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Spatial Filter Approach for Evaluation of the Surface Laplacian of the Electroencephalogram and Magnetoencephalogram

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Abstract—The surface Laplacian is a technique that has been utilized to improve the spatial resolution of the electroencephalogram (EEG) and the magnetoencephalogram (MEG). We investigate the amount of improvement to the spatial resolution afforded by the surface Laplacian by examining the spatial filters that describe the relationship between cortical current sources and the surface Laplacian. The surface Laplacian spatial filters extend into higher spatial frequencies than do raw signal spatial filters, particularly for EEG Laplacian spatial filters, indicating that substantial improvement in spatial resolution is possible. However, the response of the surface Laplacian operation to the nature and amount of noise in the raw EEG and MEG signals is of paramount importance. Spatially correlated noise, coupled with uncorrelated noise, requires additional regularization of inverse spatial filters resulting in a decrease in spatial resolution. Substantial improvements in spatial resolution may be obtained using the surface Laplacian techniques as long as correlated noise levels are small and raw signals have relatively high signal-to-noise ratios. *© 2001 Biomedical Engineering Society.* [DOI: 10.1114/1.1352642]

Keywords—Magnetoencephalogram, Brain electroencephalogram, Spatial resolution, Inverse problem.

INTRODUCTION

Recently much interest has been paid to the potential ability of the surface Laplacian operation to improve the spatial resolution of electroencephalogram (EEG) recordings. The surface Laplacian operation computes the second spatial difference of the surface EEG. Several authors have shown that this quantity, which loosely corresponds to a surface radial current distribution, presents greater spatial information than does the raw potential measured by EEG montages.[18,29,30,36,42]

The surface Laplacian is estimated from raw multichannel EEG data using one of two methods. One method obtains the second difference of the EEG recorded at adjacent locations,[9,18] and the other utilizes a spline technique applied to all electrodes in the recording array to estimate the surface Laplacian.[21,29,36]

Issues of spatial resolution may be addressed by describing the lead fields that specify the source-measurement relationship in terms of spatial filters. In the companion paper, we described how spatial filters may be used to evaluate the forward and inverse problems of the EEG and magnetoencephalogram (MEG).[5] In this paper, we examine the surface Laplacian by studying the spatial filters that describe the relationship between the source current density and the five-point discrete Laplacian obtained from EEG calculations. We also investigate how the Laplacian operation affects the tangential and radial MEG. Recently, Srinivasan and colleagues presented similar spatial filter analyses for EEG Laplacians.[39]

Forward spatial filters are low-pass functions of spatial frequency; as a result, there is less spatial information about internal sources in the external magnetic fields or electric potentials than is in the internal sources themselves. In contrast, inverse spatial filters are high pass in nature: any noise present at higher spatial frequencies is amplified by the inverse filter and leads to instabilities in inverse reconstructions. To maintain stability, inverse filters must be regularized by windowing in the frequency domain. However, there is a trade off between stability and spatial resolution as regularization leads to the loss of spatial information.[5]

The issue of noise is of crucial importance to the possible utility of the surface Laplacian, whether the Laplacian is estimated from raw potential measurements or measured directly. Some researchers,[16,19] when evaluating the performance of the surface Laplacian, add simulated uniform white noise directly to the Laplacian itself, implicitly assuming that the signal-to-noise ratio (SNR) of Laplacian ‘‘measurements’’ are roughly equal to those of EEG. But since the Laplacian operation involves the subtraction of EEG measurements, this assumption may or may not be valid. Also at issue is the assumption that Laplacian noise is uniform and random. In the case of background EEG, noise can be spatially

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correlated, further complicating the application of the surface Laplacian.

This paper presents a theoretical simulation using a cylindrical model of the head to frame the problems within a spatial filtering construct. As we stated in the companion article,[5] the loss of physiological realism by using the cylindrical head is more than offset by the intuition that can be developed by examining the analytical filter functions. In this paper, we investigate the spatial filtering nature of the source-Laplacian relationship, the increased spatial resolution available in the surface Laplacian, and the performance of the surface Laplacian in the presence of noise.

METHODS

Using a three-layer concentric cylinders model of the head, we may calculate the external magnetic fields and electric potential (the MEG and the EEG) due to simulated cortical current sources. The source model and head model are described in the companion article.[5] The surface Laplacian of the simulated EEG and MEG is defined by

$$\nabla_s^2 \Psi(r,\theta,z) = \frac{1}{r^2}\frac{\partial^2 \Psi}{\partial \theta^2}(r,\theta,z) + \frac{\partial^2 \Psi}{\partial z^2}(r,\theta,z), \qquad (1)$$

where Ψ stands for either the scalp potential from the EEG or the magnetic field from one or more components of the MEG measured at the point (r,θ,z), and ∇_s^2 represents the surface Laplacian operation. We estimate these derivatives by ''nearest-neighbor'' finite differences of the fields or potentials using essentially the same procedure employed by Hjorth,[18] with a Jacobian correction made for the cylindrical surface. We use the potentials calculated at the scalp to simulate the EEG, and the radial and tangential magnetic fields calculated in air 1 cm from the scalp surface to simulate the radial and tangential MEGs.

Because the total three-dimensional Laplacian is zero outside the source region, i.e.,

$$\nabla^2 \Psi(r,\theta,z) = \frac{\partial^2 \Psi}{\partial r^2}(r,\theta,z) + \frac{1}{r^2}\frac{\partial^2 \Psi}{\partial \theta^2}(r,\theta,z) + \frac{\partial^2 \Psi}{\partial z^2}(r,\theta,z) = 0, \qquad (2)$$

it follows that Eq. (1) may also be expressed as

$$\nabla_s^2 \Psi(r,\theta,z) = -\frac{\partial^2 \Psi}{\partial r^2}(r,\theta,z), \qquad (3)$$

because the total three-dimensional Laplacian is zero outside the source region. Similarly, the divergence of the current density at the scalp must be zero

$$\nabla \cdot \mathbf{J} = \nabla \cdot \sigma_{\text{scalp}} \nabla V = \sigma_{\text{scalp}}\left(\frac{\partial^2 V}{\partial r^2}(r,\theta,z) + \overline{\frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2}(r,\theta,z) + \frac{\partial^2 V}{\partial z^2}(r,\theta,z)} \right) = 0, \qquad (4)$$

where the last two terms are the surface Laplacian of the potential. Since the radial volume current at the scalp surface is given by $J_r(r,\theta,z) = \sigma_{\text{scalp}}[\partial V(r,\theta,z)/\partial r]$, the surface Laplacian of the EEG is proportional to the first difference of the radial volume current which is the two-dimensional divergence of **J** on the scalp surface. Physically, it corresponds to sources or sinks of current in the scalp.[28]

The physical significance of the surface Laplacian of the MEG is not as straightforward, since the radial derivatives of the radial and tangential magnetic field do not relate directly to local current flow (they include large contributions from the primary source current), but we should note that signal subtraction is common in magnetoencephalography as most sensors are gradiometers in which the signal at one spatial location is subtracted from the signal at another location. In some respects, the surface Laplacian of the MEG is tantamount to recording the MEG with a second-order planar gradiometer.

The spatial filter describing the source-Laplacian relationship is obtained by dividing the Fourier transform of the surface Laplacian by the Fourier transform of the source

$$f_{j,\nabla_s^2\psi}(r,k_\theta,k_z) = \frac{\nabla_s^2 \psi(r,k_\theta,k_z)}{j(r,k_\theta,k_z)}, \qquad (5)$$

where the lower-case symbols are used to refer to Fourier-transformed quantities in the spatial frequency domain, and k_θ and k_z represent the spatial frequencies associated with the θ and z coordinates. Likewise, the internal current sources may be calculated from the surface Laplacian according to

$$j(r,k_\theta,k_z) = f_{\nabla_s^2\psi,j}(r,k_\theta,k_z) \cdot \nabla_s^2 \psi(r,k_\theta,k_z), \qquad (6)$$

where the inverse filter $f_{\nabla_s^2\psi,j}$ is the reciprocal of the forward filter $f_{j,\nabla_s^2\psi}$. As with the external EEG and MEG, the forward filters are low-pass functions of spa-

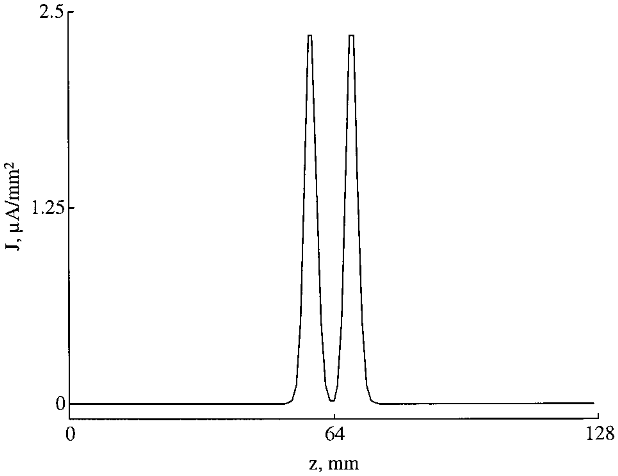

FIGURE 1. Gaussian source current density. This current source density is located 20 mm below the scalp surface at a polar angle of 0°, and produces the magnetic fields and potentials external to the cylindrical model layers.

tial frequency and the inverse filters are high-pass functions of spatial frequency.

We should note that the spatial filtering construct as we apply it merely provides us with a method to examine the spatial effects of volume conduction on external fields and potentials, and in this case, on the surface Laplacian of those signals. The surface Laplacian itself may be obtained from raw data with no prior knowledge of the sources, using one of the methods described above. We obtain the surface Laplacian by applying the five-point discrete algorithm to the EEG and MEG forward solutions from the model. The signals are calculated at the same polar angles as they were in the companion paper, at $\theta=0°$ for the EEG and tangential MEG, and $\theta=11.5°$ for the radial MEG, since the radial MEG is zero directly above the source.

To keep noise from overwhelming the reconstructions, inverse filters must be regularized. As before, we use a Tukey window.[5] We investigate two scenarios involving the noise: the direct addition of noise to the surface Laplacian with the SNR roughly the same as for the external fields and potentials, and the indirect addition of noise to the external fields before the surface Laplacian is calculated. Later, we also consider the effect of physiological brain noise.

We evaluate the results by requiring that reconstructions attain a certain stability. We use the stability parameter ξ, which varies from a value of 0, corresponding to complete instability, to a value of 1, indicating perfect stability, as defined in the companion paper.[5]

To investigate the relative information content of raw EEG or MEG calculations and the surface Laplacians, we also calculate the spatial filters relating the external fields and potentials with their surface Laplacians. The forward spatial filters relating the source current with the raw signals are given by

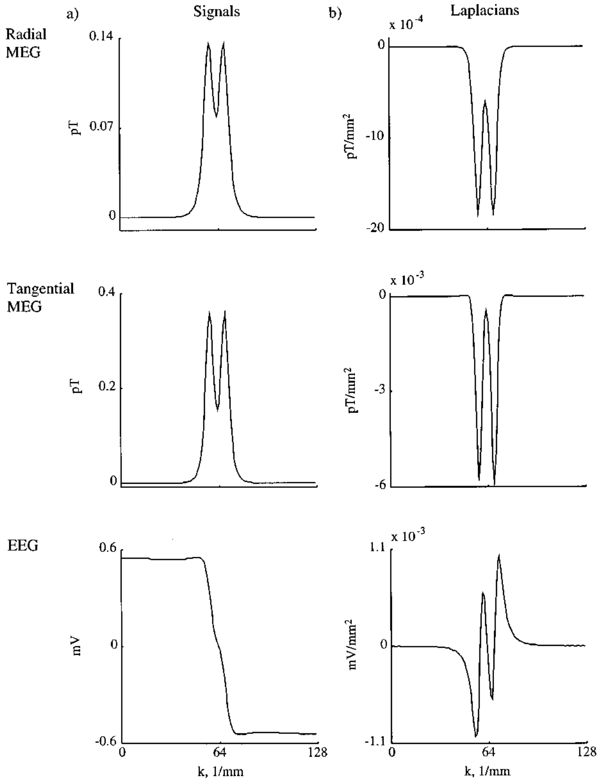

FIGURE 2. Signals and surface Laplacians. The radial MEG, tangential MEG, and EEG are shown (a) with their derived surface Laplacians (b) as calculated from Eq. (1).

$$f_{j,\psi}(\rho,k_\theta,k_z)=\frac{\psi(\rho,k_\theta,k_z)}{j(\rho,k_\theta,k_z)}. \tag{7}$$

The spatial filters relating the EEG or MEG with their surface Laplacians are given by

$$f_{\psi,\nabla_s^2\psi}(r,k_\theta,k_z)=\frac{f_{j,\nabla_s^2\psi}(r,k_\theta,k_z)}{f_{j,\psi}(r,k_\theta,k_z)}. \tag{8}$$

RESULTS

The source configuration used for this study is the effective dendritic source that we used in the companion paper, and is plotted in Fig. 1. It consists of two Gaussian-shaped pulses of strength 2.5 μA/mm^2 separated along the z axis by a distance of 1 cm. Figure 2(a) shows the resulting scalp EEG and the radial and tangential MEGs calculated 1 cm into the air. Their corresponding surface Laplacians, which were calculated according to Eq. (1), are shown in Fig. 2(b). Comparing

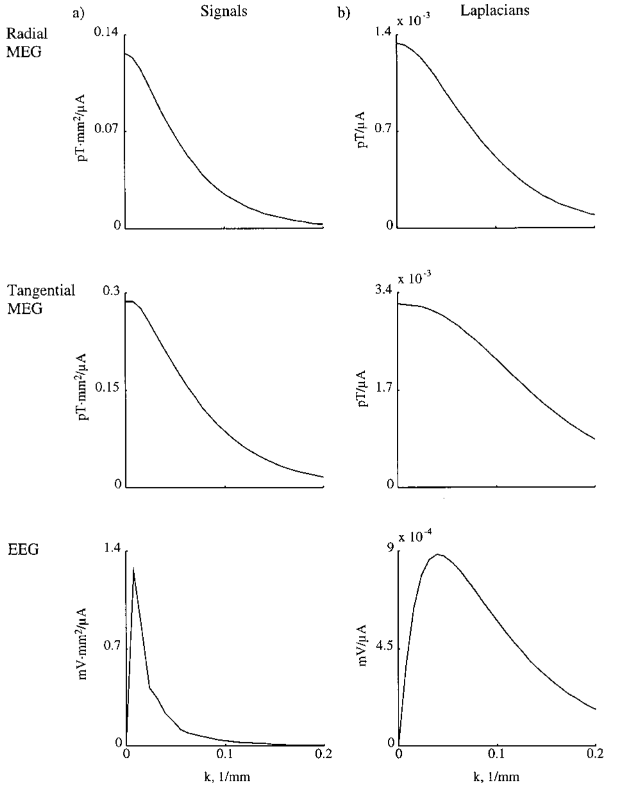

FIGURE 3. Forward filters. The forward filters relating the source current with the raw MEG and EEG signals are shown in (a). Forward filters describing the source–surface Laplacian relationship are shown in (b). Notice that the surface Laplacian operation tends to extend the spatial filters into higher spatial frequencies.

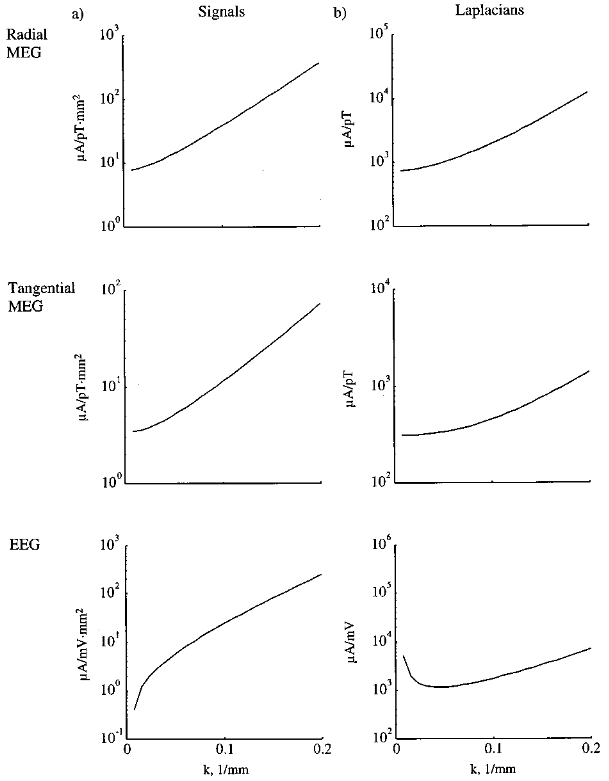

FIGURE 4. Inverse filters. The inverse filters are obtained as reciprocals of the forward filters shown in Fig. 3. The effect of the surface Laplacian is to "flatten" the inverse filter in the higher spatial frequencies, allowing for the potential utilization of higher spatial frequencies in inverse reconstructions.

the fields and potentials with their surface Laplacians, we see that the Laplacians appear to contain a higher amount of spatial information.

As an aid in determining whether there is indeed increased spatial information in the surface Laplacian, we must perform the inverse calculation. The forward spatial filters relating the source to the EEG and MEG are plotted in Fig. 3 along side the forward spatial filters relating the source to the respective surface Laplacians. The inverse filters, determined by taking the reciprocal of the forward filters, are plotted in Fig. 4. It can be seen in Figs. 3 and 4 that the effect of the surface Laplacian in the spatial frequency domain, particularly for the EEG Laplacian, is to widen the forward spatial filters, thus ''flattening'' the inverse spatial filters at lower spatial frequencies. This flattening suggests that more of the spatial frequencies will remain available to the inverse procedure before additional regularization is required. Note, however, that there is a corresponding increase in the magnitude of the inverse Laplacian filters, indicating that the surface Laplacian operation includes additional amplification during the inverse procedure.

Current source reconstructions from the surface Laplacians to which we added random, uncorrelated white noise are shown in Fig. 5. The noise level added to the EEG Laplacians is 20%, while 30% noise is added to the MEG Laplacians, consistent with the noise added in the companion study. Inverse reconstructions from Laplacians with these noise levels and the requirement that the reconstruction stability exceed 0.96 (on the right side of Fig. 5) are seen to contain a high degree of spatial resolution. Compared with inverse reconstructions from the raw data (Fig. 6), dramatic improvement is evident in the surface Laplacian signals. The improvement of the source reconstruction from the EEG Laplacian over that from the raw EEG is most striking.

DISCUSSION

Laplacian Spatial Filter

Much insight into the potential utilities and pitfalls of the surface Laplacian can be gained by examination of its spatial filters. Equation (1), when Fourier transformed, yields

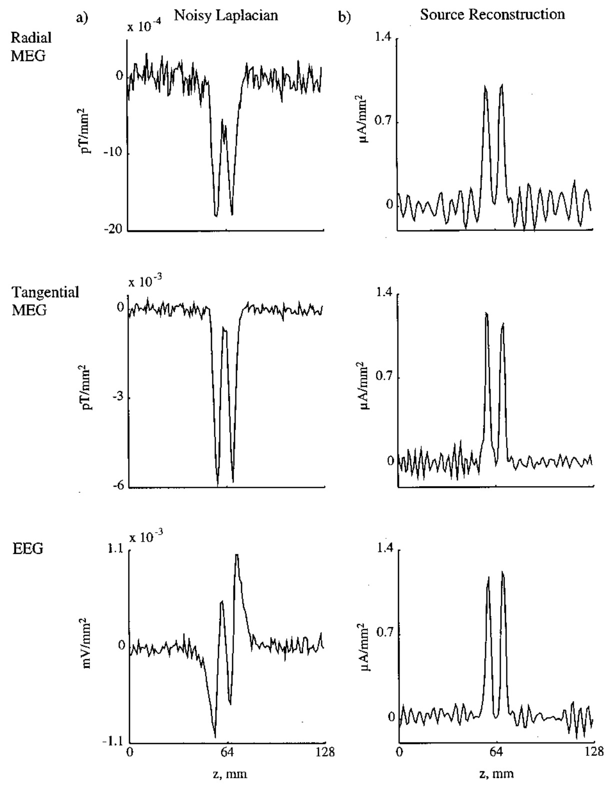

FIGURE 5. Source reconstructions from surface Laplacians. (a) Calculated Laplacians from Fig. 2(b) are shown with 20% noise added to the EEG Laplacian, 30% added to the MEG Laplacian. (b) Reconstructions are shown under the requirement that the stability ξ achieve a value of at least 0.96.

$$\nabla_s^2 \psi(r,k_\theta,k_z) = \left[\frac{k_\theta^2}{r^2} + k_z^2\right]\psi(r,k_\theta,k_z). \qquad (9)$$

The spatial filter relating the raw potential or magnetic field with its surface Laplacian is thus given by

$$f_{\psi,\nabla_s^2\psi}(r,k_\theta,k_z) = \frac{k_\theta^2}{r^2} + k_z^2. \qquad (10)$$

Since the spatial filter relating the fields and potentials with their magnetic fields are simply proportional to the squares of the spatial frequencies, the process of taking the surface Laplacian is effectively a high-pass spatial operation in precisely the same manner that obtaining an inverse solution from these signals is a high-pass operation. This simple spatial filter reveals both the power and the potential pitfall of the surface Laplacian. The forward spatial filters for the raw signals displayed in Fig. 3(a) differ from the forward spatial filters for the Laplacian shown in Fig. 3(b) by the factor k_z^2. Similarly, the inverse spatial filters of the raw signals of Fig. 4(a) differ from the Laplacian inverse filters in Fig. 4(b) by the factor $1/k_z^2$. Thus, the surface Laplacian acts to ''flatten'' the inverse filters over a larger range of spatial frequencies so that higher spatial frequencies are allowed to contribute in an inversion. Quantitatively, we can obtain some measure of the increase in spatial information by comparing the 3 dB roll-off points of the raw signal spatial filters and the surface Laplacian spatial filters. Table 1 shows that while the surface Laplacian increases the 3 dB roll-off points for the radial and tangential MEG by a modest amount, the 3 dB roll-off point for the EEG is increased by a factor of more than 5. In fact, the EEG Laplacian allows more spatial frequency information than the radial MEG Laplacian. Thus, the EEG in-

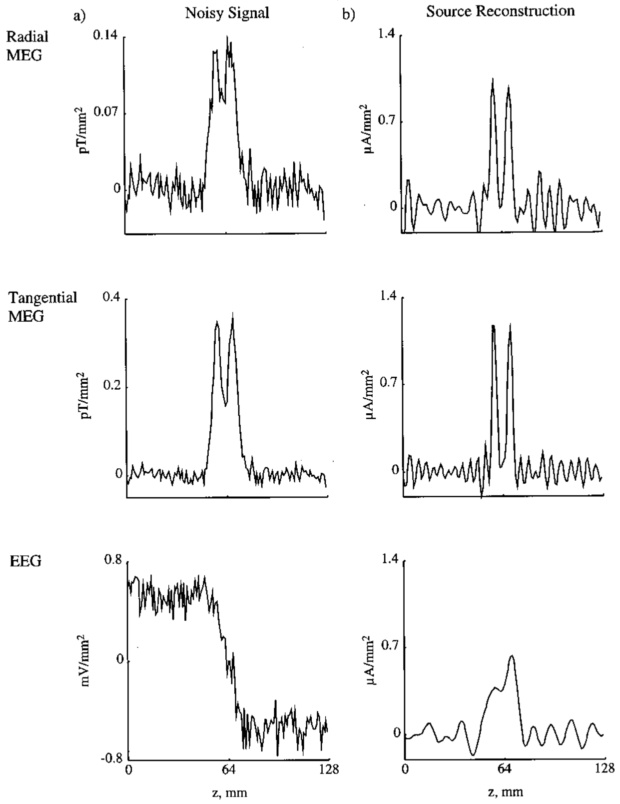

FIGURE 6. Source reconstructions from raw data. For comparison with Fig. 5, the source reconstructions (b) from the raw EEG and MEG signals (a) are shown. Compared to these reconstructions, a high degree of improvement in the spatial resolution is evident in Fig. 5, particularly for the EEG Laplacian.

TABLE 1. 3 dB roll-off points for scalp EEG, air MEG, and surface Laplacian spatial filters.

	Signal	Surface Laplacian	Ratio
Radial MEG	0.0625	0.0859	1.37
Tangential MEG	0.0703	0.1406	2
EEG	0.0234	0.125	5.34

verse reconstructions from the surface Laplacian, seen in Fig. 5, are much better resolved than inverse reconstructions from the raw signals shown in Fig. 6. The reconstructions from the MEG Laplacians are only slightly better resolved. The results could be expected to change if different model parameters were used, and specifically, different source depths or source separations. These issues were addressed in the companion manuscript in the context of the relative performance of the EEG and MEG, and the results will generalize to the issue of the surface Laplacian. A complete sensitivity analysis of parameter changes is provided elsewhere.[4]

Effect of Noise

The utility of the surface Laplacian depends on its ability to deal with noise. In addition to measurement noise, the effect of physiological brain noise, even though it is spatially low-pass filtered by the volume conducting head, is ultimately to increase the amount of noise in the external EEG and MEGs and to introduce spatial correlations to the noise. The inverse reconstructions in this work were calculated from surface Laplacians calculated from noiseless EEGs and MEGs. Simulated measurement noise levels of 20% for the EEG and 30% for the MEGs were added directly to the Laplacians. These noise levels are roughly the same as would be expected for raw EEGs and MEGs. In other words, the noise in the surface Laplacian was assumed to be exactly the same as in the raw signals. It is this assumption that introduces the potential weakness of the surface Laplacian technique, namely, its sensitivity to noise.

The procedure of taking the surface Laplacian is equivalent to a multiplication of the forward spatial filters by a factor of k^2, which extends the dynamic range of the filters and increases the spatial resolution. This multiplication process causes the surface Laplacian to preferentially amplify higher spatial frequencies over lower spatial frequencies, meaning that the surface Laplacian is sensitive to more superficial sources and less sensitive to deeper sources that might be identified by EEG. This is a frequency-domain version of the observation of several authors[33,35,41] that the sensitivity of the surface Laplacian drops much faster with distance from the source ($1/r^4$) than does the sensitivity of the potential ($1/r^2$). However, the multiplication by k^2 will also amplify any broadband noise present in the original signal.[22] For the reconstructions shown above, the noise was added directly to the surface Laplacian instead of to the raw EEG before the Laplacian operator was applied. This approach has been used by He *et al.*[16] and Johnston[19] to study the ECG Laplacian. It implicitly makes the assumption that noise in the raw signal will not affect the surface Laplacian. Later work by these authors extended their noise analyses to include noise added to the ECG signals.[15,48]

The nature of the noise is of vital importance to the potential utility of the surface Laplacian, as the presence or absence of spatial correlations in the noise will affect the action of the surface Laplacian. Spatially uncorrelated noise amplified in the higher spatial frequencies by the Laplacian operation can of course be reduced by regularization as described in Bradshaw *et al.*[5] Le *et al.*[22] used a low-pass Gaussian spatial filter for these purposes. As they noted in that paper, and as we showed for our calculations, the effect of regularizing the inverse procedure is the loss of spatial resolution. Such low-pass filtering is also utilized in the spline techniques of Nunez *et al.*[31] and Babiloni *et al.*[1]

The surface Laplacian approximates a second spatial derivative. If measurement noise in the raw signals is spatially linearly coherent, i.e., the noise in one sensor is linearly related to the noise in another sensor, then it is reasonable to assume that the subtraction process inherent in the Laplacian operation will eliminate the noise. On the other hand, spatially uncorrelated noise, or noise that is spatially correlated in a nonlinear fashion, will not be eliminated and will in fact be amplified by the surface Laplacian operation. Both types of noise should be present in both the MEG and the EEG; the ratio of the level of correlated-to-uncorrelated noise is determined by the nature and magnitude of sensor, environmental, and brain noise.

Figure 7 shows the performance of the surface Laplacian with several different types of noise present in the raw signals. Figure 7(a) shows the situation when the noise has a linear spatial correlation in both tangential directions (θ and z). In this case, the noise is perfectly eliminated by the surface Laplacian operation to within the precision of the computer. When the spatial correlation has a nonlinear nature—as is the case in Fig. 7(b) where the noise has a linear trend in θ and a nonlinear (sine wave) trend in z—the surface Laplacian subtracts the noise in θ, but since the sine wave in z has a nonzero second derivative, the surface Laplacian passes the noise arising from the second derivative of the nonlinear noise.

Uncorrelated noise in the raw signals complicates the surface Laplacian. Figure 7(c) displays noise that is correlated in one tangential direction (θ) but uncorrelated in the other (z), with the SNR (of the raw signal) set to 1.0. In this case, the SNR of the resulting surface Laplacian is 0.02, which is not satisfactory. A higher raw signal SNR results in a much less noisy surface Laplacian, as illustrated in Fig. 7(d), where the noise is the same as in Fig. 7(c), but for a raw signal SNR of 100; the SNR in the surface Laplacian in this case scales with the raw signal SNR. Noise correlated in only one dimension as in Figs. 7(c) and 7(d) is eliminated more readily by the

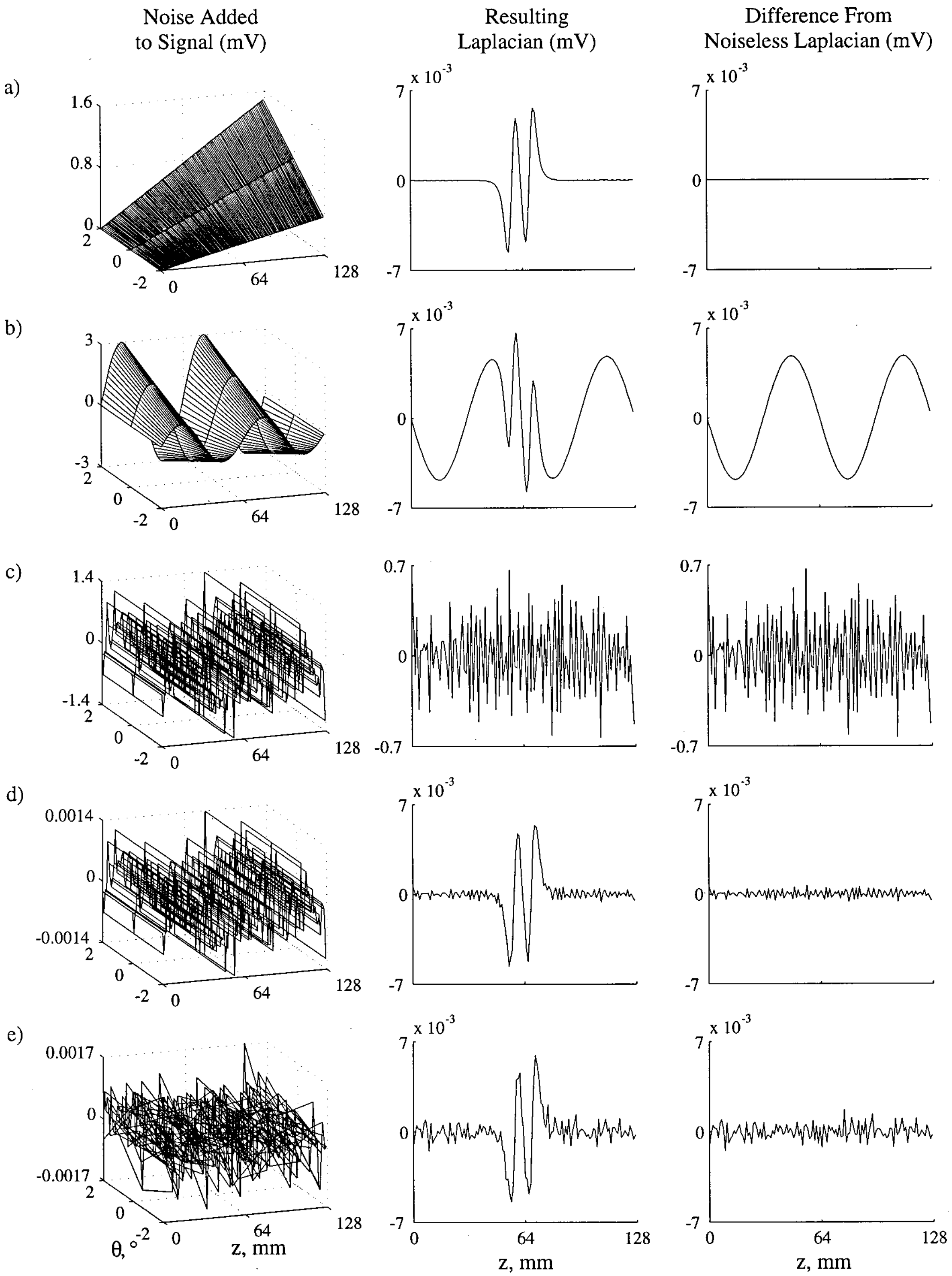

FIGURE 7. Effect of different types of noise on the surface Laplacian. The noise added to the raw EEG before the Laplacian operation is performed, shown in the left-hand column, results in the surface Laplacians shown in the middle column. The differences of these surface Laplacians from the Laplacians calculated from the EEG with no additive noise are shown in the right-hand column. Five different noise scenarios are investigated. (a) Noise linearly correlated in both θ and z directions is perfectly subtracted by the surface Laplacian. (b) Noise with a linear correlation in one dimension and a nonlinear correlation in the other is subtracted to within the second spatial derivative of the nonlinearly correlated noise. (c) Noise correlated in one direction and uncorrelated in the other (SNR=1.0) is more difficult for the surface Laplacian to eliminate. (d) Better results are obtained when the noise correlated in one dimension is subject to a higher SNR (SNR=100). (e) Completely uncorrelated noise with a SNR of 100 is handled well, but not as well as if the noise were correlated in one dimension, as in (d).

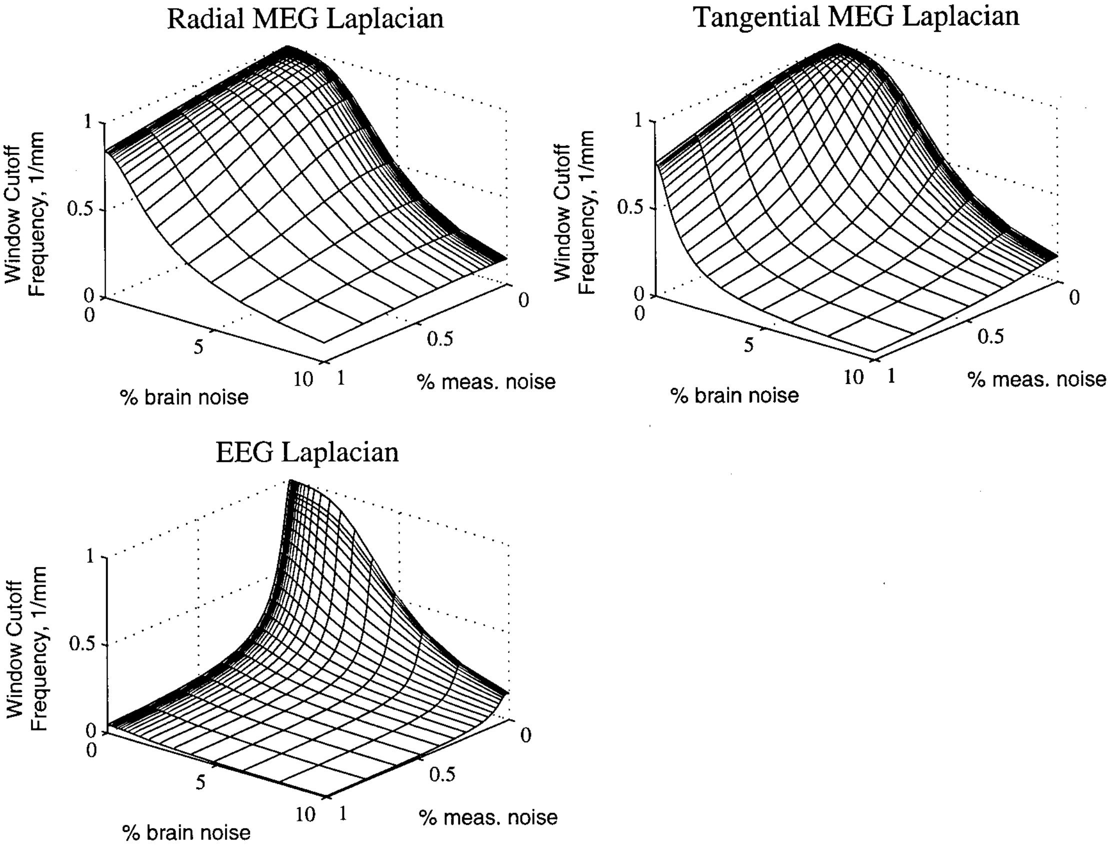

FIGURE 8. Effect of noise on spatial resolution in the surface Laplacian. Window cutoff values required to obtain stable (ξ >0.96) inverse reconstructions are plotted for varying levels of physiological brain noise applied to internal current source density, and measurement noise applied to the raw EEG or MEG signals. Note that these noise level ranges are probably unrealistically low. The EEG Laplacian, which has the greatest potential for improvement in spatial resolution, also is most sensitive to the presence of additive measurement noise, while the radial MEG Laplacian is least sensitive.

surface Laplacian than completely uncorrelated noise, shown in Fig. 7(c).

Physiological brain noise can introduce spatial correlations to the raw signals before the Laplacian operation is applied. It is therefore instructive to illustrate the behavior of the Laplacian in response to increasing physiological brain noise as well as EEG/MEG measurement noise. Figure 8 shows the spatial resolution of inverse solutions from the surface Laplacian in terms of window cutoff frequency while varying physiological brain noise in one dimension and EEG/MEG measurement noise in the other. The measurement noise in this case is applied to the raw EEG/MEG signals before the Laplacian operation is performed. Notice the extremely low-noise levels used in Fig. 8. Both MEG and EEG Laplacians have similar responses to brain noise when no measurement noise is present, but the addition of measurement noise tremendously decreases the spatial resolution from particularly the EEG surface Laplacian. The signature of the physiological brain noise in the EEG and MEG signals includes spatial correlations because it is spatially low-pass filtered by the volume conducting head. The measurement noise, on the other hand, is not spatially correlated. Thus, the surface Laplacian is able to deal more effectively with the correlated physiological brain noise than the uncorrelated measurement noise. Thus, any amount of measurement noise present in the raw signals (note the very low-noise levels in Fig. 8) aggravates the Laplacian response to brain noise and results in decreased inverse resolution. While noise effects on the MEG Laplacians are not as severe, they are more pronounced in the tangential MEG Laplacians. The response of the Laplacian inverse solutions to noise for the different modalities is in diametric opposition to the potential increase in spatial resolution. The radial MEG Laplacian, which exhibits only modest improvement over the raw MEG (Table 1), is least sensitive to noise, while the EEG Laplacian, which has the potential for the greatest improvement in spatial resolution, may be significantly affected by the presence of measurement noise in the raw signal.

EEG and MEG Spatial Resolution

The relative ability of the MEG and EEG or a combination of the two modalities to localize cortical sources has been the subject of much recent attention in the scientific literature as well as in conferences and informal discussions. While localizing resolution, which measures how accurately the location of a particular solution can be determined in comparison to the actual source, is an important issue, a concept that has not been as fully addressed is that of imaging resolution, which provides a measure of the ‘‘spread’’ of the solution space due to such effects as volume conduction. The imaging resolution is related to both the distinguishability of two different sources and the ability to image distributed sources. Most authors involved in this debate usually address the problem of localizing one or several dipole sources.[3,6,7,11,24–27,34,40,42,43,49] These studies have utilized computer models,[6,25,26,34,43] phantom models,[11,49] somatosensory mapping,[3,27] comparison with structural imaging,[40] and source implantation in the functioning human brain.[7] Nearly all of these studies have determined that the spatial localizing resolution of the MEG is superior to that of the EEG as long as the sources are not too deep and they are not radially oriented with respect to the skull surface (the MEG is insensitive to radial sources). Because of the limitations of MEG, particularly its insensitivity to deep and/or radial sources, most of these authors have found that a combination of both the MEG and EEG results in higher spatial resolution than either technique alone. However, this claim has been disputed, and discussion of some of these specific controversies is warranted.

Particularly controversial were the results of Cohen *et al.*,[7] who claimed that the EEG and MEG exhibited similar spatial resolution in a study utilizing dipole sources implanted in the functioning human brain. However, that study has been widely criticized on methodological grounds,[12,13,46] and thus, the results are called into question.

The study by Pascual-Marqui and Biscay-Lirio[34] has also recently generated some controversy as they claim to have proven that the spatial resolution of the EEG is higher than that of the MEG. In their paper, they examined three measures of spatial resolution using a volume conductor model: a differential quotient that determines how the external fields change in response to changes at the source, a measure of separability of two sources, and the distance between minimum norm inverse solutions and actual source locations. Their results indicate that the EEG provides superior localization resolution for deeper sources and is better able to resolve two deep radial dipoles than the MEG can resolve two deep tangential dipoles. However, their results indicate that for sources which are not too deep (eccentricity$>$0.86), the MEG performs better than the EEG, consistent with previous results. Also, they found that for distinguishing two tangential dipoles, the MEG performed much better than the EEG. They state that tangential dipoles are nonrealistic, but offer no evidence to support that claim. The complex topology of the cortical surface indicates that for some cortical regions, the dipolar source *must* be tangential. In fact, the study by Wood *et al.*[47] showed that evoked somatosensory EEG and MEG could only be explained by a tangential source in the superficial somatosensory cortex. Thus, Pascual-Marqui and Biscay-Lirio’s interpretation of their results is questionable.

Malmivuo and colleagues have introduced a concept, based on lead field theory, that they call the ‘‘half-sensitivity volume’’ (HSV) to compare the relative spatial information in the EEG and MEG.[24] Unlike most other measures of spatial resolution, the HSV concept is probably more closely related to imaging resolution than localizing resolution because it measures the relative spatial sensitivity of the MEG or the EEG, and thus, it may have potential utility for delineating differences between the EEG and MEG. In their study, Malmivuo *et al.* calculate the HSVs of two- and three-lead EEGs compared with axial or planar gradiometers measuring MEGs. They find that EEG half-sensitivity volumes are typically smaller than axial or planar gradiometer MEG HSVs. Since they find the sensitivity distribution of planar gradiometers to be quite similar to that of dipolar EEG leads, they conclude that the MEG and EEG record the activity of the brain in similar ways. What their study does not account for, however, is the fact that most biomagnetometer systems record the activity of the brain from multiple gradiometer leads, often combined through a nonlinear inverse algorithm for which lead field analysis may be inapplicable since it is based on the principle of reciprocity which assumes linearity. The HSV approach might be correct if MEG measurements were taken from single-lead gradiometric magnetometers and interpreted without an inverse algorithm, but MEG systems today routinely provide whole-head coverage and sophisticated algorithms to measure global brain activity. Thus, the HSVs for multichannel MEGs and EEGs must be presented and the effect of inverse algorithms on the HSV must be examined before this approach can be adequately evaluated.

Advanced EEG Methods

The prevailing opinion then, is that because of volume conduction factors, the MEG is able to provide higher spatial resolution than the EEG for tangential dipoles that are not too deep. This debate has led the EEG community to create some very insightful and innovative methods to improve the quality of noisy, spatially smeared electric potentials produced by cortical current sources.

Hjorth[18] was among the first to apply subtraction of signals from adjacent EEG electrodes to obtain an estimate of the surface Laplacian. He notes that the Laplacian operation provides a measure of source activity as it would appear at the scalp surface. Subsequent authors have provided improvements to the technique that further enhance spatial resolution. Perrin *et al.*[36] calculated the surface Laplacian using a spline interpolation technique applied to surface EEGs and then calculated the surface Laplacian of the resulting interpolated potential. Nunez and colleages[20,21,29] have used a similar approach. Le *et al.*[22] also introduced an interpolation method for determination of the surface Laplacian that may be applied to realistic head models. Babiloni *et al.*[2] developed a method for determination of the surface Laplacian for a realistic model.

In addition to the surface Laplacian techniques, the resolution of the EEG has been improved by methods that simply increase the spatial sampling density and ''de-blur'' the volume conduction effects of the skull. ''High-resolution EEG,'' so named by Nunez and Westdorp,[32] has been shown to sharply increase spatial resolution of scalp EEG.[10] These methods are combined in the ''cortical imaging technique'' of Sidman *et al.*[38] and He[14] and also further improve the spatial resolution of the EEG.

Each of these studies is motivated by the fact that important information is contained in higher spatial frequencies of brain activity. These studies have shown that spatial resolution of the EEG is not necessarily limited to that available in raw recordings of scalp potential. Nunez and Westdorp[32] suggest that these methods may potentially provide several orders of magnitude more spatial information than available from the conventional EEG. There seems to be consensus that increasing the number of recording sites and using realistic conductivity and geometry models further improves the estimate.

There are trade offs in estimating the surface Laplacian from scalp potentials. One of the important features of the EEG is its ability to sense relatively deep sources. Since the surface Laplacian operation is effectively a high-pass spatial filter, as we have shown in this paper, superficial sources will be emphasized over deeper ones. This observation is in agreement with those of Perrin *et al.*[36] and Oostendorp and van Oosterom.[33] On the other hand, it is precisely the high-pass spatial filter nature of the Laplacian that makes it a potentially attractive technique: the ability to improve the spatial resolution of superficial cortical sources.

The crucial issue that determines whether the surface Laplacian can be of any real utility in improving spatial resolution is the nature of the measurement noise. If the surface Laplacian itself can be measured with a SNR that is about the same as the raw EEG, then a significant improvement in the spatial resolution can be expected. Some authors have investigated electrode configurations designed to ''measure'' the surface Laplacian directly in electrocardiology.[17,23,41] The only difference between hardware subtraction and software subtraction to obtain the surface Laplacian is the location of the amplifier. In software subtraction, the raw EEG signal is amplified before the Laplacian is calculated, whereas the hardware method performs the Laplacian subtraction and amplifies the resultant. Since the measurement noise from individual amplifiers or electrodes may be further amplified by the software subtraction, the hardware Laplacian may have a slightly smaller SNR, but the surface Laplacian will still be limited by its response to spatially correlated noise. Data from deMunck *et al.*[8] suggest that signal and noise spectra of the EEG largely overlap, in which case application of the surface Laplacian will not result in substantially higher SNR or increased spatial resolution.

It should be noted, however, that our analysis has employed the nearest-neighbor estimate of the surface Laplacian, and not the spline technique that is gaining in popularity. The spline technique commonly uses noise filters applied before the Laplacian operation. To the extent that these noise filters are able to reduce the measurement noise, they will improve the imaging ability of the surface Laplacian.

Comparisons of the relative utility of the MEG and EEG usually use raw EEG recordings that are not enhanced by any of the techniques discussed above. The issue of imaging resolution in these comparative studies is typically addressed as the ability of a particular modality to correctly localize more than one dipole source. Visualization of the spatial filters, as presented here, allows direct identification of the ''distinctness'' of two sources by use of the Rayleigh or other imaging criteria. Also in this paper and its companion, we utilized the spatial filter construct and the concepts of spatial localizing and imaging resolution to show that cortical source reconstructions from scalp EEG signals had far less spatial resolution than reconstructions from external MEG signals as two cortical sources were undifferentiated by the scalp EEG. However, depending on the amount and nature of the measurement noise, the application of the surface Laplacian may greatly improve the spatial resolution of the EEG. The surface Laplacians of both the EEG and MEG, as well as the raw MEG, easily differentiated the two sources.

As noted, measurement noise is the predominant determining factor in the efficacy of the surface Laplacian. Our results suggest that the Laplacian responds better to correlated brain noise than to uncorrelated measurement noise; linearly correlated noise can be effectively eliminated by the surface Laplacian, whereas nonlinear correlated and uncorrelated noise require additional regularization that results in decreased spatial resolution. Very careful attention must therefore be paid to obtain raw signals with the highest possible signal-to-noise ratio, and to eliminate uncorrelated noise. Clearly, noise is different in magnitude for different EEG applications, and averaged signals or signals bandlimited to narrow frequency bands will contain less noise. When the EEG is measured with high signal-to-noise ratios, the surface Laplacian provides substantial improvement in EEG spatial resolution and moderate improvement in MEG spatial resolution. Under such circumstances, the localizing and imaging resolution of the EEG for shallow tangential sources approach that of the MEG. Because of the intrinsic insensitivity of the MEG to deep radial sources, the EEG will be superior to the MEG for such sources. For distributed sources of complex geometry, the issues of electrically silent sources and the potential independence of electric and magnetic fields should be revisited.[37,44,45]

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