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Electromagnetic induction detection techniques for craniocerebral injury: A review

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Highlights

- An induced current occurs in a conductor as a result of electromagnetic induction.
- The use of a magnetic field to generate induced current is known as electromagnetic induction, which can be used to detect craniocerebral injury.
- Induced current electrical impedance tomography, magneto-acoustic tomography, and eddy current damping sensors for imaging and detection are reviewed in the paper.

Abstract

Assessing the severity and prognosis of patients with craniocerebral damage is a major research area in medicine since it is a prevalent clinical disease. Acute craniocerebral injury, a common traumatic condition, is often caused by traffic accidents, collisions, and falls in daily life. Secondary craniocerebral injury refers to symptoms such as brain edema and intracranial hemorrhage after acute craniocerebral injury, which will aggravate the injury. Secondary craniocerebral injury can be avoided by effective and timely treatment, and real-time detection of brain edema and intracranial hemorrhage by non-invasive medical imaging is a solution. Therefore, non-invasive medical imaging technology has recently emerged as a new area of study. A new imaging technology, namely the brain injury detection technology based on electromagnetic induction, has been discovered after years of research on non-invasive detection of brain injury. Initially, electromagnetic induction technology was widely used in metal nondestructive testing. The human body, as a conductor, also has electromagnetic induction, allowing this technology to be used on the human body. This study reviews the technologies for detecting electromagnetic induction in cases of craniocerebral damage, including induced current electrical impedance tomography, magneto-acoustic tomography, and eddy current damping sensors for detection and imaging.

Keywords: Craniocerebral injury, electromagnetic induction, electrical impedance tomography, magneto-acoustic tomography, eddy current damping

Introduction

Medical imaging technologies like CT, MRI, PET, and ultrasound were developed in the 20th century, and are now the primary means of inspection in modern medicine. However, current clinical medical imaging technology is still unable to address all the clinical issues. New imaging technologies in medicine may provide more specific benefits in diagnosing certain disorders. For instance, earlier treatment within the therapeutic window is described to have greater benefits in the treatment of stroke, and current American national guidelines call for a door-to-imaging time within 25 minutes and imaging interpretation within 45 minutes [1, 2]. Thus, more time-saving detection technologies are essential. The Italian physician Luigi Galvani first discovered that biological tissue exhibits electrical qualities at the end of the 18th century by dissecting a frog and stimulating its leg with electricity. Galvani presented his findings on frog limb spasms in Animal Electricity, which inspired the research on electrophysiology [3]. In industry, electricity is used to detect metal damage by utilizing its conductive properties to detect bubbles and monitor the flow rate of process pipelines. In 1978, Henderson

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and Webster first proposed using electrical impedance for human detection [4]. They put 100 electrodes on one side of the human body and grounded the other. It was found that different tissues in the human body had varying resistivities, and organ images of the human body were obtained through measurement [5]. By the end of the 20th century, novel medical imaging technologies were developed in response to changing medical needs and scientific advancement. For instance, electrical impedance tomography (EIT), magnetic resonance electrical impedance tomography (MREIT), Lorentz force electrical impedance which also named magneto-acoustic tomography (MAT) were developed to meet specific requirements, such as being more movable, more affordable, faster, and less intrusive [6].

EIT is currently being used in clinic, primarily for chest detection, and EIT for brain is under areicle. In China, 47 hospitals were expected to have 50 EIT instruments by 2020 [7]. According to recently published research, the current EIT devices have an impedance capture range of 10 Hz to 100 kHz and exhibit excellent performance. The time stability is 0.03% CV, the SNR is 84.28 dB, and the accuracy is 99.7% [8]. Furthermore, the EIT equipment has an extremely fast scanning speed of 50 images per second, enabling the acquisition of real-time and dynamic images [9]. The information of some chronic diseases can also be detected by EIT equipment, making it a valuable addition to CT or MRI imaging.

EIT technology

Faraday discovered electromagnetic induction in 1831. Since then, the induction technology has continuously been improved, leading to numerous practical designs that are now used in many facets of life. Previously research on the detection of craniocerebral injury has revealed that clinicians frequently select CT and MRI as their primary techniques for the diagnosis [10]. CT and MRI are currently the best medical imaging methods available, although they both have limitations. CT scan uses radiation that harms human body, making frequent use unsafe. MRI scan uses electromagnetic waves to create images of the human body, which has a longer scanning duration and higher cost than the CT and cannot be used in patients with metal prosthetics [11].

Electromagnetic induction is suggested to be used for medical imaging in this situation. It uses the magnetic field generated by the external coil when it is energized to induce a current in the brain tissue, and then evaluates and interprets the recorded electrical data to reconstruct the imaging. Electromagnetic induction detection technology allows medical professionals to easily and quickly capture images without making physical contact. Furthermore, due to its simple structure and low production costs, electromagnetic induction imaging has the potential to be more widely used in clinics or even at home in the future.

Principle of EIT

EIT works based upon stimulating an organism's surface with voltage or current. The formula for calculating the electrical impedance of organisms is: $Z=R+jX$ [8]. The conductivity of lesions differs from that of normal tissues, affecting the voltage applied to the tissues. Through the electrodes, the acquisition voltage can be measured, and the digital to analog converter can transform voltage data into digital quantities. Electrical impedance imaging can be produced by processing these digital quantities.

The goal of EIT is to obtain the conductivity of the measured tissue area. It is an inverse problem of imaging technology to infer the shape of the source object using the measured electrical signals. The EIT image reconstruction algorithm employs a numerical approach to measure the boundary voltage using a measurement system, and then iteratively updates the conductivity between the calculated and measured values to ultimately determine an approximation of the impedance distribution. In the development of this method, injecting current has always been a hot topic of research. In recent years, many studies have focused on finding suitable ways to inject current into organisms wirelessly. Through the magnetic field surrounding the coil, electromagnetic induction technology produces induced current in the body of an organism. By placing the coil around the organism, the induced current is generated in its body without direct contact.

Induced current electrical impedance tomography (ICEIT)

EIT is a quick way to diagnose brain injuries, and ICEIT is an improvement of EIT. The resistivity differs among various body tissues [12]. With this method, a small and safe current is injected into the patient to measure the voltage distribution, and images are then recreated using the obtained information. Its benefits include minimal cost, real-time functionality,

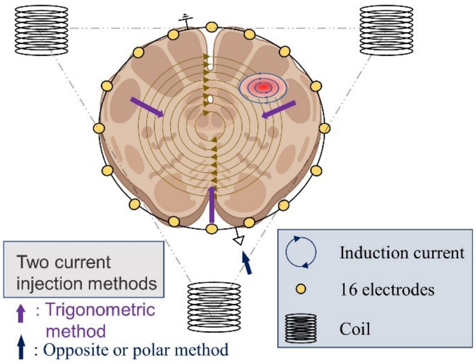

Figure 1. Schematic diagram of the imaging principle of induced current electrical impedance tomography.

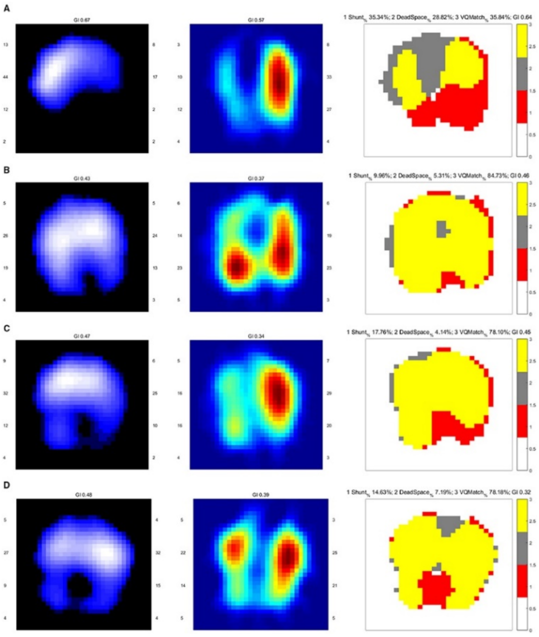

Figure 2. EIT images of the functional ventilation distribution, functional perfusion distribution, and distribution of the regional ventilation/perfusion ratios. EIT images of the functional ventilation distribution (dark blue areas indicated low ventilated regions and white areas indicated high ventilated regions), functional perfusion distribution (red areas indicated high-perfusion regions and blue areas indicated low-perfusion regions), and distribution of the regional ventilation/perfusion ratios (Ventilated regions were defined as pixels with impedance changes higher than 20% of the maximum tidal impedance variation in the functional ventilation image. Perfused regions were defined as pixels higher than 20% of the maximum bolus-related impedance change in the functional perfusion image. Gray areas indicated regions with high ventilation and low perfusion. Red areas indicated low ventilation and high perfusion regions. Yellow areas indicated good ventilation-perfusion matching). (A) On admission, there was a significant ventilation defect in the dorsal lung and perfusion defect in the right lung, leading us to perform CTPA for PE confirmation. The ventilation defect was later treated with lung recruitment and tracheal suction; (B) Ventilation improved after lung recruitment and tracheal suction. Regional perfusion in the right lung was restored after thrombolysis; (C) the image of the ventilation/perfusion (V/Q) ratio distribution; (D) On day 12, there were ventilation defects in the dorsal lung. The lung perfusion demonstrates symmetric in both lungs. This figure was cited from [19]. EIT, electrical impedance tomography.

as well as high safety. Dong et al. investigated electrical impedance imaging technology using electromagnetic induction [13]. By wrapping a few coils around the brain and delivering alternating current, ICEIT technology creates a changeable magnetic field that induces current in the brain. This is different from EIT, which provides the body with current through electrodes. Devices for ICEIT only measure output voltage, not the driving current. It is feasible to increase the signal-to-noise ratio by using a higher current density, as the induced current produced by the electromagnetic induction phenomenon is not limited by the current density at the electrode [13].

It should be noted that due to its collection of electrical pulses, EIT is susceptible to the “skin effect”, which can also be caused by current in a conductor. The “skin effect” is a phenomenon where alternating current or electromagnetic fields applied to a conductor cause the current to concentrate on the surface of the conductor, resulting in increased surface resistance. It is challenging for ICEIT technology to differentiate cerebral hemorrhage and cutaneous consequences in this incident. Therefore, researchers upgraded the EIT technique to prevent errors caused by the “skin effect” by gathering non-electric information [14, 15]. In order to minimize the impact of the “skin effect”, Yang et al. did pertinent research on injected current and induced current by MREIT [16]. They reconstructed the imaging by acquiring the magnetic induction intensity. Ongoing research on MREIT aims to improve its resolution through the development of various algorithms. At present, MREIT technology is undergoing clinical evaluation [17].

Computer simulations and brain models made of gelatin has been commonly used in studies on EIT technology for craniocerebral damage. Also, the use of EIT in clinical settings is increasing, and efforts are being made to establish universal standards for EIT imaging. Furthermore, research indicates that chest EIT technology has entered the clinical stage [18]. **Figure 1** shows the schematic diagram of EIT [13]. In the illustration, 16 electrodes are attached to the periphery of the brain, and wires are connected to collect the signals recorded by the electrodes. The wires are twisted to reduce

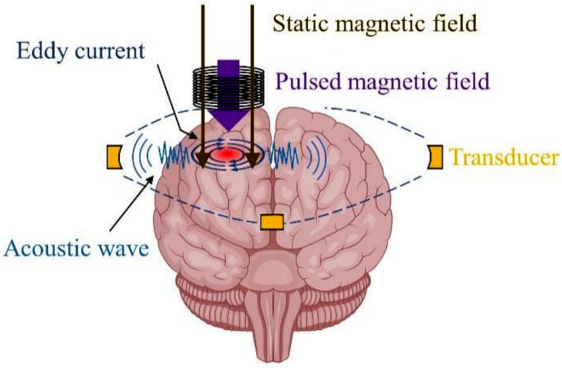

Figure 3. Schematic diagram of the imaging principle of magneto-acoustic tomography with magnetic induction.

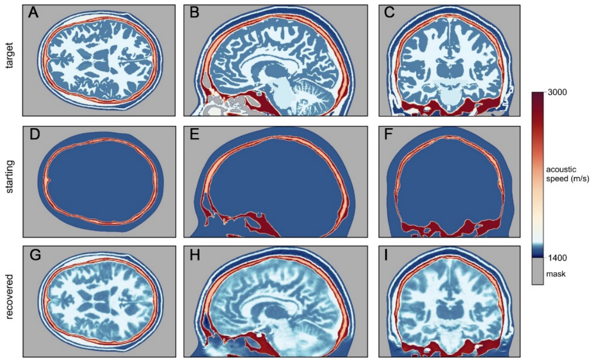

Figure 4. MAT-MI detection imaging diagram. Transverse (left), sagittal (center), and coronal (right) sections through the true (top), starting (middle), and recovered (bottom) models. Both the wavefield modelling and waveform inversion are performed in three dimensions. The starting model includes the true model of the skull, but is otherwise homogeneous. This figure was cited from [24]. MAT-MI, Magneto-acoustic tomography with magnetic induction.

the coupling area and prevent the electromotive force from interfering with the experiment. The EIT pulmonary perfusion images are shown in **Figure 2** [19]. When three or more coils are wrapped around the brain and energized, they will generate induced current in the brain. There are two primary current injection methods for measuring brain activities: the Opposite or Polar method and the Trigonometric method.

The Opposite or Polar method is to inject current from two electrodes 180° apart and measure the voltage of the remaining electrodes. Trigonometric method is to inject current into all electrodes. Generally, three coils are used to simultaneously generate induced current and measure the voltage of the electrodes.

MAT

In 1998, Wen et al. proposed magnetic imaging, which was named hall effect imaging at the time [20-22]. After academic discussions, it is now basically divided into two types: MAT with magnetic induction (MAT-MI) and MAT with current injection (MAT-CI). MAT combines ultrasound with electromagnetic induction EIT to improve the low contrast of ultrasonic imaging and achieve excellent resolution. Using captured ultrasonic waves to rebuild the image, MAT can produce non-invasive and real-time imaging. Moreover, MAT does not have a skin effect.

MAT-MI

Figure 3 shows the schematic diagram of MAT-MI [23]. As shown in the diagram, MAT requires a static magnetic field, a pulsed magnetic field, and a transducer. After placing a static magnetic field beside the brain, a pulsed magnetic field is created by energizing the coil. Brain tissue can conduct electricity, which leads to changes in the current of the coil through the principle of electromagnetic induction. This results in the generation of induced current in the conductor adjacent to the coil. In the magnetic field, the current experiences Lorentz force, leading to vibration. This vibration can be likened to a sound wave that is captured by transducers placed around the room and converted into data for imaging purposes.

Figure 4 is an MAT-MI detection imaging diagram, including pictures of the bovine rib muscle sample, with many fat contents [24]. MAT-MI is also called Lorentz force electrical impedance tomography.

MAT-CI

Another method is current injection. Instead of using electromagnetic induction to create current in the brain, MAT-CI injects alternating current into the brain from the outside. The current should flow parallel to the static magnetic field's direction outside of the device. The same method used in MAT is also used to capture the necessary signals for imaging.

Eddy current damping (ECD) sensors for detection and imaging

ECD sensors, which rely on electromagnetic induction, are utilized in intracerebral hemorrhage (ICH) imaging technology to detect eddy currents induced by a live coil's dynamic magnetic field. Eddy currents generate magnetic

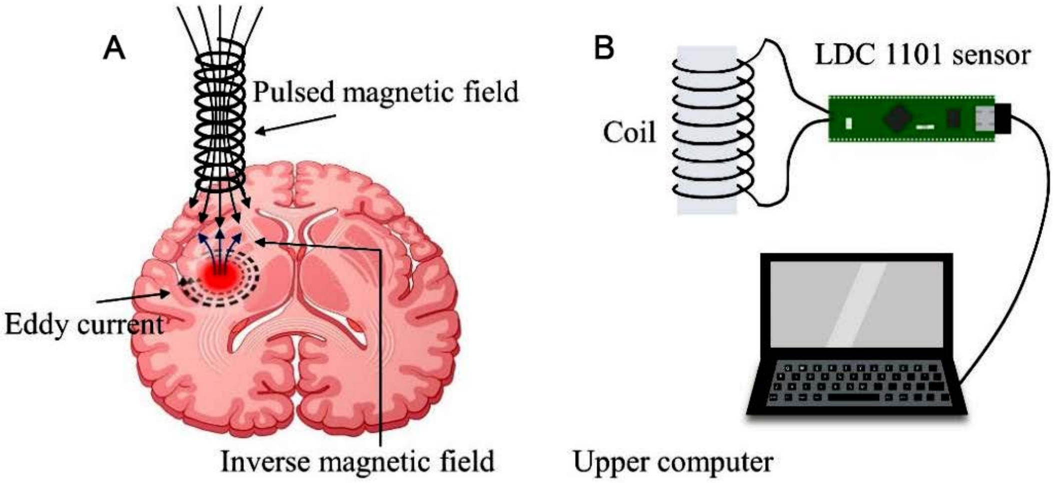

Figure 5. ECD sensor Schematic diagram and construction. (A) Schematic diagram of ECD craniocerebral injury detection; (B) ECD sensors schematic. ECD, eddy current damping; LDC, inductance-to-digital converter.

fields, and the coils repel each other in opposite ways, reducing the magnetic field intensity and impedance of the coils. It is possible to locate an ICH or hematoma by comparing the electrical conductivity of normal brain parenchyma 0.2 S/m with that of cerebral hemorrhage or hematoma 0.65 S/m [25]. In the ECD imaging technology, the afore-mentioned "skin effect" has also been addressed. According to the electromagnetic induction principle, the presence of cerebral bleeding leads to the production of eddy current, causing a decrease in the coil's inductance and an increase in resistance. The eddy currents also produce magnetic flux, which reduces the flux density of the total magnetic field [26]. By comparing the variations in magnetic flux density between normal tissue and hemorrhagic tissue, pictures of cerebral hemorrhage are created. **Figure 5A** shows that when the coil is energized, a pulsed magnetic field is generated [27]. **Figure 5B** illustrates the schematic diagram of ECD [28].

At the moment, this technique has been validated though modeling and simulation by Shane Shahrestani's team [27, 28]. The ECD Sensor Benchtop Model used a plastic skull replacement and gelatin as a substitute for the brain parenchyma in the center. To mimic blood, a diluted normal saline solution was utilized, with the conductivities of the gelatin and saline matched to those of human brain tissue and the blood. Additionally, it is necessary to prepare the coil and inductance-to-digital converter chips for the gathering of a range of data. The collected data are then filtered and used to generate images. This procedure can be finished in 3 minutes and is suitable for immediate care in detecting brain injuries. Later, in a paper written by Shane Shahrestani's group, cadavers were used in simulations and experiments to evaluate the effectiveness of ECD techniques. Although the results demonstrated the potential of ECD technology, there are still limitations. The interaction of the head and skull may affect signal acquisition, and the presence of high-conductivity materials in the detection environment may also affect the results. There is no live animal experiments having been conducted yet, but the impact of coil size on resolution is researched. The results showed that the signal-to-noise ratio decreased with coil size and that intracranial hemorrhage caused by skin effect was detected less than the scalp-skull interaction. The closer the measurement target is, the closer the coil needs to be placed to it. **Figure 6** is an ECD detection imaging diagram [29].

Discussion

This review introduces three types of brain damage detection technology about electromagnetic induction: ICEIT, MAT, and ECD sensors. To create a magnetic field through the excitation coil and induction current in the brain, all three techniques rely on the electromagnetic induction principle. The differences are that, after the induction current is generated, MAT acquires ultrasonic reconstructed images, EIT acquires the resistance data to reconstruct images, and ECD imaging uses the magnetic effects of eddy currents to collect images.

In recent years, there has been new progress in detection technology based on electromagnetic induction. This technology has gained particular attention during the recent COVID-19 pan-

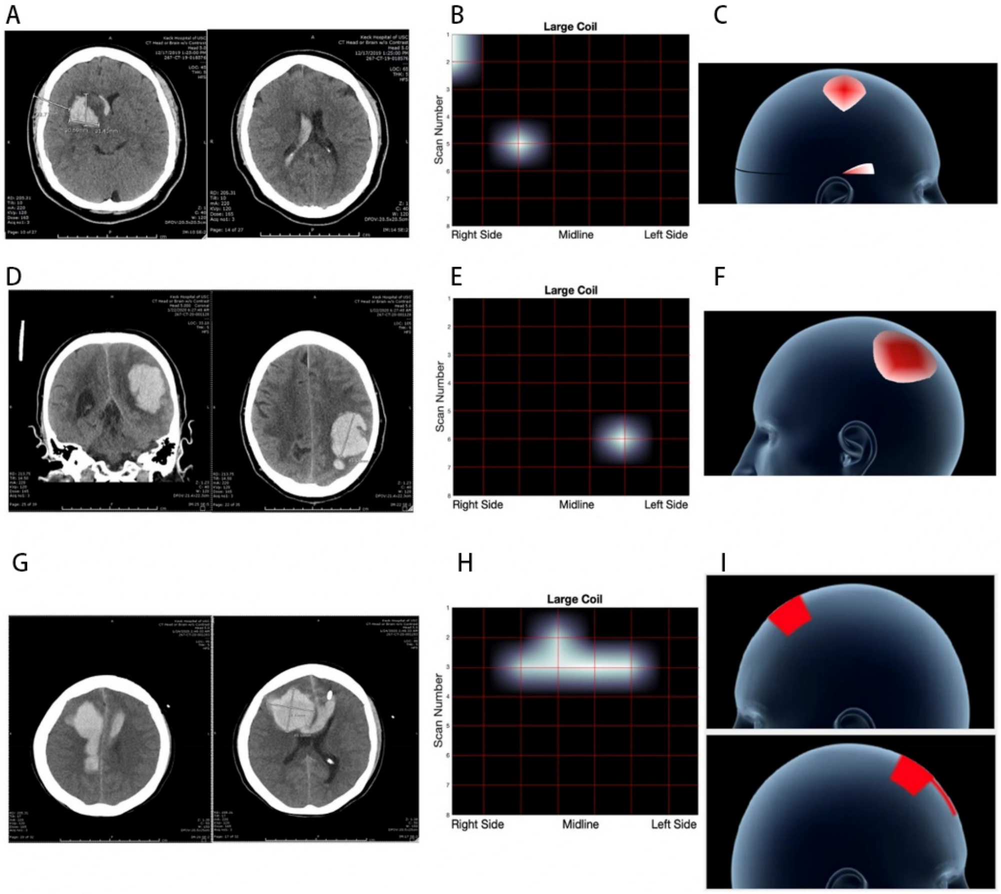

Figure 6. CT imaging, 2D ECD sensor imaging, and 3D ECD sensor imaging for three hemorrhagic stroke patients. The 2D images were produced by continuously scanning across the 8 scanning rows and then averaging each row into 8 equidistant points, with interpolation, to create an 8 × 8 heatmap. As such, lesions are shown on the vertices of the heatmap if detected. To create the 3D images, the 2D heatmaps were projected onto a hemispherical head template. (A) CT imaging showing a right basal ganglia ICH and associated IVH in patient; (B) Two-dimensional data gathered from ECD sensor. Of note, the Large Coil has the largest magnetic field depth, and thus was able to detect both hemorrhages; (C) Three-dimensional projections of each coil. 3D graphics can be created in real-time to rapidly guide clinical judgement and reduce time-to-treatment; (D) CT imaging showing a left parietal lobar ICH in patient; (E) Two-dimensional data gathered from ECD sensor scanning; (F) Three-dimensional projections of the lesion; (G) CT imaging showing bilateral ICH, right greater than left in patient; (H) Two-dimensional data gathered from ECD sensor scanning; (I) Three-dimensional projections of the lesion. The lesion crosses the midline, so two images are provided with left (top) and right (bottom) profiles. This figure was cited from [29]. ECD, eddy current damping.

demic due to its non-contact benefits. Yan et al. utilized new electrode design, more advanced reconstruction algorithm and better signal processing technology to obtain reconstructed images with higher spatial resolution and image quality [30]. In addition, multimodal imaging is also a hot research direction. Zhang et al. combined deep learning with EIT technology to optimize the acquired impedance data [31]. By interpreting deep learning with traditional algorithms, they improved the quality of reconstructed images, providing a new path for EIT reconstruction. In addition, there has been development in using electromagnetic induction detection technology for craniocerebral injury in wearable devices for long-term monitoring, which holds great promise for detecting chronic diseases.

However, despite the progress, there are still limitations in the clinical applications of EIT, MAT and ECD technologies. First, improving the spatial resolution has been the ongoing research focus in this field. Due to the complexity and non-uniformity of current propagation in tissues, the spatial resolution of EIT is still limited. Second, the depth is limited in brain detection. Currently, only implanted electrodes can reliably detect the impedance changes inside the tissue. Other non-invasive detection technologies have not adequately addressed this problem. Finally, the signals acquired by imaging are also susceptible to noise from electrode contacts and electromagnetic interference, which may lead to a low signal-to-noise ratio and compromise the quality of imaging. Although its resolution is still being investigated, some researchers reported that the spatial res-

Table 1. Technology comparison among ICEIT, MAT, and ECD

Name	Principle	Spatial resolution	Current stage	Advantage (+) and disadvantage (-)
ICEIT	Electrical Current [32]	Above micrometre [32]	Clinical stage [33]	Low cost (+), Clinical application (+), skin effect (-)
MAT	Electrical Current, Acoustics, Magnetic Field [34]	Above millimeter [35]	Simulation verification	High resolution (+), need of magnetic fields (-)
ECD	Electrical Current, eddy damping [28, 29]	During the investigation [27]	Simulation verification, Corpse experiment [28, 29]	Low magnetic intensity (+), noise interference (-)

Note: ICEIT, induced current electrical impedance tomography; MAT, magneto-acoustic tomography; ECD, eddy current damping.

olution of ECD detection equipment is superior to that of near-infrared spectroscopy [28].

Table 1 lists the spatial resolutions and stages of development of the three detection methods.

Conclusion

Currently, CT and MRI technologies cannot be replaced by electromagnetic induction for the identification of brain injuries, despite they have low cost, portability, and fast imaging. ICEIT may be the first to be used clinically, as ECD technology is still under investigation and requires further development before it can be used in clinical settings. In terms of resolution, the MAT outperforms the ICEIT, and the most publications in this subject are in recent years. The three detection methods are potential for further research, and future efforts should focus on developing portable or bedside diagnostic devices.

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