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Feasibility of geometric-intensity based semi-automated delineation of the tentorium cerebelli from MRI scans

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Abstract

This paper describes a feasibility study of a method for delineating the tentorium cerebelli in MRI brain scans. The tentorium cerebelli is a thin sheet of dura matter covering the cerebellum and separating it from the posterior part of the temporal lobe and the occipital lobe of the cerebral hemispheres. Cortical structures such as the parahippocampal gyrus can be indistinguishable from tentorium in MPRAGE and T1 weighted magnetic resonance image scans. Similar intensities in these neighboring regions make it difficult to perform accurate cortical analysis in neuroimaging studies of schizophrenia and Alzheimer's disease. A semi-automated, geometric, intensity-based procedure for delineating the tentorium from a whole brain scan is described. Initial and final curves are traced within the tentorium. A cost function, based on intensity and Euclidean distance, is computed between the two curves using the Fast Marching method. The initial curve is then evolved to the final curve based on the gradient of the computed costs, generating a series of intermediate curves. These curves are then used to generate a triangulated surface of the tentorium. For three scans, surfaces were found to be within 2 voxels from hand-segmentations.

Keywords

tentorium cerebelli; parahippocampal gyrus; fast marching method

Introduction

Quantification of cortical thinning in magnetic resonance (MR) imaging scans of human brains is important in analyzing cortical structures affected in psychiatric and neurological disease [1-10] via methods emerging in Computational Anatomy [11-14]. However analysis

of cortical regions such as the parahippocampal gyrus (PHG) can be confounded by similar intensities in neighboring regions particularly in Magnetized Prepared Rapid Gradient Echo (MPRAGE) scans [15,16]. As indicated in the top row of Fig. 1, the PHG is close to the cerebellum and is separated from it by a membrane known as the tentorium cerebelli [cf. Figs. 87.D and 88. C-D in ref. 17,18]. Further, the bottom row of Fig. 1 shows that the tentorium does not appear clearly in all slices, and appears incomplete in places because at some places the physical size (thickness) of the tentorium less than the MR voxel size, the MR scanner partial voluming effect causes the tentorium voxels to be darker at those places; also, because the cerebrospinal fluid (CSF) space between the tentorium and the medial temporal lobe (MTL) gray matter is sometimes smaller than the MR voxel size, the tentorium voxels seem to be part of the MTL gray matter at those places [cf. Fig. 89.D in ref. 17].

Anatomically, the PHG is a grey matter cortical region of the brain that surrounds the hippocampus. It is a portion of the medial temporal lobe that is continuous with the cingulate gyrus and blends into the olfactory cortex. It is superior to the collateral sulcus and inferior to the subiculum.

Functionally, the PHG forms part of the cortico-limbic network said to be associated with memory [19], and plays an important role in memory encoding and retrieval. For example, activity in the posterior parahippocampal gyrus during encoding correlated very highly with long-term free recall of non-emotional words in a long-term incidental memory test [20]. PHG activity was found to distinguish subsequently remembered versus forgotten stimuli [21,22]. Consistent with these human brain imaging findings, animal research (particularly involving primates) has heavily implicated the PHG region in “declarative” memory formation [23].

Multiple studies have shown that this area is affected by schizophrenia and Alzheimer's disease (AD) [24-30]. For example, in schizophrenia subjects, a reduction of gray matter in this region has been found [31]. Decreased volume of the PHG has been found to be associated with deteriorating executive function through Stroop Test [32], verbal intelligence [33,34] and verbal memory [33]. In AD, the entorhinal and perirhinal cortices of the PHG are areas that show the earliest signs of AD pathology [35,36]. Further decreased volume of the PHG has been found to be associated with worsening of delayed recall performance on visual and verbal memory tasks [28], and worsening of immediate free recall performance [37].

Hence in order to correctly classify voxels as part of the PHG and find accurate cortical thickness measurements, it is necessary to correctly delineate the PHG and the cerebellum. Also for image-guided surgery, it is important to delineate the tentorium in hemispherotomy and other neurosurgical procedures [18,38-41].

With these objectives, we propose a semi-automated method to extract the tentorium. We first observe that the tentorium is a finely thin geometric structure. It stands to reason that if a set of geometrically consistent curves in one direction delineating the tentorium based on intensity could be generated we would be able to generate a geometric structure separating actual gray matter in the cortex from what might appear to be gray matter in the cerebellum. Recently such a geometric intensity based method was used to delineate blood vessels appearing bright in MPRAGE scans in ventral medial prefrontal cortical and subgenual regions [42]. We now extend this to the tentorium and demonstrate its potential and effectiveness.

The rest of the paper is as follows. Section 2 describes the semi-automated method for generating the tentorium surface, data acquisition of the MR scans, anatomical definitions

and the method for validating the generated surface. Section 3 describes results from simulation experiments, generation of the tentorium from three MR scans and validation results. Section 4 concludes the paper with a discussion.

Method

Generating the Tentorium

The method to delineate the tentorium from a whole brain MPRAGE scan by evolving curves consists of three steps. First, initial curves of the tentorium are generated in approximately every 10 coronal slices via a curve tracing algorithm using manually defined start and end points on the slice. Second, for each pair of successive initial curves a curve evolution procedure based on a 3D generalization of the curve tracing algorithm is used to evolve curves from one initial curve to the other. Third the curves are converted to a triangulated mesh delineating the tentorium surface. The rest of this subsection describes the algorithm in detail and may be skipped.

Step 1.1: Initial Curves—The first step is generating an initial curve and a final curve fully contained by the tentorium. This is modeled as a minimal path problem. A method to solve the minimal path problem was proposed for 2D problems by Cohen and Kimmel [43] and later extended to 3D by Deschamps and Cohen [44]. A cost function is defined inside the image such that the desired path is the minimum of the integral of the cost between the two end points. This minimal path problem has been very well studied and a number of solutions exist, such as the Dijkstra method or the Bellman-Ford method [45]. Dijkstra [46] solved the problem using dynamic programming and graph theory. Cohen and Kimmel [43] solved the problem by propagating a front between the two end points. This method has the advantage of being geometric, unlike the Dijkstra method, which is purely topologic.

We define a cost function for a curve $\gamma(s): [0, L_\gamma] \rightarrow \mathbf{R}^3$ with fixed extremities u and v by combining the intensities of the image along the curve with the Euclidean length of the curve as follows:

$$\int_{s=0}^{L(\gamma)} (|x_{|\gamma(s)|} - \mu|^\alpha + \omega) ds \quad (1)$$

where x is the gray-value intensity of the volume at the voxel being considered, $\gamma(0) = u$, $\gamma(L) = v$, $\gamma(s): [0, L_\gamma] \rightarrow \mathbf{R}^3$ is arc-length parameterized, $L(\gamma)$ is the Euclidean length of the curve and μ is the mean of the intensities along the tentorium. Here α was set to 0.5 which is a fairly small value, reflecting the fact that the distribution of intensities along the tentorium is fairly long tailed. ω is a smoothing term that prevents arbitrary long curves and is set to 1. The distance between two voxels is defined as the minimum value of Eq. (1) over all the curves having these voxels as extremities.

The Fast Marching algorithm is used to perform the front propagation, that is, compute the distance between an initial voxel and all the other voxels. To reduce computation time, the distance is calculated from the starting point, u , outward only until it reached the end point, v , as opposed to over the entire volume. That is, only a partial front propagation is performed. Once the start and end points are selected in a single plane (such as coronal), a curve is delineated.

Once the distance map has been calculated, the actual path is extracted. A gradient descent on the distance map from the end point is used to trace a path to the start point, which is a

global minimum of the distance function. There are several gradient descent methods that can be used. Following Deschamps and Cohen [44], a steepest gradient descent was chosen because it is easily implemented, consistent and accurate. Initial curves were done in single slices because it was easier to determine if the curve is fully contained in the membrane and computationally less expensive.

Since the method uses a gradient descent, there is no guarantee for global optimality. However, since there are other structures with similar grey level intensity values very close to the tentorium, local optimality is desirable. Algorithms with global optimality such as Li et al. [47] could be used instead. However, the regularity constraints therein are expressed as hard constraints, while in our case, soft constraints enforcing regularity is more appropriate.

This is repeated to generate a series of several initial curves in a given direction, approximately 10 slices apart. The automatic delineation of these initial curves provides a major gain in processing time; its efficiency was established for delineating blood vessels in MR scans [42].

1.2 Distance Maps—Each curve is an ordered series of discrete points. For each point in the starting curve, a distance map is computed. These distance maps are similar to the ones used to trace the initial curves as they are based on the same cost function. Unlike the above-mentioned distance maps, these are computed across the volume and not just single slices. Again, only a partial front propagation is performed. The distance map for each initial point is computed until all the points in the final curve are reached. Thus, for an initial curve with n points, we compute n distance maps to be used in the curve evolution step.

Step 2.1: Curve evolution - Correspondence—The next step is determining a correspondence between the points of the initial curve and the final curve. The initial curve is arc-length parameterized and the length from one end of the curve to each subsequent point is calculated. Then for each point on the initial curve, a point on the final curve is found with the same distance from the beginning point of the final curve, which is also arc-length parameterized. Once a correspondence has been determined, then each point of the initial curve is evolved towards the final curve.

Step 2.2 Curve evolution - Evolution—Each point of the initial curve is moved one step towards the final curve in each iteration of the method. This continues until each point of the initial curve is within one voxel of the final curve. The movement of the curve is determined by the gradient of the calculated distance map by the equation:

$$\gamma(s, t+1) = \gamma(s, t) - \frac{\nabla d(\gamma(s, t), \delta(u(s)))}{|\nabla d(\gamma(s, t), \delta(u(s)))|} \quad (2)$$

where $\gamma(s)$ is the curve being evolved, δ is the final curve, t is the iteration, and d is the distance map. The gradient of the distance map between the two corresponding points on the two curves is taken and normalized. This value is then subtracted from the current location of the point on the initial curve to determine the new location. To minimize computation time, gradients are computed only for the point of consideration. Once each point's new location is calculated, the points are redistributed.

Step 2.3: Curve evolution - Point Redistribution—To avoid the possibility of two points of a curve crossing over each other, two steps are taken. First, each point is only allowed to move a maximum of one voxel at a given time. This is ensured by the

normalizing the gradient at the point. Secondly, after each new curve is found, the points are redistributed. That is, a new set of points are selected to represent the curve. These points are a specified distance apart from each other, in our case, 5 voxels. The new points are determined by linearly interpolating between the originally calculated ones. Once the points are redistributed a new correspondence is found and the iteration continues until the final curve is reached.

Step 3: Completing the curves—After a set of curves is found, the tentorium is delineated as follows. The curves are only a set of ordered points and these points are several voxels away from each other. To fill in these voxels, a straight line is drawn from each point to the subsequent ones, and all voxels in between the two points are taken to be part of the tentorium.

The algorithm was implemented in Matlab Version 7.0 (MathWorks). The front propagation was accomplished using modified functions from the Fast Marching Toolbox [48].

Segmented voxels were used to generate a triangulated surface of the tentorium by triangulating adjacent curves from the anterior boundary to the posterior boundary. A nearest neighbor triangulation method [49] was used.

Data Acquisition

Three MR scans were collected on a 1.5-Tesla VISION system (Siemens Medical Systems). The MR scanning protocol included the collection of 4 high-resolution, 3D T1-weighted MPRAGE volumes: voxel resolution: $1\text{mm} \times 1\text{mm} \times 1.25\text{mm}$, TR: 9.7ms, TE: 4.0ms, flip angle: 10° , scan time: 6.5 min per acquisition. The MPRAGE scans for each subject were aligned with the first scan and averaged to create a low-noise image volume [50,51], which was then trilinearly interpolated into $0.5\text{mm} \times 0.5\text{mm} \times 0.5\text{mm}$ isotropic voxels to produce smoother intensity histograms for more accurate segmentation.

Anatomical Definition

To manually delineate the tentorium cerebelli, we follow Gray's Anatomy [p. 1210, 52]; see also [18] and Figs. 87.D, 88. C-D and 89.D in Duvernoy [17].

The tentorium cerebelli is a crescentic, tented sheet of dura matter covering the cerebellum and separating it from the posterior part of the temporal lobe and the occipital lobe of the cerebral hemispheres. The attachment of the falx cerebri to the midline portion of the tentorium cerebelli holds the latter up like the ridgepole of a tent. It has two leaflets, each having a concave, free edge. The edges outline a large hiatus of the tentorium cerebelli. This hiatus (incisure) is occupied by the midbrain and the anterior part of the superior surface of cerebellar vermis.

The peripheral outer limit of each leaflet is attached, from posterior to anterior, to the lips of the transverse sulci of the occipital bone, posterior-inferior angles of the parietal bones and superior borders of petrous temporal bones. At the anterior end of the tentorial hiatus and the petrous attachment, the tentorial fibers cross each other to be attached to the anterior and posterior clinoid processes, respectively. At this location, the two layers of the dura (the endosteal and the meningeal) split, forming the trigeminal cave which accommodates CSF and the root and ganglion of the trigeminal cranial nerve (Cranial Nerve Five, or CN V), on each side of the midline. The attached ends of the peripheral part of the tentorium harbors the transverse and superior petrosal sinuses. The attachment of the dura to the tentorium harbors the straight sinus.

In MR scans, it may not be possible to visualize the tentorium. But it can be identified in the three orthogonal views as a thin (sometimes discontinuous) membrane separating the structures as described above. This thin membrane is not part of any temporal, occipital lobe or cerebellar voxels.

Validation

The tentorium in the three brain scans were hand segmented according to the above definition. For brain 1, initial curves were taken from every 10th hand segmented curve and the algorithm was used to generate the curves delineating the tentorium surface. The generated surface was then compared with the hand segmentation. For brains 2 and 3, two experiments were performed to test the dependence of the algorithm on the initial curves, i.e. the rater. The first experiment was the same as that for brain 1. In the second experiment, an independent rater delineated initial curves on every 10th slice using his own knowledge of the tentorium (i.e. blind to the hand segmentation) and then ran the algorithm to generate the tentorium surface which was compared with the hand segmentation.

Validation was performed by computing surface-to-hand distances and hand-to-surface distances between the triangulated tentorium and the hand traced curves in 3D space. Surface-to-hand distance was calculated for each point on the surface, S , and defined as the distance to the nearest hand segmented voxel, H , i.e. for $\forall a \in S, dist(a) = \min_{b \in H} d(a, b)$, where $d(a, b)$ is the Euclidean distance between a and b . The cumulative distribution frequency (cdf) histogram of these distances is used to yield the 90th percentile distance; in addition the mean distance is also calculated. Hand-to-surface distances were also calculated analogously with respect each hand segmented voxel.

Results

Tentorium Generation

For each of the three brains, a total of 22 initial and final curves in the coronal direction were selected in each hemisphere, and the algorithm was run 42 times. The coronal direction was selected because the tentorium varies smoothly in the coronal direction in comparison with sagittal and axial directions, allowing for better performance of the algorithm. Each curve was 10 slices apart. Any voxel that at least one curve passed through was classified as tentorium. Evolving curves took approximately 3 to 5 hours. Generating the tentorium from one whole brain scan took approximately 2 days.

Figure 2 shows the tentorium surface viewed in three different directions. We believe that this is the first time the “tent-like” structure of the tentorium has been generated in 3D. Figure 3 shows the coronal view of the tentorium surface in comparison with the expert hand segmentation for the three brains.

Validation

Figures 2-3 suggest that the generated tentorium is close to the hand segmented curves. Table 1 shows that for the entire tentorium in brain 1, 90% of the hand segmented voxels were within 1.08 mm of surface vertices and 90% of the surface vertices were within 0.88 mm of the hand-segmented voxels. Table 1 shows that for brains 2 and 3, the 90th percentile distances were larger when a naïve rater generated the initial curves. Table 2 show similar results are shown for the mean distances. It was observed that the distances increased and decreased in coronal slices between initial curves reaching a maximum about half-way between initial curves. This suggests that additional initial curves perhaps between every five slices would result in a more accurate surface at the expense of greater computational time.

Discussion

We have described a semi-automated method for delineating the tentorium cerebelli. To demonstrate feasibility, we generated three sets of manual segmentation to compare with the semiautomatically generated surfaces. The manual segmentation took approximately 3-4 hours per brain, covering the full extent of the tentorium. In the semi-automated method, it took 20 minutes for a trained rater to manually draw the initial curves in every 10 coronal slices in both hemispheres, a 10-fold reduction in manual labor time. For the three brains, generated surfaces were found to be within 2 voxels from hand-segmented based on surface-to-hand and hand-to-surface distances. Even though maximal differences of within 2 voxels is considered acceptable [e.g. ref. 53], we expect greater improvement with additional initial curves.

We consider several methodological issues. The first one is that generating a tentorium surface is computationally intensive. Typically for each side in a whole brain scan, the algorithm takes 8-12 hours to evolve the manually drawn initial curves. This is probably because computing the distance maps in the Fast Marching Toolbox is memory intensive, and a more efficient algorithm based on a Graphics Processing Unit (GPU) could be developed in the future. Since the manual labor time has been reduced ten fold, the rater can draw the initial curves in all the brains, and then let the algorithm compute the surface overnight. Second, initial curves are manually delineated. Where the tentorium appears discontinuous or completely blended with the cortical gray matter voxels in the MR image, the rater is required to apply subjective judgment. Reliability needs to be further studied. As a result, we need to investigate how much the automated curves are dependent on the placement of the manually-drawn initial set of curves, and whether the relationship between the variability in the automated curves and the variability in initial curve. Third, increased MR resolution is desirable, and may be achieved by high-field MR scanning, or partial-coverage (eg, the medial temporal lobe region) with multiple-acquisition averaging to increase signal-to-noise in smaller voxels. Finally, a generic tentorium surface used as a prior may also overcome problems where the tentorium is not readily discernable in the MR scan.

Finally the procedure can be used to delineate the tentorium in smaller subvolumes. Figure 4 shows how the tentorium is separated from the adjacent cortical structures such as the PHG in smaller subvolumes of two single scans from a recent study [54]. Notice that the cerebellum is clearly separated from the PHG and neighboring structures. Thus we expect to obtain reliable estimates of cortical thickness of the PHG and neighboring structures in neuroimaging studies of schizophrenia and Alzheimer's Disease.

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Figure 1.

Top: Coronal (left) and sagittal (right) views of the thin space separating medial temporal lobe gray matter (e.g., PHG, yellow arrow) and non-cortical tissue (e.g., cerebellum, green arrow). **Bottom:** Coronal (left) and sagittal (right) view of tentorium voxels that are visible, marked in red.

Figure 2.

Top: Axial, coronal and sagittal overlays of automatically generated tentorium surface (light blue) and hand segmented tentorium (white) for brain 1. **Bottom:** 3D rendering of generated tentorium surface (dark blue) and hand segmented tentorium (gray contour lines). Orientation is indicated by the orthogonal axes (red – sagittal, green – axial, yellow – coronal).

Figure 3.

Posterior (top), medial (middle) and anterior (bottom) coronal views of automatically generated (light blue) and hand segmented (white) tentorium in brains 1, 2 and 3 respectively: Brain ID and coronal slice are indicated by the first and second numbers respectively.

Figure 4. Coronal (left column) and sagittal (right) views of tentorium generated (blue) in two different subvolumes containing the PHG: data from Ratnanather et al. [54].

90th percentile distances between automated and hand segmented tentorium. HS represents distances between hand segmented voxels and automated surface while SH represent distances between automated surface and hand segmented voxels. OIC and XIC indicate distances with only and without initial curves respectively. Blind and Hand indicate the naively and expertly drawn initial curves respectively. Distances are in mm

		Brain 1		Brain 2		Brain 3	
		Hand	Blind	Hand	Blind	Hand	Blind
OIC	HS	0.73	1.87	0.70	2.18	0.71	2.18
XIC	HS	1.11	1.97	1.06	2.08	1.08	2.08
ALL	HS	1.08	1.96	1.03	2.09	1.05	2.09
ALL	SH	0.88	1.70	0.84	1.66	0.86	1.66

Table 2
Mean distances between automated and hand segmented tentorium. HS represents distances between hand segmented voxels and automated surface while SH represent distances between automated surface and hand segmented voxels. Blind and Hand indicate the naively and expertly drawn initial curves respectively. Distances are in mm

		Brain 1		Brain 2		Brain 3	
		Hand	Blind	Hand	Blind	Hand	Blind
ALL	HS	0.56	1.07	0.54	1.10	0.55	1.10
ALL	SH	0.46	0.90	0.43	0.88	0.44	0.88