High-resolution EEG: on the cortical equivalent dipole layer imaging

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Abstract

\textbf{Background:} Brain electrical activity is a spatio-temporally distributed process. Cortical imaging techniques have been developed to reconstruct cortical activity from the scalp electroencephalographic or magnetoencephalographic measurements. Several cortical imaging approaches, such as the epicortical potentials and a dipole layer accounting for the cortical activity, have been used to represent brain electrical activity.

\textbf{Methods:} A closed cortical dipole layer source model is used to equivalently represent brain electrical activity. The relationship between the primary brain electrical sources and the cortical equivalent dipole layer is derived from the theory of electromagnetics. Computer simulation studies were conducted using a 3-concentric-sphere head model to validate the proposed theory. The cortical equivalent dipole layer imaging approach was tested in both computer simulation and human visual evoked potential (VEP) experiments.

\textbf{Results:} The strength of the cortical equivalent dipole layer is shown to be proportional to the electrical potential over the same surface generated by primary electrical sources, had the outer medium been replaced by air. The proposed theory was validated by computer simulation in a discrete system. Simulation and VEP experimental studies suggest the feasibility of applying the cortical equivalent dipole layer imaging approach for brain imaging.

\textbf{Conclusions:} The cortical equivalent dipole layer model can equivalently represent the primary brain electrical sources throughout the entire brain surrounded by the dipole layer. The strength of the cortical equivalent dipole layer due to primary sources can be directly calculated according to the theory developed in the present study.

\textbf{Keywords:} Cortical imaging; High-resolution electroencephalogram; Equivalent dipole layer imaging; Visual evoked potential; Human brain mapping; Forward problem; Inverse problem

1. Introduction

A tremendous amount of effort has been put forth in the past decades to estimate and image brain electrical activity from non-invasive electromagnetic measurements. Of interest is the recent development of cortical imaging approach, in which a distribution of electrical potentials over the epicortical surface (Sidman et al., 1990; Le and Gevins, 1993; Srebro et al., 1993; Gevins et al., 1994; Nunez et al., 1994; Yao, 1996; Babiloni et al., 1997; Edlinger et al., 1998; Wang and He, 1998; He et al., 1999; Lian and He, 2001) or a dipole layer accounting for cortical activity (Hamalainen and Ilmoniemi, 1984; Nunez, 1987; Wang et al., 1992; Dale and Sereno, 1993; Srebro and Oguz, 1997; Babiloni et al., 2000), is used. The cortical imaging approach has been reported to provide either deblurred epicortical potentials or a dipole distribution accounting for cortical activity (Dale and Sereno, 1993).

It is of importance to interpret the results of cortical imaging, either cortical potential imaging or cortical current imaging, as any other distributed imaging approach (Pascual-Marqui et al., 1994; Gorodnitsky et al., 1995; Philips et al., 1997; Fuchs et al., 1999; Grave de Peralta-Menendez et al., 2000). The rationale for the cortical current imaging, in which a layer of current dipoles normally oriented with respect to the local cortical surface (Dale and Sereno, 1993; Srebro and Oguz, 1997; Babiloni et al., 2000), is based on the observation that scalp electroencephalogram (EEG) and magnetoencephalogram (MEG) are primarily generated by cortical sources. Therefore, by approximating cortical sources using a current dipole layer over the cortex, one may obtain a fairly good approximation of brain electrical activity as observed from non-invasive scalp EEG or MEG measurements. While this rationale is sound, a new theoretical basis is needed to interpret cortical current imaging results if the scalp EEG or MEG observation is
generated not only by cortical sources but also by neurons located in subcortical regions. Since brain sources may be located in subcortical regions (Guyton and Hall, 1996), it is important to provide a theoretical justification on the use of equivalent cortical dipole layer to account for the neural electrical activity within the entire brain.

The aim of the present study is to present and validate a new equivalent current dipole layer model, which can account for brain sources including both cortical and subcortical sources. A new theory based on electromagnetics is introduced, which gives insight on the equivalence of representing brain electrical sources by means of a closed current dipole layer surrounding the cortex. Numerical experiments have been conducted to validate the proposed theory. The cortical equivalent current dipole layer imaging approach has also been tested in computer simulation and human VEP experiments, illustrating its applicability to imaging brain electrical activity in an experimental setting.

2. Methods

2.1. Theory of the cortical equivalent dipole layer model

In this section, a theory regarding the cortical equivalent dipole layer model is introduced. We first derive the theory in a continuous system, in which an equivalent double layer is considered. It will be shown later that the equivalent dipole layer model is introduced. We first derive the theory in a continuous system, in which an equivalent double layer is considered. It will be shown later that the equivalent dipole layer turns into an equivalent dipole layer for a discrete system.

Considering an arbitrarily shaped head model as illustrated in Fig. 1, where \( S' \) represents the scalp surface and \( S \) represents a virtual cortical double layer. Denote \( V_0 \) as the volume bounded within layer \( S \), and \( V \) as the volume bounded by \( S \) and \( S' \). If all brain electrical sources are in volume \( V_0 \) and there is no active source in volume \( V \), then for any given point \( x \) within volume \( V \), the electrical potential \( \varphi(x) \) can be expressed as the following integral according to the theory of electromagnetics (Jackson, 1975):

\[
\varphi(x) = \frac{1}{4\pi} \int_S \left[ G(x, x') \left( \sigma \frac{\partial \varphi(x')}{\partial n'} - (\sigma \varphi(x')) \frac{\partial G(x, x')}{\partial n'} \right) \right] \, ds', \quad \text{for } x \text{ on } S
\]  

where \( \partial/\partial n' \) is the normal derivative at the surface \( S \) (directed outwards from inside the volume \( V_0 \)), \( \sigma \) the electrical conductivity of volume \( V_0 \), \( G(x, x') \) the Green function which is the electrical potential of a point current source inside a volume conductor model. Green function \( G(x, x') \) represents the electrical potential at position \( x \) produced by a point current source located at position \( x' \) in a volume conductor, \( ds' \) denotes that the integral is performed on sources (\( x' \) refers to source point). Note that in Eq. (1), the surface integral represents the contribution of sources in \( V_0 \) to the potential in \( V \). If there is no active source in \( V_0 \), the surface integral should be zero.

The conventional Green function method solves Eq. (1) by modifying the Green function to satisfy certain boundary conditions (Jackson, 1975). For the customary Neumann problem with the boundary condition of \( \partial G(x, x')/\partial n' = 0 \), the solution of Eq. (1) is given as:

\[
\varphi(x) = \frac{1}{4\pi} \int_S \left[ G(x, x') \left( \sigma \frac{\partial \varphi(x')}{\partial n'} \right) \right] \, ds', \quad \text{for } x \text{ on } S
\]  

Note that in Eq. (2), \( \sigma(\partial \varphi(x')/\partial n') \) can be considered as the ‘equivalent source’ with Green function \( G \). However, the major limitation of this approach is that the physical meaning of the Green function \( G \) is unclear by imposing the constraint \( \partial G(x, x')/\partial n' = 0 \), whereas \( G \) is usually expected to be only determined by the physical properties of the volume conductor, without any artificial constraint.

As an alternative to the Green function method, Eq. (1) can also be solved by keeping \( G \) unchanged, but modifying the strength of the equivalent distributed sources. Let \( \varphi(x) = \varphi(x)_V + \varphi(x)_V \), where \( \varphi(x)_V \) and \( \varphi(x)_V \) are the potentials produced by the sources in volumes \( V \) and \( V_0 \) respectively. As noted above, since \( \varphi(x)_V \) and \( (\partial \varphi(x)_V)/\partial n' \) make no contribution to the surface integral in Eq. (1), we can replace \( \varphi(x)_V \) with a proper \( \varphi'(x)_V \) (also due to sources in volume \( V \)) and have a new function \( \varphi'(x) = \varphi'(x)_V + \varphi(x)_V \), which satisfies:

\[
\varphi(x) = \frac{1}{4\pi} \int_S \left[ G(x, x') \left( \sigma \frac{\partial \varphi'(x')}{\partial n'} - (\sigma \varphi'(x')) \frac{\partial G(x, x')}{\partial n'} \right) \right] \, ds', \quad \text{for } x \text{ on } S
\]  

\( \varphi'(x)_V \) can be chosen so that

\[
\varphi'(x') = \varphi'(x')_V + \varphi(x)_V, \quad \text{for } x' \text{ on } S
\]  

and

\[
\frac{\partial \varphi'(x')}{\partial n'} = \frac{\partial \varphi'(x')_V}{\partial n'} + \frac{\partial \varphi(x)_V}{\partial n'} = 0, \quad \text{for } x' \text{ on } S
\]

Then Eq. (3) can be simplified to:

\[
\varphi(x) = -\frac{1}{4\pi} \int_S (\sigma \varphi'(x')) \frac{\partial G(x, x')}{\partial n'} \, ds' = \frac{1}{4\pi} \int_S (\sigma \varphi'(x')) G(x, x') \, ds', \quad \text{for } x' \text{ on } S
\]
Note \( G \) is the Green function of a point current source, \( G_d = -\partial \mathbb{G}/\partial n^* \) is then the Green function of a dipole on surface \( S \) oriented normally outwards, and both \( G \) and \( G_d \) have clear physical meaning. Therefore, Eq. (5) can be considered as an equivalent double layer model, with equivalent double layer strength of \( \sigma \varphi'(x) \), and with Green function of \( G_d \).

2.2. Closed solution of the spherical cortical equivalent double layer

Because the Green functions \( G \) and \( G_d \) are not limited to any specific model, Eq. (5) is valid for an arbitrarily shaped geometric model and numerical methods can be applied to calculate \( G_d \). In particular, when the cortical equivalent double layer is considered to be a spherical surface, the closed solution of the equivalent double layer can be obtained.

Since all actual sources are in \( V_0 \) and there is no source in \( V \), \( \varphi'(x) \) should satisfy the Laplace equation for \( x \) in \( V_0 \), and \( \varphi'(x) = \varphi(x)_{V_0} + \varphi(x)_{V_0} \) should satisfy the same Poisson equation as \( \varphi(x)_{V_0} \) does for \( x \) in \( V_0 \) and on \( S \). Therefore, \( \varphi'(x) \) (left-hand side of Eq. (4a)) can be considered as the solution of potential \( \varphi'(x) \) for \( x \) on \( S \), due to the actual sources in \( V_0 \) with Neumann boundary condition as described in Eq. (4b). Note that the boundary condition in Eq. (4b) corresponds to the head–air physical boundary. It has been derived that the closed solution of the surface potential \( \varphi_d \) produced by a dipole inside a homogeneous conducting sphere with this physical boundary is (Yao, 2000):

\[
\varphi_d = \frac{P}{4\pi\sigma} \left[ \frac{\vec{r} - \vec{r}_0}{r_p^2} + \frac{\vec{r} - \vec{r}_0^2}{R^2} + \frac{1}{R^2 r_p} \left( \vec{r} + \frac{r_0^2 r}{R^2 \cos \theta - r^2} \right) \right]
\]

where \( \vec{r} \) and \( \vec{r}_0 \) are, respectively, the field position and dipole position with angle \( \theta \) between them (\( r \) and \( r_0 \) are, respectively, vector lengths), \( P \) is the dipole moment, \( R \) the radius of the sphere, \( r_p \) the length of the displacement \( \vec{r}_p = \vec{r} - \vec{r}_0 \), and \( r_0 = \sqrt{1 + (r_0 R)^2 - 2(r_0 R) \cos \theta} \).

Therefore, according to Eq. (5), the source density of the equivalent double layer can be defined as:

\[
f_d = \sigma \varphi_d
\]

Eq. (7) indicates that the source density of the cortical equivalent double layer can be calculated by using the potential formula given in Eq. (6), in which \( \vec{r} \) is on the double layer, i.e. \( r = R \). Since \( \varphi_d \) is the electrical potential over the equivalent double layer when replacing the exterior space by air, Eq. (7) indicates that the source density of the cortical equivalent double layer is proportional to the potential over the same spherical surface when the exterior space of the double layer is replaced by air (by a factor of effective conductivity of the brain \( \sigma \)). In other words, the cortical equivalent double layer source density distribution may reflect the potential distribution over this layer, as in the case when the upper medium is removed during open-skull surgery.

2.3. Cortical dipole layer imaging

Based on the above theory, a new cortical dipole-layer imaging (CDI) approach is introduced, which constructs the equivalent current dipole distribution over an imaging surface. Although the cortical dipole layer is an equivalent surface source model, it represents equivalently all primary brain electrical sources surrounded by it.

The blurring effect observed in the scalp potential map can be effectively reduced because the cortical equivalent dipole layer is essentially unaffected by the low-conductivity skull layer. Thus, higher spatial resolution is expected from the deblurred CDI map.

Substitute Eq. (7) in Eq. (5), and the discrete form of Eq. (5) is given by:

\[
\varphi(x) = \int \sum_i (f_d(i) \Delta s_i) G_d(x, x'), \quad \text{for } x' \text{ on } S
\]

Denote the source density weighed by discrete grid area \( f_d(i) \Delta s_i \) as the equivalent dipole layer source strength. Then Eq. (8) linearly relates the electrical potential \( \varphi \) for \( x \) in \( V \), with the equivalent current dipole layer source strength, by the discrete Green function \( G_d \). When \( \varphi \) is the potential measurement from the scalp surface, Eq. (8) can be written in matrix form:

\[
\vec{\phi}_s = A \vec{F}
\]

where \( \vec{\phi}_s \) is the vector of measured scalp potentials, \( \vec{F} \) the vector of cortical equivalent dipole layer source strength, \( A \) the lead field matrix relating \( \vec{\phi}_s \) and \( \vec{F} \), and can be obtained by evaluating the discrete Green function \( G_d \).

Denote the pseudo-inverse of \( A \) as \( A^+ \), the cortical equivalent dipole layer source strength can be estimated as:

\[
\vec{F} = A^+ \vec{\phi}_s
\]

Both Tikhonov regularization (TIK) and truncated singular value decomposition (TSVD) can be applied to calculate \( A^+ \). Each method requires determination of a free parameter (regularization parameter in TIK and truncation parameter in TSVD), which balances the numerical accuracy and stability of the inverse solution, and different methods have been proposed for the rational determination of this parameter (for review, see Hansen, 1992).

2.4. Simulation and experimental protocols

Computer simulations were conducted to validate the forward theory of the cortical equivalent dipole layer, and both simulation and experimental studies were conducted to initially evaluate the performance of the inverse CDI approach.
A 3-sphere concentric inhomogeneous head model (Fig. 2) was used in the present study (Rush and Driscoll, 1969). The normalized radii of the brain, the skull and the scalp spheres were taken as 0.87, 0.92 and 1.0, respectively. The normalized conductivity of the scalp and the brain was taken as 1.0, and that of the skull as 0.0125. A virtual closed surface dipole layer was constructed to equivalently represent enclosed brain electrical sources (Wang and He, 1998).

In the present simulation, current dipole sources with unit moment were used to represent well-localized brain electric activity. The dipoles were oriented radially or tangentially to the sphere with varying angles between them and with varying eccentricity. For the radial dipole, the direction of the dipole moment is along the radius of the sphere. For the tangential dipole, the direction of the dipole moment is perpendicular to the radial dipole.

The validation of the cortical equivalent dipole layer theory requires that the electric field established by the simulated primary source dipoles should be equivalent to that established by the cortical equivalent dipole layer. We validated this by specifically considering the cortical potentials. The true cortical potential \( \phi_c \) generated by the primary source dipoles was calculated analytically (Eshel, 1993). The corresponding cortical equivalent dipole layer source density was calculated using Eqs. (6) and (7), then weighted by the discrete grid area to obtain the equivalent dipole layer source strength \( \vec{F} \). The cortical potential \( \phi_c^* \) produced by the cortical equivalent dipole layer was then calculated. The accuracy of the cortical equivalent dipole layer was evaluated by relative error (RE) and correlation coefficient (CC) between \( \phi_c \) and \( \phi_c^* \):

\[
RE = \frac{\| \phi_c - \phi_c^* \|}{\| \phi_c \|} \quad CC = \frac{\vec{\phi}_c \cdot \vec{\phi}_c^*}{\| \phi_c^* \| \| \phi_c \|} \quad (11)
\]

To initially evaluate the CDI inverse solution, the scalp potential \( \phi_s \) generated by the simulated primary source dipoles was calculated analytically (Perrin et al., 1987). Gaussian white noise (GWN) was added to \( \phi_s \) to simulate noise-contaminated scalp potential measurement, and the noise level was defined as the ratio of the standard deviation of GWN over that of the scalp potentials. The source strength of the cortical equivalent dipole layer was calculated analytically and also estimated using Eq. (10). The TSVD was applied to calculate \( A^+ \) in Eq. (10), and the minimal product method was used to determine the truncation parameter in TSVD (Lian and He, 2001). The normalized scalp potential map, analytical cortical equivalent dipole layer map, and the inversely estimated cortical equivalent dipole layer map were then compared.

Human VEP experiments were also conducted to initially examine the performance of CDI in mapping brain electrical sources in an experimental setting. A 34-year-old healthy male subject participated in the experiment according to a protocol approved by the Institutional Review Board. Visual stimuli were generated by the STIM system (Neuro Scan Labs). Ninety-four-channel VEP signals referenced to right earlobe were amplified with a gain of 500 and band pass filtered from 1 to 200 Hz by Synamps (Neuro Scan Labs), and were acquired at a sampling rate of 1 kHz by SCAN 4.1 software (Neuro Scan Labs). The electrode locations were measured using Polhemus Fastrack (Polhemus Inc.) and best fitted on the spherical surface with unit radius. Half visual field pattern reversal checkerboards (black and white) with reversal interval of 0.5 s served as visual stimuli and 400 reversals were recorded to obtain averaged VEP signals. The cortical equivalent dipole layer maps at P100 were estimated and compared to the corresponding scalp potential maps.

3. Results

3.1. Accuracy evaluation of the theory of cortical equivalent dipole layer

Different factors which might affect the accuracy of the cortical equivalent dipole layer model were investigated by evaluating the RE and CC between the true cortical potential generated by the primary source dipoles and the equivalent cortical potential produced by the cortical equivalent dipole layer model.

Table 1 shows the effect of source eccentricity. Four radial or tangential primary source dipoles located at \( r(\pm \sin(\pi/6), 0, \cos(\pi/6)) \) and \( r(0, \pm \sin(\pi/6) \cos(\pi/6)) \) were used to simulate 4 well-localized brain electric sources, where \( r \) is the eccentricity of the dipole sources.

<table>
<thead>
<tr>
<th>ECC</th>
<th>0.20</th>
<th>0.30</th>
<th>0.40</th>
<th>0.50</th>
<th>0.60</th>
<th>0.70</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE (rad)</td>
<td>0.0281</td>
<td>0.0281</td>
<td>0.0282</td>
<td>0.0290</td>
<td>0.0336</td>
<td>0.0652</td>
<td>0.1885</td>
</tr>
<tr>
<td>CC (rad)</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9994</td>
<td>0.9979</td>
<td>0.9842</td>
</tr>
<tr>
<td>RE (tag)</td>
<td>0.0279</td>
<td>0.0278</td>
<td>0.0280</td>
<td>0.0285</td>
<td>0.0300</td>
<td>0.0463</td>
<td>0.1759</td>
</tr>
<tr>
<td>CC (tag)</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9996</td>
<td>0.9989</td>
<td>0.9844</td>
</tr>
</tbody>
</table>
and ranges from 0.20 to 0.75. The cortical equivalent dipole layer with 1280 discrete grid was constructed at a radius of 0.80. Table 1 clearly shows that for both radial and tangential primary dipoles, low RE and high CC values were achieved for most source eccentricities, except for $r = 0.75$ (CC = 0.984) when sources were very close to the cortical equivalent dipole layer.

Table 2 shows the effect of the radius of the cortical equivalent dipole layer. Four radial or tangential primary source dipoles were located at $0.6\times(\pm \sin(\pi/6), 0, \cos(\pi/6))$ and $0.15\times(0, \pm \sin(\pi/6)\cos(\pi/6))$, while the cortical equivalent dipole layer with 1280 discrete grid was constructed at various radii ranging from 0.40 to 0.80. For both radial and tangential primary dipoles, low RE and high CC values were obtained for all cases studied, except there was minor increase in RE and decrease in CC for the superficial cortical equivalent dipole layer with radius of 0.80.

Table 3 shows the effect of the angles between primary source dipoles. Four radial or tangential primary source dipoles were located at $0.6\times(\pm \sin \theta, 0, \cos \theta)$ and $0.6\times(0, \pm \sin \theta \cos \theta)$ where $\theta$ is the angle of dipoles with respect to z-axis, and ranges from 20 to 90°. The cortical equivalent dipole layer with 1280 discrete grid was constructed at a radius of 0.80. Consistent low RE (less than 0.05) and high CC (greater than 0.999) were obtained for all cases studied.

Table 4 shows the effect of the grid density of the cortical equivalent dipole layer model. Four radial or tangential primary source dipoles were located at $0.6\times(\pm \sin(\pi/6), 0, \cos(\pi/6))$ and $0.6\times(0, \pm \sin(\pi/6), \cos(\pi/6))$ and the cortical equivalent dipole layer was constructed at radius of 0.80 with varying grid densities (320, 640, 1280, 2560, and 5120). Table 4 indicates that for both radial and tangential primary source dipoles, a denser grid of the cortical equivalent dipole layer achieves lower RE and higher CC values. When 1280 or more grids were used, the cortical equivalent dipole layer model resulted in a CC of greater than 99.9% for both radial or tangential primary source dipoles.

3.2. Cortical equivalent dipole layer imaging of brain electric sources

Fig. 3 shows two typical examples of inverse estimation of simulated brain electrical sources by means of the present CDI approach. The top panels correspond to 4 radial dipoles positioned at $0.7\times(\pm \sin(\pi/6), 0, \cos(\pi/6))$ and $0.7\times(0, \pm \sin(\pi/6)\cos(\pi/6))$ and the bottom panels correspond to the configuration of 3 dipole sources, with two radial dipoles positioned at $0.6\times(\pm \sin(\pi/6), 0, \cos(\pi/6))$ and one tangential dipole positioned at $0.7\times(0, \sin(\pi/6), \cos(\pi/6))$ 5% GWN was added in both cases to simulate the potential measurement noise. In both examples, (a) displays the noise contaminated scalp potential map, (b) shows the forward solution of cortical equivalent dipole layer, as calculated directly from the primary dipole sources, and (c) shows the inversely estimated strength map of cortical equivalent dipole layer. Notably, the scalp potential maps were severely blurred and distorted by the head volume conductor and additive noise. The forward-calculated strength maps of cortical equivalent dipole layer clearly indicate the well localized brain electrical activities corresponding to the primary dipole sources in both examples. The inverse maps show strong capability of the CDI in correcting the blurring effect caused by the head volume conductor, especially the low conductivity skull. Although the estimated cortical equivalent dipole layer maps were not as perfect as the analytic ones due to the noise effect, without the blurring effect caused by the skull layer, they clearly revealed the underlying dipole sources with much enhanced spatial resolution as compared to the scalp potential maps.

Fig. 4 shows examples of the initial application of the CDI in human VEP data. The subject was, respectively, given left and right visual field stimuli. The normalized scalp potential maps at P100 are, respectively, shown in Fig. 4(a,b), and the estimated cortical equivalent dipole layer maps are shown in Fig. 4(c,d), respectively. Notably,
in response to the left visual field stimuli, a positive potential component was elicited with a widespread distribution on the occipital area of the scalp, with a larger area of activation being observed in the left lobe than in the right lobe (Fig. 4(a)). In response to the right visual field stimuli, a widely distributed positive potential component was also found in the occipital region of the scalp, while a larger area of activation was observed in the right lobe than in the left lobe (Fig. 4(b)). On the other hand, the estimated cortical equivalent dipole layer map in response to the left visual field stimuli revealed a dominant and more localized activity in the right occipital lobe (Fig. 4(c)). Consistently, the estimated cortical equivalent dipole layer map in response to the right visual field stimuli indicated a dominant and more localized activity in the left occipital lobe (Fig. 4(d)).

4. Discussion

Brain electromagnetic imaging provides an important means of exploring spatio-temporal distribution of neural activity in the brain. Ideally, one would like to image the neural electrical sources over the 3 dimensions of the brain from non-invasive scalp EEG or MEG measurements. However, such a problem is well known to be non-unique (Von Helmholtz, 1853) and physical or physiological constraints have to be placed in order to obtain a unique solution on 3-dimensional equivalent source distribution (Pascual-Marqui et al., 1994; Grave de Peralta-Menendez et al., 2000; He et al., 2002).

The cortical imaging approach recognizes the limitation of the 3-dimensional brain electromagnetic inverse problem and uses a two-dimensional approximation of the 3-dimensional brain electrical source distribution, by confining the equivalent sources over the cortical surface. Although such two-dimensional cortical imaging does not provide information on neural electrical activity within the 3-dimensional brain, cortical imaging results have been shown to be useful since it provides a more enhanced spatial resolution as the smearing effect of the low conductivity skull has been essentially removed (Sidman et al., 1990; Wang et al., 1992; Dale and Sereno, 1993; Le and Gevins, 1993; Srebro et al., 1993; Gevins et al., 1994; Nenuz et al., 1994; Babiloni et al., 1997, 2000; Wang and He, 1998; He, 1999).

The present manuscript proposes a theory on the cortical equivalent current dipole layer model for equivalently representing 3-dimensional electrical sources within the brain. The present theory also provides theoretical justification on the use of the equivalent cortical dipole layer model to account for the neural electrical activity within the entire brain. In other words, the equivalent cortical dipole layer

![Fig. 3. Two examples of inverse estimation of simulated brain electric sources (see text for details of the two different dipole source configurations), using cortical equivalent dipole layer imaging. (a) 5% GWN contaminated scalp potential map, (b) forward calculated cortical equivalent dipole layer image, and (c) inversely estimated cortical equivalent dipole layer image. All maps are normalized for display. ‘P’ and ‘N’ denote positive and negative activity, respectively.](image-url)
model not only can be related to cortical currents directly, as it was formulated based on physiological grounds (Dale and Sereno, 1993), but it can also be interpreted as an equivalent source distribution accounting for cortical as well as subcortical neural activities. As shown in Eq. (7), the strength of the equivalent dipole layer is proportional to the electrical potential generated by all brain electrical sources at the same imaging surface had the exterior space been replaced by air. This theoretical result shows that the equivalent dipole layer images brain electrical activity at both cortical and subcortical regions. If the scalp EEG measurements are essentially originated from cortical activities, the reconstructed cortical dipole layer represents principal activities over the cortex. If the scalp EEG is also generated by subcortical activities, the reconstructed equivalent dipole layer represents an ‘equivalent’ source, which is a kind of projection of 3-dimensional sources onto the two-dimensional imaging surface, with heavier weight for cortical sources and less weight for subcortical sources. Since the present theory is applicable to arbitrary geometry, numerical solutions on the strength of cortical dipole layer may then be obtained to aid cortical current dipole layer imaging (Dale and Sereno, 1993; Liu et al., 1998; Babiloni et al., 2000).

In some of the cortical imaging approaches (Sidman et al., 1990; Babiloni et al., 1997; Wang and He, 1998), the cortical potential is reconstructed by an indirect procedure. A dipole layer is first estimated from the scalp EEG. Then the cortical potentials are calculated from the estimated dipole layer. In the present work, it is demonstrated that the dipole layer represents another kind of equivalent source model for the brain electrical activity. As shown in the present study, the cortical equivalent dipole layer source density is proportional to the potential over the same surface had the upper medium been removed, therefore higher spatial resolution is expected for the cortical equivalent dipole layer map as compared to the blurred scalp potential map. The present theory of cortical equivalent dipole layer makes it possible to examine and evaluate the equivalent source distribution directly over the cortical equivalent dipole layer, without a further calculation of the cortical potentials.

Using a 3-concentric-sphere inhomogeneous head model, we have validated the proposed theory by comparing the true cortical potentials produced by the primary source dipoles and the equivalent cortical potentials generated by the equivalent dipole layer. Different dipole sources vs. equivalent dipole layer configurations have been investigated, and low RE (high CC) values are obtained for most cases. As shown in Tables 1–4, when the source eccentricity, equivalent dipole layer radius and grid density are all fixed, the RE (CC) values are not sensitive to dipole orientations (radial or tangential), nor sensitive to the angle between the dipole sources (Table 3). The slight increase of RE (slight decrease of CC) occurs when the dipole sources are very close to the equivalent dipole layer or

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**Fig. 4.** Examples of cortical equivalent dipole layer imaging in human VEP experiments. (a) Scalp potential map at P100 elicited by left visual field stimuli. (b) Scalp potential map at P100 elicited by right visual field stimuli. (c) Estimated cortical equivalent dipole layer image corresponding to (a). (d) Estimated cortical equivalent dipole layer image corresponding to (b). All maps are normalized for display, and the viewpoint has 60° of vertical elevation from the horizontal plane, with nasion direction upward.
when the equivalent dipole layer is close to the cortical surface (Tables 1 and 2). This is mainly due to the numerical error caused by discretization of the continuous double layer into a discrete dipole layer. Numerical accuracy decreases because the discretized triangles are not sufficiently small when the dipole sources are very close to the dipole layer or when the dipole layer is very close to the cortical surface. This phenomenon is similar to what was reported previously that the numerical error increases when a dipole approaches too closely to the brain surface (Roth et al., 1997). The discrete approximation is of low-pass characteristic, and therefore partial high spatial frequency components are lost through limited degree of surface discretization. Further evidence is shown in Table 4, which indicates that a denser grid of equivalent dipole layer yields more accurate representation of brain electrical sources. As a trade-off, more computation time is required for the denser sampling of the equivalent dipole layer. Based on our simulation results and experience, it is recommended that around 1000 dipoles should be used in cortical equivalent dipole layer imaging to ensure reasonable numerical accuracy as well as calculation efficiency.

The cortical equivalent dipole layer imaging inverse problem has also been initially evaluated by both computer simulations and experimental studies. As shown in Fig. 3, the estimated cortical equivalent dipole layer maps correspond well to the analytic maps, and both of them clearly resolves the underlying dipole sources with much enhanced spatial resolution as compared to the noise-contaminated scalp potential maps. The less sharp spatial patterns of the estimated cortical equivalent dipole layer maps as compared to the analytic maps are due to the intrinsic characteristics of the inverse regularization procedure. Note that other inverse regularization procedures (Dale and Sereno, 1993; Pascault-Marqui et al., 1994; Sekihara et al., 1995; Philips et al., 1997; Grave de Peralta Menendez and Gonzalez Andino, 1998) may also be used to obtain the inverse solution, although the TSVSD procedure was used in the present study. Promising results were also obtained from cortical equivalent dipole layer imaging of P100 of VEP data (Fig. 4). It is widely accepted that the half visual field stimuli activate the visual cortex on the contralateral hemisphere of the brain. But paradoxically, the half visual field stimuli elicits larger area of positive potential distribution over the ipsilateral side of the scalp (Fig. 4(a,b)), which might be misinterpreted as ipsilateral visual cortex activation (Barrett et al., 1976). However, the estimated cortical equivalent dipole layer maps indicate that the contralateral occipital lobe was activated (Fig. 4(c,d)), thus effectively eliminating the misleading far field observed in the scalp potential maps.

In summary, a theory of the cortical equivalent dipole layer model has been developed, which provides theoretical justification on practice in cortical current dipole imaging. The present theory has been developed based on previously reported cortical current imaging, which was motivated by modeling cortical sources. The present theory shows that one can interpret cortical current dipole layer estimated from the scalp EEG as an ‘equivalent source’ of electrical activities at both cortical and subcortical regions. The present approach has been validated in computer simulations using a 3-concentric-sphere head model, and tested in simulation and experimental studies. The promising results suggest that the present work may further facilitate high-resolution EEG imaging of brain electrical activity.

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