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Original Article

Intrinsic Profile Analysis of Intracranial Cerebrospinal Fluid

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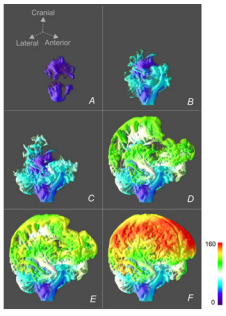
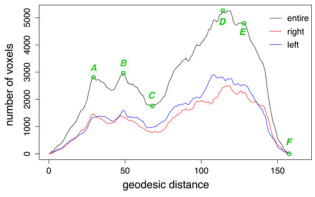
Highlights

- An intrinsic profile of the intracranial subarachnoid space is presented.
- Intrinsic profiles are analyzed for characterizing healthy and pathological cases.
- Experiments on healthy adults and hydrocephalus patients are shown.

Graphical abstract



Thresholded geodesic distance map of intracranial cerebrospinal fluid



Intrinsic profiles of the entire sphere and the left and right hemispheres with significant thresholds

Abstract

Purpose: We aim at studying intrinsic structures of the intracranial subarachnoid space.
Material and methods: Magnetic resonance images were obtained using the SPACE sequence, and the segmentation of the superior intracranial subarachnoid space was performed using geometrical features and a topological assumption of the shapes. Given such segmentation results, we present a method based on a geodesic propagation technique, which allows us to make an intrinsic profile of the space. Intrinsic profiles are then analyzed qualitatively and quantitatively, in particular for classification into healthy and pathological cases based on their intrinsic bilateral asymmetry and histogram moments.
Results: The proposed method was applied to a clinical dataset of 15 subjects, of which 7 were healthy volunteers and 8 were hydrocephalus patients. The intracranial cerebrospinal fluid is not (intrinsically) bilaterally asymmetric for healthy volunteers, while hydrocephalus would cause asymmetry. We also observed that the results of a two-class classification (healthy or not) based on histogram moments were suitable; sensitivity, specificity and precision are all 100%.
Conclusions: The effectiveness of the proposed method of intrinsic profiling analyses is shown by preliminary experiments on healthy adults and hydrocephalus patients.

Keywords: Intracranial subarachnoid space; Geodesic propagation; Intrinsic shape analysis; Classification

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1. Introduction

The central nervous system is surrounded by cerebrospinal fluid that is contained within the cerebral ventricles and subarachnoid space [1,2]. The observation of cerebrospinal fluid plays a valuable role in the clinical diagnosis of brain disorders such as hydrocephalus and Alzheimer's disease [2–4]. One example is hydrocephalus, which usually results from obstructed fluid outflows in the ventricles or subarachnoid space that leads to an alteration in fluid volumes [3]. Therefore, confirmation of changes to fluid volumes can help in its diagnosis [5]. The fluid distribution and the network of intracranial subarachnoid space were also explored using the volumetric relief map [6], and their bilateral symmetry and asymmetry were observed for healthy adults and patients, respectively.

In this article, we extend this study and expound a method based on a geodesic propagation technique to obtain not only global information but also more local shape information. Geodesic distances have been lately used in many shape processing applications, such as shape classification [7], recognition [8], retrieval [9], and symmetry detection [10], especially for articulated shapes, thanks to the robustness to shape variations by non-rigid deformations. Indeed, there exist shape variations of the human body by non-rigid deformations due to individual variation and asymmetry [11]. Here, we present a simple method based on geodesic distances to study intrinsic structures of the intracranial subarachnoid space.

Concretely, we observe geodesic propagation from specific fluid sources, which correspond to the ventricular space outputs, which are symmetrically located nearly at the brain center and can be detected due to the specific shapes. To analyze such propagation, we propose to use a geodesic propagation histogram, which allows us to make an intrinsic profile of such space. Intrinsic profiles are then analyzed qualitatively with the help of two visualization tools: 3D volume rendering and 2D volumetric relief map [6]. They allow us to understand how the geodesic propagation is made in the intracranial subarachnoid space, and thus to detect key distances where the manner of propagation evolution changes. For the quantitative analysis, a simple but effective method for detecting the bilateral intrinsic asymmetry using a geodesic histogram correlation is proposed. As a complement, classification into healthy and pathological cases based on histogram moments is also made.

The effectiveness of the proposed method is shown by preliminary experiments on healthy adults and hydrocephalus patients.

2. Material and methods

2.1. MRI data and pre-segmentation

Magnetic resonance images were obtained using the SPACE sequence described in [12] and had an isotropic voxel resolution of 1 mm. The segmentation of the superior intracranial subarachnoid space was performed based on the method given in [5], which guarantees the connectivity of the segmented volume. More precisely, the cerebrospinal fluid was first pre-segmented using geometrical features and a topological assumption of the shapes [5] and then the intracranial subarachnoid space was extracted [5]. Given such a fluid volume, we first present a geodesic propagation technique for generating its intrinsic profile, and then propose several methods for analyzing those intrinsic profiles.

2.2. Geodesic propagation in the cerebrospinal fluid

Regarding image voxel centers as 3D regular grid points $\mathbb{Z}^3$, each voxel at $\mathbf{x} \in \mathbb{Z}^3$ is represented by the closed grid cube $\Omega(\mathbf{x}) = \mathbf{x} + [-\frac{1}{2}, \frac{1}{2}]^3 \subset \mathbb{R}^3$. Given a pre-segmented voxel set $V \subset \mathbb{Z}^3$, let us consider the union of voxels whose centers $\mathbf{x}$ are in V, *i.e.*, $\Upsilon(V) = \cup_{\mathbf{x}\in V} \Omega(\mathbf{x}) \subset \mathbb{R}^3$.

Now we define a (piecewise) smooth curve γ in the region $\Upsilon(V)$ with a parameter $t \in [0, 1]$ such that $\gamma(0) = \mathbf{u}$ and $\gamma(1) = \mathbf{v}$. The length of γ is then defined as

$$L(\gamma) = \int_0^1 \|\gamma'(t)\| dt$$

where $\gamma'(t)$ is the derivative of γ.

Let $\Pi(\mathbf{u}, \mathbf{v})$ be the set of all the curves in $\Upsilon(V)$ between $\mathbf{u}$ and $\mathbf{v}$. Then, the geodesic distance between $\mathbf{u}$ and $\mathbf{v}$ in V is defined by

$$d_V(\mathbf{u}, \mathbf{v}) = \min_{\gamma\in\Pi(\mathbf{u},\mathbf{v})} L(\gamma).$$

The curve that has the minimum length is called the "shortest path."

Let S be the set of fluid sources located in the voxel set V. Let us now consider for each $\mathbf{v} \in V$ the geodesic distance $d_V(\mathbf{s}, \mathbf{v})$ from a source $\mathbf{s} \in S$. Given a fluid source set S, we can then define the minimum geodesic distance

$$Dis_V^S(\mathbf{v}) = \min_{\mathbf{s}\in S} d_V(\mathbf{s}, \mathbf{v})$$

for each voxel $\mathbf{v} \in V$. The map Dis_V^S is called a geodesic distance map of V for S. To compute this map, we apply the fast marching method based on front propagation presented in [13], which is an efficient one-pass algorithm similar to the Dijkstra algorithm [14].

One of the critical issues in the analysis of fluid propagation pathways using such geodesic propagation technique is to set the fluid source S. We set our source S at the outputs of the ventricular space, which are symmetrically located nearly at the brain center and, in practice, detectable due to the specific shapes. This source location is important to obtain the intrinsic profile that preserves the shape symmetry of a fluid volume V (if there is). Concerning the detection of S, a practical technique is explained, for example, in the next experimental section. Such fluid sources are called seeds for the geodesic propagation procedure.

2.3. Intrinsic profiling of intracranial cerebrospinal fluid

Once a geodesic distance map Dis_V^S is calculated for a fluid volume V from a given source set S, the histogram is defined by