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Fundamental Validation of Microwave-Induced Thermoacoustic Tomography Using a Hemispherical Array Sensor

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1. Introduction

Stroke is a cerebral ischemic disease caused by the occlusion or rupture of cerebral blood vessels, and rapid treatment is essential for improving patient outcomes. Although computed tomography (CT) and magnetic resonance imaging (MRI) are the gold-standard diagnostic modalities, their lack of portability and limited real-time imaging capability can hinder the timely decision-making in emergency settings. Consequently, there is a growing demand for diagnostic devices that can rapidly and accurately assess brain conditions at the point of care.

A potential solution is a novel acoustic imaging modality called microwave-induced thermoacoustic tomography (MITAT). MITAT visualizes the spatial distributions of electromagnetic (EM) energy absorption within the target tissue by detecting acoustic waves generated when pulsed microwaves are absorbed. When applied to the stroke diagnosis, MITAT has a potential to achieve transcranial imaging by leveraging the high penetration of microwaves and the contrast in thermoacoustic signal properties at lesions due to changes in electrical properties. However, the technical foundations, such as optimal MITAT parameters for generating effective thermoacoustic signals without causing thermal damage, remain underexplored.

Our group developed an experimental MITAT system using a hemispherical low-frequency ultrasonic array sensor and a coaxial EM waveguide converter. In this study, we investigated the fundamental performance of the system, including signal detection performance, through both simulations and experiments.

2. Material and Methods

2.1 SAR Simulation

Understanding microwave propagation and energy absorption in the tissue is essential for estimating the field of view and signal characteristics in a MITAT system. To address this, an EM simulation framework to estimate microwave propagation and specific absorption rate (SAR) in target objects was devised.

To simplify the various conditions, a dipole antenna that has a simple structure and well-defined radiation pattern was assumed. After deriving the spatiotemporal intensity distribution of the microwave field, the SAR was calculated using the following equation[1)],

$$SAR(\boldsymbol{r},t)=\frac{\sigma(\boldsymbol{r})|\boldsymbol{E}(\boldsymbol{r})|^2}{2\rho(\boldsymbol{r})}I(t) \qquad (1)$$

where $\boldsymbol{r}$ and t represent spatial and temporal positions, respectively, $\sigma(\boldsymbol{r})$ is the electrical conductivity, $\boldsymbol{E}(\boldsymbol{r})$ is the electric field intensity, $\rho(\boldsymbol{r})$ is the mass density, and $I(t)$ represents the temporal profile of the microwave pulse. This equation allows for quantitative estimation of localized energy absorption based on tissue properties and the spatiotemporal EM field.

EM simulations were performed using Sim4Life (ZMT Zurich MedTech AG), modeling 2.45 GHz microwaves incident on a flat phantom with a relative permittivity of 41.5 and conductivity of 0.97 S/m.

2.2 Microwave Power Intensity Measurement

Following the SAR simulation, measurement of microwave radiation profile was conducted using a coaxial waveguide converter, which was expected to offer higher directivity than a dipole antenna and to generate thermoacoustic waves more efficiently for MITAT.

A signal generator (ISC-2425-25+, Mini-Circuits) and a high-power amplifier (ZHL-2425-250+, Mini-Circuits) were used to produce a, continuous 2.45 GHz microwaves with an output power of 20 dBm. The microwaves were emitted into air through a coaxial waveguide adapter (WR-340, CPR-340G, Pasternack).

Microwave power intensity was measured at 10 mm intervals from the waveguide aperture (0 mm) up to 80 mm using a microstrip antenna.

2.3 Evaluation of Hemispherical Array Sensor for MITAT

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Prior to detecting thermoacoustic signals, we assessed the characteristics of the hemispherical ultrasound array sensor under a photoacoustic imaging setting.

The hemispherical ultrasonic array sensor (center frequency: 1.72 MHz, 256 elements, element diameter: 3 mm, array aperture: 92.2 mm, aperture angle: 114°, focal length: 55 mm, Japan Probe) was designed to detect low-frequency thermoacoustic waves propagating outward from the inside of the brain. A hemispherical gel phantom (diameter: 20 mm), consisted of physiological saline with 10% agar and 2% India ink, was prepared to mimic the shape of a small animal brain and to enhance, its optical absorption. A pulsed LED source (850 nm wavelength, 75 ns pulse width, 1 kHz PRF) was used to induce photoacoustic waves in the phantom. The signals were received by the hemispherical sensor and processed to visualize the phantom's structure.

3. Results and discussion

First, the simulation study found that the SAR was highest at the center part of the flat plate and gradually attenuates toward the periphery (**Fig. 1**). This indicates that the microwave energy absorption is strongly dependent on the spatial distribution of the irradiation pattern.

Second, in the microwave measurement experiment, the power of microwave decreased with increasing distance (**Fig. 2**). Although EM wave dispersion is a well-known phenomenon, these simulation and experimental results suggest that the microwave irradiation must be carefully designed to optimize SAR distribution and thermoacoustic signal generation.

Finally, photoacoustic waves generated in the phantom were successfully detected by the hemispherical array sensor. Delay-and-sum beamforming of the signals successfully visualized the surface shape of the phantom (**Fig. 3**). As such effective signals and imaging results could not be achieved with microwave excitation, further investigation is required to determine the optimal microwave settings for effective thermoacoustic signal generation.

4. Conclusion

This study investigated fundamental factors of MITAT, including microwave propagation characteristics and the detection capabilities of a hemispherical ultrasonic array sensor, using an experimental setup. The generation of EM field with a microwave emission system and the sensitivity of the ultrasonic array sensor to detect photoacoustic waves were confirmed. In the future study, optimal microwave excitation parameters will be investigated to generate effective thermoacoustic waves in the tissue-mimicking phantoms and biological tissues.

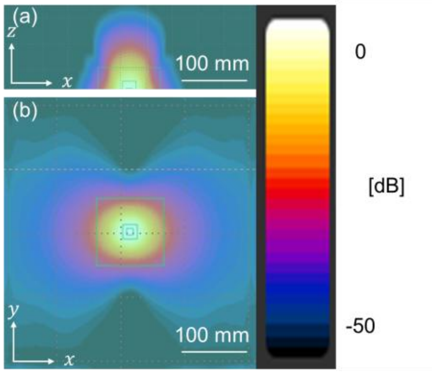

Fig. 1 The slice view of the peak average SAR ((a) in the x-z plane, (b) in the x-y plane).

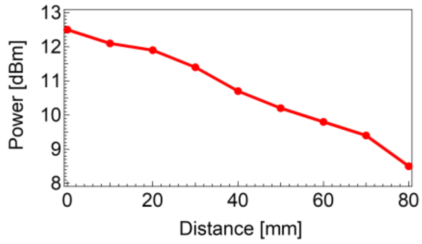

Fig. 2 Propagation characteristics of microwave power.

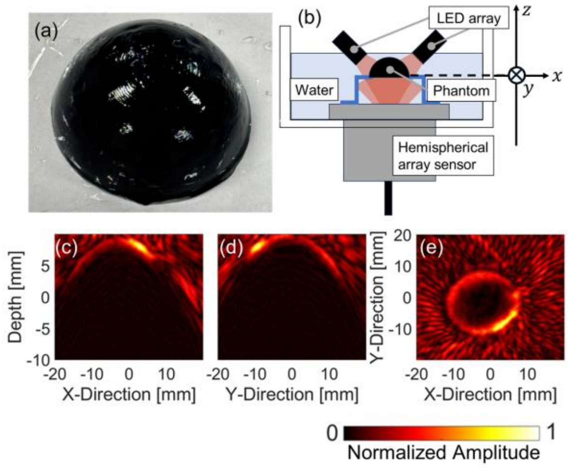

Fig. 3 (a) Phantom image. (b) Schematic of the photoacoustic imaging system. Reconstructed photoacoustic images: (c) x–depth plane, (d) y–depth plane, and (e) x–y plane.

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References

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