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3D shape analysis of the brain's third ventricle using a midplane encoded symmetric template model

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ABSTRACT

Background: Structural changes of the brain's third ventricle have been acknowledged as an indicative measure of the brain atrophy progression in neurodegenerative and endocrinal diseases. To investigate the ventricular enlargement in relation to the atrophy of the surrounding structures, shape analysis is a promising approach. However, there are hurdles in modeling the third ventricle shape. First, it has topological variations across individuals due to the inter-thalamic adhesion. In addition, as an interhemispheric structure, it needs to be aligned to the midsagittal plane to assess its asymmetric and regional deformation.

Method: To address these issues, we propose a model-based shape assessment. Our template model of the third ventricle consists of a midplane and a symmetric mesh of generic shape. By mapping the template's midplane to the individuals' brain midsagittal plane, we align the symmetric mesh on the midline of the brain before quantifying the third ventricle shape. To build the vertex-wise correspondence between the individual third ventricle and the template mesh, we employ a minimal-distortion surface deformation framework. In addition, to account for topological variations, we implement geometric constraints guiding the template mesh to have zero width where the inter-thalamic adhesion passes through, preventing vertices crossing between left and right walls of the third ventricle. The individual shapes are compared using a vertex-wise deformity from the symmetric template.

Results: Experiments on imaging and demographic data from a study of aging showed that our model was sensitive in assessing morphological differences between individuals in relation to brain volume (i.e. proxy for general brain atrophy), gender and the fluid intelligence at age 72. It also revealed that the proposed method can detect the regional and asymmetrical

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deformation unlike the conventional measures: volume (median 1.95 ml, IQR 0.96 ml) and width of the third ventricle. Similarity measures between binary masks and the shape model showed that the latter reconstructed shape details with high accuracy (Dice coefficient ≥0.9, mean distance 0.5 mm and Hausdorff distance 2.7 mm).

Conclusions: We have demonstrated that our approach is suitable to morphometrical analyses of the third ventricle, providing high accuracy and inter-subject consistency in the shape quantification. This shape modeling method with geometric constraints based on anatomical landmarks could be extended to other brain structures which require a consistent measurement basis in the morphometry.

1. Introduction

The brain's third ventricle lies in the center of the brain and is surrounded by critical nuclei structures (i.e. hypothalamus and thalamus) that are often affected by dementia. Also surrounding them are important glandular structures (i.e. pituitary and pineal glands) that regulate homeostasis and affect seasonal functions. Therefore deformations or atrophy surrounding this cavity have been acknowledged as an indicative measure of atrophy progression in certain neurodegenerative (e.g. some subtypes of dementia and multiple sclerosis) and endocrinal diseases [1–5]. Recently, the third brain ventricle has been identified crucial in the early detection of Alzheimer's Disease [6], in the diagnosis of various movement disorders like progressive supranuclear palsy and Parkinson's Disease [7], and in the identification of various disorders in children like asymptomatic interhypothalamic adhesions [8] and craniopharyngiomas [9]. Moreover, knowledge of the brain third ventricle morphology is useful in investigating the presence of lesions around the intraventricular foramen, which are difficult to surgically remove for their important adjacent structures, helping to choose the appropriate surgical approach [10].

Due to its clinical importance, several methods have been proposed to assess the shape and volume of the third ventricle. To the best of our knowledge, clinical studies related to the enlargement of the third ventricle have specifically reported data based on either its volume or some direct measurement (e.g. diameter) obtained only from a particular MRI slice [2,5,11]. The volume of the third ventricle has been used in studies of brain aging [12], schizophrenia [13,14], brain development [15], bipolar affective disorder [11,16], and multiple sclerosis [3]. However, volumetric analysis has difficulty revealing the association between regional changes in ventricle structure and clinical factors. To investigate the ventricular enlargement at specific regions where the third ventricle meets the surrounding structures, a manual measurement of the width between the left and right lateral walls of the third ventricle has been proposed [2,3,5,11,17]. But manual measurements are susceptible to human errors. Also, variability in the assessment of the third ventricle makes reproducibility and protocol comparability difficult. For example, one study measured the third ventricle width on the coronal slice immediately posterior to the last slice where the anterior commissure was clearly visible [11]. In other studies, the third ventricle width has been measured by drawing a line perpendicular to the midline of this structure at an axial slice where it is most visible [2,18]. Authors who have referred to the width of the brain third ventricle being assessed indistinctively on a coronal or axial slice, mention inter- and intra-operator variations and the different positions of the imaged head as causes for the low reproducibility of their results [18].

Against the limitations of the third ventricle measurements just mentioned, the morphological analysis using parameterized shape models can be an alternative. There is increasing evidence that shape analysis provides useful information in the analysis of pathological and aging processes [19–23]. A study [24] presented a third ventricle shape registration method based on a heat-kernel representation. In shape analysis, the achievement of biologically meaningful shape representations, robustness to noise and small perturbations, and the ability to capture representative properties of the natural biological shape variation [25] are necessary challenges to overcome. In addition, shape modeling of the brain third ventricle is challenging due to the following reasons. First, the small size of the third ventricle and the low contrast of the membranes that separate this cavity from its surroundings yield rough surface boundaries in the segmentations and complicate the anatomical quantification of its morphology from the magnetic resonance (MR) images (Fig. 1(a)). Secondly, the topological inter-individual variations in the third ventricle, especially the presence/absence of the inter-thalamic adhesion (IA), which bridges the left and right thalami across the third ventricle, makes it difficult to assure shape correspondence between the third ventricle surfaces across individuals (Fig. 1(b)). Lastly, the third ventricle is surrounded by different brain structures, such as hypothalamus and thalamus, in the left and right hemispheres of the brain. Atrophy of the surrounding structures may change the shape and size of the third ventricle, and consistency in the anatomical landmarks is required to quantify its morphological changes in relation to the anatomical positions of the surrounding structures.

1.1. *Our proposal*

In this paper, we propose a novel approach to generate a 3D shape model of the brain third ventricle out from binary masks of this structure obtained from structural MR images. We endeavor that our model guarantees good inter-subject