Geometric Structures Related to the Human Brain:
Cortical Geometry versus Functional Geometry of the Cortex

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Abstract. Using a three-dimensional mesh from T1-weighted MRI of human brain, we propose construction of geometric structures that are needed in computational neuroanatomy, such as identification of anatomical landmarks. Further, registration of neuronal signals recorded during brain information processing in a task, makes it possible to describe the dynamics of the cortical activation field in this cortical geometry. We apply these results to dynamics of response of the anterior cingulate cortex in response to heat pain.

Summary. Advances in brain imaging have opened a new branch of computational neuroscience, known as *computational neuroanatomy.* One of the promises of this emerging brave interdisciplinary subject is to combine neuroanatomy and high resolution images of the human and other brains in order to provide digital neuroanatomy of individuals with medically reliable accuracy. Clearly, in the age of personalized medicine, the research on drug effects specific for individual members of a population requires automated mechanisms to perform a host of measurements, from function to structure, and accommodating to variations of all such measurements within an appropriately large sample of population. In another direction, epidemiological studies of brain dysfunction, as well as normal brain function for control purposes, will vastly benefit from automated Personalized Digital Neuroanatomy (PDNA). In most such applications, as well as for justifiable theoretical and technical investigations, it is important to formulate stochastic and probabilistic versions of the main-stream deterministic problems in computational neuroanatomy. In particular, fundamental research and computationally efficient algorithms for extraction of relevant stochastic geometric quantities and

structural measures are the necessary steps to pave the way towards the above-mentioned applications based on PDNA and other uses in *neuroinformatics*.

The approach proposed in this research is motivated by specific research problems in neuroscience. Two such examples are: (I) study of cortical substrates of pain, and (II) noci-informatics, that is, neuroinfomatics of pain. There are a number of common threads between these two and a number of other examples. Let us briefly concentrate on problem I, to study of cortical substrates of pain. To focus the problem further and offer a concrete account of issues, let us restrict our attention further to thermal pain, that is, noxious sensations caused by bodily contact with hot or cold objects. Thermal pain carries a multitude of common characteristics with other types of pain, with the advantage of being studied more extensively and with many experimental data available for analysis. Further, experimental set up for heat/cold pain experiments on healthy volunteers and patients (who are typically very motivated to participate in experiments with the hope of pain relief.)

One of the key anatomical sites involved in cortical information processing in thermal and other kinds of pain is anterior cingulate cortex (ACC). Assessments of anterior cingulate cortex in experimental animals and humans have led to unifying theories of its structural organization and contributions to mammalian behavior. The role of anterior cingulate cortex in pain responsiveness is suggested by cingulumotomy results and functional imaging studies during noxious somatic stimulation. The affect division of anterior cingulate cortex modulates autonomic activity and internal emotional responses, while the cognition division is engaged in response selection associated with skeletomotor activity and responses to noxious stimuli. Overall, anterior cingulate cortex appears to play a crucial role in initiation, motivation, and goal-directed behaviors. These relationships provide firm biological grounds for the theoretical/computational research in this paper.

METHODS. The data consists of triangulation of the human brain based on the T1-weighted MRI. Each brain data is represented as a mesh with approximately 40,000 vertices, 80,000 edges and the appropriate number of triangles. The data at hand is made from MR images that have a resolution of 1^{mm} per slice. The average length for each edge is 3mm. There are several sets of such data available from a sample of normal subjects and patients with specific brain dysfunctions that are diagnosed. We use this mesh with its natural metric as the starting point to investigate geometric invariants in computational neuroanatomy, and then apply the result to description of dynamics in cortical information processing taking place in the cortical geometry.

Consider geometric formulations for the following problems in computational neuroanatomy that are of great interest. To answer such questions and other relevant neuroanatomical investigations, a number of geometric problems need to be solved. For example, we shall investigate the following:

PROBLEM I. Find the geodesics between given two points in the structure above.
PROBLEM II. Compute the curvature tensor at every point, principal, and geodesic curvatures.

There are also a host of problems regarding the statistical distribution of different geometric quantities among a population, to be calculated from a sample of data. For example:

PROBLEM III. Find the random variables that describe the geometric quantities, such as metric, curvature, anatomical landmarks, geodesics among points, thickness of cortical layer at different regions among various populations, e.g. organized by age, sex, or other factors.

We can use such geometric properties in order to describe the short-term dynamics of information flow in EEG, MEG, etc (i.e. local dynamics for a reasonable range of radii of neighborhoods). In fact, we could use the simplicial structure of the cortex to define a combinatorial version of the EEG/ERP and MEG fields on the cortex, and provide a combinatorial description of their dynamics, and classify such dynamic behavior using the information-theoretic arguments applied to combinatorial paths. Tools from statistical physics (such as Brownian paths, …, Monte Carlo method,…) could be used to solve a host of problems of cortical field theory.