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Scalp Thickness Adjustment of Laplacian Estimates of Cortical Potential

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Abstract. Prior methods to adjust surface Laplacian estimates of radially-oriented cortical activity from electroencephalography (EEG) using scalp thickness utilize concentric spheres models to determine the relationship between scalp potential and cortical potential. A novel method using a nonlinear function of scalp thickness is developed and compared to prior linear approximations using a boundary element model (BEM) of the head.

Keywords: EEG; Surface Laplacian; Source Localization; Introduction

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EEG measures the potential on scalp surface generated by current sources in the head. Our knowledge of the location and dynamics of the brain current sources that generate scalp potentials is limited by the blurring effect of volume conduction of current through the head to scalp. The dominant factor in head volume conduction models is the poor conductivity of the skull layer compared to the brain, cerebrospinal fluid (CSF) or scalp. Due to the skull's low conductivity, current flowing through the upper surface of the head (away from holes such as the eye sockets) moves radially through the skull into the scalp, which is observed in both concentric spheres and realistically shaped layered models of the head [Nunez and Srinivasan, 2006].

The surface Laplacian of scalp potential (or second spatial derivative in two surface coordinates) is an estimate of current density entering (or exiting) the scalp through the skull [Nunez, 1981; Nunez and Srinivasan, 2006]. Here we use the term surface Laplacian to denote the application of the Laplace-Beltrami operator to the potential distribution along the scalp surface. The surface Laplacian method requires only that the outer surface shape of the volume conductor be specified and does not require any details about volume conduction except for a poorly conducting skull. In simulations using spherical models, it has been demonstrated that the surface Laplacian closely approximates the potential at the boundary between the brain and skull [Nunez et al., 1991; Nunez & Westdorp, 1994; Srinivasan et al., 1996], providing spatial resolution on order of 1-2 cm, which is comparably to direct recording on the cortical surface such as in Electrocorticograms (ECoG) in epilepsy patients [Menon et al., 1996; Nunez and Srinivasan, 2006]. In applications to EEG data, the surface Laplacian is consistent with model based estimates of cortical surface potential, such as deblurring or cortical imaging algorithms [Nunez & Westdorp, 1994; Nunez et al., 1997]

Radial current density in the skull that enters or exits the scalp under an electrode is approximately proportional to the surface Laplacian of the potential at the electrode [Nunez 1981; Nunez and Srinivasan, 2006]. The physical basis for relating the scalp surface Laplacian to the cortical (skull/scalp) surface potential is based on Ohm's Law and the assumptions that the skull is very thin and most current flows in the radial direction through the skull into the scalp. Babiloni et al. [1997] cite this earlier work by Nunez [1981], which was based on spherical volume conduction models, using scalp thickness to refine surface Laplacian estimates of cortical activity. A similar relationship was derived by Kramer and Szeri [2004] taking into account skull and scalp radii and conductivities:

$$\varphi_{cortex} \mu \varphi_{scalp} + A_{KS} \times SL \tag{1}$$

$$A_{KS} \approx r_{skull} \times r_{scalp} \times \frac{\sigma_{scalp}}{\sigma_{skull}} \tag{2}$$

The relationship between scalp thickness (T), the surface Laplacian (SL) and radial current density (I) in a concentric spheres model of the head was generalized for use in an MRI-based realistic head model [Babiloni et al., 1997]:

$$I = K \times T \times SL \tag{3}$$

The parameter, K, is based on estimates of the scalp resistivity.

In each of these cases, the assumption of concentric spherical geometry is used to imply a linear relationship between scalp thickness and the coefficient of the surface Laplacian. While the scalp thickness adjustment is demonstrated to improve surface Laplacian estimates of cortical potential, there remains the question whether the linear relationship suggested by the concentric spheres model is the most appropriate for the realistic geometry as assumed by Babiloni and colleagues. Because the uniform scalp thickness scalp thickness of the concentric spheres model does not account for the complexity of a realistic geometry,, we consider a more general formula, where *β(T)* is a polynomial allowing for a nonlinear relationship:

$$\varphi_{cortex} - \varphi_{scalp} = \beta(T) \times SL \tag{4}$$

1. Methods

Using a boundary element technique [Stenroos et al., 2007], a forward solution is calculated for 53spherical head models of differing geometries. The first two layers, representing the brain and skull, are concentric spheres of radius 7 and 8cm, respectively. The outermost sphere's lowest point is fixed and its radius is varied from 8.625 to 9.5cm, representing scalp thickness from 0.25 to 2cm; the extremes of variation are illustrated in Fig. 1. Each scalp sphere is populated with 128 sensors, also shown in Fig. 1.

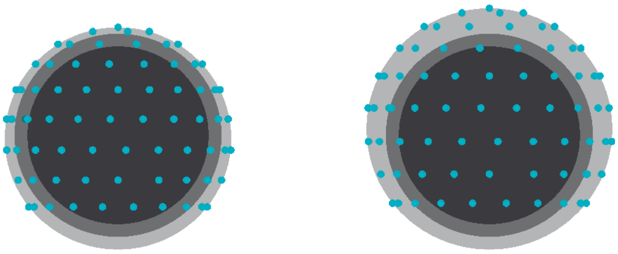

Figure 1: Side view of two examples of the non-concentric three-sphere models. Note then thin (left) and thick (right) scalp at the top of each head.

Radially-oriented dipole current sources are located on a spherical surface of radius 6cm. Simulations are generated, with each dipole source treated as independent, identically distributed Gaussians. The New Orleans Spline Laplacian [Nunez et al., 1994] is used to calculated the surface Laplacian at the scalp electrode.

To evaluate the parameter $\beta(T)$ from Eq. 2, β' is estimated from these simulations:

$$\beta' = \left(\varphi_{scalp} - \varphi_{cortex}\right) / SL \tag{5}$$

The distribution of β' with respect to scalp thickness is used to to find least-square polynomial regressions with respect to thickness, $\beta''(T)$. These regressions, in turn, are used to estimate cortical potential at the point nearest the cortex from the scalp potential and surface Laplacian:

$$\varphi'_{cortex} = \varphi_{scalp} + \beta''(T) \times SL \tag{6}$$

Finally, to illustrate the effect of the thickness adjustment, the cortical potential, scalp potential, surface Laplacian, and cortical potential estimates for a particular source distribution are all plotted.

2. Results

A cursory evaluation of the distribution of β' (Fig. 2a) suggests a nonlinear relationship with respect to scalp thickness. The quadratic regression follows the mode of β' much more closely than the linear regression, particularly at the extremes of scalp thickness. This is illustrated in Fig. 2b, where the relative error estimates of the cortical potential are compared between the linear and quadratic models. In both cases, there is a minimum near 1cm (which corresponds to a concentric spheres model), and both models perform about equally well between 0.5 and 1.6 cm. It is outside of this range that the difference is seen, with the quadratic model staying close to 10% error; for thicker scalps, the linear model error increases to 15%, and for thinner scalps, the linear model error increases to 45%.

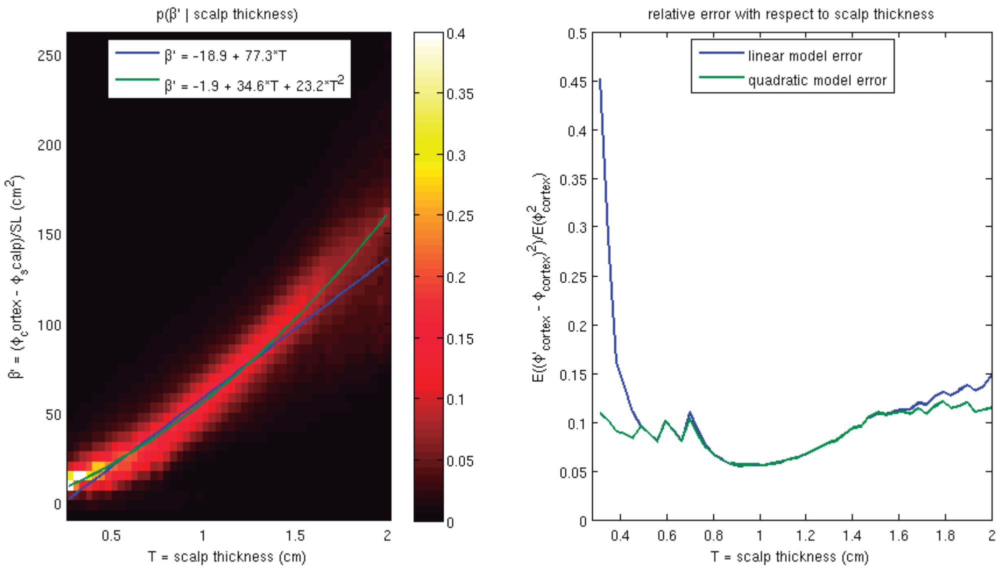

Figure 2:(left) Distribution of parameter β' *with respect to thickness with least-square linear and quadratic regressions. (right) Relative error of linear- and quadratic-model cortical potential estimates* $\varphi'_{cortical}$ *with respect to thickness.*

Figure 3 shows the simulated potentials for a particular source distribution on a head whose scalp is 0.5 cm thick at the top. Because all of the sources have equal power, the lower color intensity implies that the Laplacian underestimates the magnitude of the source on the lower-right, and the linear correction underestimates the magnitude of upper sources.

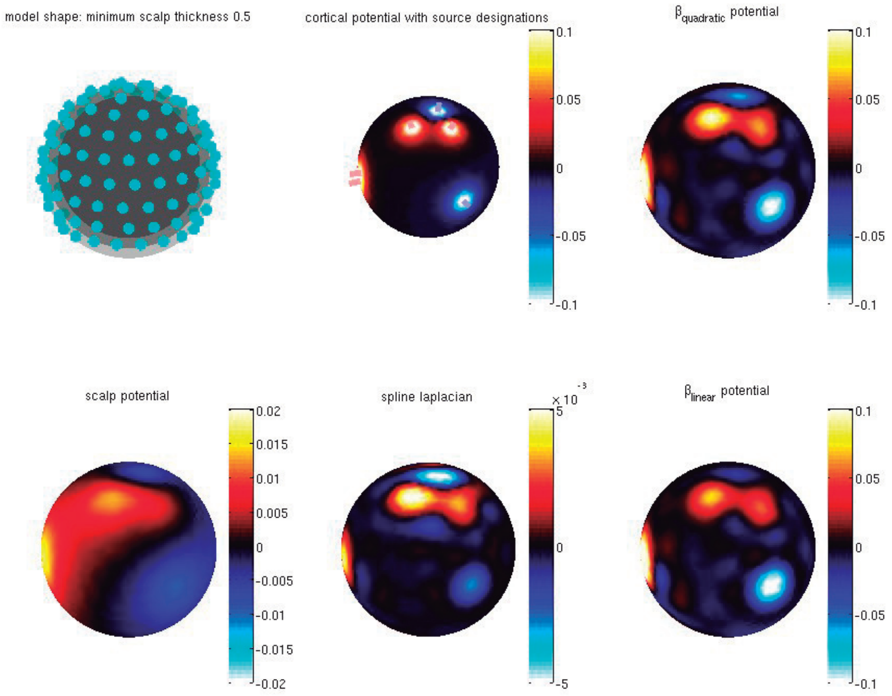

Figure 3: Simulated results of a particular source distribution. First column: sensor locations (top) and scalp potential (bottom). Second column: true cortical potential and source locations (top) and spline surface Laplacian of scalp potential (bottom). Third column: estimated cortical potentials for the quadratic (top) and linear (bottom) scalp-thickness adjustments. The largest differences between the estimates is at the top of the head, where the scalp is the thinnest.

3. Discussion and Conclusions

It is clear from these results that a nonlinear thickness adjustment to the surface Laplacian estimate of cortical activity, without the addition of any new geometric or volume conduction information, improves on the benefits seen with the linear thickness adjustment. The greatest benefits were seen at lower scalp thicknesses less than 0.5 cm, corresponding to frontal and parieto-occipital areas of the scalp [Babiloni et al., 1997]. In these regions, the linear adjustment underestimates the amplitude of cortical activity compared to the quadratic adjustment.

It remains to be seen how this technique, currently calibrated by and applied to a relatively simple head geometry, will generalize to a more realistic head model. The spherical New Orleans Laplacian is appropriate for the spherically-shaped scalps, but a Laplacian operator that accounts for a more general geometry (e.g. He et al., 2001) is necessary for any other case. The quadratic model $\beta''(T)$ is tuned to the particular distribution of scalp thickness found in the simple sphere model, which is almost certainly not the distribution of scalp thickness found in realistic heads. Further, the scalp thickness of the realistic head varies spatially more sharply than the simple sphere models used here, creating the possibility for curvature effects, not currently explicit in $\beta''(T)$. Boundary- or finite-element deblurring techniques (e.g. Gevins et al., 1994) intrinsically account for these curvature effects at the cost of further analysis and modeling of MRI data. Each of these concerns must be addressed before a thickness adjustment can be reasonably expected to provide improved estimates of cortical potential.

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