HEATING PATTERNS OF CYLINDRICAL ULTRASOUND TRANSDUCERS FOR BREAST TUMORS

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ABSTRACT

The purpose of this paper is to examine the optimal driving frequency and to configure the ultrasound energy deposition schema for a various size and location of breast tissues when a portion or the entire cylindrical ultrasound transducer is employed for breast hyperthermia treatments. This work employs a computer simulation program based on an ideal ultrasound power deposition from a cylindrical transducer. The distribution of specific absorption rate (SAR) ratio is employed to determine the heating pattern of a set of given parameters. The control parameters considered are the ultrasound frequency in the breast tissue, the active portion of cylindrical transducer, and the shifting distance between the central axes of the breast and the transducer. The effect of the breast size on the SAR ratio is also considered. Simulation results demonstrate that the breast size, the ultrasound frequency in breast tissue, the shifting distance and the active portion of cylindrical transducer are the potential parameters for influencing the distribution of SAR ratio. The distribution of SAR ratio indicates the domain of treatable tumor size and tumor depth for a given set of parameters (driving frequency, shifting distance and active portion of transducer, as well as breast diameter).

Key Words: Cylindrical ultrasound transducer, Breast tumors, Treatable domain, Optimal frequency, Shifting distance, Active portion.

INTRODUCTION

Mitsumori et al. [1] employed an ultrasound hyperthermia system with an improved planar transducer and the frequency scanning technique to minimize the hot spots and to provide improved specific absorption rate (SAR) distribution. A more advanced hyperthermia treatment system with a cylindrical transducer array applicator mounted on a three-dimensional translation table has been developed and assessed by Lu and Hansen et al. [2-3]. The system is designed to heat individual quadrants or the complete breast to a uniform temperature distribution. This work employs a simplified model for cylindrical ultrasound transducers to examine the relationship between the parameters and the distribution of specific absorption rate (SAR) ratio in the breast. The parameters, which might influence the

distribution of SAR ratio and are investigated, are the breast size, ultrasound frequency in the breast tissue, combination of ultrasound frequencies, the shifting distance and the active portion of transducer. The results demonstrate that 1) high frequencies should be used for the superficial heating treatments, and the variation of active portion of transducer can be used for obtaining a region with an appropriate SAR ratio to cover the treatment region; 2) low frequencies are appropriate for deep heating treatments and the region of high SAR ratio can be moved by shifting the transducer and its pattern is varied with the active portion of transducer; 3) the combination of low and high frequencies can be used to obtain a portion or the entire breast with more uniform SAR ratio.

METHODS AND MATERIALS

The deposition of ultrasound energy within the breast is modeled as a cylindrical transducer with uniform power emitted from the active portion of transducer face as shown in Fig. 1.a. The central axis of transducer is shifted a distance of d meter away from that of breast along the x -axis, shown in Fig. 1.b. The polar coordinates (r, θ) , with respect to the $o'-x'-y'$ system, is used to describe the power deposition within the breast. As the central axis of transducer is coincident with that of breast ($d=0$), the ultrasound power deposition within the breast is one dimensional, symmetrical to the central axis. The control parameter for the power deposition is the ultrasound frequency or attenuation (μ) in the tissue. We can obtain the ratio of SAR on the cylindrical shell with radius r meter within the breast to that on the breast surface as

$$SR(\mu, R; r; R) = \frac{R}{r} \cdot \frac{e^{-2\mu(R-r)} + e^{-2\mu(R+r)}}{1 + e^{-4\mu R}} \quad (1)$$

$SR(*)$: ratio of SAR on the shell with radius r m within the breast to that on the breast surface.

As the central axis of transducer is shifted a distance (d) away from that of breast, the ultrasound power deposition within the breast becomes two-dimensional. The control parameters for the power deposition are the ultrasound

frequency (or ultrasound attenuation in breast tissue (μ)) and the shifting distance (d). The polar coordinate (r, θ), with respect to the $o'-x'-y'$ system, is then used to describe the power deposition. The power deposition at the point (r, θ) within the breast is contributed by the ultrasound beams from both front and back directions as shown in Fig. 1b. $S(R, d; \theta)$ and $S'(R, d; \theta)$ are the penetrating distances of the ultrasound beams from the front and back directions, respectively, to the central axis of transducer with an angle θ . The ratio of SAR for a point (r, θ) within the breast to that for the point ($R-d, 0^\circ$) on the breast surface is

$$SR(\mu, R, d; r, \theta; R-d, 0^\circ) = \frac{R-d}{r} \cdot \frac{e^{-2\mu(S-r)} + e^{-2\mu(S'+r)}}{1 + e^{-4\mu R}} \quad (2)$$

$SR(*)$: ratio of SAR at (r, θ) within the breast to that on the breast surface at ($R-d, 0^\circ$).

For a cylindrical transducer with an active portion ($\varphi < 360^\circ$), symmetrical to the x' -axis, the control parameters for the ultrasound power deposition are μ , d and φ . For a point (r, θ) within the breast, we require to consider the ultrasound beams from the front and/or back directions:

a) for the point (r, θ) of the breast facing the transducer's active portion, $-\varphi/2 \leq \theta \leq \varphi/2$:

$$SR(\mu, R, d, \varphi; r, \theta; R-d, 0^\circ) = \frac{R-d}{r} \cdot e^{-2\mu(S-r)} \quad (3)$$

b) for the point (r, θ) back to the transducer's active portion, $180^\circ - \varphi/2 \leq \theta \leq 180^\circ + \varphi/2$:

$$SR(\mu, R, d, \varphi; r, \theta; R-d, 0^\circ) = \frac{R-d}{r} \cdot e^{-2\mu(S'+r)} \quad (4)$$

Equations (1-4) investigate the relationship between the parameters and the distribution of SAR ratio, as well as the treatable domain for a given set of control parameters.

RESULTS AND DISCUSSION

To examine the effects of breast size and ultrasound frequency on the distribution of SAR ratio, the breast's diameter ($2R$) is varied from 4, 8, 12, to 16 cm, and the ultrasound attenuation (μ) is from 5, 15, 25, 35, to 45 Np/m. The central axis of cylindrical transducer coincides with that of breast ($d=0$), and hence the ultrasound power deposition within the breast is symmetrical with the central axis. Fig. 2

is the distribution of SAR ratio based on equation (1). These figure reveals that a) the SAR ratio for low attenuations is always higher than that for high attenuations, and b) the ratio increases from the surface to the central portion of breast for low attenuation cases but, for high attenuation cases, it decreases initially and then increases and the value is lower than 1.0. For low attenuations, a single peak of SAR ratio appears in the central portion of the breast for all different breast sizes. As the central axis of cylindrical transducer is shifted a distance of d meter from that of breast, the ultrasound power deposition within the breast becomes two-dimensional. Frequency (or attenuation (μ)), shifting distance (d) and breast's diameter ($2R$) are the factors potentially influencing the distribution of SAR ratio. Fig. 3, based on equation (2) for an attenuation 45 Np/m with a breast diameter 12 cm and a shifting distance 4.0 cm, reveals that the distribution of SAR ratio is dramatically changed with the shifting distance. The central portion of SAR ratio is shifted with the cylindrical transducer and its value increases with the shifting distance. The region of SAR ratio higher than 0.3 converges from the superficial region of an entire breast to a small region in the right breast. The study of SAR ratio distribution is based on an ideal ultrasound power deposition from a cylindrical transducer. The interference maxima and minima in the nearfield for the cylindrical transducer oscillate within an envelope function and will be further studied using the wave equation while appropriate lengths of the sides of curved rectangular transducer elements are employed to form the entire cylindrical ultrasound transducer.

CONCLUSION

The above SAR ratio study for cylindrical transducer employs a relatively simple model of power deposition to investigate the optimal driving frequency for the ultrasound transducer, as well as the treatable domain of breast with respect to the breast size, the shifting distance and the active portion of transducer. Simulation results demonstrate the optimal attenuation to select the appropriate driving frequency for a given SAR ratio pattern. These SAR ratio patterns are the initial results that could then be modified for additional modeling that would include temperature calculations, the arrangement of transducer elements, amplitude control of each element, etc.

REFERENCES

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FIGURE CAPTIONS

Figure 1: a) Schematic diagram of the geometry for a cylindrical ultrasound transducer is used for the

hyperthermia treatment; b) The relative position between the cylindrical transducer and the breast.

Figure 2: The distribution of SAR ratio for the shifting distance (d) equal to zero and the attenuation of ultrasound in breast tissue is varied from 5, 15, 25, 35, to 45 Np/m, while the diameter of breast is 12 cm.

Figure 3: The distributions of SAR ratio for the attenuation of ultrasound in breast tissue 5 and 45 Np/m, the breast's diameter equal to 12 cm, while the shifting distance is 4.0 cm.