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Analysis of Heat Caused by Ultrasound Radiation in Tissue Phantom with Blood Vessel

血管を有する生体ファントム内の超音波照射により発生した熱の解析

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1. Introduction

Ultrasound diagnostic equipment using ultrasound pulse-echo techniques are characterized as minimally invasiveness and high versatility. It is known as very useful diagnostic method in many medical fields. Recently, ultrasound diagnostic imaging system using acoustic radiation force impulse (ARFI) has been developed. However, the safety standards for ultrasound diagnostic equipment IEC 60601-2-27 is not considered about a new technique such as the ARFI imaging system. In addition, temperature rise caused by ARFI condition is not shown clearly. For the safety of ultrasound diagnostic equipment, it is very important to research about the temperature rise in human organism caused by radiating ultrasound. Temperature rise caused by ultrasound radiation have been reported [1-2]. Many reports have assumed that blood vessels have no cooling effect to temperature rise caused by radiating ultrasound. One of the functions of blood, however, is to keep temperature constant in human tissue. Therefore, cooling effects of blood flow have to be taken account for the precise estimation of the temperature rise in the human organs.

Purpose of this study is to analyze temperature rise caused by focused ultrasound radiation in tissue phantom with the blood vessel. It is assumed that the blood vessel locate near the focal area. In this study, cooling effect of blood flow in tissue phantom is analyzed by heat flow analysis.

2. Analysis method

The numerical analysis is combined with finite difference time domain (FDTD) method and heat conduction equation (HCE) method in three-dimension [3]. Soft tissue is assumed to be liquid and analyzed by an acoustic FDTD method. Actual wave propagation in the blood vessel requires an acoustics streaming analysis. However, it is assumed that flow velocity in the blood vessel is lower than sound speed extremely. Therefore, acoustics flow is not considered in FDTD method in this study. For analyzing heat flow analysis in the blood vessel, heat conduction equation is changed as following equation [2].

$$\rho c_t \frac{\partial T}{\partial t} + (\boldsymbol{v} \cdot \mathrm{grad})T = \lambda \nabla^2 T + q \qquad (1)$$

Where T is temperature, λ is thermal conductivity, c_t is specific heat, q is calorific value per unit time and $\boldsymbol{v}$ is flow velocity. If flow direction is assumed unidirectional and if term of velocity in convective equation is assumed constant, normalized velocity distribution is required approximately as following equation.

$$\boldsymbol{v} = \frac{e^{Re} - e^{xRe}}{e^{Re} - 1} \qquad (2)$$

Where Re is Reynolds number, x is distance from surface and center of the blood vessel. Sound intensity distribution which is analyzed by FDTD method is transformed into calorific value per unit time q, as follows next equation, $q=2aI$. Where, a is attenuation coefficient, I is sound intensity. At the last, a temperature rise caused by ultrasound energy can be analyzed by HCE method inclusive of the calorific value.

3. Analysis and results of heat in tissue phantom with blood vessel

Analysis model on y-z plane in three-dimension model is shown in **Fig. 1**. Sound source in analysis is a concave focused transducer: Frequency 1 MHz, ϕ=28 mm, focus 50 mm. Blood vessel radius r is 4 mm. Speed of blood flow is 6.2 cm/s constant. Radiation conditions are as follows: Sound intensity I_{SPPA}=1 kW/cm^2, duty ratio 2% (Radiation time 200 μs), total radiation time is 30 s.

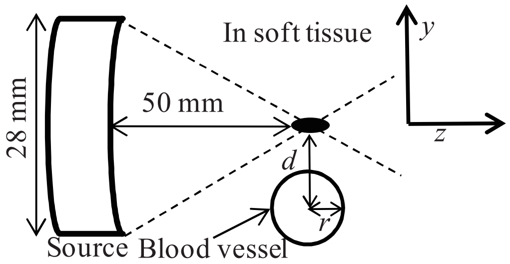

Fig. 1 Analysis model

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For obtaining blood's cooling effect, distance *d* between center of the blood vessel and focal point are decides in 6 mm and 9 mm. Physical parameters of the media used in the analysis are shown in **Table 1**. These parameters are referred to physical parameters of the tissue phantom that was made of water, agar, glycerin, *et. al.* [4]. Analysis results of temperature distribution in *y-z* axis are shown in **Fig. 2**. In the case of *d*=6 mm, temperature near the blood vessel is lower than the result of the only soft tissue. In addition, cooling effect of blood flow is appeared in focal area. However, in the case of *d*=9 mm, it is obtained that cooling effect of blood flow is not appeared in focal area. Time change of temperature rise at focal point is shown in **Fig. 3**. Rest time of 60 s after finished radiation is added as a result of Fig. 3. In the case of *d*=6 mm, cooling effect of blood flow is appeared at focal point after about 10 s from radiation start. In addition, it is obtained that temperature is cooled about 0.25 °C by blood flow at finished radiation. In the case of *d*=9 mm, cooling effect of blood flow is very little even if time passed 60 s from finished radiation. Difference in time change of temperature rise between the only soft tissue and with the blood vessel is shown in **Fig.4**. In the case of *d*=6 mm, cooling effect of blood flow becomes large gradually while radiating ultrasound, and maximum cooling effect at focal point is about 0.3 °C. However, in the case of *d*=9 mm, temperature is not cooled while radiating ultrasound, and cooling effect of blood flow is appeared slightly after finished radiation. It is thought that cooling by blood flow is not appeared while radiating ultrasound, because heat cooling by blood flow is very lower than generating heat by ultrasound radiation.

4. Conclusions

In this study, temperature rise in tissue phantom with the blood vessel is obtained by numerical analysis. When distance between center of the blood vessel and focal point is 6 mm, heat cooling by blood flow was about 0.25 °C at finished radiation. In the case of 9 mm, generating heat by radiating ultrasound is hardly cooled even if time passed 60 s from after finished radiation.

Future work, blood flow is modeled the beat of the heat, and temperature rise in tissue phantom with the blood vessel will be analyzed.

Table 1 Physical parameters of media

Parameter	Tissue phantom	Blood vessel
Attenuation coefficient [dB/cm/MHz]	0.38	0.18
Sound speed [m/s]	1525	1570
Density [kg/m^3]	1056	1070
Specific heat [J/kg/K]	3688	3860
Thermal conductivity [W/m/K]	0.64	0.54

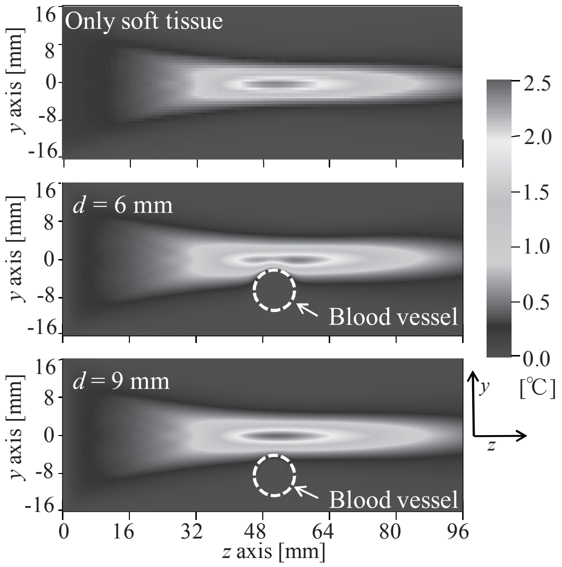

Fig. 2 Temperature distribution on y-z axis

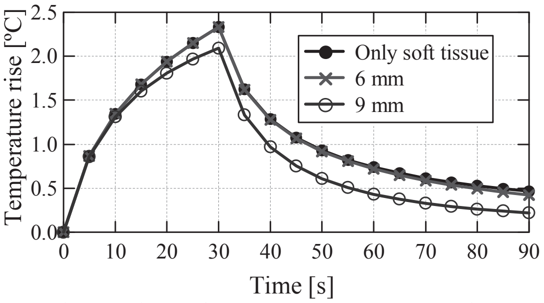

Fig. 3 Time change of temperature rise at focal point

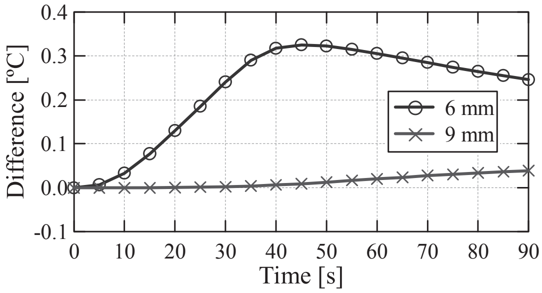

Fig. 4 Difference in time change of temperature rise at focal point

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