Investigating the Medial Prefrontal Cortex with Cortical Flat Mappings

Monica K. Hurdal[1,2], Agatha D. Lee[2,3], J. Tilak Ratnanather[2,3], Tomoyuki Nishino[4], Micheal I. Miller[2,3], Kelly Botteron[4]

Introduction

The ventral medial prefrontal cortex (VMPFC) and orbital prefrontal cortical regions have been implicated in affective disorders such as major depressive disorder and bipolar affective disorder. Studying the properties of gray/white matter surface in these regions will help in understanding the pattern of disease and provide tools for their early detection and diagnosis. Structural and functional changes include grey matter loss [1][3]. The highly curved geometry the VMPFC make morphometric analysis and visualization difficult. Figure 1 shows the subvolume containing the VMPFC delineated by pericallosal sulcus and the gyrus rectus (GR). We describe automated methods, including cortical flat mapping, in a preliminary study of the VMPFC region.

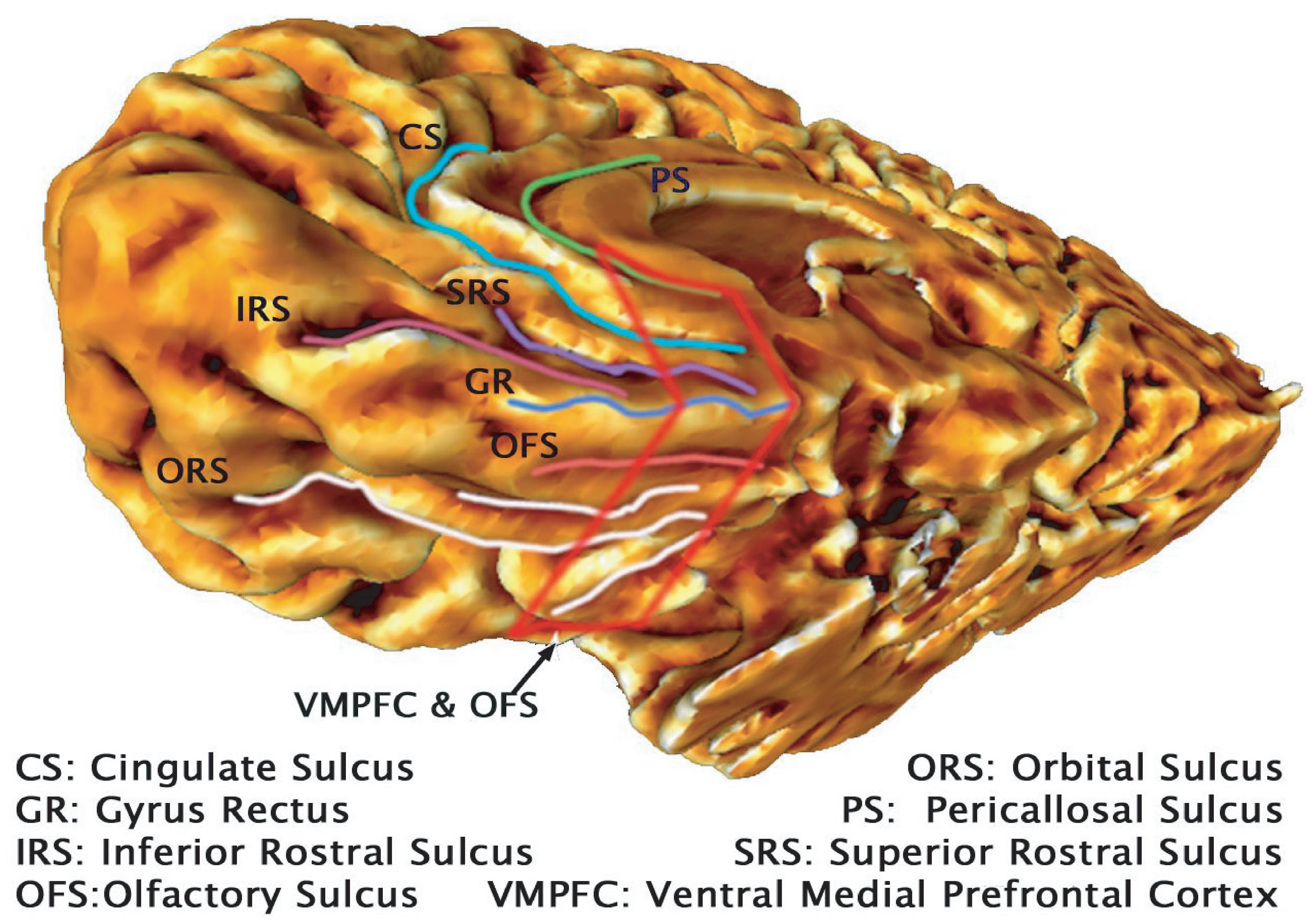

Figure1: Location of ventral medical prefrontal cortex(VMPFC)

Cortical Surface Reconstruction & Topology Correction

The gray/white matter boundary surface of the VMPFC was constructed from the MR grayscale image of the whole brain by using a Bayesian segmentation algorithm [6] on a small region enclosing the surface. The left panel of Figure 2 shows the surfaces created for the extracted region, the middle panel shows the extracted VMPFC gray/white matter boundary surface from the right side of the VMPFC. Such extracted surfaces need to be corrected for topology due to errors introduced via inadequate MR spatial resolution and ambiguities in the marching tetrahedron algorithm. The main types of defects observed are more than one connected surface component, non-manifold edges, vertex singularities, holes and handles. The Euler characteristic formula χ=v-e+f, where v is the number of vertices in the surface, e is the number of edges in the surface and f is the number of faces (triangles) in the surface, allows us to detect and correct these defects. The right panel shows such a corrected surface with curvature of the surface superimposed as a colormap.

Figure 2: The gray/white matter surface of the VMPFC is shown in red and the artificial boundar which is to be removed is showing in blue.The third panel shows a topologically corrected image

Conformal Mapping of 3D to 2D

Cortical surfaces embedded in 3D are highly convoluted. To visualize buried regions, we generate an equivalent surface in 2D via a bijective map between the vertices in 3D and those in 2D using the conformal flat mapping method based on circle packing [2][4][5]. Conformal maps are known to exist via the Riemann Mapping Theorem. In addition, they preserve the angle between intersecting curves on the surface. In practice, k-quasiconformal maps are produced where k is a measure of conformal distortion. Computation of the conformal maps using circle packing assigns a circle ci to each vertex vi. Then we generate circles ci such that two circles ci and cj are tangent to each other whenever vertices vi and vj form an edge in the surface. The surface at interior vertex vi is flattened by adjusting the radii of the neighboring circles such that the angle sum at vi is 2π. Trigonometry provides the desired "packing conditions" in the Euclidean setting:

$$\sum_{\langle i,u,w\rangle} \arccos\left\{ \frac{(r_i+r_u)^2+(r_i+r_w)^2-(r_u+r_w)^2}{2(r_i+r_u)(r_i+r_w)} \right\} = 2\pi$$

where this sum is over all faces f = <i,u,w> containing vertex vi.

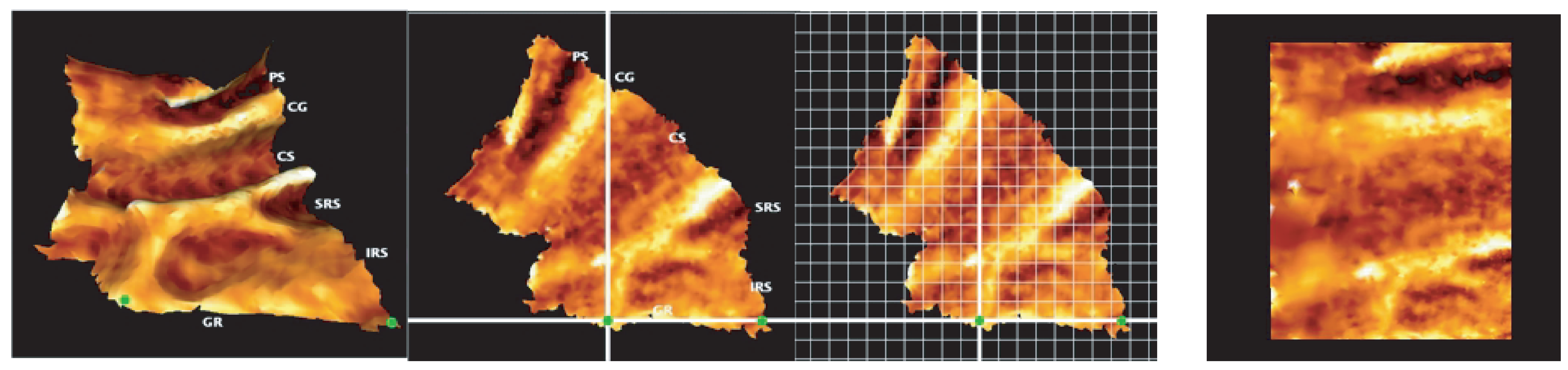

Figure 3: VMPFC coordinate system based around the the gyrus rectus and a 2D surface in a rectangular form

A conformably mapped surface can be further mapped to a rectangular form. Here 4 boundary vertices are assigned as the corners of the rectangle. The aspect ratio of the rectangle is a conformal invariant of the original 3D surface (relative to the 4 corners) and is called the conformal modulus. Such a mapped region is shown in the right panel of Figure 3.

Using a conformal map, a unique coordinate system can be imposed on region by specifying two points. For the VMPFC, these two points lie on the GR. The origin is determined by the first point of maximal mean curvature that is the closest to the ventral VMPFC boundary; the second point that lies on the positive x-axis is the end of the GR closest to the dorsal VMPFC boundary. First three panels of Figure 3 illustrate how a coordinate system is imposed on the VMPFC - an original 3D surface, a 2D surface, a coordinated 2D surface from the left.

Results & Discussion

We have applied the techniques presented here to 10 twin pairs. Figure 4 shows the results from one twin pair. The top row shows the extracted 3D surface. The middle row shows their corresponding GR oriented flat maps. The thrid row shows rectangle maps followed by the conformal modulus.

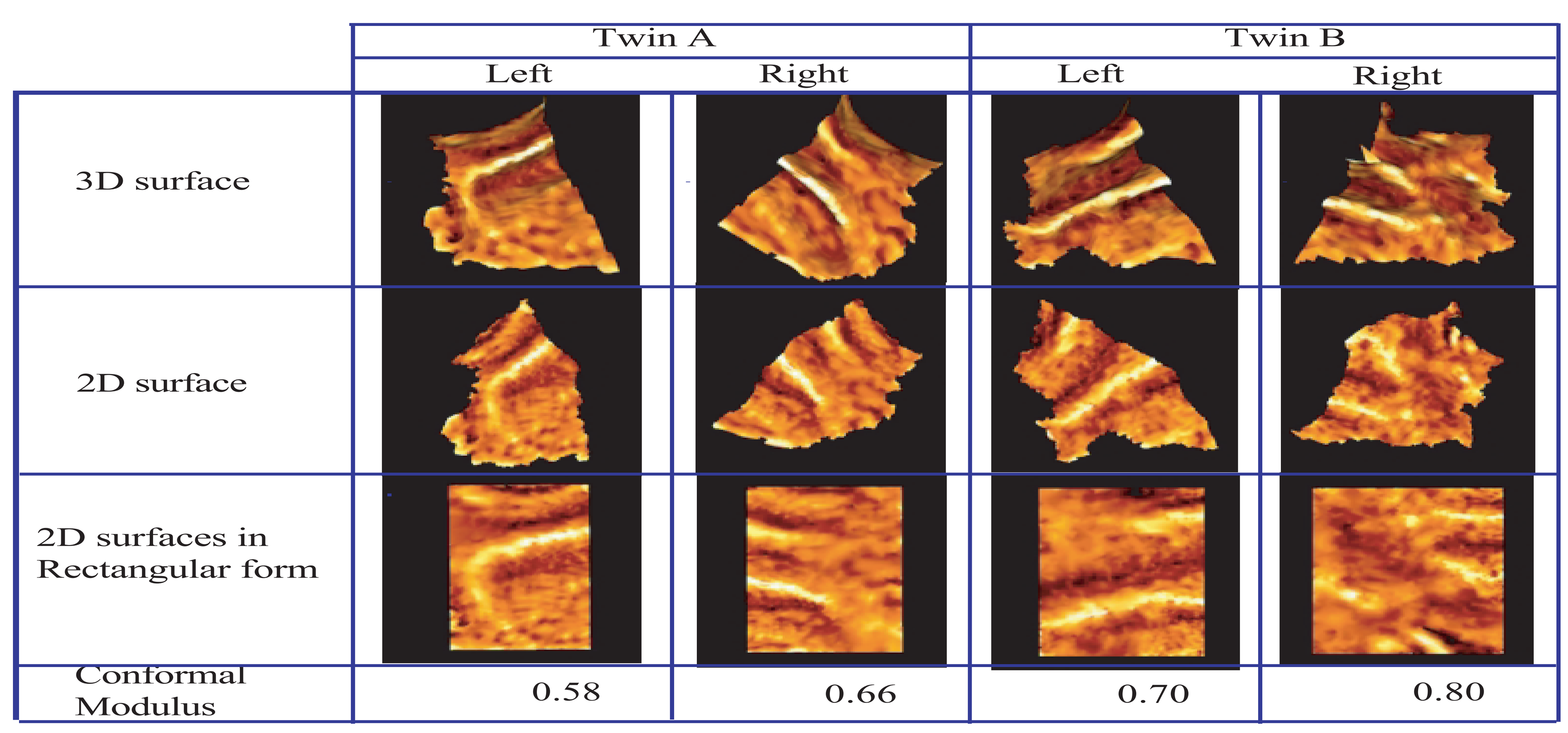

Figure 4: Cortical surfaces of one twin pair are rescontructed and mapped in 2D. The results are coled with mean curvature.

The highly curved geometry can be visualized using the techniques (i.e., conformal flat mapping) presented here. Since these flat maps are mathematically unique, a well defined local coordinate system can be imposed on the VMPFC. The mean curvature of the surface (-0.4 is black, 0.6 is white) superimposed on the 2D and 3D manifolds shows the locations of sulci and gyri as the regions of high curvature. These can then be tracking simultaneously to measure their properties. Using data from identical twins, these technologies allow us to compute surface metrics, including new surface metrics such as conformal modulus, to study how these are affected in diseased states, specifically to understand the role of VMPFC in depression.

References:
[1] Botteron, K. L. et al. 2002 *Biological Psychiatry* **51:** 342-344.
[2] Collins, C. and Stephenson, K. 2003. *Computational Geometry: Theory and Applications* 25: 233-256.
[3] Drevets, W.C. 1999. *Ann. NY Acad. Sci* : 877: 824-827.
[4] Hurdal, M. K. *et al.* 1999 *Lecture Notes in Computer Science* **1679:** 279-286.
[5] Stephenson, K. 1999. Proceedings of the 3rd CMFT conference, pp. 551-582.
[6] Ratnanather, J. T. et al (2001) NeuroImage 14: 1058 - 1069

1. Dept. of Mathematics, The Florida State Univeristy, Tallahasse, U.S.A.
2. Center for Imaging Science, The Johns Hopkins University, Baltimore, U.S.A.
3. Dept. of Biomedical Engineering, The Johns Hopkins University, Baltimore, U.S.A.
4. Dept. of Psychiatry & Dept. of Radiology, Washington Unmiversity School of Medicine, St. Louis, U.S.A.

Center for Imaging Science http://cis.jhu.edu

Research supported by: NIH P41-RR15241
NIH MH43775, MH60504, MH 52886
NSF FRG DMS-0101329
NSF NPACI