Computerized Medical Imaging and Graphics 38 (2014) 42–48

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

journal homepage: www.elsevier.com/locate/compmedimag

A study of acoustic source generation mechanism of Magnetoacoustic Tomography

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ARTICLE INFO

Article history:
Received 18 April 2013
Received in revised form 9 October 2013
Accepted 14 October 2013

Keywords:
Functional imaging
Magneto-acoustic Tomography (MAT)
Dipole
Acoustic source

ABSTRACT

Magnetoacoustic Tomography (MAT) is a non-invasive imaging modality for electrical conductivity with good contrast and high spatial resolution. We have analyzed the acoustic source generation mechanism of MAT and presented its physical model, including the simulations and experiments in this paper. In MAT, acoustic sources are generated in a conductive object placed in a static magnetic field. Pulsed current is injected into the object and produces a Lorentz force due to the static magnetic filed. Acoustic vibration was excited by the Lorentz force, and hence, ultrasound waves propagate in all directions and are collected with transducers placed around the object. The conductivity image can then be reconstructed with acoustic waves using some reconstruction algorithms. Because the acoustic source generation mechanism of MAT is the key problem of forward and inverse problems, we analyzed the physical process of acoustic source generation and presented the acoustic dipole source model according to the Lorentz force imposed on the object. In addition, computer simulations and experiments were also conducted. The results of simulations applying an acoustic dipole source model are consistent with experimental results. This study has cardinal significance for the accurate algorithm of MAT and provides a methodology and reference for acoustic source problems.

1. Introduction

Biological functional imaging has some advantages, such as non-invasive detection, reflecting functional lesion and pathological changes of biological tissues; hence, it has broad prospects in clinical applications. Because tissue electrical characteristics of normal and diseased conditions are different, their conductivities also have great differences [1], so noninvasive electrical impedance imaging has been an active research field.

At present, there are many imaging modalities to image the electrical impedance of biological tissue. Electrical Impedance Tomography (EIT) [2,3] is an early functional imaging method. In EIT, different current patterns are injected into the object and surface electrodes are used to measure electrical potentials, which are used to reconstruct the impedance distribution in the object. EIT allows real-time imaging and the contrast of the reconstructed image is good. However, the injected current cannot flow into the deep tissues because of its 'shielding effect' due to the low conductivity of the surface tissue. EIT is also limited by its low spatial resolution due to the need to solve an ill-posed inverse problem. In order to avoid the shielding effect, Magnetic Induction Tomography (MIT) [4] uses an excitation magnetic field to induce currents in the tissue, and induced currents generate a secondary magnetic field that is received by sensing coils. The conductivity image can be reconstructed by the induced secondary magnetic field. This technology overcomes the 'shielding effect' of EIT, but the secondary magnetic field is small and cannot be clearly separated with the excitation magnetic field, so the spatial resolution of the reconstructed image is still quite limited. To achieve high spatial resolution, Magnetic Resonance Electrical Impedance Tomography (MREIT) [5] also injects currents by electrodes placed on the surface of biological tissues, and uses magnetic resonance equipment to derive the magnetic flux density distribution in tissues. Compared with EIT, MREIT improves the spatial resolution of the constructed impedance image with magnetic flux density. This technology, however, needs a magnetic imaging system, and the cost is relatively expensive. Furthermore, a large current is used in order to get an acceptable Signal-to-Noise Ratio (SNR) signal. Hall Effect Imaging (HEI) [6,7] has two detection modes: the first one is a detection voltage mode that imposes ultrasonic waves on the biological tissue in the static magnetic field. The tissue ions are subjected to an Ampere force perpendicular to the magnetic field and acoustic wave propagation direction, and generate current density that is relative to conductivity in the media. The image contains the information of biological tissues. The second detection mode is

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http://dx.doi.org/10.1016/j.compmedimag.2013.10.006

ultrasonic wave detection that imposes an electrical pulse on the sample in a magnetic field, and the particles in the medium are subjected to the Lorenz force which is non-continuous on the interface between conductivities, so the waves spread from the interface. HEI still remains in the preliminary research stage.

Magnetoacoustic Tomography (MAT) [8–11] is a functional imaging method that not only has good contrast, but also has high spatial resolution. Therefore, MAT has attracted considerable interest for researchers. MAT can be used to image electrical characteristics of biological tissues, and this technology is important to early detection for some cancerous diseases. According to excitation means of acoustic sources, MAT can be divided into MAT with magnetic excitation (MAT-MI), and MAT with electrical excitation (MAT-EI). In magnetic excitation means, a pulsed magnetic field is applied to induce an eddy current in the object; however, in the electrical excitation method, pulsed current is injected into the object. Not only the eddy current, but also the pulsed current is affected by the Lorenz force and generate sound sources. The University of Minnesota group conducted theoretical and experimental research on MAT-MI and obtained good imaging results. For example, Xu and He describe the principle of MAT-MI in great detail, and deduced both a forward and inverse problem algorithm. Moreover, they conducted copper strip and metal loop experiments, reconstructed the acoustic source and verified the feasibility of MAT-MI [11]. Xia et al. demonstrated 3D MAT-MI imaging in a physical phantom by cylindrical scanning combined with ultrasound focusing and developed the corresponding reconstruction algorithm [12]. Ma and He explained why the acoustic signal can only be generated at the conductivity boundary with corresponding amplitude and polarity [13]. Xia et al. reconstructed the conductivity distribution using vectorized acoustic pressure according to certain measurement geometry [14]. Hu et al. experimental study demonstrated that the MAT-MI imaging method is able to distinguish the small electrical conductivity contrast formed by liver tumor tissues and normal tissues with high resolution [15]. Mariappan et al. presented B-Scan technology's application in MAT-MI [16]. Hu and He study demonstrated that MAT-MI is able to image the electrical impedance properties of biological tissues with better than 2 mm spatial resolution [17]. On the other hand, MAT with electrical excitation does not require a pulse magnetic field generating device, so the cost is low. Compared with MAT with magnetic induction, it is easier to achieve. Liu Zhipeng group of Chinese Academy of Medical Sciences has carried on the research of Magnetoacoustic Tomography with electrical excitation for recent years [10,18–20]. We made the conductivity models of different shape, reconstructed the conductivity boundary image, and studied the amplitude-frequency characteristics of acoustic signal. Liu Guoqiang group of Chinese Academy of Sciences also established a sheet copper ring model to study Magnetoacoustic Tomography with electrical excitation [21,22].

At present, the study of MAT is still at the stage of theoretical research and experimentation, and there are still many problems that need to be addressed and resolved. For example, theoretical research mainly concentrated on a reconstruction algorithm of electrical conductivity, and little research on acoustic source generating mechanism has been carried out. The generating form of the acoustic source determines the propagation of acoustic waves, and is important for accurate conductivity reconstruction. The acoustic source generation mechanism is, therefore, the research basis and key to forward and inverse problems. Currently, an acoustic monopole source model is used to analyze acoustic pressure and solve distribution of conductivity. In this paper, the acoustic source generation mechanism of MAT was studied in great detail. We analyzed the physical process of acoustic source generation and presented the acoustic dipole source model. Also, computer simulations and experiments of acoustic waves from a wire by MAT with electrical excitation imaging modality were also conducted.

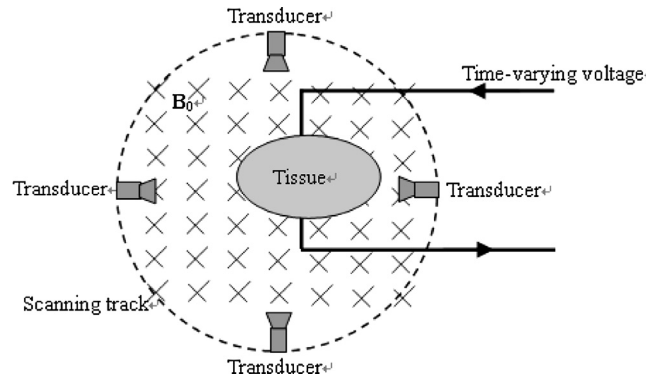

Fig. 1. MAT with electrical excitation.

2. Theory

2.1. MAT principle

MAT is a recently introduced approach to image electrical impedance distribution with high spatial resolution. In MAT, the conductive tissue is placed in a static magnetic field $\boldsymbol{B}_0$, and the pulsed current is injected into the tissue, or pulsed magnetic field induces an eddy current. Therefore, the current in the tissue will produce a Lorentz force due to the static magnetic field. The Lorentz force leads to mechanical vibration and generates an acoustic wave; hence, acoustic waves propagate in all directions and are collected with transducers around the object. Because acoustic waves contain tissue conductivity information, the conductivity image can be reconstructed with acoustic waves by algorithms such as the Linear Back Projection (LBP) or Time Reversal Method (TRM) [23,24]. LBP is also called the cumulative method; it accumulates all projections through a point, then estimates the value of the point. Time reversal of an acoustic wave is based on the invariance of the wave equation in a lossless medium under the transform $t \to -t$ (t represents the time), and can be understood as the back-propagation field from the forward-propagation field after removing the initial sources. In MAT, the time reversal formula is Eq. (3). Fig. 1 illustrates the theory of MAT with electrical excitation.

The generated acoustic waves are governed by the following wave equation [11]

$$\nabla^2 p(\boldsymbol{r}, t) - \frac{1}{c_s^2}\frac{\partial^2}{\partial t^2} p(\boldsymbol{r}, t) = \nabla \cdot [\boldsymbol{J}(\boldsymbol{r}, t) \times \boldsymbol{B}_0] \quad (1)$$

where p is the acoustic pressure, c_s is the acoustic speed in the tissue, $\boldsymbol{r}$ (bold variables refer to vectors) is the location of the acoustic source, $\boldsymbol{J}$ is the current density, and $\boldsymbol{B}_0$ is the magnetic flux density of the static magnetic field, ∇^2 and $\nabla\cdot$ are the Laplacian operator and the divergence operator respectively. After using Green's function, the solution of (1) can be written as [11]

$$p(\boldsymbol{r}', t) = -\frac{1}{4\pi}\int_v dr\, \nabla \cdot [\boldsymbol{J}(\boldsymbol{r}, t) \times \boldsymbol{B}_0] \frac{\delta(t - |\boldsymbol{r}' - \boldsymbol{r}|/c_s)}{|\boldsymbol{r}' - \boldsymbol{r}|} \quad (2)$$

where $\boldsymbol{r}'$ is the location of the transducer, $\boldsymbol{r}$ is the location of the acoustic source, and v is the volume containing all acoustic sources. This equation gives the observed pressure for an impulse source. In an inverse problem using the time reversal method the acoustic source can be described as follows [24]

$$\nabla \cdot (\boldsymbol{J} \times \boldsymbol{B}_0) \approx \frac{-1}{2\pi c_s^3} \oint_{\sum} d\boldsymbol{s}_d \frac{\boldsymbol{n} \cdot (\boldsymbol{r}' - \boldsymbol{r})}{|\boldsymbol{r} - \boldsymbol{r}'|^2} p''\left(r', \frac{|\boldsymbol{r}' - \boldsymbol{r}|}{c_s}\right) \quad (3)$$