Experimental Study of Thermo-acoustic Imaging with the Current Injection

Yanhong Li, Guoqiang Liu, Jiaxiang Song, Zhengwu Xia and Hui Xia

ABSTRACT

Thermo-acoustic imaging with the current injection (TAI-CI) is an emerging medical electrical parameter imaging technology for early detection of human diseases, it combines the advantages of high contrast of electrical impedance imaging and high resolution of ultrasound imaging. The principle of thermo-acoustic imaging with the current injection was studied and the experimental system was established. The study results demonstrate that the joule heating is produced inside the objects by injecting current to phantom through a pair of electrodes, and an acoustic signal which involves the electrical parameter information of the objects is excited due to heat expansion. An experimental set for TAI-CI was established to detect and collect the acoustic signals from the semi-circular ring gel phantom, the experiments were carried out aiming at low conductivity phantom (1S/m), the electrical parameter variation of the gel phantom was reflected through image reconstruction. The experiments verify the feasibility of the method for low conductivity medium imaging, and provides a basis for potential applications of TAI-CI in biological tissues.

INTRODUCTION

In the medical field, the electrical impedance tomography has the advantage of early diagnosis[1-2], in order to solve the problem of the low resolution[3] the coupling imaging technologies with multi-physical fields are proposed. The combination of the electromagnetics with the ultrasound is an emerging multi-physical field imaging with both of high contrast and high resolution, such as magneto-acoustic tomography with magnetic induction(MAT-MI)[4-6], microwave induced thermo-acoustic imaging(MI-TAI)[7] and magnetically mediated thermoacoustic imaging(MM-TAI)[8-9]. Thermo-acoustic imaging with the current injection is a new multi-physical field imaging method, the principle was proposed and the experiment was carried out aiming at low conductivity phantom in this paper.

In MI-TAI, 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 are estimated to be 23.5cm and 3.4cm, respectively[10].
MM-TAI has the potential of deeper penetration depth compared with MI-TAI, such as MM-TAI applying magnetic field at radio frequency below 20MHz which offers at least 15cm penetration. MM-TAI is predicted in theory and demonstrated in phantom studies [11]. A tapering metal strip experiment is used to demonstrate the generation of thermoacoustic(TA) signal, the RF pulses of exciting source has a width of 1µs and a carrier frequency at 12.4MHz.

But magneto-acoustic effect and thermo-acoustic effect are mixed in MM-TAI, and it must be noted that the electrical conductivity of animal and human body tissue is far lower than the one of metal, the magnetic thermal acoustic signal is relatively weak, so the best way of exciting and detecting should be investigated, and it needs to be explored how to obtain a high SN ratio signal in biological tissue.

In order to overcome the problem of existing methods, this paper proposes a new coupling imaging technology with multi-physical fields—Thermo-acoustic imaging with the current injection. The principle of thermo-acoustic imaging with the current injection was studied and the experimental system was established. The semi-circular ring gel phantom model with the mass fraction of 0.54% sodium chloride was injected a pulse current, which caused thermoacoustic signals. the acoustic signals from the gel phantom were detected and collected by ultrasonic transducer with the center frequency of 1 MHz, and B-scan image of the phantom was produced from the collected acoustic signals.

THEORY

The schematic of thermo-acoustic imaging with the current injection is shown in Fig.1.

By injecting a pulse current to the object through a pair of electrodes A and B, the joule heating is then produced inside objects and an acoustic signal is excited due to heat expansion, the acoustic signal is detected by ultrasound transducer and the electrical parameter image is reconstructed.

![Figure 1. The schematic of TAI-CI.](image)

The equations and boundary conditions of target were obtained under the quasi static electric field approximation condition which can be described as follows
\[
\begin{align*}
\nabla \cdot \left[ \sigma(r) \nabla \phi(r,t) \right] &= 0 \\
\phi(r,t) \big|_{r=t} &= f(t) \\
\phi(r,t) \big|_{r_s} &= 0 \\
\phi(r,t) \big|_{\Gamma_0} &= 0
\end{align*}
\]
(1)

Where \( \phi \) is an electric scalar potential, \( \Gamma_{A,B} \) is the position of electrodes, \( \Gamma_s \) is the outer boundary of the object except electrode position, \( f(t) \) is the excitation voltage and \( \sigma \) is the conductivity.

According to Helmholtz theorem, the electric field can be expressed as \( E(r,t) = -\nabla \phi(r,t) \). The current density distribution \( J(r,t) = \sigma(r)E(r,t) \) flowing into the object then leads to absorption of joule heating. The heating function is calculated as \( H(r,t) = \sigma E^2(r,t) \). The absorbed energy disturbs target’s original thermodynamic equilibrium and causes thermal expansion, which launches acoustic waves propagation, the equation of acoustic wave propagation is

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

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 \( \beta \) is the isobaric volume expansion coefficient of the object. The \( p(r',t) \) can be solved by Green’s function as

\[
p(r',t) = \frac{1}{4\pi} \int_{\Omega} \frac{\beta}{C_p} \frac{\partial H(r,t)}{\partial t} \frac{\delta(t-|r-r'|/c_s)}{|r-r'|} d\Omega
\]
(3)

Where \( r' \) is the position of transducer, \( r \) is the position of the acoustic source, \( \Omega \) is the whole area of integration which contains all the acoustic sources on the focused section of the ultrasound transducer.

**EXPERIMENT**

The experiment was designed to validate the theoretical analysis, we set up a platform for thermo-acoustic imaging with the current injection, the diagram of the experimental system is shown in Fig.2.

The platform is composed of excitation source system, electrodes, acoustic signal detection system and scanning system. The exciting source is composed of signal generator and the power amplifier, it injected the current to the phantom through the electrodes, the excitation source is impulse excitation with microsecond pulse width and a repetition frequency of 20Hz. Acoustic signal detection system is composed of transducer, amplifier, filter, data acquisition, image reconstruction, scan control and scanning system. The scanning system can realize the scanning detection through moving the transducer.

The excitation source system is a pulsed power supply with high voltage narrow pulse, it bases on the principle of capacitor stored energy, charging and discharging, and it injected the current to the object such as phantom and biological tissue through the copper electrodes.

The transducer of acoustic signal detection system is located under the insulating of tank, and the center frequency of transducer is 1MHz, the transducer is at the same height as the object.
The scanning system can realize linear scan.

Figure 2. The experimental system of thermo-acoustic imaging with the current injection.

The phantom is a cuboid gel imitation with 0.54% salinity, the conductivity of this phantom is 1S/m, the phantom is semi-circular ring, the width of the phantom is 1.1cm, the ultrasonic transducer and the phantom are kept at the same height. The distance between the interface of the transducer and the first edge of the phantom is set to be 3.6cm, the propagational speeds of sound wave in insulating oil is 1390m/s. The model of phantom is shown in Fig.3.

![Figure 3. The model of phantom.](image)

**EXPERIMENT RESULT**

Fig.4 shows the way and the result of ultrasonic signal acquisition. The distance between the interface of the transducer and the first edge of the phantom is set to be 3.6cm, the width of the phantom is 1.1cm.

The acoustic signal waveform obtained by an experiment is shown in Fig.4 (b). There are two edges of phantom, so there should be two peaks, the distances from two edges to the transducer are 0.036m, 0.047m. We analyze the acoustic travel time from edge of phantom to the transducer, we compare the experimental value. The corresponding times of every peaks are 25.89µs, 33.8µs according to theoretical calculation. Actually, the experimental results indicate that the wave peaks begin at 25.8µs and end at 33.5µs, the position precision can reach 0.417mm,
this error is related with the distance measurement of the transducer, the results of the experiment agree well with the theory analysis. The experiment result shows that the changes of the acoustic signal reflect the conductivity changes of the phantom.

![Transducer and Phantom Diagram]

(a) The relative positions of the transducer and the phantom  
(b) The acoustic signal waveform

Figure 4. Ultrasonic signal acquisition.

The B-scan image of the phantom is produced from the collected acoustic signals as shown in Fig.5, the transducer was moved in the x direction from 0mm to 50mm in the step of 1mm, the signal wave clusters were collected by the transducer as a result of the convolution between the impulse response function of the ultrasonic transducer and the acoustic pressure. The result shows that the image structure is in good agreement with the original photograph of the phantom structure in Fig.3, the two inner arc trajectories correspond to the two edges of the phantom, that displays the boundary changes of the conductivity, the signals are generated by the abrupt pressure changes at conductivity boundaries.

![B-scan TAI-CI Image]

Figure 5. B-scan TAI-CI image of the phantom.

**SUMMARY**

This paper provides the experimental study of thermo-acoustic imaging with the current injection. The acoustic signals and B-scan image of the semi-circular ring phantom(1S/m) are obtained.

The B-scan image can distinguish the edges of phantom very well, and it can show the shape of the phantom. The validity and the reliability of imaging system are verified.
The experimental results of the gel phantom validate the feasibility of imaging reconstruction for low conductivity.

The thermo-acoustic imaging with the current injection is a new multi-physical field imaging method that combines the electrical impedance tomography and thermoacoustic image techniques with both of high contrast and high resolution. It is hoped that the method can be used with bio-specimens for early diagnosis of diseases.

ACKNOWLEDGEMENT

This research was financially supported by National Natural Science Foundations of China under Grant Nos 51477161, Chinese academy of sciences under Grant No. YZ201507.

REFERENCES

1. Li X, Xu Y, He B. Imaging electrical impedance from acoustic measurements by means of magnetoacoustic tomography with magnetic induction (MAT-MI), IEEE Transactions on Biomedical Engineering. 54, 323(2007)