Topographical Mapping of Brain Electrical Activity

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Abstract

An interdisciplinary approach is applied toward the development of methods to improve spatial resolution of brain electrical activity. Methods to interpolate the potential distribution and to estimate the surface Laplacian from multi-channel data are presented and applied to human evoked potential data. Although developed for electroencephalographic (EEG) data, these spline algorithms can be applied to a variety of fields where visualization of spatial information is desired.

1 Overview

The recording and use of electroencephalograms (EEG) to visualize what "the brain is doing" has been practiced since 1928 when Hans Berger first attached two electrodes to a scalp surface and recorded the first EEG on a cathode ray tube. The evolution of EEG technology has since improved substantially, including multi-channel recording, but the basic use of the EEG systems remains the same: to record changes in potential between various locations on the scalp surface.

As the "decade of the brain" begins, many neuroscientists have turned to other methods to visualize brain function. While recognizing the vital role EEG plays in clinical diagnoses, it must be emphasized that the output of multi-page raw waveforms is rather difficult to interpret, especially for someone without long experience in EEG (example, Figure 1). Without additional training, the use of EEGs is limited to a small-user group of neurologists, psychiatrists, and psychologists. New technology such as CAT, PET, and MRI, while expensive, may yield more digestible output. These methods have contributed significantly to our understanding of the structure and dynamics of the brain over long time scales [1]. However, the above methods are still collateral to the task of viewing electrical activity; that is, they examine the structure and support processes of electrical activity, not the activity itself. Such electrical activity undergoes important changes on time scales measured in the tens of milliseconds [2,3]. The main advantage of EEG is its ability to follow such changes. Thus, EEG techniques are required to study the dynamic activity of the brain.

The shortcomings of EEG lie not so much in the lack of information obtained in raw recordings, but in how this information is represented and interpreted. A trained neurologist can sometimes detect subtle changes in brain activity by reviewing reams of EEG traces. He may often be able to diagnose abnormalities and guess their origin. However, even the highly trained neurologist finds it difficult to describe how the activity in the various regions work together and function. Using present methods alone, it is difficult to visualize the underlying activity, the dynamic process of thought and control. Thus, new methods to visualize the spatial-temporal electrical activity of the brain are needed.

One technique is to combine multi-channel EEGs in the form of topographical maps (example, Figure 2) [1,4,5]. The spatial nature of brain activity is then more clearly represented. Additionally, it is possible to study how electrical activity evolves and changes over time in a manner that is clear to even the casual observer.
This paper reviews current topographical mapping methods, problems associated with mapping, and details one method to improve spatial resolution of scalp recorded EEGs. Human data are used to illustrate these methods.

2 Issues involved in generating topographic maps

The issues associated with generating topographical maps of EEGs are much akin to issues in other fields which use spatial information to understand natural phenomena. These include areas such as meteorology, cartography and digital remote sensing. Three primary concerns are: 1) accuracy of surface potential distribution based on a finite number of spatial samples; 2) distortion of source signals between source and surface sensor locations due to both inhomogeneity of the medium and separation distance; and 3) accurate geometric representation of the surface.

Topographical mapping of EEGs requires knowledge of the potential distribution over the scalp surface. Ideally, one wishes to know the function over the entire surface. However, the procedure of recording EEGs is limited by the number of data channels. Estimation of the EEG potential distribution has been accomplished for a maximum of 124 discrete locations on the scalp surface [6]. But, in practice, due to time constraints on patient care and equipment limitations, standard protocols normally involve limiting the number of scalp electrodes to between 16 and 32 [7]. The total area of the part of the human head which covers the brain is about 500 cm². Thus, the first problem is how to estimate the potential function over the scalp surface using discrete measurements obtained with a fixed number of recording locations.

Various interpolation techniques can be utilized. These are grouped as follows: approximation algorithms, splines, and finite element or finite difference methods [8]. The suitability of estimation method depends on how well the interpolation techniques fit measured values to the actual function. A priori knowledge about how signals pass from the brain to scalp improves the ability to choose an optimal estimation method. "Optimization" is defined here in the practical sense; namely, the selection of a method that accounts for realistic signal passage through tissue.

While geometric and transmission properties of the head (the brain and its convoluted cerebrum, the cerebral spinal fluid, and the scalp) are not fully understood, it is possible to limit the appropriate volume conduction parameters to realistic ranges and make reasonable assumptions. First, the potential function on the scalp must be continuous. Though generators (cortical cells or, more realistically, cortical columns containing overlapping cells) are discrete, the transmission properties of the head "smear" (i.e., space average) the signal to create smooth, continuous functions. Second, the frequency spectrum of the potential function is composed of low frequencies, less than five kiloHertz in all applications, but often less than 20 Hz. Additionally, it is assumed that the skull and the underlying layer of cerebrospinal fluid is of near uniform thickness such that variations do not significantly alter spatially uniform transmission of cortical signals [3].

Based upon the above considerations, it is possible to choose the best method for estimating the potential function on the scalp surface. Simple approximation techniques can be used, but may require many polynomial terms and excessive computation time. More importantly, the inherent smoothness of scalp EEG is not taken into account by these methods, thereby often resulting in physically unrealistic fits. The finite-element or finite-difference models may eventually provide accurate models to estimate scalp potential functions, but current knowledge of the geometric and electrical properties of the head severely limits their application.

The spline is, for the present, the most reasonable choice of the three estimation techniques mentioned above. Spline algorithms approximate the actual function by fitting both the measured value and its derivatives to the estimated function. Because more parameters are used to achieve convergence, fewer terms are required and convergence criteria are simplified. The spline retains much of the advantages of simple approximation techniques while making use of prior knowledge of the scalp recorded EEG as in the case of finite-element or finite-difference techniques.

Another problem is due to volume conduction effects on the source signals, causing distortion of corresponding scalp potentials. Scalp potentials depend on: 1) the nature and location of the underlying current sources; and 2) the conductive and geometric properties of the head [3]. Present
techniques use only scalp potentials with minimal signal preparation. Signal processing consists primarily of limiting the bandwidth of the frequency spectrum, checking for impedance match among the electrodes, and editing for obvious artifacts [3,7].

Present methods of generating topographical maps use scalp recorded potential-based information which may or may not accurately represent underlying brain activity; that is, the potential values at specific locations may not necessarily represent underlying cortical activity.

First, one must contend with the effects of transmission through tissue, fluid, and bone. Signals are invariably altered and distorted as they are conducted through the skull and scalp. The skull has a high resistivity and serves to filter out much of the high spatial frequency activity. The "built-in" low pass spatial filter results in a smeared signal when recorded on the scalp [12].

Second, all scalp EEG recording is performed by bipolar recording methods; that is, by recording the potential between what is sometimes called the "sensing electrode" and the "reference electrode." However, this terminology obscures the fact that sources are typically distributed over the whole brain and currents are, in any case, spread out by volume conduction. Thus, measured potentials always depend on the location of both electrodes.

Additionally, brain signals must "compete" with other bioelectric signals which are of the same or larger magnitude. The reference electrode is usually located at a "quiet" spot such as the tip of the nose or the upper forehead. However, due to volume conduction, the reference potential is never constant (with respect to infinity) and can fluctuate due to muscle activity, brain activity, movement of the patient, etc. [3,7].

Present methods do not adequately separate sources from volume conductive properties. Since volume conductive properties in the head are not known accurately and recording methods are limited, it is a non-trivial matter to separate information about the sources from volume conduction effects. Thus, methods that separate the former from the latter are of considerable interest in all EEG applications.

The surface Laplacian can be defined from several different perspectives. In mathematical terms, it is the second spatial derivative of the potential map in the two surface tangent coordinates. In physical terms, the surface Laplacian is the an estimate of local radial current through the skull to the scalp [3]. Thus, the surface Laplacian can be expected to be superior to ad hoc mathematical transformations in that it is based on physical principles, e.g., current conservation is observed.

The surface Laplacian is relatively independent of the volume conductive properties of the head. Because it is a spatial derivative, the contributions to signal characteristics due volume conduction are spatially filtered. The underlying potential offset due to the choice of reference electrode is removed as is much of the "global" contribution from distant cortical sources and deep (non-cortical) sources. In essence, the surface Laplacian removes "smearing" that results as the potential passes through the skull. That is, the surface Laplacian removes global effects and enhances local surface activity [3,9,10,11].

It should be noted that the surface Laplacian is not a new method. In the 1950's, the surface Laplacian method was a topic discussed with interest, but the method was bypassed partly because, at the time, equipment limitations made such estimates more difficult, and, in any case, few EEGers understood its significance [12]. More flexible (mostly computational) techniques were developed with the advent of microprocessors and faster computers.

Research by the Tulane Brain Physics Group and other groups has shown the surface Laplacian to be a better estimator of local activity than present potential topographical mapping techniques. Perrin, Bertrand and Pernier [10,11,13] have developed methods to obtain spline generated surface Laplacians for a spherical head model. Others have used the spline-generated surface Laplacian to study the spike-to-spike variability of interictal epileptic spikes and a variety of evoked potential tests [2,14].

Another concern in obtaining a better measure of brain source activity involves accurately representing the upper surface of the human head. A similar problem is encountered in geocartography due to projection of a three dimensional object onto a two-dimensional representation; the human head is more irregular.
Planar and spherical geometries have been used as the surfaces for estimation algorithms. However, the ellipsoid provides the best fit of all simple geometries (Table 1, Figure 3) [15]. Recent studies modeling head trauma in biomechanics have used the prolate spheroid and ellipsoid to achieve a better fit of actual data to theoretical calculations. Furthermore, the Laplacian operator in ellipsoidal coordinates is known [16]. Thus, in order to achieve greater accuracy, algorithms to fit the best fit ellipsoid to the human head and to estimate the surface Laplacian for an ellipsoid have been developed and employed in generating topographical maps of brain activity [17].

3 Spline generated surface Laplacian topographic maps

Spline algorithms are used to estimate the surface potential distribution. A three-dimensional natural cubic spline, passed on earlier studies [10], was chosen as the best apparent choice of spline. In the following, we provide two examples of how these methods are used. Algorithms to estimate the surface Laplacian on a spherical surface are employed here and presented in this paper. An algorithm to estimate the surface Laplacian on an ellipsoid has been developed and is currently undergoing validation.

Two kinds of scalp recorded potentials, the somatosensory evoked potential and the auditory event-related (cognitive) response were chosen to test the methods. The somatosensory evoked potential (elicited by electrical stimulation to a specific peripheral nerve), provides well understood and apparently localized current sources. The event-related response (a cognitive response elicited by asking the subject to perform a specific task, e.g., counting oddball, high tones among series of consistent, low tones) provides much less understood phenomena with more diffuse source locations. Our tests showed that spatial characteristics obtained with the spline Laplacian to be reproducible in both kinds of studies.

Scalp potentials were recorded from 32 electrode locations over the upper surface of the human head. A Nicolet Pathfinder I Electrodiagnostic system was used to record and store data. Signals were filtered over the standard ranges for each evoked potential, and artifacts were eliminated from the averaged waveforms.

Locations on the surface of the head were digitized by a Polhemus Iso-Trak Digitizer to obtain surface locations at a minimum of 60 points. These points were then fitted to the best fit surface by nonlinear regression techniques. The scalp recorded data and regressed electrode locations were combined, and spline-generated surface Laplacian estimation algorithms were employed to produce topographical maps of brain activity. Traces of the potential wave form are shown with the potential and surface Laplacian topographical maps (Figures 4 and 5). The method provides significant information in an unambiguous presentation. Several observations can be made.

First, the topographical maps (Figures 4-b,c and 5-b,c) are much more readily digestible than the temporal waveforms (Figures 4-a and 5-a). The topographical maps provide information about amplitude and spatial location directly without need for "Gestalt" processes by the investigator.

Second, the Laplacian maps (Figures 4-c and 5-c) show greater resolution and specificity than the potential-based topographical maps (Figures 4-b and 5-b). Additionally, the auditory event-related potential (Figure 5) more closely agrees with the usual ideas of where much of the cognitive response occurs in the brain, i.e., in the prefrontal cortex. The location of generators of the P300, a cognitive evoked response that occurs around 300 milliseconds after presentation of stimuli, is an issue which has been argued for several decades [18]. The potential peak occurring over the vertex of the head (Figure 5-b) has no special anatomical correlate. The location of this peak is believed to be due to volume conduction and the choice of reference electrode(ears). The Laplacian map in Figure 5-c shows greater resolution of activity and presents various regions of cortical activity. While conclusions about the location of P300 generation will require studies of many more subjects, surface Laplacian maps are likely to be a useful tool for the neuroscientist in future P300 studies as well as many other studies of brain dynamics.

4 Significance and future application

New methods to improve spatial resolution of topographic EEGs are vital to the continuing progress of non-invasive (scalp) cortical electrodiagnosis. Present methods are diverse and may not necessarily have valid physical foundation [3].
The surface Laplacian provides a mathematically and physically sound estimate of brain electrical activity. The methods developed here can be easily implemented in most systems, including PC based systems which are readily available to the ordinary clinician. Currently, these methods use a variety of systems which include an IBM 3081 KX mainframe, a microVAX, VAX workstation, and an IBM-PC. The Brain Physics Group plans to implement these methods on one workstation. Additionally, the surface Laplacian approach will be applied to a variety of clinical issues such as localization of epileptic spikes, cognition studies, and a variety of spontaneous and stationary evoked potential studies. It is anticipated that the EEG community eventually will accept and regularly use the surface Laplacian as a standard tool in electroencephalography. The reader is referred to several review articles for additional applications [14, 19, 20].

5 Conclusion

Topographical mapping of brain electrical activity presents temporal and spatial information from EEGs in a direct and clear manner. The process of generating a topographical map that provides a good estimate of brain activity draws from a variety of disciplines. In addition, the methods, principles, and strategies presented here can be applied to other areas where spatial and temporal information requires visualization.

In the case of electroencephalography, the spline-generated surface Laplacian estimate is apparently the best method for the purposes of improving spatial resolution based on known and assumed knowledge of neural sources and volume conductive properties of the head. An ellipsoidal surface and ellipsoidal Laplacian operator should be employed to retain geometric integrity of the resultant topographical maps.

References


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* RMS errors and maximum residuals are defined in terms of the distances between fitted surfaces and the actual head, measured along the radius vector from the origin (best fit center) to each digitized head location.
Figure 1. Event-related brain potentials. Time series plots, 15 of 31 recorded channels shown. 10–20 system montage shown on right.

Figure 2. Event-related brain surface Laplacian maps. Map at 0, 100, 200, and 300 msec of data shown in Figure 1.

Figure 3. Digitized head geometry with best fit sphere and ellipsoid. Digitized head: solid lines. Best fit geometry: dashed lines.

Figure 4. Time records for 7 of 32 recorded channels, Median Somatosensory Evoked Potentials and Laplacians.
Figure 4b and 4c. Topographical maps, Somatosensory Evoked Potentials (4b) and Laplacians (4c).

Figure 5a. Time records for 5 of 31 recorded channels, Auditory Evoked Response Potentials and Laplacians.

Figure 5b and 5c: Topographical maps, Auditory Evoked Response Potentials (5b) and Laplacians (5c).