Conductivity Reconstruction and Numerical Simulation for Magnetically Mediated Thermoacoustic Imaging

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Magnetically mediated thermoacoustic imaging is an emerging medical electrical parameter imaging technology, it has the advantages of high contrast situation of electrical impedance imaging and high resolution of ultrasound imaging, it can realize the early diagnosis for disease in the tissues comparing with structure imaging technology. The magnetically mediated thermoacoustic effect is analyzed in this paper through the theoretical inference and the numerical calculation method. Pulsed excitation is presented in the analysis that is different with previously reported researches. The low conductivity sample such as gel phantoms (0.2S/m) is put in the pulse magnetic field, then the joule heat is generated and motivates thermoacoustic effect. The acoustic signal is detected and the image is reconstructed from heating function to conductivity. The study has laid foundation for the imaging in biological tissues.

***Index Terms*—Biomedical imaging, Electromagnetic analysis, Numerical simulation, Thermal expansion, Magnetically mediated thermoacoustic imaging.**

I. INTRODUCTION

Current medical structure imaging techniques can not satisfy the early diagnosis of tumour very well, and the change of electrical parameter for biological tissues is often before the change of structure, then electrical parameters image reconstruction is of great significance. Electrical impedance imaging can realize the early diagnosis for disease, but it has the lower sensitivity and spatial resolution at present. Multi-filed coupling imaging technology has attracted increasing attention because of the limitations of a single physical field, the combination of electromagnetic and ultrasound is the emerging multi-physic imaging which combines high contrast situation and high resolution, such as magneto-acoustic tomography with magnetic induction(MAT-MI), microwave induced thermo-acoustic imaging(MI-TAI) and magnetically mediated thermoacoustic imaging(MM-TAI).These multi-physics Imaging methods use the electromagnetic excitement and receive the ultrasonic to rebuild conductivity of target sample, but the mechanisms of sound source are different.

In addition to the advantages of the high contrast of electrical impedance imaging and high spatial resolution of ultrasonic tomography technology, MM-TAI is also a non-contact induction magnetic field excitation imaging technology, it dispenses magnet that simplifies the complexity of equipment and reduces the cost. MM-TAI has the potential of deeper penetration depth compared with MI-TAI. In MI-TAI, the imaging depth depends on the microwave frequency used for irradiation. For commonly used frequencies such as 3GHz, the penetration depths for fat and muscle are estimated to be 9cm and 1.2cm,respectively; while at 500MHz, the penetration depths for fat and muscle are estimated to be 23.5cm and 3.4cm, respectively[1]. Much deeper penetration can be achieved in principle by using lower frequencies, such as 20MHz which offers at least 15cm penetration[2].

Magnetically mediated thermo-acoustic effect is predicted in theory and demonstrated in phantom studies by research group of Singapore[2]. A tapering metal strip is used to demonstrate thermoacoustic(TA) signal generation by the RF pulses which are with a width of 1μs and a carrier frequency at 12.4MHz, the thermoacoustic image is formed by the back projection method.

But vitro animal and human body tissue conductivity is far lower than the metal, the magnetic thermal acoustic signal is relatively weak, how to acquire high signal-to-noise ratio magnetic thermal acoustic signal of biological tissue is the focus of this paper. The image reconstruction procedure from heating function to conductivity is also the key point in the thesis.

II. THEORY

Schematic diagram of the principle of magnetically mediated thermoacoustic imaging is shown in Fig.1.

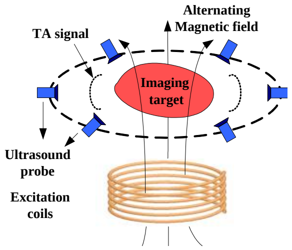

Fig.1 Schematic diagram of magnetically mediated thermoacoustic imaging

MM-TAI relies on multi-physics and coupled principle, induced electric field is generated in the inside of the target by imposing alternating magnetic field to imaging target, then the Joule heat is generated and motivates thermoacoustic effect. The acoustic signal is detected and the image is reconstructed.

The magnetic field at different location and time can be computed with the law of Biot and Savart, according to the Maxwell's equation, an alternating electric field is generated by the alternating magnetic field, then according to Ohm's law, the electric field will induce conductive current

$J(r',t)=\sigma(r')E(r',t)$ in the imaging target, that causes absorption joule heating. The heating function is calculated as $H(r',t)=\sigma E(\sigma)^2$. The absorbed energy disturbs target' original thermodynamic equilibrium and rise its temperature slightly, causing thermal expansion that launches acoustic waves propagation, the equation of acoustic wave propagation is

$$\nabla^2 p(r,t) - \frac{1}{{c_s}^2}\frac{\partial^2}{\partial t^2} p(r,t) = -\frac{\beta}{C_P}\frac{\partial H(r',t)}{\partial t} \qquad (1)$$

where $p(r,t)$ is the acoustic pressure, c_s is the acoustic velocity, c_p is the specific heat capacity of the object, and β is the isobaric volume expansion coefficient of the object. The wave equation can be solved with Green's function method under linear acoustic theory

$$p(r,t)=\frac{1}{4\pi}\iiint_{\Omega}\frac{\beta}{C_P}\frac{\partial H(r',t)}{\partial t}\frac{\delta(t-|\boldsymbol{r}'-\boldsymbol{r}|/c_s)}{|\boldsymbol{r}'-\boldsymbol{r}|}dr' \qquad (2)$$

where $\boldsymbol{r}$ is the position of transducer, $\boldsymbol{r}'$ is the position of the acoustic source, Ω is the whole area of integration which contains all the acoustic sources on the focused section of the ultrasound transducer.

III. INVERSE PROBLEM

The inverse problem of the MM-TAI explains how to reconstruct the conductivity distribution using the collected ultrasonic pressure signals around the object. The acoustic source term, which is on the right side of the wave equation Eq.(1), can initially be reconstructed by the time reversal technique which is shown in Eq.(3), $H(r')$ can be obtained from p .

$$H(r')\approx -\frac{C_p}{2\pi c_s^3\beta}\oint dS_d\,\frac{\boldsymbol{n}\cdot\boldsymbol{e_R}}{R}\frac{\partial}{\partial t}p(r,|r'-r|/c_s) \qquad (3)$$

where $\boldsymbol{r}'$ is the sound source position of the object, $\boldsymbol{r}$ is the location of the transducer, $R=|\boldsymbol{r}'-\boldsymbol{r_d}|$, $\boldsymbol{e_R}=\frac{\boldsymbol{R}}{R}$, S_d is the surface on which the ultrasound probes are placed. After the reconstruction of the source term by Eq.(3), the conductivity of the target can be further reconstructed.

Heating function is expressed as

$$H=\sigma E^2=\sigma\boldsymbol{E}\cdot\boldsymbol{E} \qquad (4)$$

Considering the low electrical conductivity of biological tissue, the intensity of electric field component can be expressed as

$$\boldsymbol{E}=-\nabla\phi-A_1 \qquad (5)$$

Where A_1 is space component of the magnetic vector potential, ϕ is space component of electric scalar potential.

According to the current continuity theorem

$$\nabla\cdot\sigma(\nabla\phi+\boldsymbol{A}_1)=0 \qquad (6)$$

The conductivity can be reconstructed by Eq.(7).

$$\sigma=\frac{H}{\boldsymbol{E}\cdot\boldsymbol{E}}=\frac{H}{\left(\nabla\phi+\boldsymbol{A_1}\right)\cdot\left(\nabla\phi+\boldsymbol{A_1}\right)} \qquad (7)$$

IV. NUMERICAL SIMULATION

A. Design of Simulation

To demonstrate the validity of the proposed theory of MMTAI, computer simulations were conducted with a 2-D model to calculate the acoustic pressure $p(r,t)$ at the position of the transducer by COMSOL and MATLAB. The conductivity distribution(0.2S/m-2.5S/m-4S/m) of the model and the acoustic pressure signal(0.15,0) are shown in Figure 2.

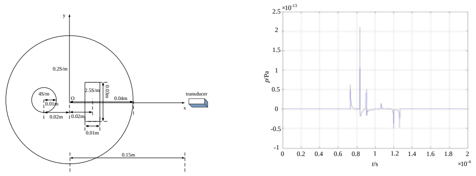

Fig.2 Simulation model

B. Simulation of Image Reconstruction

Basing on the back projection algorithm of Eq.(3) and Eq.(7), the conductivity is reconstructed.

V.EXPERIMENTS

Phantoms made of gel were used in experiments. The tested phantom is shown in Figure3(a). the received acoustic signal is shown in Figure3(b).Figure3(c) shows the reconstructed conductivity distribution of the salinity gel object. Control system can realize the scanning detection through rotation moving the transducer.

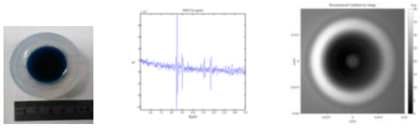

Fig.3 Experimental results for gel phantom model. (a). (b). (c)

VI. CONCLUSION

In this paper, the analytical formula of the acoustic pressure is investigated and the conductivity reconstruction method is proposed for the MM-TAI. The numerical simulation with low conductivity model and the salinity gel phantom experiments demonstrate the validity of the proposed method in reconstructing the conductivity using ultrasound measurements.

VII. ACKNOWLEDGEMENTS

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