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The Surface Laplacian, High Resolution EEG and Controversies

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Summary: The surface Laplacian estimate (i.e., current source density) as obtained with spline functions is evaluated in the context of some recent controversies concerning high resolution EEG and source localization. In simulation studies, the spline-Laplacian provides much better estimates of cortical surface potential than is obtained from raw scalp potential, provided dense electrode arrays (e.g., 64 or more electrodes) are used. Spline-Laplacians (which are relatively independent of volume conductor model) provide estimates of cortical potential distribution which are quite similar to those obtained with a cortical imaging algorithm based on a four sphere model.

Key words: Spline-Laplacian; Cortical imaging; Source localization; EEG; Spatial resolution.

In a recent letter published in Vision Research, van Dijk and Spekreijse (1992) question applications and physical interpretations of EEG surface Laplacian estimates. In this correspondence, corrections to these arguments are suggested and the surface Laplacian approach is evaluated in the context of High Resolution EEG. The term "High Resolution EEG" refers to several approaches by which the spatial resolution of scalp recorded data is dramatically improved over conventional EEG. Such methods involve a combination of high electrode density (e.g., 64 or more electrodes) and computer algorithms which "know" some important features of head volume conduction. These algorithms provide predictions of cortical surface potential distributions which may be far more accurate than those obtained from raw potential maps.

In order to fully appreciate the motivation to obtain High Resolution EEG, a review of the severe limitations of conventional EEG is appropriate. The spatial resolution available with conventional EEG is limited by: 1. Spatial sampling; 2. Reference electrode distortion; 3. "Smearing" of cortical potentials by CSF, skull and separation of sensors from sources; 4. Failure to exploit information about the physics of volume conduction. This issue overlaps #3, but includes additional effects.

Consider, for example, the following idea, which has often been part of EEG folklore (sometimes made explicit, but more often implicit in conclusions drawn from the data):

If a "quite reference" is used, scalp potential is mainly due to sources under the "recording electrode".

The accuracy of this idea is illustrated in figure 1. In these simulations, 4200 dipole sources (i.e., sources at the macrocolumn scale) are assumed to be located at cortical gyri, as shown in the upper row. A three-concentric spheres model (brain, skull, and scalp) of the head (Rush and Driscoll 1969; Nunez 1981; Fender 1987) is used to calculate resulting potentials at each of 660 scalp surface locations. These analytic solutions are plotted without interpolation (lower row).

In both simulations of figure 1, a right ear reference is assumed. The region adjacent to the right ear in each source plot indicates that no sources are located within about 5 cm of the ear (e.g., a "quiet" reference). The source distribution on the left consists of three major clumps of sources indicated by the + and - signs, within a background of random positive and negative sources (blank spaces denote negative sources at every location except the ear region). These three major source clumps are unchanged in the simulation at the right; however, background sources in the right side plot also form clumps. Comparison of the two potential plots shows that the potential over part of the positive clump switches from positive to negative and the potential over the two negative clumps switches from negative to positive even

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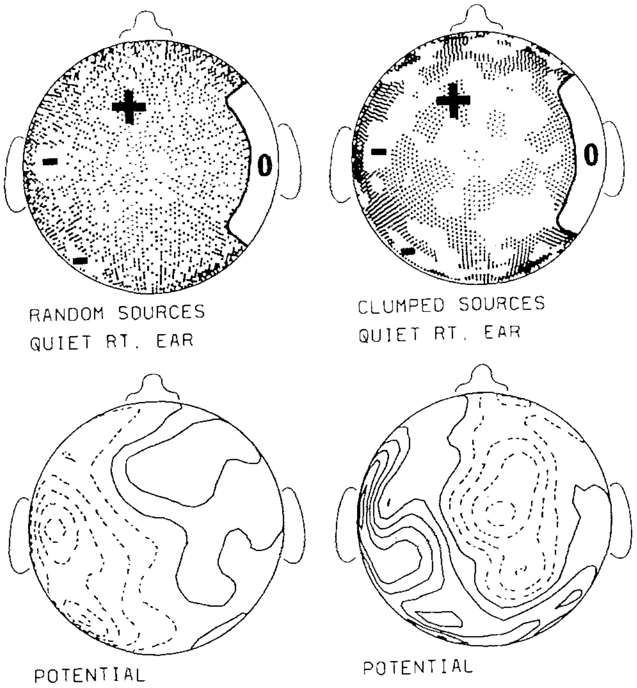

Figure 1. Simulations with 4200 radial dipole sources at the macrocolumn scale. Dots indicated positive source magnitudes. Empty spaces are negative magnitudes except near the right ear (region labeled 0) where no sources occur. The three clumped regions denoted by plus and minus signs do not change. However, background sources change from random to clumped (upper right). The corresponding scalp potential maps (analytic potential with respect to right ear reference) are calculated using a three-concentric spheres model of the head. The potential over part of the positive clump changes from positive to negative, and the potential over the two negative clumps changes from negative to positive when background sources change from random (left) to clumped (right). Maps based on average reference or potential with respect to infinity are similar to this example. None of these potential maps is able to pick out source clumps of moderate scale even though spatial sampling is very high (660 points).

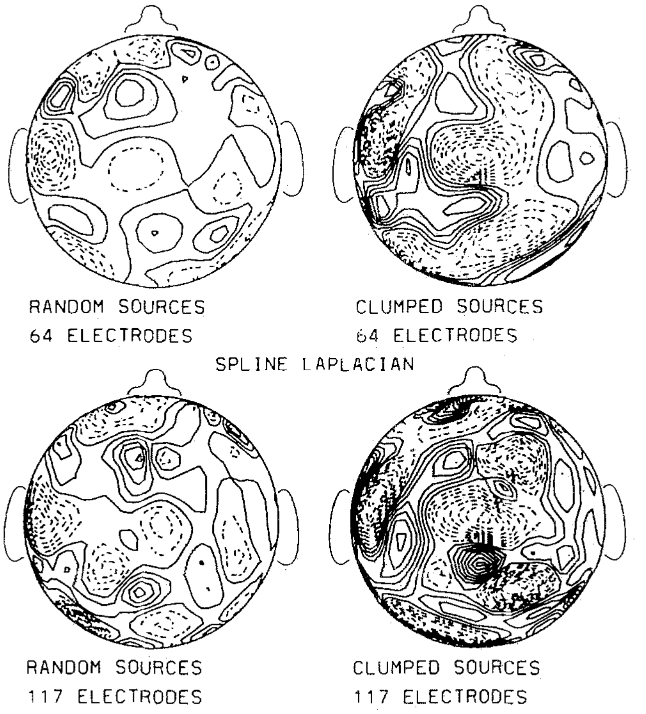

Figure 2. Surface spline-Laplacian estimates for the two simulated source distributions shown in figure 1. Analytic surface potential is sampled at either 64 (upper row) or 117 (lower row) locations on the outer sphere ("scalp"). In the simulations at left, the Laplacian picks out the three major source clumps from the random background as well as several other regions which have significant excesses of either positive or negative sources. In the simulations at right, the Laplacian pattern matches all major source clumps.

though the three underlying source clumps are unchanged. These simulations illustrate limitations of conventional EEG due to the non-local character of scalp potentials, even when no sources are located close to the reference electrode.

Further illustration of the non-local character of scalp potentials is provided by additional simulations which show that even with a very large number of spatial samples (660), the surface potential (with respect to infinity) map does not reveal patterns of cortical source activity at moderate scales (Nunez et al. 1991). This inaccuracy occurs even with no reference electrode distortions. By contrast, the surface Laplacian (independent of reference) converges to the pattern of cortical sources at scales greater than about 1-3 cm in these simulations as the number of electrodes is increased above about 50. In order to illustrate this point, spline-Laplacian estimates for the distributed cortical sources of figure 1 are shown in figure 2 as obtained with 64 samples (upper row) and 117 samples (lower row). By contrast to the potential map, the scalp spline-Laplacian map provides a reasonably accurate estimate of cortical potential pattern. Also, the addition of 20% random (i.e., spatially uncorrelated) noise to 64 or 117 sample potentials or setting one of the potentials to zero (simulating a "bad" electrode contact) have almost no effect on the Laplacian estimate obtained with a 3-dimensional spline function. Finally, simulated artifact generated outside the electrode array (e.g., eye movements) causes much less contamination of the surface Laplacian than the raw potential map. Similar simulations involving tangential dipoles (e.g., in fissures and sulci) also indicate that the surface Laplacian is a much more accurate indication of cortical potential than is raw scalp potential (Nunez et al. 1993).

The physical basis for the surface Laplacian estimate is illustrated by the following large scale approximation (Nunez 1981; Katznelson 1981):

$$V_B \sim V_S + A_{KS} L_S \tag{1}$$

Here V_B and V_S are potentials at the inner and outer surfaces of the skull, respectively. The parameter A_{KS} depends on skull (ρ_K) and scalp (ρ_S) resistivities, and skull (d_K) and scalp (d_S) thicknesses. In the simple, but probably unrealistic case of a homogeneous skull $A_{KS} = (\rho_K/\rho_S)d_K d_S$. By convention, we define L_S to be the negative Laplacian (typically measured in $\mu V/cm^2$) which matches local positive skull current and positive cortical potential. The validity of equation (1) is partly dependent upon Ohm's law in the skull and the fact that skull resistivity is much larger than that of the brain (assumed here to roughly equal scalp resistivity). The latter condition assures that skull current is mostly perpendicular to its surface. It should be emphasized that equation (1) is independent of the nature and location of sources or assumptions about the head volume conductor, except to the extent that these variables influence the direction of skull current. The relationship (1) is mathematically crude; it is most accurate at the large scales appropriate for scalp recordings, i.e., when the variables V_B, V_S and L_S are space-averaged over about $1cm^2$ or more. However, its apparent robust nature and relative independence of assumptions about sources or volume conductor provides the primary motivation for its application to EEG.

Since simulations predict that potentials vary relatively slowly through scalp thickness (Nunez et al. 1993), measured scalp potentials approximate V_S. The closeness of inner skull surface potential V_B to cortical potential V_C dependents on CSF thickness, dipole orientation, and other factors. For example, the difference between V_C and V_B may be expected to be larger for tangential dipoles than radial dipoles due to enhanced tangential CSF current generated by tangential dipoles.

Thus, if one records scalp potential ($\sim V_S$) and estimates scalp Laplacian (L_S), cortical potential ($\sim V_B$) may be crudely estimated from (1), provided the resistivity ratio ρ_K/ρ_S, scalp, and skull thickness are known. However, this step is evidently not necessary in most applications. One reason is that the ratio of scalp to cortical potential is typically at least 2 to 4 in the case of widely distributed cortical sources and even larger for localized cortical sources (Nunez 1981, 1990). These data which have been established in EEG for several decades (refer, for example, to Penfield and Jasper 1954) imply that the second term on the right side of (1) is often much larger than the first, i.e., cortical potential is roughly proportional to scalp Laplacian. Furthermore, the estimate of relative cortical potential magnitudes obtained from the 2nd term in equation (1) is independent of head model, except that variations in resistivities or thicknesses over the surface, will, of course, cause some distortion of the cortical potential estimate.

We have suggested that the surface Laplacian provides an estimate of cortical surface potential which is relatively crude, but nevertheless is generally a much more accurate representation of cortical potential than raw scalp potential. Our surface Laplacian methods are similar to those originally applied to EEG by the French group (Perrin et al. 1987). We have used several hundred simulations involving 4200 distributed cortical sources (in 3 or 4 sphere models) to predict correlation coefficients between calculated cortical and scalp potentials that are typically in the 0.4 to 0.5 range. By contrast, these same simulations predict correlation coefficients between cortical potential and scalp Laplacian in the 0.8 to 0.9 range. Furthermore, the Laplacian estimates are independent of both head model (other than the assumption of a spherical scalp surface) and reference electrode. Recently, a surface Laplacian algorithm has been derived for general ellipsoidal surfaces, which provide more accurate representations of actual head shapes (Law and Nunez 1991; Law et al. 1993).

A legitimate question is whether this mixture of theoretical arguments and simulation studies holds up in actual EEG practice. In order to study this question, our surface Laplacian estimates have recently been compared to cortical images estimated with a sophisticated algorithm developed at the Swinburne Centre for Applied Neurosciences in Melbourne, Australia (Nunez et al. 1993). Both our Laplacian algorithm and the Australian cortical imaging algorithm use spline functions so that all estimates are "global", i.e., estimates of Laplacian or cortical potential at each location depend on the potentials recorded at all electrodes, rather than only nearest-neighbor electrodes as, for example, in the case of the five-electrode Laplacian (Hjorth 1975). Our methods involve interpolation in three-dimensional space, whereas the Australian interpolation is on a sphere. Our methods are independent of head model, except for the original choice of spline and the assumption of a spherical scalp surface. The Australian methods use a four-concentric spheres model. Even though these two approaches have quite different theoretical bases, the resulting predictions of cortical potential are quite similar when applied to either alpha rhythm or steady-state visual evoked potentials (recorded with 64 electrodes). That is, correlation coefficients between estimated cortical images and Laplacian patterns typically vary between 0.8 and 0.95 (Nunez et al. 1993). In the case of EEG data, we do not know actual cortical potential. However, correlation coefficients between either spline Laplacian or estimated cortical image and raw scalp potential for these data are typically in the 0.3 to 0.5 range, consistent with results obtained with simulated data.

Comparison of the spline-based surface Laplacian with cortical imaging methods involves several considerations. One is the sensitivity of the cortical imaging method to noise and/or head model errors. The Australian group approaches this problem by incorporating a smoothing algorithm such that large smoothing provides cortical potential estimates which are close to raw scalp potential. By contrast, minimal smoothing provides cortical potential estimates which are similar to the Laplacian. In theory, one can accept just the right amount of spatial detail in the cortical potential estimate, consistent with noise level and uncertainty in the head model.

The Australian algorithm works very well in simulations involving 3 or 4 concentric spheres with either isolated or distributed sources. However, its accuracy in real heads is more difficult to access, other than in terms of its consistency with the Laplacian. Recently, a new finite element-based cortical imaging algorithm has been developed (Le and Gevins 1993), which agrees well with cortical potential measurements when sources are relatively isolated. However, finite element-based algorithms can be expected to provide improvement over concentric spheres models only if both the geometric and electric properties of tissue are fairly well-known. Whereas accurate geometric information can be obtained from CT and MRI, estimates of electrical properties are more difficult to obtain. A few estimates of skull resistivity in living subjects have been obtained by passing current through scalp electrodes (Rush and Driscoll 1969), and suggestions for using known sources to estimate skull resistivity have been advanced (Nunez 1987); however, the accuracy of these methods has not yet been established.

Cortical imaging methods hold significant promise for future advancement. The two cortical imaging methods cited here provide accuracies which do not appear to be dramatically different from that obtained with our spline-Laplacian. All three of these methods are, however, generally much more accurate than raw scalp potential, local (e.g., Hjorth) Laplacians, or early cortical imaging algorithms. For current usage, the primary advantages of the Laplacian are its independence of both reference electrode and head model. (The reference introduces no fundamental limitations on cortical imaging; however, head models which are accurate near the reference electrode may be required. This may present practical problems in certain cases, e.g., that of a mastoid or ear reference.) Thus, one can view the spline-Laplacian first as an excellent interim approach to be employed in many applications, at least until such time that cortical imaging proves to be more accurate in obtaining High Resolution EEG. Even if more accurate cortical imaging methods are developed, the spline-Laplacian is likely to remain an important tool in all EEG applications for which methods required to obtain more accurate head models (e.g., MRI, CT) are not practical, as is likely to be the case in many clinical or research settings.

The relationship of High Resolution EEG (as defined here) to dipole localization algorithms deserves a short discussion. Whereas High Resolution EEG may depend to varying degrees on the accuracy of the head model (depending on specific approach), it is independent of assumptions about sources. That is, estimates of cortical potential distribution are made form scalp potential measurements, and possible estimates of source distribution comprise a separate (and perhaps much less accurate) step in the data analysis procedure. By contrast, dipole localization algorithms depend on both the accuracy of head model and on the assumption of a single or small number of isolated sources. Thus, they are limited to those few EEG phenomena for which such assumptions are relatively accurate.

What are the most promising applications of High Resolution EEG, i.e., the surface spline-Laplacian and/or cortical imaging? It is difficult to provide a general answer to this question since the most sophisticated and accurate methods have been adopted by only a few groups. However, it is estimated that the amount of new, useful information potentially available from EEG involving distributed neocortical sources is increased by at least several orders of magnitude over that obtained with conventional EEG by making the high spatial frequency information shown in the Laplacian plot of figure 2 available for study. It has been argued that methods like the Laplacian or cortical imaging really provide no new information since they are simply transformations of raw potential data. A similar argument would be that MRI images do not contain any more information than the numerical output stored in the MRI computer. However, MRI images contain far more useful information for the clinician since the numbers have been combined in a manner consistent with their physical basis to create images. Similarly, High Resolution EEG algorithms contain information about head volume conduction (e.g., current conservation, Ohm's law) so that raw potential measurements may be suitably combined to obtain estimates of cortical potential distribution. The question of how to make the best use of this vast amount of useful new information remains mostly unanswered; however, several applications come to mind:

1. Studies of intra and interhemsipheric coherency

during cognitive task performance. Coherency is a correlation coefficient expressed as a function of frequency which can change dramatically between physiologic states. It has been shown that the simple five-electrode Laplacian (Hjorth 1975) partly eliminates the problem of erroneous high coherence estimates (due to volume conduction) that occur with conventional EEG methods (Nunez and Pilgreen 1991). As a result, measured coherency changes between different brain states are much larger and robust. However, it must be remembered that Laplacian estimates tend to remove long range coherencies between signals, some of which may be generated by the brain itself (i.e., not due to volume conduction).

2. The use of steady-state visual evoked potentials in cognitive studies (Silberstein et al. 1990). The use of continuous stimuli during both task and non-task conditions allows for the study of spatial patterns in narrow frequency bands (e.g., 0.005 Hz). Spatial structures (with detail revealed by High Resolution EEG) are created in these narrow bands which are insensitive to moderate artifact and are stable during fixed cognitive tasks. With this paradigm, some of the most severe problems that have plagued traditional studies of cognition are eliminated.

3. Localization of epileptic foci. We have shown that the scalp surface Laplacian is especially sensitive to superficial sources. It might at first appear that the Laplacian is not appropriate for epilepsies dominated by deep sources, e.g., in mesial cortex. However, the presence of distributed superficial cortical sources is likely to confound any efforts to locate deep sources. For example, a major problem with existing dipole localization algorithms is that widespread superficial cortical sources are likely to be interpreted by the algorithm as localized deep sources (Nunez 1990). If the Laplacian can be used to identify cortical sources, these sources can perhaps be applied as constraints on dipole localization algorithms, thereby making more accurate localization of deep sources much more likely.

In summary, further development of model-sensitive methods like cortical imaging and dipole localization should be encouraged. However, there is no need to delay implementation of the spline-Laplacian approach to High Resolution EEG. This approach is now available and works very well in a number of applications. Unfortunately, the recent letter by van Dijk and Spekreijse (1992) contains several misleading statements which have apparently lead some researchers astray. For example, that letter contains simulations which show that the 2-dimensional Laplacian is not proportional to current density at any particular depth in the scalp. While this is correct, it misses the point. We have shown that the scalp surface Laplacian (averaged over about 1 cm2 or more) provides a relatively good approximation of local, perpendicular skull current (averaged over the same area). Because of this, it generally provides a much better picture of cortical potential than does the raw potential. Another erroneous statement in the letter by van Dijk and Spekreijse is "The 2-dim Laplacian field is not suitable to localize sources....". This is correct for deep sources, but not correct for cortical sources. Scalp surface Laplacians due to deep sources are very small, typically below noise levels. For this reason, the Laplacian is evidently able to "pick out" cortical sources from deep sources.

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