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# Automatic Morphometry of Normal Cerebral Ventricular Dimensions from MRI

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The volume, shape and size of cerebral ventricular system may change due to various pathologies directly or indirectly. Estimation of size of cerebral ventricles is important for evaluating changes due to growth, aging, intrinsic and extrinsic pathologies. Quantification using *ex vivo* techniques has considerable errors. *In vivo* studies using air or contrast media also introduce volumetric changes in the ventricles. Imaging of ventricular anatomy avoids these problems and allows repetitive studies following progression of ventricular system changes due to disease or natural processes. We have developed a methodology for automated extraction of ventricular system from magnetic resonance imaging. Once extracted, landmarks are located on the surface of ventricular system automatically. These landmarks are then used for calculation of the ventricular shape, volume and size. A total of 30 cases were analyzed. Physical dimensions of normal ventricles are presented in this paper.

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## Introduction

Human cerebral ventricles are filled with cerebrospinal fluid and have a peculiar morphology and size. Ventricles may change in volume and shape due to intrinsic or extrinsic pathologies and have been a subject of measurement by researchers and clinicians. Both *in vivo* and *ex vivo* attempts have been made to quantify ventricular shape and volume. Most of the measurements of ventricles reported in literature have been on postmortem studies or pneumoencephalograms that may distort the actual configuration of the ventricles due to deformation of slices during sectioning or introduction of external agents in the ventricles.[1-4] With the advent of magnetic resonance imaging (MRI), volumetric datasets are routinely acquired for studies of normal and abnormal human brain. Considerable efforts have been made for the quantitative analysis of ventricular spaces from MRI data. The ventricular system shows such size variation in normal population that it is difficult to make any precise measurements that can be deemed as a normal value.

A key issue in all of these clinical studies is the method used to quantify ventricular system in MR images. The majority of clinical studies rely on the visual, qualitative, or semiquantitative grading of ventricular features by experienced raters. Ventricular volumes have been estimated by 3D ultrasonography and MRI in various diseases.[5-7] These methods lack the accuracy required for longitudinal studies. Also with the data explosion, it is nearly impossible for clinicians to manually analyze the amount of data produced by modern MRI acquisition sequences. It is imperative that an automated system is developed to do the task of morphometry more efficiently by using computer-aided, quantitative image segmentation techniques. Although a number of methods have been proposed for the segmentation of MR images, only a few researchers have focused specifically on the quantitation of ventricular system.[8,9] In order for these techniques to become clinically acceptable tools, the accuracy and reliability of the obtained results must be demonstrated.

## Materials and Methods

A total of 30 MRI studies were analyzed. All the subjects were healthy volunteers who underwent high resolution brain spoiled gradient-recalled acquisition (SPGR) (repetition time (TR) =45 milliseconds; echo time (TE) =2.3 milliseconds) MRI studies at 2 centers (1 in Japan and 1 in Singapore). Whole brain 3D volume data were acquired with the voxel size less than 1 $mm^3$. The data were reformatted with axial slices in the anterior-posterior commissure (AC-PC) plane. No preprocessing of data was done. The volunteers ranged

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from 25 to 35 years of age, and included 10 females and 20 males; 10 Chinese, 14 Japanese, 4 Indians and 2 Caucasians.

A knowledge-driven algorithm for rapid, robust, accurate and automatic extraction of the cerebral ventricular system from MR neuroimages has been developed by us previously.[10,11] Its novelty is in combination of neuroanatomy, radiological properties and variability of the ventricular system with image processing techniques. The ventricular system is divided into six 3D regions: bodies and inferior horns of the two lateral ventricles, third ventricle, and fourth ventricle. Within each ventricular region, a 2D region of interest (ROI) is defined based on the studies of anatomy and variability (Figure 1). The distribution histogram of radiological properties is calculated in each ROI and is modeled as a mixture of 5 Gaussian distributions; the least square method was used for estimation. The intensity ranges of cerebrospinal fluid (CSF), grey matter (GM), and white matter (WM) for extracting each region are automatically determined, and are moderated adaptively during extraction of the ventricular system to cope with the partial volume effect and intensity inhomogeneity. A seed point pixel is located within the ROI, and pixels surrounding this seed point pixel are compared to it. If the pixel intensity values are within a certain threshold level then these surrounding pixels are recruited as a region and pixels next to them are analyzed. In this way a region is grown in three dimensions till a border of pixels with intensity higher than the threshold are reached. These pixels form the boundary of the region. Detection and control conditions for leakage are formulated and embedded into the method, so that it can handle the partial volume effect causing "leakages" from the ventricles to the extraventricular space. The extraction method is designed to include all ventricular parts, even if they appear unconnected on the images.[11] The method is fully automatic and takes less than 5 seconds to be executed on a Pentium 4 2.0 GHz PC. The user interface is very simple and after reading the study in the memory a single click would extract the whole ventricular system (Figure 2). Surface rendered, detailed and interactive image of the ventricle can be obtained for more detailed study (Figure 3).

The method has been validated on 68 MRI studies previously. The extracted ventricular volume was compared with one manually extracted by a radiology expert (AA). We used the overlap metric analysis[12] for estimating the efficiency of the computational method against the radiology expert's opinion. The mean and the standard deviation of the overlap metric between the results of a radiology expert and our method were 0.9723 and 0.01087, respectively.[11]

After the extraction of the ventricular system, anatomical landmarks are identified automatically. Analysis of landmark locations has been used in applications such as computer-assisted neurosurgery,[13] MRI-based morphological analyses of whole brain,[14] landmark-based

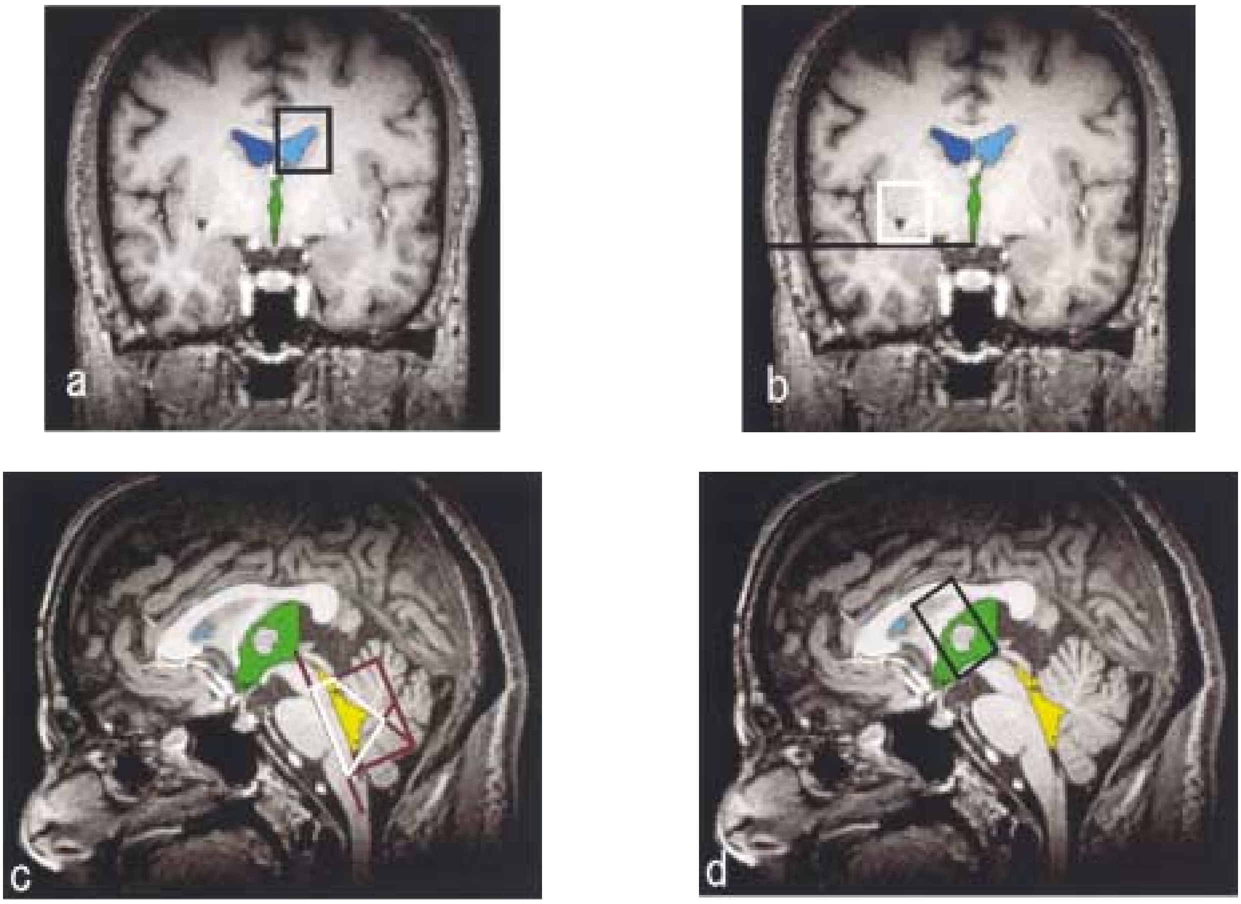


**Figure 1.** Region of interest set for (a) the body, (b) the temporal horn of the lateral ventricle, (c) the fourth ventricle and (d) the third ventricles.

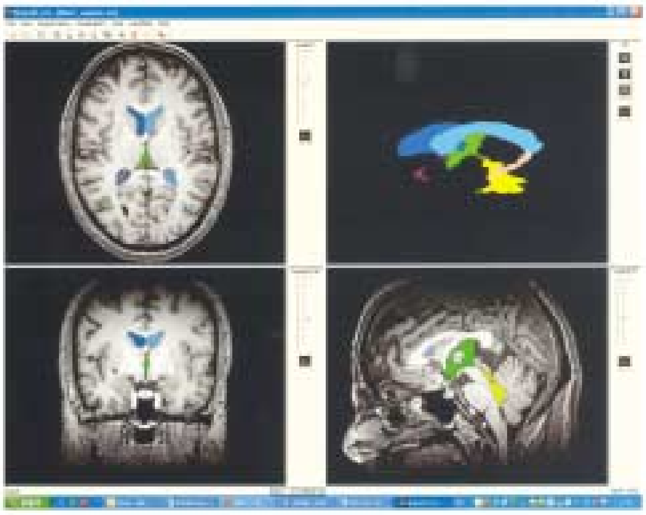

**Figure 2.** The ventricular extraction software showing the axial, coronal and sagittal images with extracted ventricles in different colors, and 3D image of the extracted volume of ventricular system.

**Figure 3.** 3D surface rendered image of the extracted ventricles.

registration and measurement of MRI,[15] and in the assessment of psychiatric disorders.[16]

We defined various landmarks on the ventricles relative to a coordinate system in 3D space with the images in conventional radiological position; the x-coordinate running from subject's right to left, y-coordinate from anterior to posterior, and z-coordinate from superior to inferior. Thus, x-z plane is coronal, y-z plane is sagittal, and x-y plane is axial (parallel to the AC-PC line). There were 14 pairs of landmarks for lateral ventricles (8 pairs on coronal and 6 pairs on axial planes), 5 landmarks for third ventricle (2 on the axial and 3 on the midsagittal planes), and 6 landmarks for fourth ventricle (1 pair on the axial and 4 on the midsagittal planes). The distance is automatically calculated between various landmarks for lateral ventricles (Figure 4), third ventricle (Figure 5) and fourth ventricle (Figure 6), giving the dimensions of the ventricles in pixels and millimeters. The volume is estimated by counting the voxels in the extracted region. The aqueduct of Sylvius was also measured in its length and diameter.

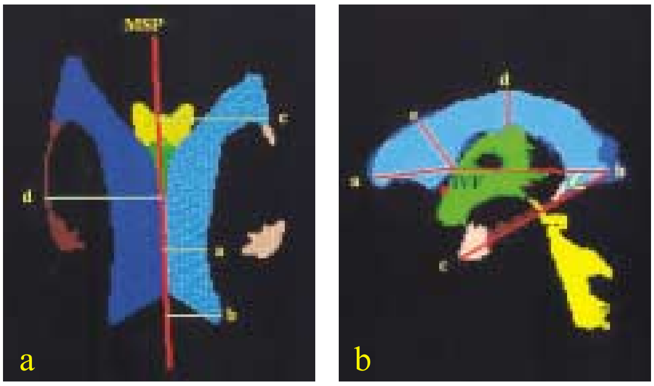


**Figure 4.** Dimensions of the lateral ventricles: (a) axial view (MSP: midsagittal plane; MSP-a: maximal spread of the body; MSP-b: maximal spread of the anterior horn; MSP-c: maximal spread of the posterior horn; MSP-d: maximal spread of the temporal horn); (b) sagittal view (IVF: interventricular foramen; IVF-a: length of the anterior horn; IVF-b: length of the posterior horn and body; a-b: total length of lateral ventricle; b-c: length of the inferior horn; d: thickness of the body; IVF-e: height of the body).

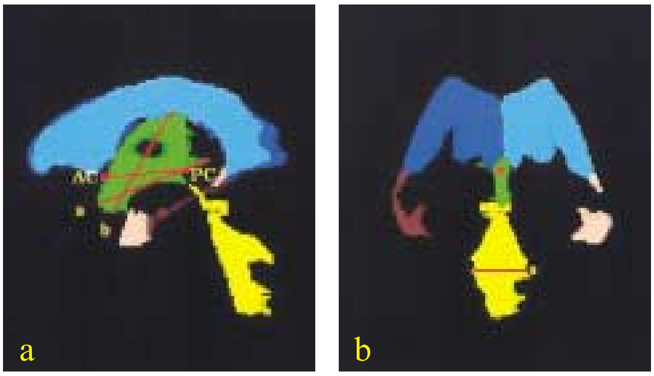


**Figure 5.** Dimensions of the third ventricle: (a) sagittal view (AC: anterior commissure; PC: posterior commissure; AC-PC: axial length; a: maximal length; b: maximal height); (b) coronal view (a: maximal width; b: maximal height in the coronal plane).

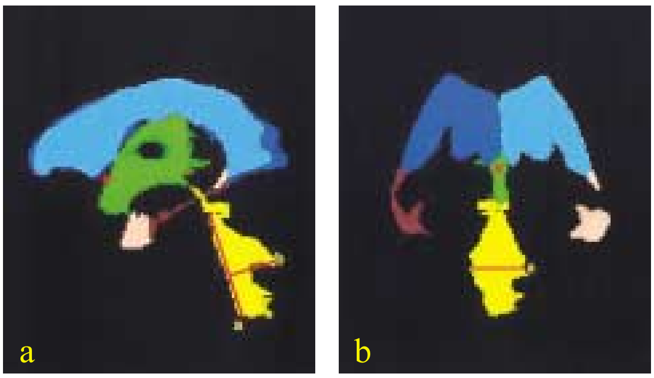


**Figure 6.** Dimensions of the fourth ventricle: (a) sagittal view (a: length of the floor; b: maximal height from floor to festigium); (b) coronal view (a: maximum breadth).

## Results

All the measurements were performed automatically without any human intervention. The algorithm calculated the distances between the landmarks, and with scan parameters known from the DICOM header files, the distances were converted from pixels to millimeters, and volumes were converted from voxels to cubic centimeters. It was assumed that there was no distortion of the images, or that if any it had been adjusted by quality control procedures for the MRI scanners.

*Lateral ventricles*

The two lateral ventricles are complicated in shape but the algorithm segmented them successfully. The distances between various landmarks were calculated and are presented in Table 1. The right lateral ventricle was slightly larger than the left one (10,077 and 9,849 mm$^3$, respectively) with more prominent difference in overall antero-posterior length (97 and 93 mm, respectively). The total volume was calculated by counting the extracted voxel for the ventricles and adjusting it for the voxel dimensions. The antero-posterior length is the distance between the anteriormost point on the anterior horn and the posteriormost point on the occipital horn of the lateral ventricle. The anterior horn length is the distance between the anteriormost point of the anterior horn to the interventricular foramen while the posterior horn length is the distance from the posteriormost point of the occipital horn to the interventricular foramen. The maximal spread of the parts of ventricles is the horizontal distance between the mid-sagittal plane (MSP) and the lateralmost points of those parts (body, anterior, posterior and temporal horns).

*Third ventricle*

The volume of the third ventricle varied from 639 to 1,735 mm$^3$ with the average of 1,038 mm$^3$. The width, height and length of the third ventricle also varied much as shown in Table 2.

*Aqueduct of Sylvius*

The aqueduct was also measured. Its overall length varied between 4 and 22 mm with the average length of 14 mm. The angle between aqueduct and the AC-PC plane was between 27 and 61 degrees with the average of 41 degrees. The area of the cross section of the aqueduct varied from 1.3 to 8 mm$^2$ with the mean of 5 mm$^2$ (Table 3).

*Fourth ventricle*

The fourth ventricle was much more complicated and was difficult to measure. The measurements are summarized in Table 4.

**Table 1.** Measurements of parameters of lateral ventricles

| Parameter | Mean±standard deviation, Minimum-Maximum | |
|---|---|---|
| | Left ventricle | Right ventricle |
| Volume (mm$^3$) | 9,849±1,283, 8,795-10,609 | 10,077±1,561, 8,774-10,981 |
| Antero-posterior length (mm) | 93±27, 77-115 | 97±32, 79-125 |
| Anterior horn length (mm) | 33±11, 27-43 | 33±7, 28-36 |
| Posterior horn length (mm) | 67±21, 54-83 | 70±37, 47-100 |
| Maximum superoinferior thicknees of body (mm) | 11±10, 6-20 | 12±11, 6-22 |
| Maximum spread of the anterior horns (mm) | 17±6, 13-21 | 19±4, 17-22 |
| Maximum spread of the bodies (mm) | 15±6, 11-19 | 17±6, 13-22 |
| Maximum spread of posterior horns (mm) | 37±6, 32-40 | 37±8, 32-43 |
| Maximum spread of temporal horns (mm) | 37±6, 34-43 | 37±7, 30-40 |
| Total volume of both lateral ventricles (mm$^3$) | 20,726±2,840, 17,569-21,590 | |

**Table 2.** Measurements of parameters of the third ventricle

| Parameter | Mean±standard deviation, Minimum-Maximum |
|---|---|
| Volume (mm$^3$) | 1,038±775, 639-1,735 |
| Antero-posterior length (mm) | 34±14, 25-45 |
| Superioinferior length (mm) | 22±8, 16-27 |
| Lateral width (mm) | 7±5, 4-11 |

**Table 3.** Measurements of parameters of the aqueduct of Sylvius

| Parameter | Mean±standard deviation, Minimum-Maximum |
|---|---|
| Total length (mm) | 14±13, 4-22 |
| Angle making with AC-PC plane (degree) | 41±24, 27-61 |
| Largest cross sectional area (mm$^2$) | 5±4, 1.3-8 |

**Table 4.** Measurements of parameters of the fourth ventricle

| Parameter | Mean±standard deviation, Minimum-Maximum |
|---|---|
| Volume (mm$^3$) | 1,676±1,101, 1,032-2,599 |
| Height (mm)[a] | 10±4, 7-13 |
| Length of the floor (mm) | 29±13, 19-37 |
| Maximum width at the body (mm) | 12±3, 11-15 |
| Height of the posterior recesses (mm) | 16±7, 11-21 |

[a]From floor to the festigium.

## Discussion

Morphometry and accurate measurements of the cerebral ventricles is an important clinical problem as various diseases affect the size and morphology of the ventricles. We propose a computational method for automatic extraction of the ventricular system that has been validated qualitatively and quantitatively. The mean and standard deviation of the overlap metric between the computational extraction and that by a radiology expert were 0.9723 and 0.01087, respectively.[11] This entails that the automatic ventricular extraction algorithm is of high fidelity and can be trusted as to represent the ventricular system without any major distortions. The algorithm is fast to execute regardless of the complexity of the ventricular system and severity of leakages, with no intervention required.

The dimensions of the ventricles measured by our algorithm generally did not differ much from those quoted in the literature,[1-3] although the reference values available in literature are calculated by invasive studies that may distort or disfigure the ventricles in the process of measurements (postmortem changes, distortion while sectioning, air or contrast material introduced in the ventricles may change the volumes).

The lateral ventricles are the largest and the dimensions are more or less constant. The volume calculated for right ventricle (10,077 mm$^3$) is slightly larger than that calculated for left one (9,849 mm$^3$). These volumes are closer to those measured previously.[1] Our data, however, are in contrast to the previously published data that the left ventricle is larger than the right.[17] In our study the right ventricle appears to be consistently larger. This might be due to right handedness of the majority of our population.[18] In all the other measurements, there was no major difference in the right or left sides or between our values and those mentioned in the literature. The total volume of the lateral ventricles has been calculated as 22.4 mL[1] and 21.2 mL[19] in the literature and our value of 20.73 mL is close to these values.

The third ventricle is complex in shape and the variability in its dimensions is even larger. The volume of the third ventricle as calculated by our algorithm (1.04 mL) is not much different from that mentioned in the literature.[20] The width of the third ventricle is the most important parameter and has been measured in various studies, ranging from 2 to 15 mm in normal individuals. Our values of 4 to 11 mm with a mean of 7 mm fall well within this range. We have also calculated the length and height of the third ventricle, which have not been mentioned in the literature.

The aqueduct also varies in length and dimensions. The definition of starting and ending points of aqueduct varies in literature. The length of 14 mm as calculated by us falls in the range of 13 to 18 mm quoted in the literature.[4] The angle we calculated (between the length of aqueduct and the AC-PC plane) is more realistic to imagine and easier to calculate than the "ventricular angle" mentioned in the literature.[4] We have also calculated the area of cross section since we can see the ventricles in three dimensions and can calculate any distance as opposed to limited projections of radiography.

The fourth ventricle is complex in shape and is difficult to measure. We have devised landmarks that would grossly describe the dimensions of the fourth ventricle in three dimensions. The height as measured by us is 10 mm, which differs from those mentioned in the literature; however the height measured from encephalograms[21] is not different much from ours. The floor length[4] also does not differ from our study. The volume as calculated by us (1.68 mL) is larger than that mentioned in the literature[4] (0.85 mL). This may be due to the fact that postmortem studies tend to drain out the cerebrospinal fluid and the size of the ventricles is reduced than *in vivo* measurement.

There are some limitations to our studies. The algorithm developed has worked accurately on the data sets that we have tested. However 30 cases are still not enough to have reliable statistics regarding the dimensions of the ventricles and further studies in larger groups are necessary. The data should comprise of larger ethnic mixture and wider age range.

In our study the results have not been compared with those by any other technique for estimating ventricular volume and the algorithm is assumed to have high fidelity to accuracy.[10,11]

Only SPGR images have been used for analysis and it would be essential to conduct measurements on other pulse sequences as well to examine whether the variation in ventricular dimensions depends on the voxel intensity.

## Conclusion

We have demonstrated the morphometric application of the algorithm that we developed for the segmentation of the human cerebral ventricular system.[10,11] Our algorithm works very efficiently, robustly, quickly and with high accuracy on SPGR 3D brain MRI studies to segment the ventricular system. We have defined various landmarks on the ventricles and used them to automatically measure certain distances and volumes. The volumes calculated by us are within the range quoted in the reference literature. This further supports that our algorithm is clinically useful. Our study opens up the door in fully automated and fast demonstration of the ventricular system in quantifiable dimensions.

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