International Journal of Medical, Medicine and Health Sciences
ISSN: 2517-9969
Vol:6, No:5, 2012

Uniform Heating during Focused Ultrasound Thermal Therapy

To-Yuan Chen, Tzu-Ching Shih, Hao-Li Liu, and Kuen-Cheng Ju

***Abstract*—**The focal spot of a high intensity focused ultrasound transducer is small. To heat a large target volume, multiple treatment spots are required. If the power of each treatment spot is fixed, it could results in insufficient heating of initial spots and over-heating of later ones, which is caused by the thermal diffusion. Hence, to produce a uniform heated volume, the delivered energy of each treatment spot should be properly adjusted. In this study, we proposed an iterative, extrapolation technique to adjust the required ultrasound energy of each treatment spot. Three different scanning pathways were used to evaluate the performance of this technique. Results indicate that by using the proposed technique, uniform heating volume could be obtained.

***Keywords*—**focused ultrasound, thermal therapy, uniform heating, iteration, extrapolation, scan

I. Introduction

HIGH intensity focused ultrasound (HIFU) is a new modality for ablating solid tumors, such as uterine fibroids [1] and benign prostate hyperplasia [2] and cancers of liver [3], kidney [4], prostate [5] and breast [6]. The nature of focused ultrasound is that the ultrasound energy can be focused to induce a localized high temperature region and result in irreversible tissue necrosis. Because the focus of a HIFU transducer is small and the resulting treatment spot is also small. To heat a large tumor, several treatment spots distributed throughout the target volume and heated one by one. If the energy delivered to each treatment spot is fixed, it could resulted in insufficient heating of the intervening tissues between initial spots and over-heating of later spots, which is caused by the effects of thermal diffusion. Hence, to produce a uniform heated volume, the energy delivered to each treatment spot should be properly adjusted.

Zhou et al. [7] proposed an iterative, linear extrapolation method to adjust the pulse numbers of treatment spots to get a uniform thermal lesion. The iteration was repeated until uniform lesion was obtained. It usually takes 5~10 iterations. However, the relationship between the deposited HIFU energy and the resulting thermal dose is not linear. In this study, we modified Zhou's study to accelerate the converge speed of iteration.

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Simulation results show that, the proposed method takes only 1~2 iterations to get a uniform heating. This technique could be an alternative optimization method for uniform heating during HIFU thermal therapy.

II. Methods

A. System Configuration

The HIFU transducer used in this study is similar to the Yuande HIFU system (FEP-BY02, Beijing, China), which consists of 251 plane disk PZT elements. Each element is driven at 1 MHz, in phase and arranged on a concave spherical surface, resulting in a large, geometrically focused HIFU transducer with a diameter of 33.5 cm and a radius of curvature 26 cm. For simplifying the simulation, we use a spherically focused transducer with the same diameter and radius of curvature instead, as shown in Fig 1. The HIFU transducer is driven at a burst mode with a fixed output power. The deposited energy at a treatment spot could be controlled by adjusting the pulse number.

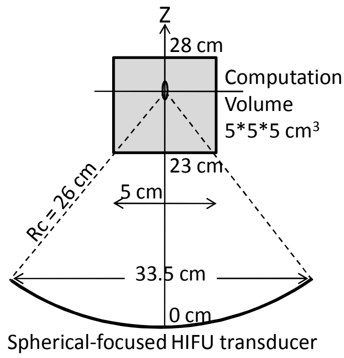

Fig. 1 System configuration of the HIFU system

B. Scanning Pathway

In a treatment, a number of treatment spots are sequentially sonicated to produce the desired heating patterns. Conventionally, raster scanning is used in clinical HIFU treatment. Zhou et al. [8] proposed two new scanning pathways and evaluated the effect of different scanning pathways on lesion production. In this study, we followed Zhou's study on the settings of the arrangement of treatment spots and the scanning pathway. 25 treatment spots were distributed in a shape of a diamond with a grid of 4 mm. Figures 2(a) to 2(c) show the arrangement of treatment spots and three different scanning pathways, raster scanning, spiral scanning from the below

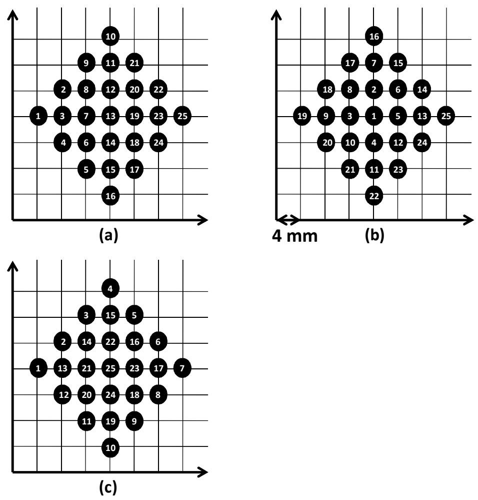

Fig. 2 Scanning pathway used in this study. (a) raster scanning, (b) spiral scanning from the center of the treatment area to the outside and (c) spiral scanning from the outside to the center

C. Acoustical Model

The acoustic model was a simple water–tissue model. Assuming the density and the speed of sound in the two layers are close, the reflection and refraction at the water–tissue interface can be ignored [9]. The acoustic pressure field generated by the ultrasound transducer was calculated by using the Rayleigh–Sommerfeld integral to sum up the contribution of each point source on the surface of the transducer.

$$p(x,y,z) = \frac{i\rho ck}{2\pi}\int u \frac{e^{-(\alpha+ik)(r-r')}}{|r-r'|}dS \tag{1}$$

Parameters used in our simulation are listed in Table I. The absorbed power density can be obtained from

$$q = \frac{\alpha|p|^2}{\rho c} \tag{2}$$

where α is the ultrasound absorption coefficient of tissue, ρ is the tissue density, c is the speed of sound. In this study, the absorption coefficient was set to be the same as the attenuation coefficient of the ultrasound within tissues, assuming that the attenuated power is absorbed locally.

D. Thermal Model

The temperature response produced by focused field can be calculated by the bioheat transfer equation (BHTE) [10]

$$\rho c_t \frac{\partial T}{\partial t} = k\nabla^2 T - w_b c_b (T - T_{ar}) + q \tag{3}$$

The absorbed acoustic power deposition q obtained from equation (2) was substituted into the BHTE and a three-dimensional finite difference method was used to determine the temperature response.

A thermal dose (TD) is used to quantify the effect of emperature and heating duration on tissues and to estimate the necrotic tissue volume, and it was numerically modeled using the following equation [11-12]:

$$TD = \int_{t_0}^{t_f - t_0} R^{(T-43)} dt \tag{4}$$

where R = 2 for $T \geq 43°C$ and R = 4 for $37°C < T < 43°C$. t_0 is the start time of heating and t_f is the time when temperature is 37°C. The range of the thermal dose causing necrosis for soft tissue is from 50 to 240 min [13-14]. In this study, a 240 min thermal dose was considered to be the threshold value for successful treatment.

E. Procedure of Pulse Number Adjustment

In Zhou's study [7], they proposed an iterative procedure to find appropriate pulse number of each treatment spot to get a uniform heating. The flowchart of the iteration procedure is shown in Fig. 3. They did not describe the detail of how the pulse numbers were updated. We hypothesize the new pulse numbers were obtained by the linear extrapolation equation:

$$x^* = \frac{y^* - y_{k-1}}{y_k - y_{k-1}} \times (x_k - x_{k-1}) + x_{k-1} \tag{5}$$

where y is the thermal dose, x is the pulse number. y^* is the expected thermal dose (240 min, in this study) and x^* is the predicted pulse number. The subscript k and k-1 indicate current and previous data, respectively. In Zhou's study, it takes 5~10 iterations to converge and a uniform heating volume can be obtained. However, in Eq. (3) and (4), it is clear that the relationship between accumulated thermal dose and delivered ultrasound energy is faster than a linear relationship. A simple linear extrapolation could result in an over-estimated pulse number, and consequently follows slow convergence. We modify Eq. (5) into

$$x^* = \sqrt[4]{\frac{y^* - y_{k-1}}{y_k - y_{k-1}}} \times (x_k - x_{k-1}) + x_{k-1} \tag{6}$$

and evaluate its performance of uniform heating.

The initial pulse number of each treatment spot was 60 pulses. In each HIFU pulse, the transducer was turn ON for 0.15 s and turn OFF for 0.15 s. Between each treatment spot, it took 6 s for a short cooling. After completing all treatment, the calculation of BHTE and thermal dose was kept going until the maximum temperature was lower than 43°C. The accumulation of thermal dose is very slow when temperature is lower than 43°C.

TABLE I
PARAMETERS USED IN ACOUSTIC AND THERMAL MODEL

Symbol	Parameters	Value
c	speed of sound	1500 m/s
ρ	tissue density	1000 kg/m^3
α	absorption coefficient	5 Np/m
K	thermal conductivity	0.5 W/m°C
c_t /c_b	specific heat(tissue / blood)	3770 J/kg°C
w_b	blood perfusion rate	5 kg/m^{3}s

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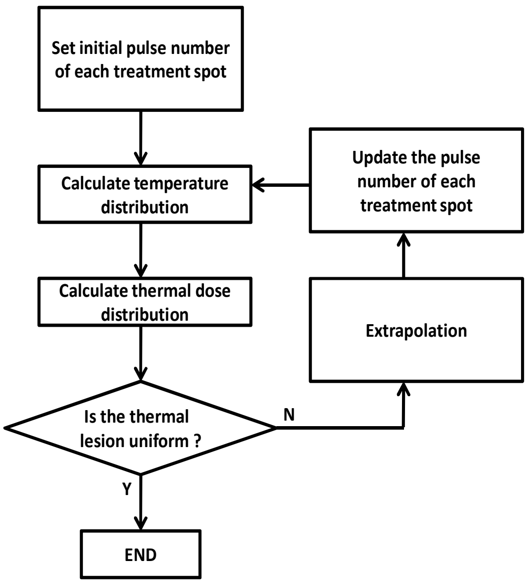

Fig. 3 The iterative procedure for finding pulse number of each treatment spot to achieve uniform heating

III. Results and Discussion

Fig. 4 shows the simulation result when 60 pulses were used for each treatment spot. It is obvious that 60 pulses are not enough to supply sufficient energy deposition on treatment spots; the intervening tissues among treatment spots were not completely heated to the therapeutic threshold of thermal dose.

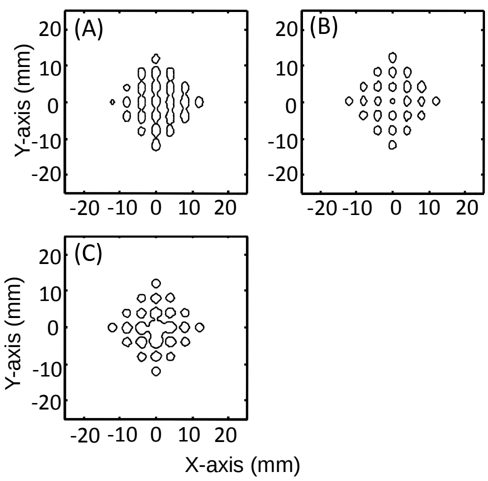

Fig. 4 Simulation results when 60 pulses were supplied to each treatment spot. (A)-(C) show the contour of thermal dose 240 min for scanning pathway corresponding to Fig. 2

After the iteration procedure, the pulse number of each treatment spot using different pathways are shown in Fig. 5, and the resulting thermal dose distributions are shown in Fig. 6. For raster scanning, the pulse number of the treatment spots at the boundary (# 1,2,4,5,9,10,16,17,21,22,24 and 25) were found to be larger than others at the central portion.

Similarly, beginning treatment spots need more pulses to overcome thermal conduction at the boundary for spiral scanning from outside to the center and vice versa for spiral scanning from the center to the outside. Although the scanning pathway and the total pulse number were different, the resulting thermal dose contours were similar. The total pulse number for three different scanning pathways were 3611, 4423 and 4855, respectively. This indicates that the raster scanning needs less treatment time comparing to the other two scanning pathways.

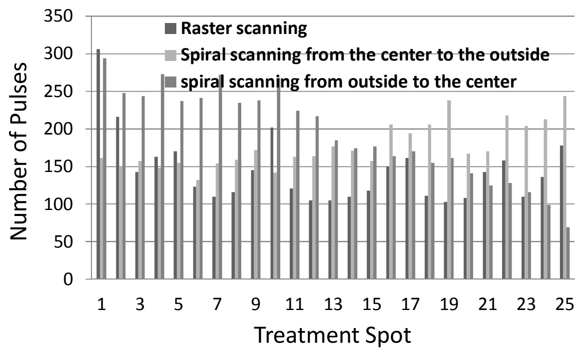

Fig. 5 The pulse number of each treatment spot using different scanning pathway

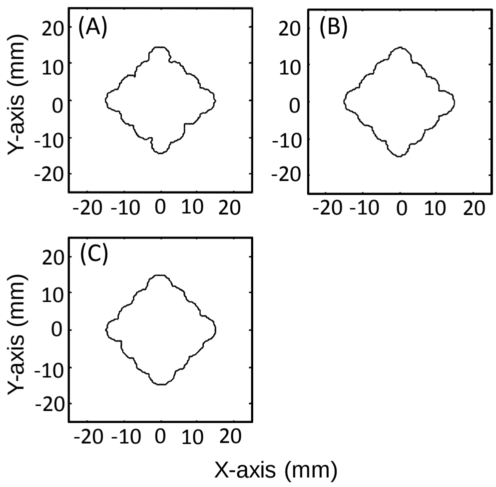

Fig. 6 Simulation results when heating pulses were adjusted by the iteration procedure and supplied to each treatment spot. (A)-(C) show the contour of thermal dose 240 min for the scanning pathway corresponding to Fig. 2

IV. Conclusion

The required HIFU pulse numbers for uniform heating are different in various heating sequence of treatment spots. As expected, the treatment spots at the boundary need more HIFU pulses to overcome the thermal conductions to the unheated region. By using the proposed iteration procedure, temperature at the intervening tissues between treatment spots could be raised and accumulate sufficient thermal dose to a therapeutic level. Comparing to previous study, the iteration number was reduced from 5~10 times to 1~2 times. This technique could be used to optimize the required ultrasound energy delivered to each treatment spot.

ACKNOWLEDGMENT

This work was supported in part by National Science Council of Taiwan with Grant No. NSC 100-2221-E-214 -022 and NSC 99-2632-E-214-001-MY3-2.

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