The significance of relative conductivity on thin layers in EEG sensitivity distributions

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Abstract
Volume conductor head models contain thin tissue layers, some of which have highly contrasting conductivity values relative to neighboring tissues. We expound the cerebrospinal fluid (CSF) and the six cortical layers of the gray matter. The dual nature of the CSF competes with the well-known shunting behavior of the skull. The incorporation of the six ultra thin cortical layers demonstrate the significance of the electrical attraction and shunting of lead field currents in multi-layered tissues owing to the inherent conductive properties of each tissue. We relate the similar effects of the CSF to the diploe, i.e., the soft bone between the two hard bone layers of the skull. A natural subsequence of this article will allow researchers and clinicians to conceptually understand the measurement sensitivity distribution of a bipolar electroencephalography (EEG) lead. We recommend including the highly conductive thin layers such as the diploe of the skull and the CSF into head models as well as further investigation into the cortical layers I–VI of the gray matter. Comprehensive, when a thin tissue layer differs in relative conductivity from its neighboring layers, it should be included in the model owing to its influence upon the EEG lead fields, i.e., the measurement sensitivity distributions.

Keywords: attracting and shunting sublayers; cerebrospinal fluid (CSF); conductivity; current density; lead fields; thin layers.

Introduction
Volume conductor head models are being constructed as piecewise homogeneous multilayered models, which follow the natural layering of tissues from the scalp to the white matter of the brain. These layers comprise part of the geometrical construction from concentric spheres to realistically shaped head models. Often it is not possible to construct realistically shaped patient-specific models for all electroencephalography (EEG) patients owing to lacking computed tomography (CT) or magnetic resonance image (MRI) data.

These image sets could be missing owing to the medical specialists requesting a different set of images such as a positron emission tomography (PET) scan for cancer patients and the minimization of radiation and tracers to the patients [31]. Furthermore, clinical images often contain too few slices to reconstruct a whole head model and use too few imaging sequences or tracers to demarcate some tissues. A realistically shaped, generic head model could fulfill this gap; however, it would be necessary to understand the electrical significance of each tissue layer and the interaction between each layer as well as the knowledge of the craniometric dimensions to build a generic head model representing the patient [38, 39]. Recent investigations determined that the cerebrospinal fluid should be included as a layer in the model [10, 30, 36]. Moreover, cranial-vault thickness variations and perturbations [4, 5, 15, 16, 25] influence the lead field, i.e., sensitivity distributions [17, 18]. Previous studies have analyzed the influence of tissue conductivities on realistic head models according to their electric surface potentials [7, 10, 11]; therefore, the aim of this study was to investigate how various thin tissue layers and their conductivities influence the EEG lead fields, which would explain previous studies reporting on the electric surface potentials.

A key to identifying the significance of a layer is to determine how the layer contributes to the EEG sensitivity distribution. By considering stacked conductive tissue layers, the lead field current entering through the top layer (i.e., the exterior) is either electrically attracted to or shunted away from the layer beneath it [9, 17]. This is as a result of the relative conductivity of the two juxtaposed layers, which pose two possible phenomena. The first phenomenon stems from the layering of a less-conductive layer over a more-conductive layer, i.e., attractive sublayer, and the second reverses the layering to a more-conductive layer over a less-conductive layer, i.e., shunting sublayer. These two possible configurations provide the framework for describing how the form of the lead field is affected relative to neighboring layers.

The present study extends our previous study [37] to qualitatively address the interactive nature of layered tissues focusing on how thin layers affect the lead field. In the previous study, we concentrated on the significance of the CSF, which neglected its influence as a thin layer within the brain and flowing into the sulci. In this study, we discuss the influence of the CSF layer as well as cortical layers I–VI [2, 23, 24, 29, 32]. Models including these layers illustrate the importance of thin highly conductive layers, which are significant both to the forward and inverse EEG problems. To accomplish our supposition, our study incorporates both spherical and realistic models to confirm our theory about the electrically attractive and shunting sublayer phenomena.
of thin layers. In one of our realistic models, we augment the gray matter by including six thin cortical layers to compare with the normally segmented brain containing white and gray matter partitions. Together, the spherical and realistic models depict to researchers and clinicians the distribution of the measurement sensitivity of bipolar EEG leads.

**Methods**

**Spherical models**

**Geometries** We use concentric spherical models to identify, isolate and illustrate the underlying phenomena of lead fields in tissues. To further determine the significance of each layer, we model different skull thicknesses with and without the cerebrospinal fluid (CSF). We create three geometric models and parametrically vary their conductivities to identify their sublayer relationships. All spherical models are concentrically constructed and have external scalp and skull boundaries with radii of 9.0 cm and 8.45 cm, respectively [37]. Our control model, i.e., the CSF model, represents the most accurate spherical model of the head. The control model has four layers including the scalp, skull, CSF and brain, where the skull and CSF thicknesses measure 6.5 mm and 3.5 mm, respectively (Table 1). We remove the CSF layer from the thin skull and thick skull models to understand the significance of previously published 3-shell models. The thin skull model has the same skull thickness as the CSF model of 6.5 mm. The thick skull model has a thicker skull measuring 10 mm thick. All tissue thicknesses follow the logic of our previous study comparing models constructed with CT and MRI [36].

**Juxtaposed tissue layers** In the head models, the attractive sublayers emerge as the interfaces at the skull-CSF (control model) and the skull-brain (CSF-lacking models, i.e., the thin and thick skull models). The second phenomenon, the shunting sublayer, emerges from the boundary interface between the scalp-skull (all models) and the CSF-brain (control model).

**Realistic models**

In addition, we use the realistic Visible Human Woman model from the Visible Human Project [22] to confirm the theoretical physical interactions explained with the spherical models. We calculate the sensitivity distributions via the finite difference method according to the conductivities reported previously [30]. We down-sampled the original resolution from 0.33 mm×0.33 mm×0.33 mm to a mesh of 1 mm×1 mm×1 mm, containing 212 columns, 177 rows and 222 slices. We formed a second realistic model by removing the CSF layer and replacing it with the gray matter conductivity, thus following the logic of the spherical models. Lastly, we constructed a realistic model with six cortical layers from the original 0.33 mm×0.33 mm×0.33 mm resolution. The cortical layers were obtained by dilating the white matter by 1, 2, 4, 6, 7 and 8 pixels to obtain six differently coded layers in the left parietal-occipital lobe [2, 29]. The opposite sides of the model were down-sampled along the X-, Y- and Z-axes to solve the model, resulting in an average resolution of 0.46 mm×0.46 mm×1 mm on the opposite side of the model; thereby, the total number of voxels was 27,500,000 (Figure 1). We used this model for a validation study by placing a radial dipole in the cortex in the center of the cortically enhanced region.

**Leads**

We added two electrodes to each model, spacing them from 20° to 60° apart for the spherical models (Table 2). These

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Control</th>
<th>Thin skull</th>
<th>Thick skull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalp (mm)</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Skull (mm)</td>
<td>6.5</td>
<td>6.5</td>
<td>10</td>
</tr>
<tr>
<td>CSF (mm)</td>
<td>3.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Brain (mm)</td>
<td>74.5</td>
<td>78</td>
<td>74.5</td>
</tr>
</tbody>
</table>

*Figure 1* Realistic model with six cortical layers. (A) Down-sampled transverse slice. (B) Zoomed-in view of the cortically enhanced left parietal-occipital lobe.
angles approximate the spacing of the 128-channel montage to the visually evoked potential studies, respectively [28, 33, 37]. All electrodes are modeled as simple recessed electrodes [34] with a standard diameter of 10 mm for evoked potential studies and high resolution EEG caps [26]; therefore, we use the finite element method to solve the spherical models with realistic electrode dimensions instead of using analytically solvable point electrodes because we wanted to simulate three-dimensional electrodes and its ability to approach the real solution with smallest error [8, 26, 34]. We selected three common leads for the realistic model having approximately the same angles of separation as the spherical models – Fz-Cz, Fpz-Cz and Fpz-Oz (Figure 2).

**Conductivities**

We selected our parametric settings for the spherical model tissue conductivities of the brain, CSF, and scalp compartments as 0.25 S/m, 1.79 S/m and 0.45 S/m, respectively [3, 6]. We parametrically varied the skull conductivity to draw conclusions about the debatable conductivities of the skull by using brain-to-skull conductivity ratios \( \sigma_{\text{Br}} / \sigma_{\text{Sk}} \) of 5, 10, 15, 20 and 80 according to the literature [10, 13, 27, 30, 35]. We selected a wide range of values to represent the diverse skull conductivity values found in the literature; however, we modeled the realistic model with the values cited by Ramon et al. [30], which use a scalp-to-skull conductivity ratio of 15:1 [27]. Cortical layers of the brain were modeled from layers I to VI as 0.316 S/m, 0.285 S/m, 0.271 S/m, 0.285 S/m, 0.259 S/m and 0.285 S/m [1, 2, 10, 11, 14, 29].

**Lead fields**

We obtained the lead field [19–21], i.e., sensitivity distributions, in both the spherical and realistic models by feeding a reciprocal unit current through a bipolar electrode pair according to the reciprocity theorem [12]. We calculated the lead voltage \( V_{LE} \) for each model according to the following equation:

\[
V_{LE} = \int \frac{1}{\sigma} J_{LE} \cdot J \, dv,
\]

where \( J_{LE} \) is the lead field current density and \( J \) is the volume source density [17]. The density and direction of the lead field current indicate the measurement sensitivity distribution. This identifies the areas of the brain with higher sensitivity being primarily measured by the lead.

We compare percentages of the maximum current density in our models, ranging from 1% to 100%. Particularly, our analysis uses the half-sensitivity volume (HSV) [18] and the fifth-sensitivity volume (FSV) concepts [36] to outline the area of the top 50% and 20%, respectively, of the current density iso-sensitivity surfaces in the brain. We also compare the iso-sensitivity maps of the whole head to identify the cumulative effect of thin layers upon layered tissue pertaining to the electrical contribution of the lead field. Comprehensively, these maps illustrate their influence on cortical measurements.

**Results**

We analyzed our spherical and realistic maps according to two types of sensitivity distributions: whole head and brain only. The whole head distributions show the entire lead field, whereas the brain distribution depicts the region of interest. The control model with \( \sigma_{\text{Br}} / \sigma_{\text{Sk}} \) of 15 shows that the whole head sensitivity distributions concentrate near the electrode and spread more deeply into the tissue for \( \sigma_{\text{Br}} / \sigma_{\text{Sk}} \) of 5 (Figure 3). The sensitivity distributions within the whole head (Figure 4) penetrate most deeply into the highest conducting region (i.e., the CSF layer) when compared against the parametrically equivalent models from the CSF-lacking, thin and thick skull models. Furthermore, the 2% iso-sensitivity surfaces at 50° (Figure 4B) or the 3% isosurfaces at 40° (Figure

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**Table 2** The angular distance between each lead and brain-to-skull conductivity ratios used for each model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Lead spacing</th>
<th>Conductivity ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control/CSF model</td>
<td>20°, 40°, 50°, 60°</td>
<td>5, 10, 15, 20, 80</td>
</tr>
<tr>
<td>Thin skull model</td>
<td>20°, 40°, 50°, 60°</td>
<td>5, 10, 15, 20, 80</td>
</tr>
<tr>
<td>Thick skull model</td>
<td>20°, 40°, 50°, 60°</td>
<td>5, 10, 15, 20, 80</td>
</tr>
<tr>
<td>Realistic model</td>
<td>Fz-Cz, Fpz-Cz and Fpz-Oz</td>
<td>15</td>
</tr>
<tr>
<td>Realistic model without CSF</td>
<td>Fz-Cz, Fpz-Cz and Fpz-Oz</td>
<td>15</td>
</tr>
<tr>
<td>Realistic model with six cortical layers</td>
<td>Parietal lobe dipole</td>
<td>40, 45</td>
</tr>
</tbody>
</table>

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**Figure 2** Realistic model. (A) Midsagittal slice selected to show the results from the three-dimensional model. (B) Selected surface EEG electrodes FPZ, FZ, CZ and OZ used in the simulations.
Figure 3  Three-dimensional isosensitivity surfaces of the lead field. (A–D) All model configurations show electrodes as the two small cylindrical disks in each Figure. Panels (A) and (C) depict the whole head isosensitivity surfaces using brain-to-skull conductivity ratios of 5. Panels (B) and (D) depict the whole head isosensitivity surfaces using brain-to-skull conductivity ratios of 15. (A–D) All subcaptions list the model with the electrode angle superscripted and the brain-to-skull conductivity ratio subscripted. The isosurface colors designate the five increments diminishing from 10% (blue), 5% (green), 3% (yellow), 2% (purple) to 1% (red) current density values.

4E) do not merge in the thin skull models similar to those of the corresponding thick skull models (Figure 4C,F,I). Likewise, the lead field current penetrates into the sulci of the brain following the CSF and secondarily the gray matter boundaries (Figure 5). Clearly, the high conductivity of the CSF models (Figures 3A,C,E and 4A,D,G) attract the lead field current deeper into the tissue than do models without a highly conductive sublayer.

Larger HSV and FSV in the brain region confirm the effect of a highly attractive thin sublayer upon the lead field in the whole head (Figure 6, left column vs. center and right columns). We have previously published HSV and FSV of the spherical models [37]. We can correlate the spherical model results with the realistic model results. We currently found the realistic model to have an HSV and FSV of 7760 cm$^3$ and 190 cm$^3$, respectively, modeled with CSF, and an HSV and FSV 4674 cm$^3$ and 137 cm$^3$, respectively, modeled without CSF. Moreover, the spherical model results reveal the general underlying phenomena, when they correlate with and explain the realistic model results. The CSF layer of the control model resides in exactly the same depth location as the cortex of the thin skull model. Thus, the comparison of their maximum current densities, 630 A/m$^2$ and 380 A/m$^2$, for the CSF layer of the control model and the brain of the thin skull model, respectively, supports the attractive sublayer phenomenon. As the CSF is not included in the CSF-lacking models, the boundary ratio $\sigma_{CSF}/\sigma_{Sk}$ is 10; whereas, the control model incorporates the CSF layer, introducing a boundary ratio $\sigma_{CSF}/\sigma_{Sk}$ of 72. In essence, the higher ratio from the CSF boundary to the layer below, i.e., the brain, attracts the lead field current more than the lower

Figure 4  Spherical whole head isosensitivity surfaces of the lead field. (A–F) ZX-plane and (K–O) (***There is no figures for part labels K–O. Please provide***) XY-plane. (G–I) Each Figure in the second row uses the same brain current density scale (%) shown in the Figure below it. All subcaptions list the type of isosensitivity surface and the model type with the electrode angle superscripted and the brain-to-skull conductivity ratio subscripted. The isosurface colors designate five increments of current density values: 10% (blue), 5% (green), 3% (yellow), 2% (purple) to 1% (red) current density values.
Figure 5 Realistic model isosensitivity distributions of the lead field. (A–C) Whole head isosurfaces. (D–F) Brain isosurfaces. (A, D) Bipolar electrode pair FZ-CZ. (B, E) Bipolar electrode pair FPZ-CZ. (C, F) Bipolar electrode pair FPZ-OZ. All Figures are shown in logarithmic scale.

ratio of the skull-brain interface of the CSF-lacking models (thin and thick skull models).

Shifting our focus to the phenomenon of the shunting sublayer arrangement, i.e., a more-conductive over a less-conductive layer, we can observe that this phenomenon acts oppositely to the previous relation. In this relation the current density penetration is shallower than what would naturally be for a purely homogeneous volume conductor. More concisely, the lower layer tends to naturally repel the lead field current because lead field current preferentially flows in the least resistive path [9, 17]. The effect of this phenomenon can be seen within the whole head by examining the scalp-skull interaction within the whole head beneath the electrodes (Figure 5). This effect can be observed from the spherical figures when comparing the control models with the same electrode configuration but differing in conductivity ratios, 5 and 15 (Figure 3, left column vs. right column). In these subfigure combinations, the lead field current spreads more in the scalp layer of the models with the higher conductivity ratio because less lead field current penetrates the skull.

Essentially, the higher the conductivity ratio for the superior layer, the less the lead field current that passes into the inferior layer. As less lead field current passes to the layers below, the subsequent brain sensitivity distributions (Figure 6, center and right columns) are more homogeneous and appear larger in the thick than in the thin skull model. The HSV occupies 2% of the brain for the control, 1.3% for the thick skull and 0.5% for the thin skull, and the FSV occupies 0.125% for the control, 0.075% for the thick skull and 0.02% for the thin skull, all of which are measured with electrodes at 40° distance and a brain-to-skull conductivity ratio of 10. This happens because the brain sensitivity distributions are calculated as percentages based upon the maximum-current densities [37] (Wendel et al. 2008 change to [37]). Additionally, the lead field current distribution that does pass into the brain (Figures 5 and 6) is more spatially spread outwards owing to the shunting nature of the skull that caused the lead field current to initially spread in the scalp. Finally, the validation study of the electric surface potentials in Figure 7 confirms the significance of thin layers through the incorporation of the six cortical layers varying in conductivity and thickness.

Discussion

As the $\sigma_{\text{Br}}/\sigma_{\text{Sk}}$ increases, the phenomenon of the shunting sublayer, i.e., more-over-less conductive layers takes precedence over the attractive sublayer, i.e., less-over-more conductive layers because the reciprocal lead field current first passes through the scalp before entering the skull. Furthermore, the models with the high $\sigma_{\text{Br}}/\sigma_{\text{Sk}}$ value of 80 suppress even the effects of the highly conductive CSF layer, even though it conducts 573 times more than the skull [37]. In fact, the shunting sublayer phenomenon will always overshadow the observation because the reciprocal lead field current will always first pass through the scalp. This precedence can be identified when comparing the CSF-lacking models in Figure 4H,I.
Figure 6  Spherical brain isosensitivity surfaces of the lead field. (A–C) Zx-plane and (D–I) XY plane. (D–F) Each Figure in the second row uses the same brain current density scale (%) shown in the Figure above it. All subcaptions list the model type with the electrode angle superscripted and the brain-to-skull conductivity ratio subscripted. The isosurface colors designate the ten increments diminishing from 100% to 10% current density values.

When the electrodes come within less than 40° distance, the depth of lead field penetration decreases in the whole head and brain (Figure 5A). The secondary shunting sublayer takes precedence in the realistic and CSF models by limiting the amount of reciprocal lead field current penetration from the CSF into the brain in the region beneath the electrodes. Even though the thin skull head model experiences some effect of the attractive sublayer phenomenon with the skull-brain interface, it cannot experience the secondary shunting sublayer effect of the CSF-brain interface owing to the non-existence of the CSF layer.

By shifting our analysis to the sensitivity distributions in the brain, the lead field current density patterns of the brain confirm the effects of the two bilayer phenomena. In the results section, it was established that only the control model shows effects of both attractive and shunting phenomena caused by the CSF. As a result, more current concentrates in the CSF layer, causing less lead field current to enter the brain and thus altering the shape and size of the lead field sensitivity distribution [36]. Lastly, comparing the control model with the CSF-lacking models, i.e., the thin and thick skull models, Figure 6 reveals that the CSF layer causes the control models to have a slightly greater depth of the lead field, which is due to the limited current density in the CSF model spreading relatively over the same sized area as the thin skull model.
Our elucidation upon the significance of including the CSF layer can be applied to other thin layers within the head. We can surmise that the diploe, i.e., the middle porous layer of a trilayer skull, will similarly influence EEG measurement sensitivity because the diploe is a highly conducting layer sandwiched in between the two lower conducting skull layers such as the CSF in between the skull and the gray matter or the 25% conductivity variations in the cortical layers I–VI that cause perturbations in the scalp potentials. In the CSF and diploe cases, the conductivity ratio between the layers of interest is an order of magnitude greater, and secondly the surrounding tissues are not thick enough to suppress the influence of the highly conducting layer. In contrast, neighboring layers where the tissues electrically conduct in a similar manner could be combined into one layer for three reasons: insignificant contribution to the path of current flow, incomplete knowledge of the actual conductivity values and inaccuracies in tissue segmentation. Therefore, three possible tissue layers that could be combined are skin, fat and muscles. This combination could make numerical models more tractable without down-sampling the mesh, while focusing on more significant boundary layers such as the CSF-cortex.
boundaries. Conclusively, thin tissue layers of contrasting conductivity should be included to obtain accurate simulations of the scalp potentials.

Conclusion

Modelers often omit thin tissue layers from their head models. They justify leaving out these layers either due to their belief that thin layers are insignificant or the taxing numerical computational complexity of a thin layer. Highly conducting thin layers surrounded by poorly conducting layers channel the current and reshape the lead field, i.e., sensitivity distribution, in the layer below. Their duality competes with the well-known shunting behavior of the skull. Consequently, modelers can use the phenomena of attractive and shunting multilayered tissues to identify the relative significance of including a tissue under investigation. We support the findings of previous authors that claim that the CSF and diploe of the skull should be included in EEG modeling studies. However, we advance this claim by asserting that all thin layers should be evaluated as possibly attracting or shunting thin layers when a conductivity difference exists between the adjacent tissue layers. This extension led us to conclude that the six cortical layers are also significant and thereby warrant further examination.

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