CONFORMAL CONTOUR MAPPING FOR NEUROSURGERY OUTCOME EVALUATION

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ABSTRACT

Contour mapping of surgical resection of cortex is very important in neurosurgery outcome evaluation. Based on advanced MR and PET imaging technologies and our landmark-constrained brain conformal mapping, we present a practical and accurate approach to map the resection contour on the cortical surface from post-surgery brain images to pre-surgery ones. The approach can accommodate and combat the possible changes of the brain in shape and size over time. To free the user from manually defining the resection contours, we propose an automatic identification algorithm based on dynamic region growing on the cortical surface. We also present an effective method to calculate the area of the region enclosed by the resection contour on the cortical surface. The overall framework provides surgeons an accurate assessment of the agreement between functional PET abnormalities and the extent of surgical resection.

Index Terms— Conformal Mapping, Resection Contour, PET Imaging, Registration.

1. INTRODUCTION

It is well known that following surgical resection of brain tissue, there is a shift and displacement of the remaining tissue. This displacement makes the assessment of the amount of functional abnormality (defined in pre-surgical image data) and which was resected extremely difficult, even when post-operative MR images are available. The question whether the whole PET abnormality was removed or whether it was only partially removed is very important for clinical management of patients undergoing resection.

Another problem arises when the area of the region enclosed by the resection contour on the cortical surface needs to be measured. For a convex region on a surface, given all of its vertices, there exist many methods to decide those points on the surface that are inside the region. Consequently, the area can be computed as the summation of a set of triangles consisted of these inside vertices. However, sometimes the resection contour may not be flat and convex, it is often difficult to obtain all the inside vertices for computing the area in the aforementioned way.

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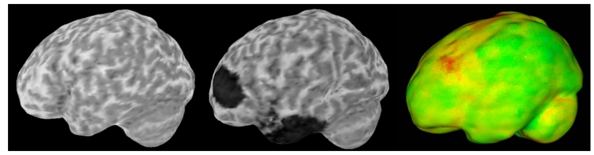

(a) (b) (c)

Fig. 1. (a) shows a pre-surgery brain. (b) shows the corresponding post-surgery brain. (c) shows the inverse gradient fusion of MR and PET data of the pre-surgery brain.

In this paper, we present a landmark-constrained conformal contour mapping which is a powerful technique able to accurately map the resected region (which is segmented from post-operative MR) into the pre-operative MR images, where the location of resection can be evaluated against the coregistered functional PET data (see Figure 1). Subsequently, the spatial relationship between the resection site and pre-surgically obtained PET data can be quantitatively assessed. We also develop an effective method to compute the area of the resection region.

2. RELATED WORK

The solution to this application is partly related to brain image registration and matching. For brain image registration, there have been many published research work, for example, brain warping [1]. Images of the same subject may be warped into correspondence over time, to help analyze shape changes during development or degenerative diseases. Brain warping approaches can be divided into two classes, those based on volume-to-volume matching and those based on surface-to-surface matching [1]. Fischl *et al.* [2] demonstrated that surface based brain mapping can offer advantages over volume based brain mapping, especially when localizing cortical deficits and functional activations. However, the problem is still open since there is no optimal method to obtain a map between brains. Recently, several research groups have reported on brain surface conformal mapping. Hurdal, Stephenson [3] reported a discrete mapping approach that uses circle packing to produce "flattened" images of cortical surfaces on the sphere, the Euclidean plane, or the hyperbolic plane. They obtained maps that are quasi-conformal approximations to classical conformal maps. Haker *et al.* [4] implemented a fi-

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nite element approximation for parameterizing brain surfaces via conformal mappings. Gu *et al.* [5] proposed a method to find a unique conformal mapping between any two genus zero manifolds by minimizing the harmonic energy of the map. They demonstrated it by conformally mapping the cortical surface to a sphere. They also proposed to optimize the conformal parameterization by composing an optimal Möbius transformation so that it minimizes the landmark mismatch energy. Zou *et al.* [6] presented an approach based on landmark constrained conformal parameterization of a brain surface from high-resolution structural MRI data to a canonical spherical domain.

3. BASIC IDEA OF LANDMARK-CONSTRAINED CONFORMAL MAPPING

In order to map the resection contour from post-surgery brain to pre-surgery one, it is necessary to establish a mapping that specifies a unique correspondence between each location in one brain and the corresponding location in another. Since gyral and sulcal landmarks are typically accurate indicators of the many functional areas, using these features to drive the registration of the cortical surfaces will result in a more accurate alignment of corresponding functional areas.

Zou *et al.* [6] introduced a novel method to register cortical surfaces in the spherical domain, which not only explicitly match those labeled landmarks, but also make use of surface's intrinsic geometry via conformal mapping to optimize the alignment for other anatomical features. First, they manually labeled the major anatomical features as landmarks on the two cortical surfaces as discrete point sets based on the initial surface rendering of the brain. Then, they chose one cortical surface to be conformally mapped to the unit sphere without constraining the location of landmarks. The generated result is regarded as the Standard Conformal Brain Model, which is used as the exemplary template to indicate the locations of major landmarks, as well as other cortical structures in the spherical domain. Once this template is established, another cortical surface can be conformally mapped to it with landmarks constraints at specific locations, such as aligning its central sulci with the corresponding ones of the template.

In summary, the method is guided by a combination of conformal geometry and feature alignment, which still tries to minimize the harmonic energy, while every labeled point is constrained to be aligned with its counterpart at the spherical domain of the template.

4. BRAIN RESECTION CONTOUR MAPPING

Assume we have two MR images of pre-surgery and post-surgery brains, and we have generated corresponding triangular meshes from them. If we want to map the points of the resection contour on the post-surgery mesh to pre-surgery one, and assume these two meshes are nearly identical in size, shape, location and orientation in the same world coordinate system, a simple and crude approach is to use shortest distance mapping. Unfortunately, the post-surgery brain may change greatly in shape and size compare to the pre-surgery one, especially for a growing child. In these cases, shortest distance mapping will produce poor results since these two brains are not well registered.

We apply Marching Cubes and topological correction to obtain the cortical surface triangular mesh, then we use Maximum Intensity Projection of certain length to generate the texture. To free the user from manually defining the resection contour, we propose an automatic segmentation algorithm based on region growing. First a patch which we call a seed region is found on the brain mesh by checking the triangles with low intensity, i.e. $I_{seed} < 0.1 \cdot I_{average}$. The largest connected region is chosen to be the seed region. After we obtain the seed region, the initial seed patch will then grow to fill the resection region within finite time steps. In each time step new vertices are generated in tangential direction of boundary vertices to form a new outlier on the cortical surface. The boundary tangential flow is depicted by the formula $\Delta C = \alpha\kappa\vec{n}$, where C is the current boundary with ΔC as the displacement, α is a predefined constant, κ is the curvature of a boundary vertex, and $\vec{n}$ is a unit vector on the boundary. This algorithm is described below in detail:

1. Calculate the vector $\vec{T}$ for each boundary vertex, such that $\vec{T} = \alpha\kappa\vec{t}$, where $\vec{t}$ is the tangential direction of that vertex.

2. By projecting $\vec{T}$ to the cortical surface we get $\Delta C'$. Then we check the gradient on the surface along the mapped vector. If a point v' with gradient higher than threshold is found, the boundary stops at this point and v' will be marked as *stopped* after being added to the patch; otherwise v' will be the end point of the mapped vector. Thus ΔC is determined and two faces associated with v' will be added to the path, see Figure 2.

3. The mesh growing stops if all boundary vertices are marked as *stopped*. At this time the patch boundary will be the contour of the resection.

The algorithm of our conformal contour mapping of brain resection region can then be illustrated as follows:

1. Create the triangular mesh from the post-surgery brain images and render it with Maximum Intensity Projection showing the shaded gyri and sulci.

2. On the mesh, manually select some landmarks used for constraints.

3. Perform conformal surface mapping without landmarks constraints and obtain a template spherical brain.

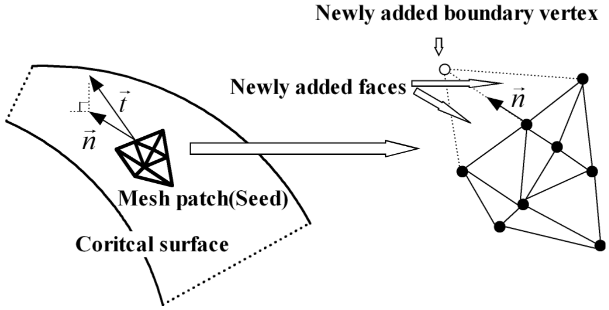


Fig. 2. Region growing on the cortical surface

4. Create the triangular mesh of pre-surgery brain and render it with texture displayed.

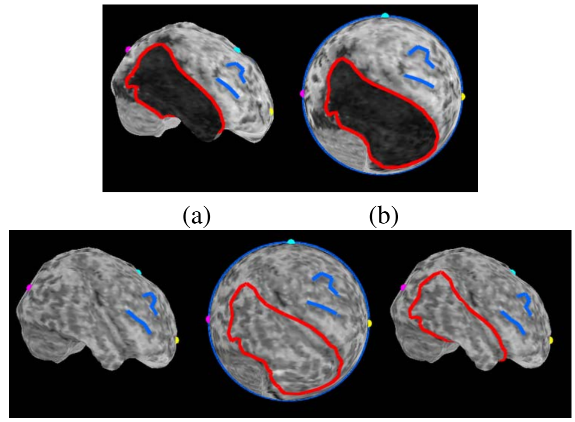
5. On the mesh, manually mark corresponding landmarks same as the ones selected on the post-surgery data. Here, "corresponding" means anatomically the same.

6. Perform conformal surface mapping with landmark constraints to register the pre-surgery spherical brain to the template generated in Step 3.

7. Map the resection contour on the template spherical brain to the pre-surgery spherical brain.

8. Reversely map the resection contour on the pre-surgery spherical brain back to the actual pre-surgery brain.

Figure 3 shows a pipeline of the aforementioned brain resection contour mapping. Figure 3(a) shows a post-surgery brain. Figure 3(b) is the template spherical brain conformally generated from (a). Figure 3(c) is the pre-surgery brain. Figure 3(d) is the pre-surgery spherical brain mapped to the template spherical brain by landmark-constrained conformal mapping. Figure 3(e) is the pre-surgery brain with the resection contour reversely mapped.



(a) (b)

(c) (d) (e)

Fig. 3. Brain resection contour mapping using landmark constrained conformal mapping. The blue curves on the surfaces are selected landmarks for matching. (a) The post-surgery brain with resection contour marked. (b) The template spherical domain generated from (a). (c) The pre-surgery brain. (d) The pre-surgery spherical brain generated from (c) by landmark constrained conformal mapping to the template. Now data in (b) and (d) are registered. The resection contour are mapped from (b) to (d) using its spherical coordinates. (e) The actual pre-surgery brain with the resection contour reversely conformally mapped from (d).

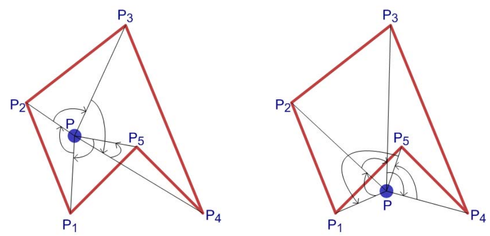
5. COMPARE RESECTION WITH PET ABNORMALITY

In brain surgery outcome evaluation, the ROI (the resection region) mapped to the pre-surgery brain is often compared with PET abnormality defined before surgery to check whether the resection had been performed in the right place. In that case, some statistical results need to be calculated, such as the area of ROI, the area of PET abnormality, and their intersection and union. Since we use a triangular mesh structure to represent the brain surface, the area of ROI or PET abnormality can be estimated by summing the areas of all the inside triangular faces, if these triangles have at least two vertices that are considered as inside ROI or PET abnormality. In this scheme, we can focus on how to decide whether a particular vertex of the triangular face is inside the ROI. The ROI can be represented as a 3D surface patch in practice, and the difficulty lies in the fact that this patch may be heavily curved, see Figure 3(e). To simplify our discussion, we first consider a 2D patch on a plane.

Testing whether a point is inside a 2D patch is a basic operation in computer graphics. A simple yet effective method is to sum the signed angles formed at the point by each edge's endpoints [7]. Suppose there is a patch $P_1P_2...P_n$ on the plane, either convex or concave, with all of its vertices P_i given clockwise or counter-clockwise, and we need to decide whether a point P is inside it. We can define counter-clockwise spin angle as positive and clockwise spin angle as negative, or vice versa. We accumulate all the signed spin angles from PP_1 to PP_2, PP_2 to PP_3, ..., PP_n to PP_1. If this point is inside, the sum will be 360° or -360°; otherwise it will be 0, as illustrated in Figure 4.

Assume that the ROI on the sphere is not large enough, which is usually true in reality, the angle summation method can be easily extended to perform inside point testing.

After Step 7 of our mapping algorithm, we can obtain the boundary vertices of the resection region on the mesh of the pre-surgery spherical brain. Suppose that the sample points are $P_1, P_2, ..., P_n$ in clockwise or counter-clockwise sequence and O is the center of the unit sphere, we can use the algorithm below:



(a) (b)

Fig. 4. Angle summation method. (a) The angle summation is 360°, then the point is inside. (b) Angle summation is 0, then the point is outside.

1. Calculate the center C of the ROI

$$\overrightarrow{OC} = normalize((\overrightarrow{OP_1} + \overrightarrow{OP_2} + ... + \overrightarrow{OP_n})/n)$$

2. Calculate the maximum radius D of ROI

$$D = max(|\overrightarrow{CP_1}|, |\overrightarrow{CP_2}|, ..., |\overrightarrow{CP_n}|)$$

3. For each vertex P of the subject sphere mesh:

   (a) If $|OP| > D$, discard P.

   (b) If P is $P_i(i = 1, 2, ..., n)$ or nearly on a edge, mark P.

   (c) Accumulate all signed spin angles, and get the summation S.

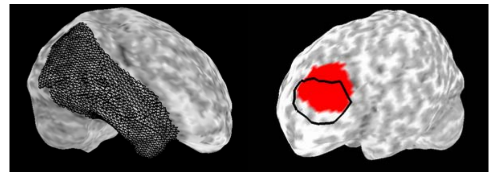
   (d) If $|S|$ is nearly 360°, mark P, otherwise discard P.

4. Reverse map of marked vertices into pre-surgery native space.

In practice, we use dot product to calculate the magnitudes of spin angles. For spin direction, we calculate cross product, and if the result vector is close to $\overrightarrow{OC}$ in direction, we consider the spin direction counter-clockwise and positive. Figure 5 shows the experimental results. The PET abnormality region is determined by comparing its PET sampling with the normal pattern derived from the statistical analysis of normal subjects [8].

6. CONCLUSION AND DISCUSSION

In this paper, we presented a practical method to map resection contour from post-surgery brain images to pre-surgery images based on landmark constrained conformal mapping. This framework and software tool allows surgeons to evaluate the result of the resection outcome even if the post-surgery brain largely differs in shape and size. An algorithm which can perform identification of resection contours is presented to make the procedure automatic. We also proposed an effective method to assess the agreement between functional PET



(a) (b)

Fig. 5. Experimental results. (a) Mapped ROI of Figure 3(e), whose inside triangular faces are all found and marked. (b) Mapped ROI of Figure 1(a), which is compared with PET abnormality (red region). Related statistical results can then be computed.

abnormalities and the extent of surgical resection. Further clinical evaluation is under investigation. Our next step is to advance the surface-based scheme to a full volumetric case, so that surgical evaluations can be done volumetrically.

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