several assumptions have been offered to use water specific heat capacity from energy transfer. So we can do experiment to measure the applied tissue power. The reason using two methods measure the applied tissue power on the different power output and heating-up time conditions is to demonstrate the accuracy of experimental results.

Methods

In previous experiments and studies, many works have ignored the crucial factor of power loss, including transmission loss and other loss, to lead some faulty studies. Thus, considering the lose energy is benefit for studies to improve the feasibility and accuracy of experimental data. What is more, transmission loss could be calculated by dynamometer. Using standard symbols, the governing equations describing the imposed energy phenomenon are given as follows:

$$p_1 = p - p^{'} \qquad (1)$$

where p_1 is the net power output(W), p is the imposed power(W), $p^{'}$ is the loss power of cable(W). And the net power output is measuring by power meter without the power of cable(in Fig.1). However, the applied tissue power excludes not only the loss power of cable, but also the loss power of antenna itself, which is the whole power to be absorbed by tissue. Fig.1 shows the distribution of different powers.

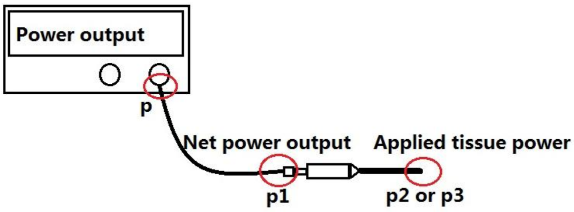


Figure1. The distribution of different powers

Water specific heat capacity measurement

The specific heat capacity is the absorbed energy of unit mass when the temperature is increasing by 1℃. This word is connected with energy and temperature which is relate to our study without other influencing factors. The power of microwave is becoming the absorbed energy per second of water to increasing the water temperature. And due to the large value about water specific heat capacity, changes of the water temperature, compared with other substances, will be small at the same conditions. So it has a great feasibility to study the applied tissue power through using water specific heat capacity. The equation describing the heat transfer phenomenon in water is given by:

$$Q_{r1} = cm\Delta T \qquad (2)$$

where Q_{r1} is the absorbed energy of water, which is the applied tissue energy(J); c is the water specific heat capacity($4.2 \times 10^3 J/(kg \cdot ℃)$); m is the water quality(kg); ΔT is temperature difference(℃).

Among that, we should do experiments to get the value of water quality and temperature difference. We use the antenna insert water, and release energy to cause heating in the special organic glass with heat preservation. Then we applied the thermometer to observe and record temperatures at different times(before the heating starts and after the heating ends). In order to have accurate data, we apply 10 minutes[10] in the heating up time to ensure that the water temperature is diffusing equably on the different powers. Finally, though formula of specific heat capacity, we can get the results of water absorbed energy.

According to the physics knowledge, the relationship between energy and power is as follows.

$$p_2 = Q_{r1}/t \qquad (3)$$

Where Q_{r1} is the absorbed energy of water(J),t is the heating up time(s); p_2 is the applied tissue power(W).

To make sure the importance and significance of p_2, we choose the ratio η_1 to explain the relation of applied tissue power and net power output.

$$\eta_1 = \frac{p_2}{p_1} \times 100\% \qquad (4)$$

Bio-heat transfer equation

The treatment of microwave ablation is based on the Pennes' bio-heat transfer equation[11], which has been widely used in the biological heat transfer field. It is followed by:

$$\rho C\frac{\partial T}{\partial \tau} = \nabla \cdot K\nabla T + W_b C_b (T_a - T) + Q_m + Q_r \qquad (5)$$

where ρ is the tissue density(kg / m^3); C is tissue specific heat capacity($J/(kg \cdot ℃)$); K is the thermal conductivity of tissue($J/(m \cdot s \cdot ℃)$); T is the temperature of tissue(℃); τ is the time (s); C_b is the specific heat capacity of blood($J/(kg \cdot ℃)$); W_b is the blood perfusion rate(kg/ (m^3·s)); T_a is the blood temperature in the heating zone; Q_m is the heat energy of biological tissue($kg/(m^3 \cdot s)$); Q_r is the energy of the external heat quantity.

In the ex vivo experiment, there is no metabolism and blood flow perfusion. Besides, Sherar MD[12] considered that if the duration time of the energy emission could keep less than 10s, the influence of thermal diffusion in tissue could reduce to minimize. Because the influence of temperature changes only depends on microwave energy, and the factors of heat conduction and convection is not considered. Moreover, the thermal conductivity is ignored due to 10s heating-up time. On this condition, the equation(5) could be simplified as:

$$\rho C\frac{\partial T}{\partial \tau} = Q_r \qquad (6)$$

According to our previous studies and experiments, Q_r is equal to specific absorption rate[13]. Thus, $\partial T / \partial \tau$, which describes temperature rise curve, represents slope between temperature and time, as well as it is the crucial numerical value to achieve the purpose of calculating applied tissue power in our study. Consequently, in order to compute Q_r , we should get the slope between temperature and time at the first ten seconds in the experiment.

In the experiment, we use some temperature needles of thermocouple to capture changes of temperatures at different points. On account of slope which indicates per-point of measuring temperature in temperature rise curve, Q_r indicates the power per unit volume. Thus we should apply integration algorithm to calculate the whole power that is the applied tissue power. Based on the volume, calculate the whole power is following as equation(7).

$$p_3 = \iiint Q_r dV \qquad (7)$$

At the same principle, we also measure the net power output from the formula(1). In statistics, the ratio between applied tissue power and net power output could predict influence of applied tissue power in experiments and emphasizes the importance as well as significance of this study.

$$\eta_2 = \frac{p_3}{p_1} \times 100\% \qquad (8)$$

According to the method of bio-heat transfer equation, we chose a special material to make a tissue phantom, which is similar to livers in thermophysical parameter[14] (Table 1). Instead of ex vivo liver, this tissue phantom could avoid the other factors to affect the ablation results

Table 1 The parameters of the tissue phantom and liver

	$\rho\,(kg/m^3)$	C$(J/(kg\cdot℃))$	$\sigma\,(s/m)$
tissue phantom	1.070	3567	0.116
liver	1.060	3600	0.148

Results

In this study, we have calculated the results of applied tissue power and net power output by above-mentioned two methods at the same initial conditions including the same power 40W, 60W and 80W respectively.

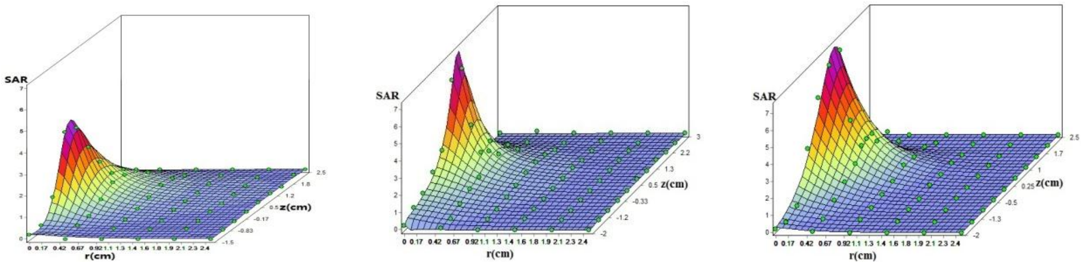
On the basis of the specific heat capacity method, the experiments were divided into three groups, including 40W, 60W and 80W. Meanwhile, the heating-up time was all set as 600s[10], which caused the homogenization of the temperature distribution to get accurate data. Besides, we have taken experiments of every group to repeat five times so as to reduce the artificial errors. When power output was 40W, the net power output was about 39.4W. Moreover, we calculated that the applied tissue power by the method of specific heat capacity was 32.2W, and the percentage η_1 was 81.73%. The detail result is as table2 below.

Table2 Net powers of different power outputs

	net power output(p_1)	applied tissue power(p_2)	the ratio(η_1)
40W	39.4W	32.2W	81.73%

60W	57.5W	46.6W	81.04%
80W	74.7W	58.5W	78.31%

According to the other method, bio-heat transfer equation, we have also calculated the net power output and applied tissue power. Based on the fitted equation and multiple integral to get the results, different distributions about power per unit volume were showed as Fig.2.



(a)The power output is 40W (b)The power output is 60W (c)The power output is 80W

Figure2. The different distributions of SAR

In Table3, when the power output was 40W, the net power output was about 39.4W, and the applied tissue power was 29.2W, the percentage η_2 is 74.11%. Besides that, we found that when we set power output as 60W, the net power output was about 57.5W, the applied tissue power was 41.3W. So the percentage to illustrate the power utilization was 71.82%. Furthermore, in case of power output 80W, the net power output and applied tissue power were about 74.7W and 47.7W, respectively. What's more, the percentage was 63.86% shown in Table 3. As we known, with the power output increasing, the net power output and applied tissue power were rising in sequence. However, it showed that the rising range of the applied tissue power was smaller and smaller with increasing the power output, this meant that the power output was higher, the power loss was more. Moreover, the change of power loss was nonlinear.

Table3 Net powers of different power outputs

	net power output(p_1)	applied tissue power(p_3)	the percentage(η_2)
40W	39.4W	29.2W	74.11%
60W	57.5W	41.3W	71.82%
80W	74.7W	47.7W	63.86%

In experiment, the net power output could be measured by power instrument. But calculating the applied tissue power is very difficult. To get the applied tissue power efficiently, building the numerical relationship between the net power output and the applied tissue power is the best way. Owing to the limitation of valid data, we have fitted the curve when the net power output was from 0W to 80W. Fig.3 is presented two curves to illustrate tendency of applied tissue power with increasing the net power output between the two methods. Based on the fitting curves, we got the fitting equation, and the fitting equation is as Equation (9) by the method of water specific heat capacity. And the other formula is showed as Equation (10) by the second method of bio-heat transfer equation.

$$y_1 = -3.428663 \times 10^{-5} x^3 + 2.945353 \times 10^{-3} x^2 + 7.544372 \times 10^{-1} x + 5.173639 \times 10^{-15} \quad (9)$$
$$y_2 = -9.550572 \times 10^{-5} x^3 + 7.991748 \times 10^{-3} x^2 + 5.745011 \times 10^{-1} x + 3.352874 \times 10^{-15} \quad (10)$$

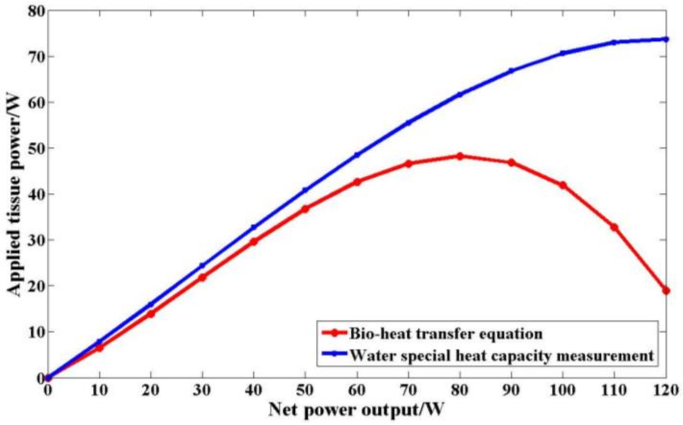


Figure3. The power curve by fitting equation

To validate the rationality of this equation, we made an experiment of 70W power output by the two methods. When the power output was 70W, the net power output was 69.1W, and the applied tissue power was 45.4W by the method of bio-heat transfer equation. Additionally, the applied tissue power was 46.3W by fitting equation of power curve. In a similar way, the net power output was 69.1W, and the applied tissue power was 53.2W by the water specific heat capacity and the data 54.88W by fitting equation of power curve.

Discussion and Conclusion

In this study, we presented the results of net power output and applied tissue power by two different methods. According to the results, the range between the applied tissue power and the net power output is changing larger and larger as the power output increasing. However, the power loss by the method of water specific heat capacity is smaller than that by the method of bio-heat transfer equation. Among that, the rates of applying the tissue power are 81.73%, 81.04% and 78.31% respectively by the method of water specific heat capacity. And the rates are 74.11%, 71.82% and 63.86% in the situation of bio-heat transfer equation method. It's observed that the gap of power conversion between the two methods is from 7.62% to 14.45%. The percentage implies that with the net power output increasing, percentage is reducing gradually, which illustrates that net power output is higher and the heat loss is more. Consequently, it’s essential to calculate the applied tissue power to help doctor to achieve the best effect of microwave ablation in clinic.

It was reported that studying the applied tissue power was calculated in the ex-vivo and in vivo experiments[10]. When the power output was 80W, the applied tissue power was 47.3W in ex-vivo experiments. In our study, the applied tissue power is 47.7W by the method of bio-heat transfer equation while the power output is 80W. But the applied tissue power is 58.5W by the other method. Compared between them, the error(0.85%) by the method of bio-heat transfer equation is much less than that(22.64%) by the method of water specific heat capacity. Owing to thermal loss, it's inevitable to cause inaccuracy in the experiment by the method of water specific heat capacity, which leads to measure aberration of temperature. In the experiment, as the water heats up during the ablation procedure, the temperature becomes higher and higher, but the effect of heat preservation is not as good as assumption. Because it will take long time to release into the water completely and spread evenly to lead water to have a balanced temperature in microwave ablation. As a result, thermal loss and unbalanced temperature engender inaccurate data to get deviation of applied tissue power. Thus, compared with the method of water specific heat capacity, the other method is very precise to calculate the applied tissue method.

For the sake of verifying the best method to calculate the applied tissue power, we have compared the whole applied tissue powers through the two fitting curves with other study[15]. In Table4, it's presented the applied tissue powers of calculating two equations and other's study results, as well as the percentage errors between them. It can be seen that percentage errors about Eq.(10) are all smaller than those about Eq.(9). Among that, the whole percentage errors are all less than 8.76%. What is more, when the net power outputs are 45W, 57W, 64W and 71W respectively, the percentage errors are 0.91%, 2.50%, 1.11% and 2.90% in sequence. So the equation(10) could be applied to calculate the applied tissue power according to the net power output. Nevertheless, the percentage errors about Eq.(10) are 8.76% and 6.47% perceptively when the net power outputs are 37W and 75W. So the limitation is not to be neglected, and the range of application about this equation is between 37W and 75W of net power output.

Table4 The comparison of applied tissue powers

net power output in previous study	37.0W	45.0W	57.0W	64.0W	71.0W	75.0W
applied tissue power in previous study[15]	25.1W	33.0W	40.0W	45.0W	48.3W	51.0W
power by equation(9)	30.2W	36.7W	46.2W	51.3W	56.1W	58.7W
power by equation(10)	27.3W	33.3W	41.0W	44.5W	46.9W	47.7W
percentage error about Eq.(9)	20.32%	11.21%	15.50%	14.00%	13.90%	15.10%
percentage error about Eq.(10)	8.76%	0.91%	2.50%	1.11%	2.90%	6.47%

Depending on the power curve, we could achieve the aim to get the applied tissue power according to the net power output, not using complicated algorithmic method any more. Likewise, this research of the applied tissue power is important and it can reduce unsuccessful operations caused by many uncertainties in clinic, especially uncertain applied tissue power which is the biggest effect factor in microwave ablation. Owing to our data validation, the power curve by the method of bio-heat transfer equation as shown in Figure2, is suitable for calculate the applied tissue power. This fitting equation of power curve is scientific and reasonable to apply to compute applied tissue power, which is also attributed to our clinical treatment.

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