The influence on acoustic frequency characteristics of conductivity gradual-varying tissue in magnetoacoustic tomography (MAT)

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ABSTRACT

Background: As a functional imaging technology, magneto acoustic tomography (MAT) has broad application prospect in early tumor diagnosis and image monitoring during treatment.
Method: The influence on the acoustic field characteristics of the gradual change in conductivity was studied in magneto-acoustic tomography with current injection (MAT-CI) in this article.
Result: Theoretical analysis showed that the value of electro-acoustic conversion ratio (E-ACR) was different in different source frequencies under the same conductivity gradual-varying boundary.
Conclusion: The frequency characteristics of the acoustic pressure tend to shift towards the low frequency region. This conclusion provides a theoretical foundation for the MA signal detection and processing system optimization in the area of conductivity gradual-varying.

1. Introduction

As a conductivity imaging technique, Magneto Acoustic Tomography (MAT) takes electric conductivity parameters of the tissue which can reflect the physiological and pathological state of the tissue as the characteristic value [1,2]. It has relatively high contrast and improved spatial resolution for taking full advantage of coupling of magnetic-electric-acoustic field [3–6]. MAT exhibits prosperous application potential in early tumors diagnosis and clinical monitoring during treatment for its virtue such as no intervention, non-radiation and relatively low inspection fees due to its lower operating costs compared to MRI. With the development of EIT and conductivity reconstruction for biological tissues [7–9], major breakthrough was gained in theoretical research as well as experimental methods in MAT by several teams from international since Towe proposed magnetic acoustic imaging method in 1988 [1]. Bin He et al. studied on theory and experimental methods of magneto acoustic tomography with magnetic induction (MAT-MI) systematically, achieved the detection of gel phantoms in 2007 [8], in-vitro tissue organization in 2014 [9] as well as live animals in 2016 [10]. Zhipeng Liu et al. proposed the idea of magneto acoustic tomography with current injection (MAT-CI)of biological tissue [11], carried out preliminary research and obtained the imaging of copper ring in 2011 [12]. Guoqiang Liu et al. developed the research of MAT-CI based on the research of MAT-MI, studied the theoretical system of MAT-CI which included the positive and inverse problems of electromagnetic field as well as acoustic field, designed and constructed experimental platform. On the basis of this, physical model tests and in-vitro tissue experiments were performed, magneto-acoustic images of copper ring in 2009 and biological tissue pigskin were obtained in 2014 respectively [13–15]. Zheng Sun et al. developed the research of vascular endoscope MAT(EMAT-MI), which expanded the application of MAT [16].

The conductivity of the sample in previous studies was assumed to be block uniformity, the boundary of which was treated as image target. However, the biological tissue determined that its electrical conductivity is gradual-varying model according to its characteristics. It was found that malignant tumors, especially breast tumors, are mostly infiltrative in the early stages, which have irregular shapes and unclear edges and combined tightly with the surrounding tissues, through the research on the tumor samples of multiple organs. At the same time, edema formed due to abnormal hyperplasia and its infringement on surrounding normal tissues, there will be a gradual-varying region of conductivity around the tumor [17,18]. Therefore, it is of great significance for early tumor detection and paracancerous tissue

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diagnostication to investigate the influence on the magneto acoustic (MA) field of conductivity gradual-varying tissue. Qingyu Ma et al. discussed the influence of conductivity variation on the acoustic source in MAT-MI based on the dipole source analysis, and discovered that the amplitude of acoustic source at the boundary is proportional to the gradient of the electrical conductivity, while the internal is proportional to the electrical conductivity. This conclusion provides a reference for the MA signal of continuous conductivity gradual-varying model [19].

In this paper, the frequency characteristics of the acoustic field in MAT-CI with conductivity gradual-varying were discussed. Based on theoretical analysis, one-dimensional time-harmonic wave equation of acoustic pressure was established and its Green's function solution was obtained for gradual-varying conductivity with linear law. The influence on amplitude and frequency of acoustic pressure was analyzed in different width of the conductivity gradual-varying region. The result showed that the amplitude of magnetoacoustic pressure (MAP) is not only relates to the conductivity difference in gradual-varying region, but also relates to the frequency of the excitation, and changes with frequency for the same gradual boundary condition. Therefore, the electro-acoustic conversion ratio (E-ACR) will be different in different frequency for same gradual-varying boundary. The E-ACR in higher frequency components are smaller, which will result in frequency shift of the acoustic pressure towards the lower frequency region under complex excitation. As a result, it is necessary to consider the signal characteristics of the conductivity gradual-varying region in the detection and signal processing of acoustic field.

2. Principle and mathematical model

The schematic diagram of the MAT-CI system illustrated in Fig. 1, target with conductivity distribution $\sigma(r)$ which is a function of spatial location, is placed in a magnetic field B (the bold variable refers to a vector and the white one denotes the scalar in this paper). A time-varying electric field $E(r, t)$ is generated in the target when applied a time-varying voltage $V(t)$ to the target tissue by electrode. Then a time-varying current $J(r, t) = \sigma(r)E(r, t)$ which can be expressed as a function of r and t, is generated in the tissue according to Ohm's law. Under the interaction between the magnetic field B and the current $J(r, t)$, acoustic vibration at position r can be generated by the excited of Lorentz force. Assuming that the acoustic characteristics of the target are similar to those of the fluid around it, the acoustic vibration will go through the tissue and the surrounding fluid on the basis of radiation theory, and then can be detected by the ultrasonic transducers placed

Fig. 1. Schematic diagram of MAT-CI.

around the sample.

Assuming that the acoustic properties of the target are similar to the surrounding fluid, the viscous loss and acoustic difference between the surrounding fluid and the target are ignorable. In space acoustic field, the acoustic pressure $p(r, t)$ at r satisfies the acoustic pressure wave equation

$$\nabla^2 p(r, t) - \frac{1}{c_s^2}\frac{\partial^2 p(r, t)}{\partial t^2} = \nabla\cdot[J(r, t) \times B] \tag{1}$$

Where p and c_s are the acoustic pressure and acoustic speed in the fluid, respectively, ∇^2 and ∇ are the Laplacian and divergence operators, respectively, $B = B_0 + B(t)$ is a combined magnetic field of static magnetic field B_0 generated by external source and additional magnetic field $B(t)$ generated by inject current. According to the electromagnetic characters of biological tissues, it is known that the amplitude of the static magnetic field B_0 is much larger than the additional magnetic field $B(t)$, that is $B_0 \gg B(t)$. Therefore, the dipole source at the right side of Eq. (1) can be expressed as $Q(r, t) = \nabla\cdot[J(r, t) \times B_0]$. Because the magnetic field is an irrotational field in target area, i.e. $\nabla \times B_0 = 0$, the acoustic source can be expressed as

$$Q(r, t) = \nabla\cdot[J(r, t) \times B_0] = B_0\cdot[\nabla\sigma(r) \times E(r, t)]$$
$$+ B_0\cdot\sigma(r)[\nabla \times E(r, t)] \tag{2}$$

It can be observed that the acoustic source is generated by the magnetic field B_0, the induced electric intensity $E(r, t)$ and the conductivity distribution $\sigma(r)$. The source strength composed of $B_0\cdot[\nabla\sigma(r) \times E(r, t)]$ and $B_0\cdot\sigma(r)[\nabla \times E(r, t)]$. The boundary source marked as $Q_1 = B_0\cdot[\nabla\sigma(r) \times E(r, t)]$ is produced by the cross product of the gradient of conductivity distribution and the intensity of electric field, while the inner source marked as $Q_2 = B_0\cdot\sigma(r)[\nabla \times E(r, t)]$ is generated by the product of the conductivity and the curl of the induced electric intensity [19]. The magnetic effect of the injected current is ignorable due to the electromagnetic characteristics of the biological tissue, therefore the curl of the electric field intensity in the conductor is approximately to zero, i.e. $\nabla \times E(r, t) = 0$, and then $Q_2 = 0$. Therefore the acoustic field characteristics of the MAT-CI are determined by boundary source Q_1. So that the acoustic pressure wave equation can be expressed as

$$\nabla^2 p(r, t) - \frac{1}{c_s^2}\frac{\partial^2 p(r, t)}{\partial t^2} = B_0\cdot[\nabla\sigma(r) \times E(r, t)] \tag{3}$$

Assuming that the static magnetic field B_0 is along z axis, the electric field E is along y axis, and the conductivity is only varying with the x-coordinate, which is marked as $\sigma(x)$, therefore the acoustic pressure wave equation can be simplified to one dimension form as follows:

$$\frac{\partial^2 p(x, t)}{\partial x^2} - \frac{1}{c_s^2}\frac{\partial^2 p(x, t)}{\partial t^2} = \frac{d\sigma(x)}{dx}E(t)B_0 \tag{4}$$

Setting $B_0 = B_0 e_z$ as a uniform magnetic field, the electric field E as a uniform distributed in space and changed as sine wave with time, i.e. $E(t) = E_0\exp(j\omega_0 t)$, where $\omega = 2\pi f$ is angular frequency at frequency f. Therefore, Eq. (4) can be transformed into time harmonic field wave equation as follows:

$$\frac{\partial^2}{\partial x^2}P(x) + k^2 P(x) = f(x) \tag{5}$$

Where P is the acoustic pressure phasor in harmonic field, $k = \frac{\omega}{c_s}$ is acoustic wave number, $f(x) = B_0 E_0 \frac{d\sigma(x)}{dx}$ is the function of acoustic source distribution. The influence on amplitude and frequency characteristics of the acoustic field of conductivity gradual-varying boundary was investigate in this paper. The conductivity difference was defined as $\Delta\sigma = \sigma_2 - \sigma_1$ for convenience of description. The acoustic field satisfies the infinity radiation condition according to the real physical model of MAT-CI. Two situations as follows were discussed in accordance with the conductivity distribution characteristics:
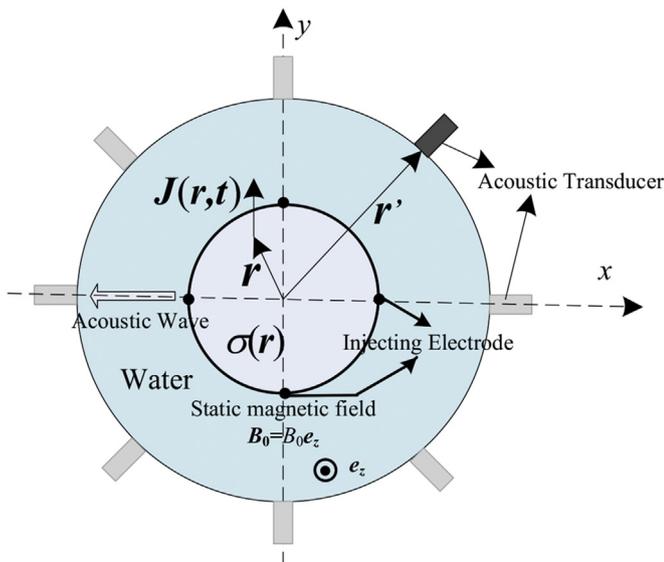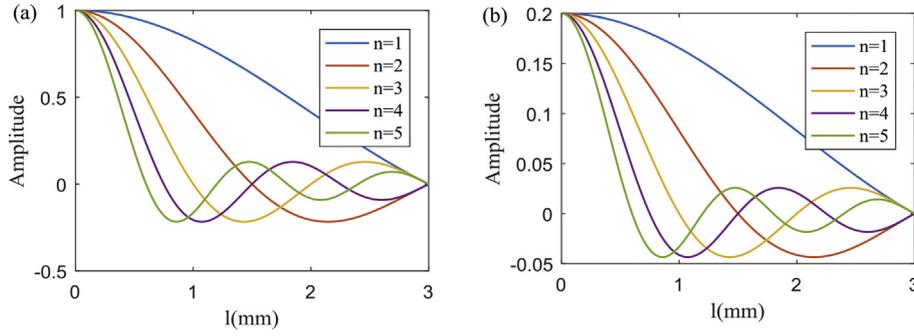
Fig. 2. The variation of E-ACR with the width of conductivity gradual-varying region at different frequencies in condition of (a) $\Delta\sigma = 1$ S/m and (b). $\Delta\sigma = 0.2$ S/m.

(1) Conductivity abrupt boundary

When the conductivity has an abrupt change from σ_1 to σ_2 at the point of $x = x_0$, which can be expressed as a step function: $\sigma(x) = \Delta\sigma \text{step}(x - x_0)$, makes the acoustic source $f(x)$ can be expressed by a Dirac function: $f(x) = B_0 E_0 \Delta\sigma \delta(x - x_0)$. According to the free-space Green's function, solution of the acoustic field can be expressed as follows:

$$P(x) = -B_0 E_0 \Delta\sigma G_0(x, x_0) = jB_0 E_0 \Delta\sigma \frac{1}{2k} e^{-jk|x-x_0|}$$

Where $G_0(x, x_0) = -j\frac{1}{2k}e^{-jk|x-x_0|}$ is the Green's function solution of the acoustic field under the unit sinusoidal excitation. If conductivity abrupt changes at point $x_0 = 0$ and acoustic field detection point located in the positive half of the x axis, the above formula can be written as follows:

$$P|_{l=0}(x) = jB_0 E_0 \Delta\sigma \frac{1}{2k} e^{-jkx} \tag{6}$$

Eq. (6) shows that the frequency characteristics of acoustic pressure are consistent with that of the power supply at the conductivity abrupt-varying boundary. For comparison studies, the abrupt-varying boundary acoustic pressure at the conductivity difference is 1 S/m, i.e. $\Delta\sigma = 1$ S/m was taken as the normalized research reference, which can be expressed as

$$P_0 = P|_{\substack{l=0 \\ \Delta\sigma=1}}(x) = jB_0 E_0 \frac{1}{2k} e^{-jkx}$$

Where P_0 was named as unit-boundary magnetoacoustic pressure (UB-MAP) in this paper.

(2) Conductivity gradual-varying boundary

Conductivity gradually varies linearly from σ_1 to σ_2 along the x-coordinate in interval of $[-\frac{l}{2}, \frac{l}{2}]$, and evenly distributes in the remaining region. The conductivity function in the gradual-varying region can be represented as follows:

$$\sigma(x) = \frac{\Delta\sigma}{l}x + \frac{\sigma_2 + \sigma_1}{2}$$

The value of l is inversely proportional to the conductivity gradient. A small l indicates the greater the conductivity gradient, it indicates an abrupt-varying boundary when $l \to 0$, on the contrary, it indicates uniform distribution of conductivity when $l \to \infty$. The acoustic source can be expressed by step function:

$$f(x') = B_0 E_0 \frac{\Delta\sigma}{l}[\text{step}(-\frac{l}{2}) - \text{step}(\frac{l}{2})]$$

Where x' indicates the source position. Eq. (6) is a 1-D non-homogeneous Helmholtz equation, the solution of which can be written as follows:

$$P(x) = \int_{-\frac{l}{2}}^{\frac{l}{2}} G_0(x, x')f(x')\mathrm{d}x' = \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{j}{2k} e^{-jk(x-x')} \frac{\Delta\sigma}{l} \mathrm{d}x'$$
$$= jB_0 E_0 \frac{1}{k^2} \frac{\Delta\sigma}{l} e^{-jkx} \sin(\frac{kl}{2})$$

Substituting the UB-MAP P_0 into the formula above, which can be transformed into

$$P(x) = P_0 \Delta\sigma \frac{\sin(\frac{kl}{2})}{\frac{kl}{2}} = P_0 A \tag{7}$$

Where $A = \Delta\sigma \frac{\sin(\frac{kl}{2})}{\frac{kl}{2}}$ is defined as the electric-acoustic conversion ratio (E-ACR) which represents the ratio of the acoustic pressure generated by the gradual-varying boundary to P_0 under the same excitation conditions. The value of A indicates the relative amplitude of acoustic pressure. The larger A means the higher signal-to-noise ratio for the same signal detection system, which is more conducive to post-signal processing. From the definition, it is known that A is not only proportional to the conductivity difference $\Delta\sigma$, but also relates to the acoustic wave number k and the width of conductivity gradual-varying region l. Moreover, the wave number of acoustic field $k = \frac{\omega}{c_s}$ is proportional to the frequency of power supply. Therefore, the equivalent E-ACR A has different value for different stimulation frequency under the same conductivity gradual-varying boundary. Fig. 2 shows the variation of A with l under the sinusoidal stimulation of 500 KHz and its multiple frequency: A is equal to $\Delta\sigma$ at each frequency in case of $l = 0$, which means the acoustic pressure at the conductivity abrupt-varying boundary is $\Delta\sigma$ times of the unit boundary acoustic pressure P_0. That is, under the same excitation condition, amplitude of acoustic pressure is proportional to the conductivity difference $\Delta\sigma$ for the same width of gradual-varying region. At the same time, A gradually decreases with l increasing, and will obtain zero value at $\frac{kl}{2} = \pi$, $l = \frac{c_s}{f} = \lambda$, and then vibrates with attenuation in small amplitude with increasing of l. In addition, the value of A decreases faster with l under higher frequency.

It can be obtained from the above analysis that the influence of conductivity difference on the amplitude of acoustic pressure is independent of frequency, and the MAP compliant the frequency characteristics of the power supply under the time-harmonic excitation. At the same time, the E-ATR A decreases with the width of gradual-varying region l increases and decreases faster under higher frequency.

According to the definition of Fourier transform, an arbitrary function can be equivalent to a Fourier series as follows:

$$s(t) = a_0 + \sum_{n=1}^{\infty} [a_n \sin(n\omega_0 t) + b_n \cos(n\omega_0 t)]$$

Where a_0 is the DC component of the series, ω_0 is the fundamental frequency of the series, a_n and b_n is the amplitude of corresponding harmonic component. The arbitrary waveform source can be treated as a sequence of sinusoidal excitations in different frequencies. According

to the previous analysis, the E-ACR in higher frequency component is smaller than it in lower frequency. Therefore, the overall acoustic pressure frequency characteristics will tend to shift towards the lower frequencies region under arbitrary excitation.

Any excitation source can be equivalent to a sinusoidal sequence of different frequencies according to the definition of Fourier series, and the conductivity gradual-varying with arbitrary laws can be equal to the superposition of a series of linear gradual-varying regions according to the definition of derivative. Therefore, the conclusions of time-harmonic analysis about linear gradual-varying conductivity have general applicability.

3. Numerical analysis

3.1. Simulation model

According to the previous analysis, when the direction of conductivity gradient $\nabla\sigma(x)$, the constant magnetic field $\boldsymbol{B}_0$ and the excitation electric field $\boldsymbol{E}$ are perpendicular to each other, the MAT-CI model can be simplified to 1-D calculation model. A 1-D model was established in COMSOL multiphysics, the conductivity of which was set as a linear function of x, i.e. $\sigma(x) = \frac{\Delta\sigma}{l}x + \frac{\sigma_1 + \sigma_1}{2}$ in the internal of $[-\frac{l}{2}, \frac{l}{2}]$, and uniform distribution in the rest of the region, as shown in Fig. 3. 1-D acoustic field module was employed for FEM calculation. B_0 was set as a uniform static magnetic field of 1 T, and the injection electric field was set as half wave sine pulse function with 1μs width and 1 V/m amplitude marked $f(t)$ to facilitate analysis. Therefore the dipole acoustic source was $q = \sigma(x)f(t)$ according to Eq. (1). The acoustic differences among materials are ignored in this research and all computational regions were set as the same type of non-viscous fluid, the density and acoustic velocity of which are 1000 kg/m^3 and 1500 m/s, respectively. The boundary condition of the problem was set as acoustic impedance boundary according to the actual physical model of MAT-CI. The acoustic field was calculated by FEM under different $\Delta\sigma$ and l, and the acoustic pressure at point P was extracted for amplitude-frequency characteristics analysis.

3.2. Influence of conductivity difference $\Delta\sigma$ on frequency characteristics of acoustic field

In this part the frequency characteristics of the acoustic field was investigated in different $\Delta\sigma$. In the condition of abrupt-varying boundary and 2 mm width gradual-varying boundary, MAP was calculated by FEM and normalized when the conductivity difference $\Delta\sigma$ was 0.2 S/m, 0.5 S/m and 1 S/m respectively. The amplitude-frequency characteristics of MAP are shown in Fig. 4. The comparative analysis shows that the amplitude of MAP is directly proportional to conductivity difference, and the difference has no effect on the frequency characteristics of MAP.
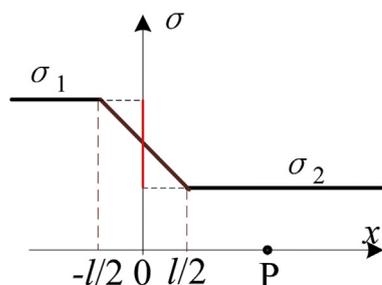
3.3. Influence on MAP frequency characteristics of conductivity gradual-varying width

The MAP frequency characteristics in different width of conductivity gradual-varying were investigated in this part. MAP was calculated by FEM and normalized at the width of conductivity gradual-varying region is 2 mm, 5 mm, 10 mm respectively in the condition of $\Delta\sigma = 1$. It can be seen that the waveform of the MAP becomes wider and the amplitude decreases with l increasing, as is shown in Fig. 5(a). The amplitude frequency characteristics are shown in Fig. 5(b). When $l = 0$, the amplitude-frequency characteristics of MAP keep consistent with the power supply, and gradually shift towards the low-frequency region with l increasing. The results of compute are consistent with the theoretical analysis.

Therefore, for a complex excitation, the MAP characteristics coincide with that of excitation on the conductivity abrupt-varying boundary, and will shift towards the low frequency region when the conductivity gradual-varying. At the same time, the MAP amplitude is greater in larger conductivity difference. According to the characteristics of biological tissues, the distribution of conductivity is more complicated. Therefore, it is necessary to consider both the amplitude and the frequency characteristics in the detection and analysis of the MAP.

4. Discussion and conclusion

The main work of this paper is to discuss the frequency characteristics of magnetic acoustic field under the condition of conductivity gradual change. For convenience, target was set to be homogeneous conductivity within each block in most of the previous researches. As a result, the acoustic source can be described by spatial Dirac function. The frequency characteristics of MAP are consistent with stimulation source according to Green's function solution of wave equation, which is consistent with the result discussed in this paper on the conductivity abrupt boundary. However the conductivity of actual biological is often continuously gradual changing. Therefore, it is necessary to consider the characters of MAP when there are conductivity gradual varying boundaries. Qingyu Ma discussed the influence on the distribution of acoustic source of the conductivity gradual varying based on the analysis of acoustic source [19]. In this article, theoretical analysis as well as numerical calculation of the acoustic field both indicates that the frequency characteristics of the MAP tend to shift towards the low frequency region. As a result, the signal of the conductivity gradual-varying area may be missed to detect by narrow band transducer and leading to invisible area of detection. Therefore, low-frequency or wideband transducers are required to detect the MAP in case of conductivity gradual-varying, but this will reduce the spatial resolution of MAT. As a result, it is necessary to explore new acoustic field detection methods or use boundary modification methods to increase the E-ACR in the gradual-varying region to improve signal-to-noise ratio and expand the boundary detectable range.

MAT-MI has been proposed as a technique to image electrical conductivity. The results in this article indicate that when imaging early tumors and paracancerous tissue, conductivity gradual varying has a significant effect on the acoustic signal in amplitude as well as frequency. Therefore, it is necessary to consider both the characters of time domain as well as frequency domain of the MAP to obtain more thorough information for the detection of MA signals in conductivity gradual-varying regions.

Conflicts of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be
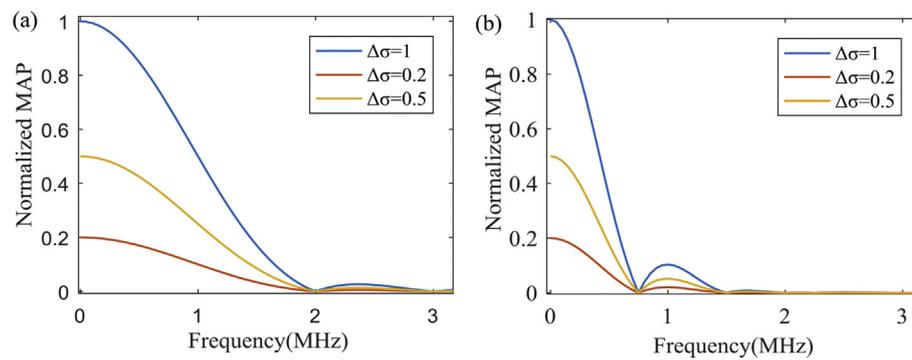
Fig. 3. Distribution of conductivity in 1-D model.

Fig. 4. MAP analysis with different conductivity differences ((a): Conductivity abrupt boundary; (b): Conductivity gradual-varying boundary, $l = 2\,\text{mm}$).
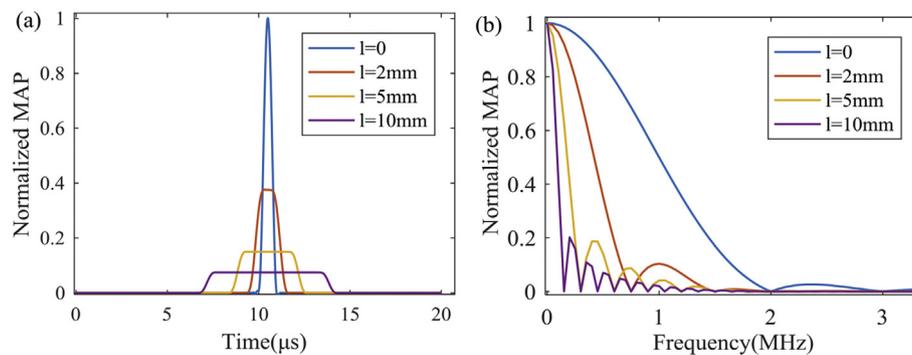

Fig. 5. MAP characteristics of the pulse stimulation ((a): waveforms in time domain; (b): amplitude-frequency characteristics).

construed as influencing the position presented in, or the review of, the manuscript entitled "Research on Acoustic Field Characteristic in Magneto Acoustic Tomography (MAT) for Conductivity Gradual-Varying Tissue".

Acknowledgments

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