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REVIEW ARTICLE

A Review of Source Imaging Techniques Based on EEG

Jianping Wu[1,*], Chunlin Zhao[2]

[1]*Postgraduate Brigade, Engineering University of PAP, Xi'an 710086, Shaanxi Province of China*
[2]*College of Equipment Management and Support, Engineering University of PAP, Xi'an 710086, Shaanxi Province of China*

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ABSTRACT

Electroencephalogram (EEG) is the electrical potential changes that occur in the cerebral cortex, as the response of the discharge of nerve cells in the brain, and can reflect the feature of the electrical activity of the brain. From the discovery of EEG in 1929 to the present, it has been extensively studied by scholars from all over the world. Nowadays, the research of EEG continues to deepen, and the scope of application is gradually extensive, such as clinical application, medical teaching and scientific research. EEG Source Imaging (ESI), which through the collection and processing of EEG to identify brain activity information, can be used to assist the diagnosis and treatment of epilepsy, depression, attention deficit hyperactivity disorder and other diseases. ESI has attracted much attention in the brain research, which is commendable in improving the clinical diagnosis ability of brain physiological diseases and other diseases. This paper introduces the basic principle and research status of ESI briefly, focuses on the positive and inverse problems of EEG, analyzes three important factors affecting the positioning accuracy of ESI, analyzes the existing problems and development prospects of ESI in the end. The purpose of this paper is provide a solid theoretical basis for continuously improving the positioning accuracy of ESI technology, more accurately locating abnormal brain function areas, and further understanding and treating brain diseases by studying the source imaging technology based on brain electricity.

1. INTRODUCTION

The research of brain science is of great significance, and it is one of the hot spots that attracts people's attention. The human brain system is huge and complex, and the study of the human brain needs to integrate multiple disciplines and various means. With the emergence of big data and the improvement of information processing ability, the study of EEG has been developed rapidly and deeply. ESI technology based on EEG, combined with high temporal resolution of EEG and high spatial resolution of source imaging, has been widely used in clinical medicine and basic scientific research. In clinical medicine, ESI technology has a good auxiliary effect on doctors' operation when diagnosing and treating brain physiological diseases or other diseases induced by them [1,2]. In terms of basic scientific research, combining the patterns of brain activity and functional connectivity with ESI technology for analysis, the interaction between various cognition-based tasks and resting brain regions has achieved good results [3,4]. The key of ESI technology research lies in EEG, and the important link is the construction of the forward problem EEG model and the solution of the reverse problem. The positioning accuracy of ESI technology is also different due to various factors.

2. SOURCE IMAGING TECHNOLOGY BASED ON EEG

2.1. The Concept of EEG

When the brain is active, many neurons generate postsynaptic potentials simultaneously, and these potentials are superimposed together to form EEG, which is defined as an electrical activity generated by brain neurons and recorded on the scalp surface [5]. Spontaneous and induced EEG are two types of EEG, which are distinguished by the presence or absence of external stimuli. When there is no external stimulation, because the rhythmic potential changes generated by the brain nervous system itself are called spontaneous brain electricity, which is commonly used in brain electrical rhythm and cortical slow potential. When subjected to external stimuli (light, electricity, sound, etc.), the electrical potential changes generated by the brain are called evoked potentials, such as visual, auditory, tactile evoked potentials, etc [6]. EEG is a kind of bioelectrical signal, which records the relationship between time and potential difference, and contains a lot of physiological information. EEG has a high temporal resolution and can reflect the firing activity of neuronal clusters in the sub-millisecond level [7]. It is highly

*Corresponding author. Email: 512049120@qq.com

non-stationary and has been widely used in the diagnosis and research of diseases such as depression, epilepsy, brain tumors and Alzheimer's disease [8,9].

2.2. The Concept of ESI

In recent years, neuroimaging technology has been rapidly developed, and the functional brain imaging ESI (EEG source imaging, ESI) technology based on EEG is relatively mature at present. ESI technology is based on the mathematical model of the head tissue and uses EEG to derive the source of intracranial neural activity in a non-invasive way for brain imaging [10]. ESI technology first records EEG signals, combines the known internal brain source signals, establishes a volume conduction model, and then fits the simulated EEG signals with the collected EEG signals. Then, the collected EEG electrical signals are matched with the corresponding conduction model, and the electrical activity of the brain power source on the cerebral cortex is derived in reverse [11]. EEG can provide millisecond time resolution and has direct electrophysiological basic characteristics. Some cognitive behaviors are related to neural activities and can also be accurately reflected by EEG [12]. Compared with other imaging technologies, ESI technology based on EEG has the characteristics of higher time resolution, providing information related to the physiological function of EEG, and detecting the spontaneous or evoked information of organisms without damage.

2.3. Research and Application of ESI Technology

Abnormal brain activity, as well as abnormal areas, can be detected and identified using ESI technology. ESI technology can be used to better study the brain structure and function of patients with Alzheimer's disease, depression and epilepsy through EEG data [13–15]. When Vecchio et al. studied brain electricity during seizures in patients with focal frontal temporal epilepsy, they analyzed higher connectivity in the affected and unaffected hemispheres than in the affected hemispheres in the alpha band. When Grain-Yatsenko et al. studied healthy controls and patients with early depression, they found that depressed patients had increased activity in the alpha and theta bands in the parieto-occipital region. Miraglia et al. analyzed the resting state data of Alzheimer's disease (AD), AMnestic mild cognitive impairment (aMCI), and healthy controls, and found that the small-world structure of aMCI presented an intermediate topology between AD subjects and healthy controls [16].

With the advancement of science and technology, ESI technology has been used more and more in clinical practice to locate the abnormal brain function area or effective cortex of patients before surgery and make surgical planning based on the location. For example, ESI technology is designed to analyze connectivity analysis at the brain-source level for diagnosing epilepsy and locating seizure initiation and seizure stimulation areas [17]. The neural mechanism of brain activity can be analyzed by ESI technology, which can diagnose and treat cognitive and functional disorders such as ADHD patients. In the study of resting state EEG in patients with depression, ESI technology was used to map source estimation, and it was found that pre-conditioned EEG connections within α2 rhythm had predictable value in the treatment effect of electroconvulsive therapy [18].

3. FORWARD AND REVERSE PROBLEMS OF EEG

There are two important concepts in ESI technology: forward EEG problem and reverse EEG problem [19,20]. The EEG forward problem is to predict the electrical activity on the scalp surface of the brain when the brain source activity is known and combined with the head volume conductor model. EEG reverse problem: From the recorded EEG signal, the source location and activity intensity of the source generated by the signal are deduced back [16]. The forward problem of EEG realizes the conversion from the brain power supply activity to the scalp potential, and the reverse problem of EEG realizes the conversion from the scalp potential to the brain power supply activity. The forward problem and the reverse problem of EEG are two opposite problems [21]. The relationship between the forward problem and the inverse problem of EEG is shown in Figure 1. For ESI technology, the solution of the inverse EEG problem is based on the forward EEG problem, so the forward EEG problem must be solved first.

3.1. The Forward Problem of EEG

The forward problem of brain electricity is to estimate the electrical activity of each electrode on the head surface when the specific brain region and directional dipoles are known. The study of the EEG forward problem can compare the calculated results with the actual collected EEG signals to help estimate the location of the brain power source, thus providing assistance for the solution of the EEG reverse problem [13]. The current distribution model and the current dipole model are two commonly used source models, the fundamental difference between them is the difference in density. The more classical source model is the current dipole model, which assumes that several discrete sources constitute brain activity. The synchronized electrical activity of most neurons in the cerebral cortex can be represented by a superimposed dipole, which is called an equivalent dipole. In the current distribution model, it is assumed that the continuous current distribution on the cortex is electrical activity, and the active area of the cerebral cortex is segmtioned small enough to represent the source activity of a small area with a dipole [22].

Head model is the basis of brain forward problem calculation. There are three common head models: ball, ellipsoid and real head model. The spherical model is supposed to be a uniform medium with the same direction and the same conductivity everywhere. There are some differences between the real head model and the hypothetical ball model, which leads to a large error in solving the inverse problem. Salu et al. hypothesized

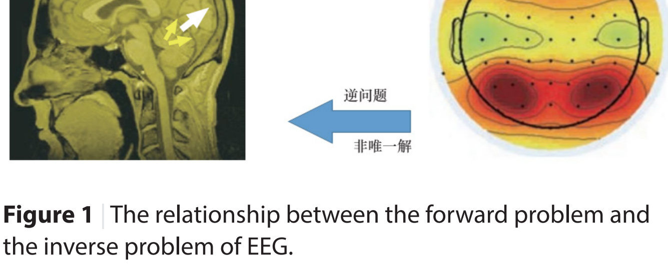

Figure 1 The relationship between the forward problem and the inverse problem of EEG.

that the brain is a three-layer concentric sphere (scalp, skull, and cortex), which is called the three-layer concentric sphere model [23,24]. In order to get closer to the real brain, some researchers put forward the ellipsoid model, but the experimental results show that compared with the ball model, the ellipsoid model has little influence on the calculation accuracy, and cannot reflect the actual situation of the brain. With the development of medical imaging technology (MRI, CT) [25,26], the real anatomical information of human brain can be easily obtained, and the real head model can be constructed as a reference for simulation, and the calculation and positioning accuracy of the real head model can be significantly improved. However, the shape of the real head model is irregular and the structure is complex. The analytical solution of the forward EEG problem with the real head model cannot be obtained, and the numerical solution can only be obtained by finite element [27], finite difference [28] and boundary element algorithm [29].

3.2. The Inverse Problem of EEG

The inverse problem of EEG is to invert the information of the source of brain electromagnetic activity according to EEG signal, head model and distributed impedance [30]. In order to reconstruct the cortical source, the head surface topographic map is used to estimate the source direction, source size, source location and source amplitude. The EEG reverse problem steps is shown in Figure 2.

There are two kinds of inverse EEG problem solving models: one is the equivalent current dipole model, based on the parameter method, a current dipole can replace the electrical activity of a certain part of the brain. Since the parameters of the dipole are not known, the relationship between the source parameters and EEG is non-linear, and it is difficult to adjust the parameters. Based on the non-parametric method, the distributed source model transforms the whole continuous cerebral cortex region into discrete sub-regions, each region is regarded as a source, and the source imaging problem of the distributed source model is transformed into linear solution [31]. Many brains have different patterns of activity, but all can produce the same topographic map of the head surface, so the solution to the inverse brain electrical problem is not unique. Therefore, it is necessary to limit the solution space, and the limiting conditions are usually prior assumptions and regularization methods [16]. The introduction of Tihnonov regularization is the most classical method, including minimum L1 and L2 norm method. In comprehensive degenerative diseases such as Alzheimer's disease, standard low-resolution electromagnetic tomography (sLORETA) [32] is used to trace the current density distribution of the cerebral cortex, which is a standardized version of the minimum norm estimation algorithm (MNE) [33]. In recent years, nonlinear optimization, multi-signal classification, tensor analysis, beamforming, deep learning and other inverse algorithms have also appeared, which can be learned from.

4. THE INFLUENCING FACTORS OF ESI TECHNOLOGY ACCURACY

4.1. Number of Electrodes to Collect EEG

Generally, the number of electrodes placed is too small, which is easy to make scalp potential sampling fail to meet the demand. A certain number of electrodes can be added to improve the spatial resolution of EEG. Sohrabpour et al., in their study on the relationship between the number of EEG channels and brain-source localization in pediatric epilepsy patients, proved that the accuracy of brain-source localization improved with the increase of the number of electrodes [34]. Ryynanen et al. conducted an experiment to test the influence of different number of electrodes on spatial resolution for high-density EEG under different noise levels, and found that the spatial resolution of the international 10–20 system was mainly limited by the number of electrodes [16]. However, as the number of electrodes increases, the impact of noise on spatial resolution also increases. With the same number of electrodes, EEG localization accuracy is higher than magnetoencephalogram [35]. Although the number of electrodes is more accurate, the improvement of positioning effect is weakened, so in order to achieve the target accuracy, the appropriate number of electrodes should be determined according to the actual situation. Although the number of electrodes is more accurate, the improvement of positioning effect is weakened, so in order to achieve the target accuracy, the appropriate number of electrodes should be determined according to the actual situation to achieve the balance between positioning accuracy requirements and equipment costs.

4.2. Way of Recording

Different head tissues have different electrical conductivity, which will affect the brain conduction field. Therefore, the positioning accuracy of ESI technology will vary according to the different EEG recording and magnetoencephali recording

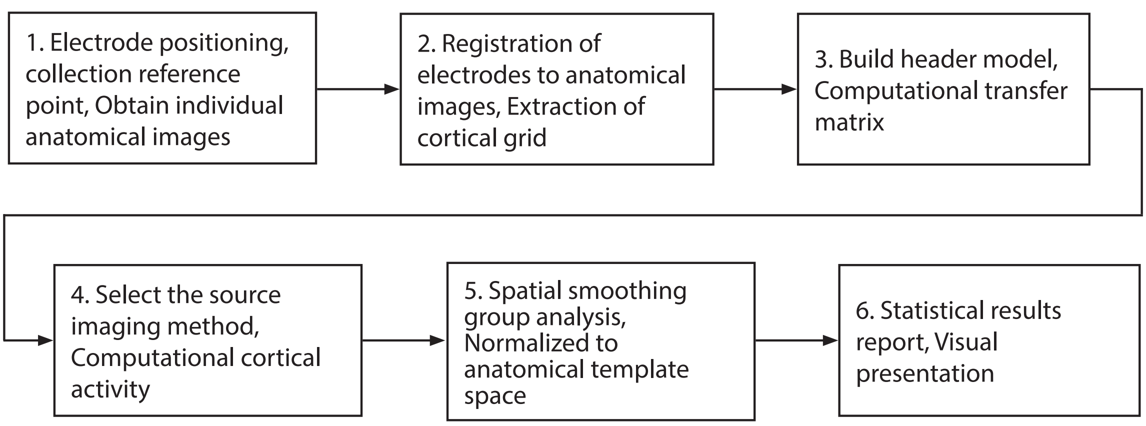

Figure 2 Steps of EEG reverse problem.

methods. The experimental results of Liu et al. show that when the number of electrodes is the same, considering the location and direction of the brain source comprehensively, the positioning accuracy of EEG is higher than that of EEG [36]. Malmivuo and his team proved the source in the use of the cortex of the conductivity of the skull of the spherical model, when the skull or the brain and the electrical conductivity of scalp ratio of 5/1, 10/1, 15/1, magnetic, electrical sensitivity volume less than half a brain for spatial resolution of EEG is better than that of the brain magnetic [37]. Antonakakis et al. found that the influence of different modes on source reconstruction of P20/N20 component could not be ignored. Magnetoencephali positioning was stable and was less affected by head modeling and stimulation methods, but EEG helped to determine the direction and intensity of source. Therefore, the complementary information of EEG and magnetoencephalitis can be combined based on the detailed personalized head model [38].

4.3. Head Model Construction

The construction of the head model requires first collecting the T1-weighted NMR images, then segmenting the scalp, skull, cortex, white matter and cerebrospinal fluid, then rebuilding according to the anatomical structure partitions, linear registration into the standard template space, coordinate transformation and affine transformation, and finally smoothing processing [39]. The head model (volume conduction model) is the key to the accurate positioning of the brain power source, and the closer the head model is to the actual head model, the more accurate the positioning. Due to the differences in measured sample conditions and conductivity measurement methods, the physiological and anatomical information of different head models is significantly different [40], and the imaging accuracy of different head models is also greatly different. Huang et al. developed the NewYork Head volumetric conduction tissue with a six-layer structure, which not only has a high accuracy in source imaging, but also in targeting transcranial electrical stimulation. The positioning error of the ordinary BEM model is 10.8 mm. In contrast, the positioning accuracy of the personalized head model New York Head is as high as 6.9 mm [41]. It can be seen that it is essential to build a head model close to the real one to improve the accuracy of brain source localization.

5. CONCLUSION

This paper briefly introduces the basic concept of ESI technology, the related research and application of ESI technology, the forward and reverse problems of EEG, and the important factors that have a great influence on the localization accuracy of EEG source. Through simulation experiments, it can be seen that the accuracy of electrode position can be improved, and the spatial accuracy of ESI can be greatly improved when combined with the scanning of individual structural images. The result of source imaging is comparable to that of functional magnetic resonance imaging (FMRI) in locating the active region [5]. However, how to improve such high spatial accuracy in practice is an urgent problem to be solved. On the one hand, the head model can be constructed in the forward problem by combining magnetoencephography, diffusion tensor imaging, magnetic resonance imaging, functional magnetic resonance imaging [42], etc., and spatial prior can be provided in the reverse problem, and connection information can be provided in the brain network inference to improve the accurate positioning of ESI technology. On the other hand, efforts should be made to continuously explore and optimize the inverse problem solving algorithm. In recent years, the algorithm introduced by Tihnonov regularization is constantly updated, and the future should strive to be better, more precise positioning, and improve the accuracy of ESI technology.

ESI technology can analyze the activity of brain neurons, improve the knowledge and understanding of brain diseases, and help researchers familiarize themselves with brain structure and function. Besides, the use of ESI technology in the treatment of brain diseases has broad prospects and great significance. In the future, we can develop source imaging algorithms with strong scene applicability, integrate multi-channel EEG detection algorithms, use big data to improve the computing speed, and continuously improve the positioning accuracy of ESI technology. In terms of clinical treatment, ESI technology makes the positioning of abnormal brain function more accurate, improves the safety factor of brain surgery, reduces the risks of brain surgery, and lays a solid foundation for better clinical treatment of brain diseases. In terms of basic scientific research, ESI technology makes a deeper understanding of brain activity and structural function, so that the scientific research is more efficient and higher quality. The scientific research content is more in-depth and breadth, and it will promote further research in the human brain.

DECLARATIONS

Conflict of Interest

The authors declare that they have no conflicts of interest.

Authors' Contribution

JW is mainly responsible for the topic selection and design, the collection and sorting of data, the conception, writing and revision of the paper. CZ is mainly responsible for the analysis and interpretation of data, the guidance and answer of key theories, and the revision suggestions of the paper.

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