On the relationship between distances along the cortical surface and distances in the volume

Bruce Fischl\textsuperscript{1,2,*}

*Author to whom correspondence should be addressed:
Bruce Fischl
\textsuperscript{1}Nuclear Magnetic Resonance Center
Bldg. 149, 13th St.
Charlestown, MA 02129
tel: 617 726 4897
fax: 617 726-7422
fischl@nmr.mgh.harvard.edu

\textsuperscript{1}NMR Center, Dept. of Radiology, MGH, Dept. of Radiology, Harvard Medical School, \textsuperscript{2}MIT AI Lab.

Keywords: MRI, fMRI, smoothing.
Abstract - The neurons of the human cerebral cortex are arranged in a highly folded sheet, with the majority of the cortical surface area buried in folds. Cortical maps are typically arranged with a topography oriented parallel to the cortical surface. Despite this unambiguous sheet-like geometry, the most commonly used filtering technique applied to functional neuroimaging data is volumetric Gaussian smoothing. Here, we elucidate the relationship between volume smoothing and surface-based smoothing, and show that in general, to implement the same level of smoothing, significantly larger surface-based kernels are required.

1 Introduction.

The cerebral cortex is the largest part of the human brain. Although it is highly folded in many mammalian species, the intrinsic 'unfolded' structure of the cortex is that of a 2-D sheet, several millimeters thick. In experimental animals, it is well-accepted that: 1) many functional dimensions (e.g. retinotopy, orientation tuning, ocular dominance, somatotopy, tonotopy, etc.) are mapped on the cortical surface; 2) these mapped parameters vary much more rapidly in the two dimensions parallel to the surface than they do through the several millimeters of cortical thickness (i.e. they are 'columnar'); and 3) different cortical areas are arranged in a characteristic pattern, or mosaic, across the cortical surface. Estimates of the amount of 'buried' cortex range from 60-70% [1, 2]. Thus, distances measured in 3-D space between two points on the cortical surface will substantially underestimate the true distance along the cortical sheet, particularly in cases where the points lie on different banks of a sulcus. For example, the lateral tip of the central sulcus frequently lies within a centimeter of the superior temporal gyrus when the distance is measured in the Cartesian embedding space. The distance between the same two points as measured along the actual cortical surface is more than 10 centimeters due to the depth of the sylvian fissure.

From a functional standpoint, nonhuman primate neocortex is composed of a mosaic of visual, auditory, somatosensory, and motor areas, with visual areas alone occupying more than half of the total cortical surface area [3-5]. The bulk of the remaining half is comprised of auditory, somatosensory, motor, and limbic areas, each occupying about 1/8 of the total neocortex [6, 7]. The majority of these areas are defined by their topographic maps of the sensory periphery (e.g. retinotopic, tonotopic, somatotopic). Typically, the metric encoding the relationship between these maps and the sensory periphery which they represent is not known (see, [8, 9] for a notable exception). However, the two dimensional nature of the maps as well as their topographic arrangement strongly suggest that a two dimensional surface-based metric is more appropriate for analyzing their functional properties than the more typically used volume-based metrics. A number of techniques and toolkits have been developed and distributed for surface-based analysis [2, 10-32], and these tools have been used for analysis of cortical properties in a growing number of studies [2, 33-48].

While surface-based approaches have a number of advantages, they are nonetheless not the dominant form of data analysis in the neuroimaging community, even for studies primarily concerned with cortical regions. Volume-based analysis is much simpler to perform, and consequently far more common. Here, we examine the relationship between the two, and in particular, compute the mapping between surface-based distances measured along the cortical sheet, and contrast them with distances between the same points as measured using the standard Euclidean metric in the volume. This is of particular interest, as the question of the size of the optimal smoothing kernel arises frequently. Volumetric smoothing kernels with a full-width half-max in the range of 10 mm have been suggested as optimal for event-related fMRI experiments [49]. While the exact kernel size will certainly vary as a function of location and task, it is important to note that surface-based smoothing distances are always at least as large as volumetric ones, and that therefore the corresponding surface-based smoothing kernels should in general be larger to obtain the equivalent amount of smoothing.

In this paper, we use surface-based analysis techniques [17, 19, 21, 50] to build models of a large number of subjects,
in order to explicitly quantify the relationship between surface and volume distances in the human cortex. The results show that for many cortical locations, volumetric distances in the range of 10 mm can correspond to surface-based distances of multiple centimeters. This effect arises as the volume distance exceeds the separation between adjacent banks of a sulcus, and for locations on the pial surface, can be as small as a few millimeters.

2 Methods.

160 datasets were acquired as part of an ongoing study of aging and Alzheimer’s disease, and were made available for this study by Randy Buckner in association with the Washington University Alzheimer’s Disease Research Center (ADRC). The subjects ranged in age from 18 to 93, and a significant portion of them (57) have been diagnosed with probable Alzheimer’s disease. For further clinical characterization of the participants contributing data, see Head et al. (in press) and Salat et al. [51]. Each subject was scanned between two and four times with a high contrast-to-noise MP-RAGE sequence on a Siemens Vision system at Washington University in St. Louis (Siemens 1.5-T Vision System, resolution 1x1x1.25 mm, TR = 9.7 ms, TE = 4 ms, FA = 10°, TI = 20 ms, TD = 500 ms). Each of these scans was motion corrected and averaged to generate a single volume with excellent gray/white contrast, then used as input to a set of tools for constructing and analyzing models of the cerebral cortex [17, 19, 50, 52]. Briefly, the volumes were interpolated to be 1mm³ isotropic, intensity normalized to remove bias fields and aligned with the Talairach atlas using a set of automated procedures [53, 54]. The skull was then removed from the normalized volumes, and an oriented filter was applied in order to segment white matter voxels [16, 17]. The cortical hemispheres were separated, subcortical components were removed, and surface-base representations of each hemisphere were generated. These initial models were topologically corrected [50], inflated [19], and deformed to generate accurate representation of both the gray/white and pial surfaces [52]. The surfaces were then mapped into spherical form using a quasi-isometric mapping that minimizes metric distortion [19]. The importance of the relative preservation of the metric properties of the cortical sheet is that it allows the closed-form calculation of the geodesic distance between any two points in the cortex by simply computing the length of the great circle connecting them. Finally, the spherical surfaces were used as input to an inter-subject registration procedure designed to align cortical folding patterns [21].

After registration, each pair of points v₁ and v₂ in the surface models at the midpoint of the gray matter for each subject was examined. Points whose Euclidean distance dₑ exceeded a threshold of 2 cm were discarded. For each of the remaining pairs, the surface-based distance dₛ was computed in the spherical coordinate system¹ described above. This pair of distances {dₑ,dₛ} was added to a joint histogram at each of the two locations v₁ and v₂, resulting in a 2D histogram at each point in the spherical coordinate system, representing the relationship between volumetric and surface-based distances at that point in the cortex. The histograms were then averaged across the surface to generate a representation of the average relationship between the two types of metric, as well as sampled at various points. Dividing by the total # of entries in the histogram allows the joint histogram to be interpreted as a joint probability density function (PDF). Each horizontal row then gives the probability that a given volume distance corresponds to various surface distances.

3 Results.

The average joint histogram across all 160 subjects is shown in Figure 1. As can be seen, volumetric distances are uniformly less than or equal to surface-based ones (geometrically this should be exactly true, although in our case, there are some cases for which this assumption fails due to distortions introduced by the differing Gaussian curvature of the cortex and the sphere). For small distances, the two metrics are similar, although by 6 mm, the most likely surface-based distance is already 9 mm. Given the significantly non-Gaussian shape of these distributions, computing the mean is not informative. Plots of horizontal lines of this histogram show for volumetric distances of 6 mm, 8 mm, 10 mm and 12 mm are given in Figure 2, showing the increasing weakening of the relationship between the two metrics as the volumetric distance increases (these plots can be interpreted as the probability of a particular surface-based distance given a volumetric distance). For example, while the mode of the 10 mm volumetric kernel is 14 mm in terms of surface-based distances, the surface-based distance is as likely to be 20 mm as it is to be 10 mm. At 14 mm distance in the volume, the

¹ Note that some metric distortion is introduced in the spherical mapping, as the surfaces in question have different Gaussian curvature. Nevertheless, this distortion is unbiased, and less than 20% for cortical locations [19]. Fischl, B., M.I. Sereno, and A.M. Dale, Cortical Surface-Based Analysis II: Inflation, Flattening, a Surface-Based Coordinate System. NeuroImage, 1999. 9: p. 195-207., and so does not significantly change these results.
surface-based distance is as likely to be 4.5 centimeters as it is to be 14 mm.

The variability of these results across different cortical locations is illustrated in Figure 3, which shows the joint histograms at 10 locations distributed across the cortex. Note the very different shapes of the joint histograms reflecting the local cortical geometry. For example, the histogram for the point in the inferior frontal gyrus is relatively compact, while the one just above it, representing a point in the superior temporal sulcus, has a clear bimodal aspect to it.

The bimodal nature of many of these plots is further detailed in Figure 4, which shows the joint PDF (left) and a horizontal line through it at a volume distance of 10 mm on the right. The highest peak occurs around 20 mm, but a second broad peak can be seen centered around 50 mm. This peak occurs as there are points at the ventral tip of the central sulcus and also on the banks of the superior temporal sulcus that are within 1 cm (Euclidean) of the depths of the sylvian fissure, despite the fact that they are 5 cm distant along the surface.

Figure 1. Joint histogram of volume distances (vertical axis) vs. surface distances (horizontal axis). The white line indicates the region of the histogram representing equal surface-based and volumetric-distances.
Figure 2. Plots of the probability of a given volume distance corresponding to various surface distances for 6, 8, 10, 12 and 14 mm volume distances.

Figure 3. Joint histograms of volume vs. surface distances for a variety of locations in an average brain.
Figure 4. Left: histogram of volume and surface distances for a point in the sylvian fissure. Right: plot of surface-based distances that correspond to 10 mm distance in the volume for the same point.

4 Conclusion.

Smoothing of neuroimaging data is ubiquitous due to limited signal-to-noise (SNR) and to the tradeoff between SNR and resolution. Typically, this smoothing is done with circularly symmetric 3D Gaussian kernels. While such kernels are easy to implement and use, they have a distinctly non-Gaussian effect when applied to cortical data. The shape of the kernels in the cortex is complex, and in many cases, not even simply connected, due of course to the highly folded nature of the cortex. Furthermore, the 3D Euclidean metric these kernels are based on will always underestimate the distance as measured by minimal geodesics along the cortical manifold.

It is not possible in general to mimic the behavior of a 3D volumetric kernel with a 2D surface-based one. Nevertheless, it is possible to evaluate the relationship between the metrics in the two spaces in order to understand how smoothing in one space relates to smoothing in the other. As shown here, surface-based kernels in general must be substantially larger in order to generate a comparable amount of smoothing as the “equivalent” volumetric kernel. In this context, it is important to note that the results presented in this paper are somewhat conservative. All volumetric distances were computed at the midpoint between the gray/white junction and the pial surface. Worst-case analysis would have used distances measured between points on the pial surface. Given that the average thickness of the cortex is approximately 2.5 mm, this would have shifted the histograms presented in section 3 down by 2.5 bins. The plot in Figure 4 left, would then, for example, correspond to a volumetric distance of 7.5 mm instead of 10 mm, making the discrepancy between the two metrics even more dramatic.

It is also worth noting that the analysis provided here has been a purely geometric one, and it is likely that the difference between optimal surface-based and volumetric kernel sizes is even greater for true cortical neuroimaging data. This conjecture comes from the observation that as volumetric kernels increase in size, they begin to include substantial amounts of data from voxels that do not contain gray matter. Such voxels typically have minimal amounts of signal, and therefore decrease the efficiency of any statistical estimates based on them. This effect can be mitigated by using tissue segmentation to limit analysis to only those voxels containing significant amounts of gray matter [56], but in general is not an issue for surface-based analysis, which implicitly only includes cortical voxels. In addition, while the use of segmentation masks can help, they do not contain topological information, and cannot therefore distinguish to which bank of a sulcus a gray matter voxel should be assigned.

For functional neuroimaging studies, therefore, it is apparent that significantly larger smoothing kernels can be used in surface-based analysis than are feasible in volumetric analysis. This derives both from geometry, in that surface-based distances are larger than volumetric ones, but also from neuroanatomy and neurophysiology in that most of the signal of interest is contained within the cortical gray matter that defines the cortical manifold. This latter effect in particular, allows users of surface-based analysis to analyze their data with kernels that are many times larger than would be possible for volumetric analysis without completely attenuating the underlying effect.
5 Acknowledgments.

This research was jointly funded by the National Center for Research Resources (P41-RR14075 and 1 R01 RR16594-01A1) and the Mental Illness and Neuroscience Discovery Institute. Thanks to Randy Buckner for generously allowing his data to be used for this paper, and to David Salat, Evelina Busa, Cristie Cicero and Brian T. Quinn for helping in the analysis. Thanks also to CogMGH for suggesting that this was an interesting problem. Finally, thanks to Anders Dale and Marty Sereno for starting me down the surface-based road in the first place.

6 References.


