Abstract—Brain electrical impedance tomography (EIT) is an emerging method for monitoring brain injuries. To effectively evaluate brain EIT systems and reconstruction algorithms, we have developed a novel head phantom that features realistic anatomy and spatially varying skull resistivity. The head phantom was created with three layers, representing scalp, skull, and brain tissues. The fabrication process entailed 3D printing of anatomical geometry for mold creation followed by casting to ensure high geometrical precision and accuracy of the resistivity distribution. We evaluated the accuracy and stability of the phantom. Results showed that the head phantom achieved high geometric accuracy, accurate skull resistivity values, and good stability over time and in the frequency domain. Experimental impedance reconstructions performed using the head phantom and computer simulations were found to be consistent for the same perturbation object. In conclusion, this new phantom could provide a more accurate test platform for brain EIT research.

Index Terms—heterogeneous resistivity distribution, electrical impedance tomography (EIT), realistic shape, phantom, rapid prototyping (RP)

I. INTRODUCTION

Electrical impedance tomography (EIT) is a safe, non-invasive, real-time, low-cost, and functional imaging technology. Its principle is that alternating current is injected into the body and the voltage is measured on the object surface, based on which impedance distribution or change can be reconstructed [1]. Brain EIT is an emerging application of EIT with great potential in monitoring brain injuries, such as intracranial hemorrhage, ischemia, and cerebral edema [2]-[4]. Phantom study plays an important role in exploring the application of brain EIT to the aforementioned diseases. A head phantom is usually required to perform some experiments in brain EIT. First, a head phantom is able to test the performance of hardware and software before a brain EIT system can be applied in vivo. Second, due to the electrical and geometrical parameters and properties which are similar to real tissues, head phantoms can simulate human normal and pathological conditions to carry out various experimental studies which would be difficult to do in vivo.

An ideal physical phantom for EIT is supposed to accurately reflect the electrical and geometrical characteristics of the internal organs of the object as well as to realistically simulate the current distribution inside the object. In fact, the skull resistivity is so high that only a small amount of current applied on the scalp can penetrate the skull. Also, the current distribution in the head is nonuniform because the skull is characterized by an irregular shape and spatially varying resistivity [5]. Accordingly, these important characteristics of the skull should be incorporated into head phantoms.

Existing head phantoms fail to fully meet these requirements. At present, the main categories of head phantoms fall into digital models, human cadavers, artificial physical models, etc.[6]-[9].These different models possess their respective advantages as well as disadvantages. The digital phantoms were effective tools for studying brain EIT on computers but would not be helpful in testing the EIT hardware performance or system stability over time. Although human cadavers could provide models with realistic anatomy, the resistivity of the devitalized tissue varied greatly from that of the living tissue. Resistivity changes of the object directly lead to changes in the current distribution within the object. Moreover, artificial physical phantoms were established in many forms. For example, cylindrical phantoms were relatively simple and easy to achieve [10]. However, their shapes were so different from the human head that they are not ideal for studying brain EIT. Although resistor network phantoms possess high repeatability and stability over time [11], they could not simulate the continuous behavior of biological tissues and would require complex connections to build accurate 3D models. Spherical or hemispherical phantoms filled with salt solution, paraffin, or gel could well mimic the resistivity properties of tissues [8], [9], [12].However, they lack true geometrical information of the...
skull. In addition, Tidswell et al. employed a real human skull in EIT study and used skillfully the skin of a marrow or giant zucchini to provide impedance simulation of human skin [13], [14], but the skull resistivity was different from data of living skull. Collier et al. (2012) manufactured a head phantom with realistic geometrical shape [15], yet they ignored the important fact that the resistivity distribution varies spatially in a real skull. In short, in almost all volume conductor models the skull was considered to have a uniform resistivity distribution, which greatly affected the accuracy of EIT measurements.

The aim of this study was to fabricate a reproducible head phantom with more anatomical details and more accurate impedance distribution than those of the previous ones, which could make the current distribution in the phantom closer to the in vivo situation. The phantom was a 3D physical model with three layers, including scalp, skull, and brain. In this study, we first carefully selected a material simulating the skull and investigated its electrical properties. Next, we used rapid prototyping (RP) technology (3D printing) and the impression technique usually applied in prosthdontics to build the head phantom. These techniques could fabricate a skull shell with a highly precise geometrical shape, thereby avoiding errors caused by cylindrical, spherical, or semi-spherical phantoms. Finally, the test results showed that the head phantom achieved some satisfactory performances in terms of geometrical shape, electrical impedance distribution, stability over time as well as in a wide frequency range. This developed multi-layer head phantom would facilitate the assessment of the data-acquisition hardware, verification of the current injection mode, and evaluation of the reconstruction algorithms in brain EIT research.

II. MATERIALS AND METHODS

A. Material and Its Electrical Property

The human skull has a relatively high resistivity which greatly shields the injected current. The material simulating the skull is generally assumed to have the following characteristics: (a) high similarity to the skull in terms of resistivity within an environment akin to the human body (including temperature and humidity); (b) a stable resistivity in a wide frequency range; (c) steady resistivity over time; (d) easy shaping; and (e) high rigidity that ensure no deformation. Thus far several materials are suitable for simulating the skull for brain EIT: conductive silicone rubber, carbon doped resin and plaster, all of which are able to meet the requirements in terms of stability and reproducibility [16]-[19]. However, it is technically difficult to integrate parts of rubber or resin into one. Also, as conductive powder is mixed with rubber or resin during processing, it is possible to cause nonuniform resistivity distribution and difficulty in regulating electrical properties. Furthermore, conductive rubber is prone to deformation under a given pressure. Contrarily, plaster is a material without foregoing defects. Plaster resistivity has been reported to correlate with the ratio of distilled water to plaster powder [4], [9]. According to previous literature, the resistivity of dental grade plaster remained approximately constant in a wide frequency range (1 Hz to 1 MHz), which was similar to the electrical characteristic of skull [10], [20]. Therefore, we chose dental grade plaster (calcium sulfate, Dental Stone III, Shanghai Medical Instruments Ltd., China). However, some issues remained to be addressed. In previous studies, for example, temperature and humidity were not strictly controlled according to the human body. The range of the ratio of distilled water to plaster powder was also relatively narrow. In addition, no specified formula was provided to determine plaster resistivity and the ratio of distilled water to plaster powder. Thus, it was of necessity to conduct related research to solve these problems.

In this study, distilled water was mixed with plaster powder according to the ratios shown in Table I first. After thorough stirring, the plaster was quickly filled into a cylindrical silicon mold. Bubbles were removed with a vibrator and then the plaster was taken out after coagulation. The diameter and the height of the plaster cylinder were 29 mm and 70 mm, respectively. For each ratio, six plaster cylinders were produced simultaneously.

Plaster cylinders were soaked in a saturated solution of calcium sulfate for two weeks to stabilize the resistivity. Before resistivity measurement, the saturated solution was placed in an infant incubator, the temperature and humidity of which were set to 36.5±1°C and 98±1% RH. In this study, we employed a 4-electrode assembly reminiscent of the reported ones to measure the impedance [5], [21]. Measurements were carried out by SI 1260 and SI 1294 impedance analyzers (Schlumberger Technologies Ltd., Farnborough, Hampshire, England) with a current magnitude of 1.25 mA in the frequency range from 1 Hz to 1 MHz. The system is calibrated by conductivity standard solution (12.88 mS/cm, Mettler-Toledo Instruments Ltd., China). However, some issues remained to be addressed. In previous studies, for example, temperature and humidity were not strictly controlled according to the human body. The range of the ratio of distilled water to plaster powder was also relatively narrow. In addition, no specified formula was provided to determine plaster resistivity and the ratio of distilled water to plaster powder. Thus, it was necessary to conduct related research to solve these problems.

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<table>
<thead>
<tr>
<th>No.</th>
<th>Distilled water (g)</th>
<th>Plaster powder (g)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>100</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>100</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>100</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>33</td>
<td>100</td>
<td>0.33</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
<td>100</td>
<td>0.36</td>
</tr>
<tr>
<td>6</td>
<td>39</td>
<td>100</td>
<td>0.39</td>
</tr>
</tbody>
</table>

The resistivity can be calculated by:
\[ \rho = \frac{RS}{L} \]
(1)
where \( R \) is the real part of impedance of the plaster cylinder, \( S \) is the cross-sectional area of the plaster cylinder, and \( L \) is the height of the plaster cylinder.

The measured data were fitted using Origin 8.0 (OriginLab, Northampton, Massachusetts, USA) (Fig. 1(a)). The regression equation can be expressed as:
\[ y = 7.0575 \times 10^7 e^{-x / 0.0204} + 38.4366 \]
(2)
where \( x \) is the ratio of distilled water to plaster powder and \( y \) is the resistivity of the plaster. \( R^2 \), the correlation coefficient, is 0.9931.

The maximal resistivity of a living human skull as measured
Fig. 1. The electrical property of plaster: (a) the relationship between the resistivity and the ratio of distilled water to plaster powder ($f=50$ kHz); (b) the resistivity change of the plaster soaked in the calcium sulfate saturated solution over time for the weight ratio of 0.33 (the results of groups with other weight ratio presented the same tendency).

by Tang et al. (2008) is $265.46 \, \Omega \cdot m$ and the minimal resistivity is $57.82 \, \Omega \cdot m$ [20]. Thus, the minimal and maximal ratios of distilled water to plaster powder calculated by Eq. (2) were 0.258 and 0.308, respectively, which were included by the tested ratio range.

According to the literature, the resistivities of the human scalp and brain are $2.00$ and $3.30 \, \Omega \cdot m$ [22], [23], respectively, which are far less than the resistivity of the skull. The resistivities of the scalp and brain are of the same order of magnitude. Therefore, we reasonably simplified the design and set their resistivities to both $4.00 \, \Omega \cdot m$. The resistivity of the saturated solution of calcium sulfate was reported to be $4.00 \, \Omega \cdot m$ [21], which qualified this solution to simulate the scalp and the brain. Another advantage of this solution is the prevention of plaster dissolution to ensure the stability of the phantom. Preliminary experiments showed that the resistivity of a plaster cylinder soaked in the calcium sulfate saturated solution was gradually stabilized over time (Fig. 1(b)). The stabilization time of different plasters varies only from 8 to 12 days. Consequently, we chose a time period of two weeks to stabilize the resistivity of the plaster samples.

**B. Geometrical Shape**

Laser RP technology (3D printing) has many advantages in the manufacturing industry. However, the materials processed by this method are mostly resin or metal [24], [25], which do not easily simulate electrical properties of skull characterized by spatially varying resistivity distribution. Consequently, we first constructed a high-precision resin model through laser RP (3D printing), and then we fabricated a plaster phantom with realistic geometrical shape using a resin model and an alginate impression material.

The fabrication process of this skull phantom is shown in Fig. 2.

An adult male patient’s head without brain disease was scanned by spiral CT (Light Speed VCT, GE Healthcare, Waukesha, Wisconsin, USA). The scan parameters included 0.625 mm slice thickness, 578 slices, 120 kV tube voltage, and 240 mA tube current. The acquired image data were saved as a standard file format: Digital Imaging and Communications in Medicine (DICOM).

After importing the DICOM files into the Mimics 10.0 software (Materialise, Leuven, Belgium), we identified and extracted the skull area, followed by reconstruction of the 3D skull model. Next, we optimized the 3D model in Magics V10 (Materialise, Leuven, Belgium) (Fig. 3(a)) and divided it along the sutures into eight parts: one frontal bone, two sphenoid wing bones, two temporal bones, two parietal bones and one occipital bone (Fig. 3(b)).

The reconstructed 3D model was meshed into triangle grids and exported in Stereo Lithography (STL) format files which could be processed by RP. After that, the poly-N-salicylidenevinylbenzylamine resin as raw material was sintered layer by layer via a selective laser sintering (SLS) RP machine (model AFS360, Beijing Longyuan Automated Fabrication System Co., Ltd., Beijing, China) so that separate resin skull phantom parts were obtained. Finally, the surfaces of
the resin phantoms were polished to eliminate burrs and edge bumps.

C. Spatially Varying Skull Resistivity Distribution

To build a skull phantom with realistic resistivity distribution, we set the resistivities of separate skull parts and sutures (Table II) in accordance with the skull anatomy and the results on living human skulls reported by Tang et al. (2008) [20]. The ratio of distilled water to plaster powder for separate skull parts and sutures were calculated using Eq. (2).

D. Fabrication of Impression and Phantom

Impressions of separate resin phantom parts were constructed with alginate. After shaping of the impression, the resin phantoms were removed and the fabricated plaster was immediately poured into the impression placed on the vibrator. Plaster with different ratios corresponded to separate skull parts and sutures were calculated using Eq. (2).

E. Resin Tank and Bracket

In clinical monitoring, the electrodes of brain EIT system are attached to the patient’s scalp and typically located on the same plane. To simulate the actual monitoring environment, we built a resin tank which was skull-like in shape and slightly larger than the phantom. Electrodes were set in the inner surface of the resin tank.

The fabrication process of the resin tank was similar to that of the resin skull phantom (Fig. 4).

The outer surface of the 3D skull reconstruction was extracted and expanded 5 mm outwards to form the scalp layer, followed by another 5 mm outward extension with identical shape as the 3D reconstruction of the tank (Fig. 5). After optimization, STL format files were imported into the SLS RP machine to produce the resin tank.

To study the impedance changes in different cross-sections of the head, two layers of electrodes were set on the inner surface of the resin tank. The 16 electrodes on first layer were equally spaced across the eyebrows, temporal bone and inion. The second layer was 20 mm below the first one with identical electrode distribution (Fig. 6).
F. Geometrical and Electrical Characteristics and Stability Performance

With the advantage of high precision RP technology has been widely used in surgery and other medical fields [26]-[29]. Likewise, alginate is a high-precision impression material commonly applied in prosthodontics [30]-[33]. Therefore, the plaster skull phantom made with alginate impression via RP technology is expected to possess high precision. Nonetheless, a morphometric analysis is still necessary to validate the feasibility of the construction method and the geometrical precision of the actual phantom. However, the irregular shape of the skull made the quantification of morphometric precision relatively difficult. Thus, some key points on the skull phantom must be determined for quantitative analysis. Measurements and analysis methods of all skull phantom parts were similar and we herein take the phantom part of left parietal bone as an example (Fig. 7). The intersection of the sagittal and coronal sutures was assumed to be A, where the thickness was t1; the intersection of the lambdoid and sagittal sutures was B, where the thickness was t2; the intersection of the lambdoid and parietotemporal sutures was C, where the thickness was t3; the intersection of the sphenoid wing and the parietotemporal suture was D, where the thickness was t4; and the linear distance from the midpoint of the sagittal suture to the superior temporal line was L. In the case where the parietal bone phantom is placed horizontally, the height of the highest point in the phantom was h1, the height of midpoint of parietotemporal suture was h2 and the height of midpoint of sagittal suture was h3. To reduce the measurement error, all key points on the phantom (plaster or resin) were marked simultaneously and the average of three consecutive measurements was considered as the final result for each key point. Agreement between the plaster and the resin phantom was evaluated.

While casting each plaster part of the skull phantom, six plaster cylinders (70 mm in length and 29 mm in diameter) with the same ratio were made to facilitate the measurement of the resistivity corresponding to that plaster part. Measurement temperature and humidity were respectively set to 36.5±1 °C and 98±1% RH. Measurements were carried out using SI 1260 impedance analyzer with SI 1294 interface. The current magnitude was 1.25 mA and the frequency range was from 1 Hz to 1 MHz. One-sample t test was used to evaluate the difference between the measured resistivity of each plaster part and that of the corresponding human skull part [20], where \( P<0.05 \) was considered statistically significant.

To test the phantom stability, transimpedances were measured over time and the results were compared with the simulation values. In the phantom measurement, Ag/AgCl electrodes were connected to SI 1294 via shielded wire. The skull phantom was soaked in saturated calcium sulfate solution for two weeks prior to measurement to stabilize the resistivity of the phantom. The amplitude of the driving current was 1.25 mA and the frequency range was from 1 Hz to 1 MHz. The measurement was performed thrice daily for one week. To elucidate the measurement process, we defined that when driving current was injected via Electrode Pair (EP) 1-9, the measured voltage from EP 2-3 was denoted as No. 2, the measured voltage on EP 3-4 was denoted as No. 3, and so on (Fig. 8).

In computer simulations, the transimpedances were obtained from the 2D skull model with real boundary and resistivity distribution with identical parameter configuration (Fig. 9).

G. EIT Experiments Based on the Head Phantom

To evaluate the reliability of the head phantom in practical application, an EIT imaging experiment with resistivity perturbation was carried out and the results were compared with those of computer simulations.

In this study, an optimized adaptive damped least-square (DLS) method was applied in computer simulations [3]. The DLS method was used to mesh the skull region according to the real boundary and to set different resistivities depending on different skull regions (Fig. 9). For our brain EIT system, an opposite driving/adjacent measuring pattern was employed for the 16-electrode measurement with 1.25 mA driving current at 50 kHz. The main performances of the brain EIT system included 90 dB signal-to-noise ratio, 75 dB common mode rejection ratio, 0.01% measurement precision, 0.1% deviation of reciprocity, operating frequency range from 1 Hz to 190 kHz, and a data-acquisition rate higher than 1 f/s [34]. The perturbation object was an agar cylinder with a resistivity of 1.43 \( \Omega \cdot \text{m} \) (diameter 20 mm, height 50 mm). A comparison was made to test the phantom stability, transimpedances were
made between reconstructions of computer simulations and physical experiments with the perturbation at four positions.

III. RESULTS

A. Skull Phantom and Experimental Platform

Separate plaster parts were successfully reproduced from resin parts by the impression technique and were joined to form a complete skull phantom (Fig. 10).

A bracket made of plexiglass was designed for accurate positioning during the experiment, which was light and did not induce any electromagnetic interference. In addition, a vernier with a precision of 0.02 mm was mounted on the bracket. The vernier was capable of moving up and down and rotating freely (Fig. 11).

B. Geometrical Approximation

For a key point on the phantom parts, shape distortion rate (SDR) is defined as:

$$E = \left| \frac{M_r - M_p}{M_r} \right| \times 100\%$$  (3)

where $M_r$ and $M_p$ are the measurement results of a plaster and resin phantom part, respectively.

Take the left parietal bone phantom part as an example. Morphological measurement results of the key points are shown in Table III. By comparing the results of the plaster and resin phantom parts with respect to the corresponding key points, the absolute values of differences ($M_r - M_p$) were found to be less than 0.60 mm and the average SDR was 0.75%.

According to the measurement results, the SDRs of the plaster phantom parts of frontal bone, left sphenoid wing, right sphenoid wing, left temporal bone, right temporal bone, right parietal bone, and occipital bone were 0.37%, 0.40%, 0.29%, 0.73%, 0.62%, 0.50%, and 0.43%, respectively. The average SDR of the complete plaster skull phantom was 0.51%.

<table>
<thead>
<tr>
<th>Key point</th>
<th>Plaster phantom (mm)</th>
<th>Resin phantom (mm)</th>
<th>Difference (mm)</th>
<th>SDR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>125.04</td>
<td>125.04</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>BD</td>
<td>114.96</td>
<td>114.72</td>
<td>0.24</td>
<td>0.21</td>
</tr>
<tr>
<td>t1</td>
<td>8.66</td>
<td>8.64</td>
<td>0.02</td>
<td>0.23</td>
</tr>
<tr>
<td>t2</td>
<td>7.18</td>
<td>7.18</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>t3</td>
<td>13.40</td>
<td>12.22</td>
<td>0.18</td>
<td>1.47</td>
</tr>
<tr>
<td>t4</td>
<td>2.88</td>
<td>2.84</td>
<td>0.04</td>
<td>1.41</td>
</tr>
<tr>
<td>L</td>
<td>54.56</td>
<td>54.20</td>
<td>0.36</td>
<td>0.66</td>
</tr>
<tr>
<td>h1</td>
<td>49.32</td>
<td>49.50</td>
<td>-0.18</td>
<td>0.36</td>
</tr>
<tr>
<td>h2</td>
<td>27.24</td>
<td>27.80</td>
<td>-0.56</td>
<td>2.01</td>
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<tr>
<td>h3</td>
<td>19.36</td>
<td>19.58</td>
<td>-0.22</td>
<td>1.12</td>
</tr>
</tbody>
</table>

C. Resistivity Distribution

The resistivity measurement results of each separate plaster skull phantom part are shown in Table IV. All data were presented as mean±SD ($n=6$). Statistical analysis showed no statistical significance in terms of resistivity differences between the plaster phantom parts and those of real human skull (P>0.05).

D. Stability of the Head Phantom

Based on the experimental platform including the head phantom, a comparison was made from 1 Hz to 1 MHz between the simulated data and the measurement results regarding the real parts of transimpedance (Fig. 12). The current injection pattern of EP 1-9 was adopted. As shown in Fig. 12, in the measurement frequency range, the real part of the transimpedance of the head phantom presented an almost flat tendency, which agreed well with the simulated data. However, the results had a slight deviation from the simulated values around 1 MHz. Presented in Fig. 13 is the comparison of transimpedance magnitude between the simulated data and the measurement results at 50 kHz over one week. All data are expressed as mean±SD. Compared with the simulated data, the measurement results had a slight variation over a long period of time. The results of the No. 7 and No. 9 were 51.33±2.02 (V/A) and 52.03±2.47 (V/A), respectively, which exhibited a larger deviation than the others.

E. Application in EIT Experiment

The brain EIT system could stably work and acquire data after connection of the head phantom. With this platform, we could conveniently carry out various experiments and effectively...
Fig. 12. Comparison of the real part of the transimpedance between simulated data and measurement results (driving electrodes: EP 1-9). Sim: simulated data; Meas: measurement results.

Fig. 13. Comparison of the transimpedance magnitude between simulated data and measurement results over one week (f=50 kHz, driving electrodes: EP 1-9). validate the hardware system and imaging algorithms. Besides, selection of a different imaging plane was achieved via an alternative interface (Fig. 14).

For the same perturbation at different positions, images of resistivity change were reconstructed in both computer simulation and physical phantom experiment (Fig. 15). The reconstruction value of the perturbation was expressed by an arbitrary unit (AU), which was a relative unit to show the ratio of measured voltage to a predetermined reference voltage. The results demonstrated that, for a perturbation at the same position, the AU of computer simulation was close to that of physical experiment.

IV. DISCUSSION

A. Accomplishments

This study mainly focused on building a new head phantom with realistic geometrical shape and spatially varying skull resistivity distribution to simulate the actual conditions as accurately as possible and provide a platform with reliable performance for brain EIT study. Presently, although RP technology (3D printing) is a powerful tool for building objects with complicated structures, it is not an ideal method to directly fabricate a head phantom with spatially varying skull resistivity distribution. Therefore, with plaster we employed the impression technique together with RP technology (3D printing) to achieve geometry as well as electrical characteristics approximate to those of real human skull.

According to the experimental results of plaster, the smaller water content was, the larger resistivity would be. This could be related to the microstructure of hydrated plaster. It is seen from the SEM figures (Fig. 16), with small proportion of water, the structures of the plaster crystals are incomplete, presenting tiny fibrous or sheet-like aggregates. In the opposite case, the structures of the plaster crystals are integrated with aggregates that exhibit short column shape and dense structure. The porosity of the plaster increases with the water content. In fact, dry gypsum crystal is nonconductive. After hydration, gypsum crystals will become aggregates with many pores. The pores...
The measurement results in our study showed stability of the real part of transimpedance on each measuring EP was stable for one week, which demonstrated a good stability of our phantom over time. The one week time span could meet the time requirement of continuous measurements in many EIT experiments. However, measurement results of certain EPs had small deviations from the simulated data. For the head phantom with spatially varying skull resistivity distribution, these deviations might be attributed to the different positions of measuring EP given a particular current injection EP. As shown in Fig. 13, the deviations of No. 7 and No. 9 were probably caused by different positions of measuring EPs on the occipital bone region where the thickness varied. This finding also suggested that the spatially varying skull resistivity distribution of the head phantom should not be ignored.

Given the fact that crystallization and dissolution will reach a dynamic equilibrium in saturated calcium sulfate solution, the use of this solution to simulate the brain and the scalp was important to maintain the resistivity stability of the head phantom, which were conducive to the accuracy and consistency of the measurements.

With regard to EIT imaging in this study, the construction values obtained from the head phantom had slight deviations from those of the computer simulation, which might derive from system noise or the error between prior information and real resistivity. The imaging results suggested that through this head phantom not only physical experiments could be carried out but also the hardware performance and imaging algorithms of brain EIT could be assessed.

Although attention should be paid to some details including a more skillful impression technique and more accurate electrode positioning, this head phantom performed quite well. First, the head phantom possessed complex anatomical structure that included the major tissues in the head: scalp, skull, and brain. Second, the head phantom achieved spatially varying skull resistivity distribution, which was a key factor that affected current distribution. Finally, the head phantom showed stable performance over time and in a wide frequency range.

### B. Comparison with Prior Work

In earlier studies of brain EIT, various head phantoms with advantages and disadvantages were developed for different applications [6]-[8], [10], [11], [15]. Nonetheless, a head phantom similar to the human head both in anatomy and in resistivity distribution was unavailable, which restricted the further researches of brain EIT.

Bagshaw et al. (2003) and Tidswell et al. (2001) presented head phantoms with realistic shape and homogeneous resistivity distribution to study epilepsy [4], [13]. Spertino et al. (2012) produced a four-shell diffusion head phantom for EIT [12]. There is a major difference between their studies and the current study. This is attributed to a different focus by our group, which are positioning accuracy and resolution of the brain EIT system for monitoring brain diseases. The key performance of the brain EIT system requires a precise head
phantom for validation. The different focus may lead to the different phantom types, construction methods and phantom accuracy among many research groups. In addition, the lack of resistivity data of living human skull was also an unfavorable factor that restricted phantom accuracy in other studies.

Furthermore, a skull phantom with spatially varying skull resistivity distribution is difficult to accomplish by traditional casting method. Therefore, we utilized RP (3D printing) technology to manufacture each separate resin phantom part and then cast the parts with impression technique to complete a head phantom with realistic geometry and spatially varying skull resistivity distribution. The new head phantom is expected to be useful for future brain EIT researches.

C. Remaining Challenges

With the development of current technologies, there is still room for improving the new head phantom. Although this phantom accurately simulates the human head in a 2D plane across 16 electrodes, it is just an approximation of the human head in a 3D domain, which is due to the very complicated structure and morphology of the human skull. Actually, the thickness and resistivity of the human skull at different positions are spatially dependent. Therefore, some error could be introduced if this phantom is applied to 3D EIT imaging. In future studies, a head phantom with improved approximation degree in 3D is required to serve more experiments. Furthermore, similar to many previous studies [9], [12], [35]-[38], this study did not consider the effect of facial bones on EIT measurements but we do acknowledge that the effects of the facial bones and other off-plane structures on EIT measurements needs further investigation. In addition, the cerebrospinal fluid (CSF) and skin are usually ignored because their resistivities are much lower than that of the skull [14], [22], [23]. Although this practice is common in many head phantoms, some errors might occur. The material simulating CSF and skin are supposed to not only represent the resistivity of real tissues but also contact stably with other materials simulating scalp and skull. We will include the CSF and skin in our future study if the suitable materials or methods are available.

V. CONCLUSION

A precise head phantom is highly important to validate the hardware and imaging algorithms of the brain EIT system. In this study, based on CT images of human head, RP technology (3D printing) and impression technique were utilized to fabricate a new head phantom with a realistic geometry and spatially varying skull resistivity distribution. This head phantom includes scalp, skull and brain layers. The main innovation of the head phantom is the varying skull resistivity which is close to the data of live human skull. Experiment results show that the proposed method of head phantom construction is feasible. The new head phantom achieves spatially varying skull resistivity distribution, smaller geometrical distortion, and good stability over time as well as in a wide frequency range, which endows the new head phantom with a high practical value. Our research is an attempt to adopt advanced techniques from other fields for brain EIT modeling.

Future studies will focus on how to achieve 3D accuracy in heterogeneous resistivity distribution of the head phantom.

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REFERENCE


