A Method and System for Anatomy Structure Segmentation and Modeling in an Image

Field of the invention

The present invention relates to a method and system for segmenting anatomy structures in an image, a method and system for constructing a 3D surface model of a segmented structure. The particular application example is the segmentation and modeling of brain ventricular system in medical images, such as MR images and CT images.

Background of the Invention

As shown in Fig. 1, the human cerebral ventricular system consists of four intercommunicating chambers, namely the left lateral ventricle, right lateral ventricle, third ventricle and fourth ventricle. The ventricles are filled with cerebrospinal fluid (CSF), surrounded by white matter (WM) and gray matter (GM). The two lateral ventricles, located within the cerebrum, are relatively large and C-shaped, roughly wrapping around the dorsal aspects of the basal ganglia. Each lateral ventricle extends into the frontal, temporal and occipital lobes via the anterior, inferior and posterior horns respectively. The lateral ventricles both communicate via the interventricular foramina with the third ventricle (found centrally within the diencephalon) whereas the third ventricle communicates via the cerebral aqueduct (located within the midbrain) with the fourth ventricle (found within the hindbrain). Abbreviations in the figure are defined as: **AC**: Anterior Commissure; **BC**: Basal Cistern (Interpeduncular Cistern);**CC**: Corpus Callosum; **CP**: Cerebral Peduncle; **CQ**: Corpora Quadrigemina **HP**: Hypophysis (Putuitary Gland); **ICV**: Internal Cerebral Vein (in transverse fissure); **IS**: Infundibular Stalk; **LT**: Lamina Terminalis; **LV**: Lateral Ventricles; **MI**: Massa Intermedia (Middle Commissure); **MO**: Medulla Oblongata; **OC**: Optic Chiasma; **PC**: Posterior Commissure; **PG**: Pineal Gland; **SP** Septum Lucidum; **TC**: Tuber Cinereum; **TF**: Transverse Fissure (Subarachnoid Space Under Corpus Callosum); **V3**: The Third Ventricle; **V4**: The Forth Ventricle.

MR imaging has made it possible to obtain in vivo 3D images of the human brain noninvasively. Since changes in the CSF volume and ventricle shapes are commonly associated with several intrinsic and extrinsic pathologies, segmentation and

quantification of the ventricular system from MR images are therefore of primary importance.

Since manual segmentation of ventricles is time consuming, subjective and non-reproductive (or non-repeatable), a number of automated methods have also been proposed for the segmentation of ventricles. In general, methods for segmentation of ventricles can be classified into either model-based methods or non model-based methods depending on whether 3D ventricular models are used.

Non model-based methods, such as intensity thresholding [17] and region growing [12, 13, 19] are adaptive to the shape and size variations of the ventricular system. However, since these methods do not utilize the shape prior-knowledge of the ventricles, "leakage" from the ventricular regions to the non-ventricular regions may arise. Furthermore, some ventricular regions may be left out by these methods due to the non-homogeneity of the images or the presence of noise and partial volume artifacts in the images. The accurate segmentation of the third ventricle is especially challenging when using these non model-based methods since the precise boundaries of the third ventricle depend on the shape and topological constraints of themselves and their relationship with surrounding objects.

On the contrary, model-based methods, such as atlas warping [4] or geometrical and parametric model deformation [3, 6, 18], adopt an explicit or implicit model to act as the shape prior knowledge of the ventricles. These methods are robust to noise and are able to achieve precise segmentation when the variation between the shapes of the model and the studied object is small. However, due to the large variation in the shapes and sizes of the ventricles, it is difficult to design a reasonable energy or similarity function to achieve a model deformation adaptable to every variation. Furthermore, the local minimization problem which causes the false segmentation inevitably exists in these methods.

In general, there are two main difficulties in the segmentation of anatomic structures from images. First, transition regions between a studied structure (for example, the ventricular system) and its surrounding tissues (for example, gray matters) may be present due to the partial volume effect. If these transition regions are completely excluded, the structure may be under-segmented or broken into several disconnected

components. Second, some boundaries between the studied structure and its surrounding tissue are too thin to be detected in the image. As a result, some object regions may "leak" (i.e. connect) to other non-object regions. Currently, no existing method can detect the transition regions and at the same time, prevent the "leaking" of object regions to non-object regions.

Summary of the invention

The present invention aims to provide a method and system for the segmentation and constructing 3D surface models of structures in an image.

Specifically, the present invention proposes a method for segmenting one or more ventricles in a three-dimensional brain scan image composed of brain scan data. The method comprises of the steps:

(a) registering a brain model, which comprises one or more respective ventricle models of each of the one or more ventricles, with the image, thereby forming a correspondence between locations in the brain model and respective locations in the brain scan image;

(b) according to said correspondence, defining one or more respective regions of interest in the image based on the one or more ventricle models;

(c) performing region growing on the one or more regions of interest using the brain scan data to form respective volumes indicative of the respective ventricles; and

(d) segmenting the brain scan image using the respective volumes.

The invention may further include a step of constructing a surface model of the segmented anatomy structure and editing the surface model to accurately describe the features and details lost in segmentation.

Step (c) may include generating the volumes in the form of connected regions, and prior to step (d) there may be steps of trimming the volumes based on anatomical knowledge specific to the ventricle concerned.

The invention may alternatively be expressed as a computer system for performing such methods. This computer system may be integrated with devices for acquiring the image. The invention may also be expressed as a computer program product, such as

one recorded on a tangible computer medium, containing program instructions operable by a computer system to perform the steps of the methods.

Brief Description of the Figures

An embodiment of the invention will now be illustrated for the sake of example only with reference to the following drawings, in which:

Fig. 1(a) – (c) illustrate one example of the human cerebral ventricular system.

Fig. 2 illustrates the main flow chart of a system which is an embodiment of the invention comprising method steps 202 and 204;

Fig. 3 illustrates the flow chart of the method 202 for segmenting a ventricular system from an image;

Fig. 4 illustrates a flow chart of a method 204 for generating an accurate 3D surface model of a ventricular structure from its segmentation output of method 202;

Fig. 5 illustrate a process of modifying a surface model using an amendment point according to an embodiment of the present invention;

Fig. 6 illustrates the results obtained by segmenting a left ventricle in data set IBSR-18 using method 202;

Fig. 7 illustrates the results obtained by segmenting a third ventricle in data set IBSR-18 using method 202;

Fig. 8 illustrates the results obtained by segmenting a fourth ventricle in data set IBSR-18 using method 202;

Fig. 9 illustrates four ventricular structures segmented from four different brain volume sets in data set BIL-20 using method 202.

Detailed Description of the Embodiments

Referring to Fig. 2, the steps are illustrated of a method 200 which is an embodiment of the present invention and which generates 3D surface models of ventricles.

The input to method 200 is a volume image. In step 202, the ventricles in the volume image are segmented. In step 204, a 3D surface model is built for each ventricle and the 3D surface model is edited to improve its accuracy. Note that in other embodiments step 202 may not be followed by step 204. Furthermore, the methods of steps 204

have other possible applications than in the method 200, and may be performed separately, or in combination, in a wide range of 3-D modelling situations.

Step 202: Segment ventricles in volume image

Referring to Fig. 3, the steps are illustrated of a method 202 which is an embodiment of the present invention and which generates a volume image indicating a ventricular system.

The input to method 202 is a volume image. In step 302, the image is reformatted to the standard Talairach space and the standard ventricular model is then warped onto the image according to a plurality (e.g. 10) of automatically identified ventricular landmarks. In step 304, the region of interest for each ventricle is specified using the deformed ventricular model. In steps 308, 310 and 312, the lateral, third and fourth ventricles are segmented. Hysteric thresholding (that is, thresholding with a hysteresis) is performed in steps 306a, 306b and 306c to generate a connected CSF region containing a ventricular component, with the CSF region containing minimal non-ventricular regions.

Step 302: Reformat image

Given a volume image I, Talairach transformation [9] is commonly used to reformat the image I into the standard Talairach space [14] so that it can be processed or understood with anatomical knowledge. However, occasionally when the Talairach landmarks cannot be located automatically, the Talairach transformation cannot be automated.

Therefore, in example embodiments, a cortical outline-based registration approach is used to reformat the image. A cortical outline of a brain is an approximation convex hull of its cortical surface. The cortical outline S_1 in the image is automatically extracted using morphologic analysis [11] and the cortical outline S_2 in the 3D Talairach space is generated by interpolating [8] the 2D digital electronic version of the 3D Talairach-Tournoux (TT) brain atlas and the ventricular system in the 3D TT brain atlas [8] is taken as the standard volumetric ventricular model.

The outlines S_1 and S_2 are represented by triangular meshes, with vertices denoted as Q_1 and Q_2 respectively. Applying the Iterated Closest Points (ICP) method [2] to register the point set Q_1 to Q_2, a linear transformation is obtained and is used to reformat the image I into the Talairach space. The standard radiological convention (http://www.grahamwideman.com/gw/brain/orientation/orientterms.htm) is adopted to define a coordinate system (xyz) in the Talairach space with its origin located at the anterior commissure of the 3D TT atlas, with x running from the subject's right to left, y running from the subject's posterior to anterior and z running from the subject's inferior to superior.

Step 304: Specify region of interest

In example embodiments, to specify the region of interest for each ventricular component, ten ventricular landmarks [7] are first identified in the image and in the 3D TT atlas. A model-based semi-global approach is used to automatically identify the ten ventricular landmarks in the image whereas the tool Medical Image Understanding Environment (MIUE) [7, 8] is used to interactively specify these landmarks in the 3D TT atlas as domain knowledge.

In one example, four of these landmarks are on each lateral ventricle and they are the most posterior point, the most superior point, the anterior lateral frontal pole and the posterior center-line intersection of each lateral ventricle. The landmarks also include the anterior pole on the third ventricle and the posterior-superior point on the fourth ventricle.

Based on the ten ventricular landmarks in the image and the TT brain atlas, the standard ventricular model is then registered onto the image. Since the localization of the automatically detected landmarks may not be accurate [7, 10], a thin plate spline approximation approach [10] is used to obtain the registration (or warping) function.

The warped (or deformed) volumetric ventricular model is then divided into four sub-volumes: V_1 (left lateral ventricle), V_2 (right lateral ventricle), V_3 (third ventricle) and V_4 (fourth ventricle and adequate). The corresponding regions of interest Ω_i for each ventricular component are then defined by expanding the corresponding warped sub-volume V_i according to Equation (1).

$$\Omega_i = \begin{cases} \{p \mid s(V_i, p) \le d_0\} - V_0 & (i = 1,2) \\ \{p \mid s(V_i, p) \le d_0\} & (i = 3,4) \end{cases} \quad (1)$$

In Equation (1), the regions of interest Ω_1 to Ω_4 are used for the segmentation of the left lateral, right lateral, third and fourth ventricles respectively. $s(V_i,p)$ indicates the signed minimal Euclidean distance of the voxel p ($p = (p_x, p_y, p_z) \in R^3$) to the boundary of the volume V_i, with a positive value of $s(V_i,p)$ indicating that the voxel p is outside the volume V_i and a negative value of $s(V_i,p)$ indicating that the voxel p is inside the volume V_i. In one example, d_0 is set to 6mm so that each region is just large enough to contain three type of brain tissue: gray matter, white matter and CSF including the related ventricular component. This allows the threshold for the related ventricular component to be subsequently estimated in the region. In addition, V_0 represents the middle sagittal slab. In one example, the thickness of V_0 is set to 8mm according to Equation (2) and V_0 is excluded from Ω_1 and Ω_2 to prevent the "leakage" of the two lateral ventricles into the inter-hemisphere CSF or the "leakage" of the two lateral ventricles into each other.

$$V_0 = \{p \mid -4 \le x \le 4\} \quad (2)$$

Steps 306a, 306b and 306c: Perform hysteretic thresholding

Although several methods [5, 15, 16, 21] are available to segment CSF regions from brain volumes, the extracted CSF regions usually contain not only the ventricular regions but also a large part of the non-ventricular regions. It is difficult to segment the ventricular regions from the numerous inter-connected non-ventricle regions. As a result, these methods may fail to locate the transition regions between the ventricular CSF and the non-ventricular tissues, resulting in under-segmentation. Although existing methods [20] are available for extracting transition regions, these methods are either gradient-based or local entropy-based. Therefore, they are likely to extract a large part of non-ventricular CSF regions as transition regions.

In example embodiments, the regions of interest Ω_1 (Ω_1 to Ω_4) specified in step 304 are used as a guide in steps 306a, 306b and 306c to collect a connected CSF region X

that contains its corresponding ventricle component. In steps 306a, 306b and 306c, hysteretic thresholding is used to collect the region X corresponding to region Ω_i according to the following sub-steps:

Step 1: Two pairs of intensity thresholds for the ventricular component in each region Ω_i is calculated respectively.

In one example, step 1 is performed according to the following steps.

Firstly, the fuzzy c-mean method [1] is used to classify all voxels of the image in the region Ω_i into five clusters according to their intensities. These five clusters represent three types of tissue (GM, WM and CSF) and two transition regions CSF_GM (between CSF and GM) and GM_WM (between GM and WM)).

Next, denoting the membership of intensity g to cluster k as $u_k(g)$ and the intensity of each cluster center as c_k (k = 1, 2, ..., 5) and without loss of generality, supposing that $c_1<c_2<...c_5$, the intersection point g_k of two membership functions u_k and u_{k+1} is then calculated such that $u_k(g_k) = u_{k+1}(g_k)$ where k = 1, 2, ..., 4. The low and high thresholds t_{kL} and t_{kH} of cluster k are then set to g_{k-1} and g_k respectively, with g_0 and g_5 being set to the possible minimum and maximum intensities respectively.

According to domain knowledge, two clusters corresponding to the CSF and CSF_GM are then picked out. In one example, in the T1-MR images, the first cluster with intensity thresholds $[t_{1L}, t_{1H}]$ is selected as CSF and the second cluster with intensity thresholds $[t_{2L}, t_{2H}]$ is selected as CSF_GM. The threshold containing the CSF cluster is taken to be the narrow threshold $[T_{L1}, T_{H1}]$ whereas the threshold containing both the CSF and the CSF_GM clusters is taken to be the wide threshold $[T_{L2}, T_{H2}]$. In other words, $T_{L1} = t_{1L}$, $T_{H1} = t_{1H}$, $T_{L2} = \min\{t_{1L}, t_{2L}\}$, $T_{H2} = \max\{t_{1H}, t_{2H}\}$.

Step 2: For each Ω_i a corresponding kernel region K of the ventricular component is collected according to the narrow thresholds $[T_{L1}, T_{H1}]$;

In one example, step 2 is performed according to the following steps.

Firstly, the image I is binarized with the low and high thresholds T_{L1} and T_{H1} to obtain the CSF cluster $\{p|T_{L1} \leq I(p) \leq T_{H1}\}$. Next, the maximum connected region K is extracted from the CSF cluster according to the 6-neighbor connectivity. Since the region Ω_i is generated by expanding the deformed ventricular component, which is a rough fit of the corresponding ventricular component in the image, naturally, the region K is or at least includes the main part of the related lateral ventricle in the region Ω. In other words, the region K obtained from the region Ω_3 includes the main part of the third ventricle, while the region K obtained from each of the other regions, is the main part of the left lateral ventricle, right lateral ventricle, or the fourth ventricle. The region K is denoted as a kernel region of the related ventricle component.

Step 3: The region K is adaptively expanded to include transition regions according to the wide thresholds $[T_{L2}, T_{H2}]$.

In one example, step 3 is performed using a boundary patch-based region growing procedure to adaptively expand the region K to include the transition regions of the ventricular component and at the same time to avoid "leaking" of the region K to non-ventricular regions.

A boundary voxel p of the volume is taken to be an active voxel if at least one of its 26 nearest-neighbors q is such that $q \in \Omega - K$ and $T_{L2} \leq I(q) \leq T_{H2}$. Active boundary voxels of K are then grouped into a set of boundary patches $\{\partial_1, \partial_2, \ldots, \partial_n\}$ according to the 26-neighbor connectivity, where n represents the number of patches. All voxels within a patch ∂_i are 26-neighbor connected, while two different patches ∂_i and ∂_j $(i \neq j)$ are disconnected.

Region growing is applied on each patch ∂_i separately. Initially, $\partial_{i,0}$ is set as ∂_i and $\partial_{i,k+1}$ is repeatedly generated from $\partial_{i,k}$ according to Equation (3). In Equation (3), $N_{26}(\mathbf{p})$ represents the 26-neighbor of the voxel p.

$$\partial_{i,k+1} = \bigcup_{p \in \partial_{i,k}} \{q \mid q \in N_{26}(p), T_{L2} \leq I(q) \leq T_{H2}, q \in \Omega\} - (K \cup_{j=0}^{k} \partial_{k,j}) \quad (k=0, 1, 2, \ldots) \qquad (3)$$

The procedure of generating $\partial_{i,k+1}$ from $\partial_{i,k}$ continues until ∂_{i,k_i+1} at k=k_i is empty or until the number of voxels in ∂_{i,k_i+1} is more than twice the number of voxels in ∂_{i,k_i} i.e. $\#\partial_{i,k_i+1} > \#\partial_{i,k_i} * 2$. The stopping condition of $\#\partial_{i,k_i+1} > \#\partial_{i,k_i} * 2$ is to avoid "leaking" of the transition regions to the non-ventricular regions since the size of the transition regions is expected to be of the same scale as that of $\partial_{i,0}$.

At the end of the procedure, a new volume $V_i = \bigcup_{n=0}^{k_i} \partial_{i,n}$ is obtained from the patch $\partial_{i,0}$. Finally, the newly expanded volume V_i and the kernel region K are combined to generate a connected CSF region X according to Equation (4).

$$X = \bigcup_{i=0}^{n} (\bigcup_{n=0}^{k_i} \partial_{i,n}) \cup K \qquad (4)$$

In steps 306a, 306b and 306c of steps 308, 310 and 312 respectively, the connected CSF region is further trimmed according to the domain knowledge about the shape, intensity and anatomy of the ventricular system as follows.

Step 308: Lateral ventricle segmentation

To segment the two lateral ventricles, hysteretic thresholding is applied on the regions Ω_1 and Ω_2 separately to obtain two volumes X_1 and X_2 which are the main parts of left and right ventricles. To detect the possible remaining parts of the lateral ventricles in the middle sagittal slab V_0, the boundary patches ∂_1 and ∂_2 of X_1 and X_2 that are inside the region V_0, respectively, are first located and the boundary patch-based region growing procedure is then used to adaptively expand ∂_1 and ∂_2 in the region V_0. Two new volumes $\underline{X}_1$ and $\underline{X}_2$, which contain the remaining parts of the left and right lateral ventricles, are hence obtained.

Step 308a: Lateral ventricle separation

When the septum pellucidum between the two lateral ventricles is large enough (in one example, at least one voxel thickness in the sagittal direction. This occurs in about 30% of subjects in the test data sets), $\underline{X}_1$ and $\underline{X}_2$ are separate (i.e., the overlap $\underline{X}_{12}=\underline{X}_1 \cap \underline{X}_2$ of the volumes $\underline{X}_1$ and $\underline{X}_2$ is empty), and $X_1 \cup \underline{X}_1$ and $X_2 \cup \underline{X}_2$ are taken to be the left and right ventricles respectively. In the case when the septum pellucidum is very thin, the two regions $\underline{X}_1$ and $\underline{X}_2$ may be joined together by the non-empty overlap region $\underline{X}_{12}$, it is then necessary to separate the left and right lateral ventricles according to the following steps: first, $\underline{X}_{12}$ is removed from $\underline{X}_1$ and $\underline{X}_2$ to obtain two regions $\underline{X}'_1=\underline{X}_1-\underline{X}_{12}$ and $\underline{X}'_2=\underline{X}_2-\underline{X}_{12}$. Then, for each voxel p in $\underline{X}_{12}$, if its distance to the boundary of region $\underline{X}'_1$ is less than that to region $\underline{X}'_2$, i.e., $s(\underline{X}'_1, p)<s(\underline{X}'_2, p)$, the voxel p is distributed into $\underline{X}'_1$, otherwise if $s(\underline{X}'_1, p)>s(\underline{X}'_2, p)$, the voxel p is distributed into $\underline{X}'_2$. If $s(\underline{X}'_1, p)=s(\underline{X}'_2, p)$, p is regarded as a voxel from the septum lucidum. Finally, the unions $X_1 \cup \underline{X}'_1$ and $X_2 \cup \underline{X}'_2$ are taken as the segmentation of the left and right ventricles, i.e., X_1 and X_2 are updated to $X_1 \cup \underline{X}'_1$ and $X_2 \cup \underline{X}'_2$, respectively.

Step 310: Third ventricle segmentation

Hysteretic thresholding is first applied to region Ω_3 to obtain a connected CSF volume X_3.

Next, voxels identified to be a part of either the left or right lateral ventricle are removed from X_3. In other words, X_3 is updated to be $X_3 - (X_1 + X_2)$. Finally, other extra-ventricular voxels are removed from X_3.

Step 310a: Projection-based non-ventricular region trimming

In one example, a projection-based trimming method is used to remove non-ventricular voxels from X_3. Since the third ventricle is a narrow opening in the middle of the brain and the non-ventricular part contained in the volume X_3 is much wider than the third ventricle along the sagittal (left-to-right) direction. The steps of the project-based trimming method are as follows.

Step 1: A two-dimensional image f(y,z) is generated by projecting the volume X_3 onto the middle sagittal plane x = 0 according to Equation (6).

$$f(y,z)=\#\{p|p_y=y,\ p_z=z,\ p\in X_3\} \qquad (6)$$

In Equation (6), # represents the cardinal of a set i.e. at a point (y, z) in the plane x = 0, f(y,z) represents the number of voxels of volume X_3 on the project line at the point (y, z).

Step 2: A fuzzy c-mean method is then used to classify all non-zero values $\{f(y,z) \neq 0\}$ into two clusters and an adaptive threshold h is obtained whereby f(y,z) is less than h in one cluster and is more than h in the other cluster.

Step 3: For each voxel $p\in X_3$, if $f(p_y, p_z) > h$, the voxel is removed from X_3.

Step 310b: Landmark guided non-ventricular region trimming

After applying the projection-based extra-ventricle trimming method, X_3 may still contain a small narrow non-ventricular region at the anterior-inferior part of the third ventricle. In one example, a landmark guided non-ventricular region trimming method is used to remove this non-ventricular region. In the landmark guided non-ventricular region trimming method, all voxels anterior to the anterior pole of the third ventricle are removed. The landmark (anterior pole of the third ventricle) is identified in the image using the model-based approach [7].

Step 310c: Shape-based non-ventricular region trimming

At the superior of the third ventricle, X_3 may contain a thin C-shaped region composed of the Transverse Fissure and the ICV. Furthermore, from the PC (or PG) towards the inferior-posterior, X_3 may contain one or more small narrow paths "leaking" to the basal cistern. In one example, these "leakages" are removed using a shape-based non-ventricular region trimming method based on the strip-like shape features of the "leakages". Firstly, all candidate components for removal are located by grouping connected regions on coronal slices from posterior to anterior. Next, from these candidate components, strip-like "leakages" are identified and removed. In one example, the following sub-steps are performed in the shape-based non-ventricular region trimming method.

Step 1: A candidate leakage component set $\Re$ and a temporary component set $\Re_0$ are initialized.

In step 1, the most posterior coronal slice $y_0=\min\{y|\ p(x,y,z) \in X_3\}$ of the volume X_3 is located, and $\Re$ is set to empty whereas $\Re_0$ is set to $\{\ \{C_0\} \mid C_0 \in S_0\ \}$, where C_0 denotes one of all the 8-neighbor connected regions S_0 of X_3 on the coronal slice indexed by y_0, $\{C_0\}$ is a candidate leakage component composed of region C_0.

Step 2: All candidate leakage components are located by tracing each component in $\Re_k$ to generate $\Re_{k+1}$ (k=0,1,2...).

For each component $L_k=\{C_0, C_1, \ldots, C_k\}\in\Re_k$, if there is a 8-neighbor connected region C_{k+1} on the coronal slice indexed by y_0+k+1, and C_{k+1} is connected to C_k in the sense that there is at least one voxel $p_{k+1}\in C_{k+1}$ that is a 26-neighbor of another voxel $p_k\in C_k$, the region C_{k+1} is appended to the component L_k to form a new component $L_{k+1}=\{C_0, C_1, \ldots, C_k, C_{k+1}\}$.

If the area ratio of the voxels in C_{k+1} to the voxels in C_k is greater than a given threshold r (in one example, r is set as 3), L_{k+1} is appended into $\Re$. Otherwise L_{k+1} is appended into $\Re_{k+1}$ for further growing. If $\Re_{k+1}$ is not empty, step 2 is repeated by generating $\Re_{k+2}$ from $\Re_{k+1}$.

Step 3: In step 3, the C-shape leakage component on the superior of X_3 is removed.

A candidate component $L_{k+1}= \{C_0, C_1, \ldots, C_k, C_{k+1}\} \in \Re$ is identified as the C-shape leakage component composed of transverse fissure and the ICV if it satisfies the following three conditions.

(1) C_{k+1} is a branch region, i.e., there is another connected region $C'_k \in S(k)$ and $C'_k \neq C_k$.

(2) The angle $\angle P_k P_{k+1} P'_k$ is less than 30°, where P_k, P_{k+1}, P'_k are the mass centers of region C_k, C_{k+1} and C'_k, respectively, and,

(3) each region $C_i \in L_{k+1}$ (i=0,1,...k+1) is on the superior of all voxels of X_3 in the coronal slice indexed by y_0+i, i.e., $\max\{z|\ p(x,y_0+i,z) \in C_i\} > \max\{z \mid p(x,y_0+i,z) \in X_3 - C_i\}$

If $L_{k+1}=\{C_0, C_1, \ldots, C_k, C_{k+1}\}$ is identified as the C-shape leakage component, $C_0, C_1, \ldots, C_k$ are removed from X_3, and L_{k+1} is removed from $\Re$.

Step 4: In step 4, strip-like leakage components on the posterior of X_3 are removed.

For each candidate component $L_{k+1}=\{C_0, C_1, \ldots, C_k, C_{k+1}\} \in \Re$, if it is located at the posterior of mass center G(x, y, z) of the region Ω_3, i.e., $y_0+k+1<G_y$, then it is identified as a leakage component. $C_0, C_1, \ldots, C_k$ are then removed from X_3 whereas L_{k+1} is removed from $\Re$.

The final X_3 region is the segmentation result of the third ventricle.

Step 312: Fourth ventricle and adequate segmentation

Since there is no well-defined boundary between the fourth ventricle and the adequate, they are segmented simultaneously. Applying hysterical thresholding on the region Ω_4, a volume X_4 is obtained. At the joint of the aqueduct and the fourth ventricle, since the posterior wall (i.e. corpora quadrigemina) of the aqueduct becomes very thin and may not be identified from the image, X_4 may "leak" from the fourth ventricle to the basal cistern surrounding the cerebellum. At the same time, since the aqueduct is only a narrow path connecting the third and fourth ventricles, a part of the aqueduct or the entire aqueduct may not be included in X_4.

Step 312a: Shape-based trimming of the fourth ventricle

To remove the "leakage", the number of voxels f(z) in each axial slice of volume X_4 indexed as coordinate z is calculated. The slice z_{max} where f(z) reaches its maximum is located. For slices with f(z) > 0, the relative increase ratio from the slice z_{max} to subsequent slices in the superior (or dorsal) direction is calculated according to Equation (7).

$$q(z)=[f(z+1)-f(z)]/f(z) \quad (7)$$

The first leakage slice from z_{max} towards the ventral direction (denoted as the axial slice z_{leak}) is located at where q(z) reaches its positive maximum since f(z) increases greatly at where the "leakage" begins. If the maximum value of q(z) is not positive, this implies that X_4 did not "leak" to the basal cistern. In this case, z_{leak} is set as the maximum z coordinate of the voxels in V_4.

Since the adequate slants anterior to join with the third ventricle, denoting y_{leak} as the most posterior of the volume X_4 on the leakage slice z_{leak}, all voxels from z_{leak} onwards in the dorsal direction with y coordinates less than y_{leak} are taken to be "leakage" and are removed from the volume X_4.

From the slice z_{max} down towards the inferior (or dorsal) direction, it is required that f(z) does not increase. Therefore, if there is a slice z_{min} such that $f(z_{min} + 1) > f(z_{min})$, all voxels with z coordinates less than z_{min} would be trimmed from X_4.

The final X_4 region is the segmentation result of the fourth ventricle.

To find the adequate, denoting $[T_{L2}, T_{H2}]$ as the wide threshold obtained in region Ω_4, $N_{z+}(p)= \{(p_x+i, p_y+j, p_z+k)|\ i,j=-1,0,1,\ k=0,1\}$ as the directional neighbors of a voxel p(x,y,z) and S_0 as all voxels of volume X_4 in the slice z_{leak}, S_{n+1} is generated from S_n by directional region growing according to Equation (8).

$$S_{n+1} = \bigcup_{p \in S_n} \{q \mid q \in N_{z+}(p), T_{L2} \le I(q) \le T_{H2}\} \ (n=0,1,2,\ldots) \quad (8)$$

S_{n+1} is repeatedly generated from S_n until S_{n+1} is empty or until the number of voxels in S_{n+1} is greater than the number of voxels in S_0 (i.e. $\#(S_{n+1})>\#(S_0)$). The adequate volume is then taken as $S_1 \cup S_2 \ldots \cup S_n$. If the procedure of repeatedly generating S_{n+1} from S_n stops when $\#(S_{n+1})>\#(S_0)$, this may be because the detected adequate reached the third ventricle. On the other hand, if the procedure of repeatedly generating S_{n+1} from S_n stops when S_{n+1} is empty, this may be because that the detected adequate failed to reach the third ventricle due to partial volume effects. In most situations, the procedure stops when $\#(S_{n+1})>\#(S_0)$.

Step 204: Build and refine surface models for ventricles

Fig. 4 illustrates a flow chart of a method 204 for generating an accurate 3D surface model of a ventricular structure from its segmentation output of method 202. In step 402, a surface model is constructed for the ventricular structure and in step 404, details of the surface model are refined by local sine warping.

Step 202 produces segmentation results of ventricles. However, some details may still be missing or inaccurate in the case where distances between slices are big and/or the studying image is of a poor quality. In such circumstances, a geometric surface model is more flexible and smoother for describing anatomical structures with subtle features lost in between image slices or disrupted by image quality. To build accurate surface models of ventricles, the well known Marching-cube method [22] can be used to generate initial surface models from the ventricle volumes output from step 202. Then the initial surface models presented as triangulated meshs are simplified [23] to reduce computing time and increase efficiency for the subsequent processing.

To enhance the accuracy, the system in the example embodiments supports user modification of the surface model using the local sine warping method. Based on domain knowledge, users can indicate the missing subtle features by placing amendment points on the 3D model space. The local sine deformation (LSD) function warps a confined region to smoothly approach the amendment points to recover the lost subtle features without losing the continuity of anatomy structures (as shown in Fig. 5).

Fig. 5 illustrates a process of modifying a surface model using an amendment point according to an embodiment of the present invention.

Suppose a user placed an amendment point A near the model M, indicating that a detail feature is missing in the model. The model is presented as a polygonal mesh, for each vertex *V* on the mesh, the distance from A to V is denoted as d(A,V). The distance between *A* and the model is d(A, M) = min(d(A,V) | V∈M). Given a radius R > d(A,M), (R is adjustable in the system), a limited set of vertices points $P=\{p_1, p_2, \ldots p_k \mid d(A,p_i) < R\}$ is constructed. For each point p_i in the set P, a corresponding point q_i is calculated as follows: q_i is positioned on the line along A to p_i {i=1,2,...k} and the distance from A to q_i is computed by the LSD function according to Equation (9):

$$d(A,q_i) = \mathrm{Sin}(\frac{\pi d(A,p_i)}{2R}) \qquad (i=1,2,\ldots k) \qquad (9)$$

By replacing each p_i with q_i {i=1, 2, ...k} computed as above, the local region of the surface model is warped towards the amendment point *A* so that the missing subtle anatomy features can be recovered.

The surface model enhancement procedure in step 204 is an interactive procedure and can be carried out iteratively until the output is satisfactory.

Experimental results of step 202

Fig. 6 illustrates the results obtained by segmenting a left ventricle in data set IBSR-18 (IBSR-18-02.img, slices 144a, 57c, 120s) using method 202 and the lateral ventricle segmentation approach according to an embodiment of the present invention. Contours 1202 – 1218 indicate the region of interest automatically defined for the left lateral ventricle. Contours 1220 – 1230 indicate the region of interest of the left lateral ventricle model expanded into the middle sagittal slab. Contours 1232 – 1242 indicate regions obtained by the narrow thresholds and the contours surrounding contours 1231 – 1242 indicate the additional regions obtained by the wide thresholds.

Fig. 7 illustrates the results obtained by segmenting a third ventricle in data set IBSR-18 (IBSR-18-02.img, slices 142a, 60c, 128s) using method 202 according to an embodiment of the present invention. The four columns from left to right illustrate the axial, coronal, sagittal and 3D views. The first row shows the region of interest

automatically defined for the third ventricle. The second row shows the results of the hysteretic thresholding in the ROI. The third row shows the results obtained by project-based trimming and the fourth row shows the final result after the landmark-guided trimming of the anterior part and shape-based trimming of other extra-ventricular components.

Fig. 8 illustrates the results obtained by segmenting a fourth ventricle in data set BIL-20 (BIL-Ja03, slices 44a, 102c, 129s) using method 202 according to an embodiment of the present invention. The four columns from left to right illustrate the axial, coronal, sagittal and 3D views. The first row shows the region of interest automatically defined for the fourth ventricle, the second row shows the results obtained by applying hysteretic thresholding in the ROI and the third row shows the final result after "leakage" removal.

Fig. 19 illustrates four ventricular structures segmented from four different brain volume sets in data set BIL-20 using method 202 according to an embodiment of the present invention. The first to fourth rows show the volume images of an abnormal adult's brain (with brain tumor), a normal adult's brain, a child's brain and an elder's brain. The four columns from left to right illustrate the axial, coronal, sagittal views of the original scans and the 3D views of the extracted ventricular systems respectively.

Advantages of example embodiments

A volumetric deformable model is used in step 202 as domain knowledge to automatically define a region of interest for the segmentation of the structure to be studied, for example the ventricular structure in the example embodiments. A proper ROI is critical for an accurate segmentation. If the ROI is too small, it may not contain the structure to be studied. On the other hand, if the ROI is too large, it may contain too much unrelated information leading to wrong segmentation. In step 202, the model is first deformed to roughly fit its corresponding structure in the image by a 3D point landmark-based warping approach and the ROI is then defined by expanding (or dilating) the deformed model. The resulting ROI takes the prior shape of the structure to be studied and hence, the amount of unrelated information in the ROI is minimized. Therefore, step 202 is robust to noise and to large shape and size variations.

Furthermore, a hysteretic thresholding approach is employed for the region growing procedure in a given region of interest in step 202. In the hysteretic thresholding approach, two pairs of intensity thresholds, namely a narrow one and a wide one, are used. The range of the narrow thresholds is contained in the range of the wide thresholds. The pair of narrow thresholds is used to collect a kernel part excluding the transition regions whereas the pair of wide thresholds is used to collect the transition regions of the structure. The region growing procedure stops when "leakage" is detected. The region growing procedure in step 202 is capable of detecting transition regions while minimizing "leakage". This is advantageous since the capability of transition region detection is critical for correct segmentation whereas "leakage" minimization greatly alleviates the burden for the region trimming procedure.

In addition, the multiple knowledge-based strategies, such as project-based, landmark guided, and shape-based trimming proposed for the region trimming procedure in step 202 are critical for the correct segmentation of the third ventricle.

Also, step 202 is advantageous over the prior art methods, for example [19]. The method proposed in [19] relies on the accurate identification of AC, PC and MSP and hence may fail to work if the supplied positions of AC, PC and MSP are not highly accurate (errors in the positions of AC and PC need to be less than 3mm). In addition, in the method proposed in [19], only one pair of thresholds is used within a region of interest, therefore the method fails to cope with the partial volume problem which may cause disconnection of some parts of components. Particularly, the shape of the ROI used in the method in [19] is rectangular which is very different from the shape of the ventricles. Therefore, a large amount of non-ventricle tissues are included in the ROI, leading to potential segmentation errors and "leakages" in [19]. In contrast, in step 202, ten ventricular landmarks are used to warp the ventricular model to fit its corresponding ventricle structure in the image. Since the thin plate spline approximation approach [10] is used to obtain the warping function and the deformed model is further expanded to a thickness of 6mm, step 202 is more tolerable to large landmark identification errors (up to 3.4mm in the IBSR-18 (as shown in Table 2 in [7]). Although an erroneous identification of the anterior pole of the third ventricle can affect the accuracy of third ventricle segmentation by step 202, the effect of this is local and small since the anterior pole of the third ventricle is only used to trim the posterior of the third ventricle which is a relatively small portion of the entire third ventricle. Furthermore, the use of

hysteretic thresholding in step 202, which employs two pairs of wide and narrow thresholds to develop the region of interest adaptively, ensures that transition regions are included in the ROIs while at the same time minimizing non-ventricle regions. Also, since the ROIs used in step 202 are derived from the ventricular shapes in the brain atlas, the shapes of the ROIs are very close to the shapes of the target structures, hence significantly reducing potential segmentation errors and "leakages".

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Claims

1. A method for segmenting one or more ventricles in a three-dimensional brain scan image composed of brain scan data, the method comprising the steps of:

(a) registering a brain model, which comprises one or more respective ventricle models of each of the one or more ventricles, with the image, thereby forming a correspondence between locations in the brain model and respective locations in the brain scan image;

(b) according to said correspondence, defining one or more respective regions of interest in the image based on the one or more ventricle models;

(c) performing region growing on the one or more regions of interest using the brain scan data to form respective volumes indicative of the respective ventricles; and

(d) segmenting the brain scan image using the respective volumes.

2. A method according to claim 1 wherein the step (a) comprises the sub-steps of:

(i) reformatting the image into a coordinate system of the brain model;

(ii) identifying landmarks in the reformatted image corresponding to landmarks in the brain model; and

(iii) registering the brain model with the image based on the identified landmarks.

3. A method according to claim 2 wherein the step (i) comprises the sub-steps of:

(iv) defining a first cortical outline in the image;

(v) defining a second cortical outline in the brain model;

(vi) registering points in the first cortical outline to points in the second cortical outline to obtain a linear transformation; and

(vii) reformatting the image into the coordinate system of the brain model using the linear transformation.

4. A method according to claim 3 wherein the points are registered in the step (vi) by applying an iterated closest points method.

5. A method according to any of claims 2 to 4 wherein the step (iii) comprises the sub-steps of:

(viii) obtaining a registration function using a thin plate spline approximation approach; and

(ix) registering the brain model with the image based on the identified landmarks using the registration function.

6. A method according to any of the preceding claims wherein the step (c) comprises, for each of the one or more regions of interest, the sub-steps of:

(x) calculating a respective narrow pair and a wide pair of intensity thresholds;

(xi) defining a kernel region of the region of interest according to the narrow pair of intensity thresholds; and

(xii) expanding the kernel region to include transition regions around the region of interest according to the wide pair of intensity thresholds to form said volume as a connected region.

7. A method according to claim 6 wherein the step (x) comprises the sub-steps of:

(xiii) clustering voxels in the region of interest according to their intensities;

(xiv) calculating a pair of intensity thresholds for each cluster based on the intersection points of each cluster with neighboring clusters;

(xv) defining the pair of intensity thresholds for the cluster containing the intensity of the region of interest as the narrow pair of intensity thresholds; and

(xvi) defining a lower limit and an upper limit of a combination of the pairs of intensity thresholds for the cluster containing the intensity of the region of interest and the cluster containing the intensity of the transition regions as the wide pair of intensity thresholds.

8. A method according to claim 6 or claim 7 wherein the step (ii) comprises the sub-steps of:

(xvii) binarizing the image with the narrow pair of intensity thresholds to obtain a cluster; and

(xviii) extracting a maximum connected region from the cluster according to a 6-neighbor connectivity approach to be the kernel region.

9. A method according to any of claims 6 to 8 wherein the step (iii) comprises the sub-steps of:

(xix) determining active boundary voxels of the kernel region;

(xx) grouping the active boundary voxels into boundary patches according to a 26-neighbor connectivity approach;

(xxi) applying region growing on each boundary patch to obtain expanded boundary patches; and

(xxii) expanding the kernel region to include the expanded boundary patches to form a connected region.

10. A method according to any of claims 6 to 8 comprising a trimming step, prior to step (d), of removing voxels from the connected region by a process step specific to the corresponding ventricle.

11. A method according to claim 10, in which one of said regions of interest corresponds to a lateral ventricle, and the trimming step for that region of interest comprises the following steps:

(xxiii) locating a common boundary voxel set of the connected region with a middle sagittal slab;

(xxiv) generating a first new region using a maximum 26-neighbor connected region of the common boundary voxel set as a seed point;

(xxv) repeatedly generating a subsequent new region from a previous new region until the subsequent new region is empty; and

(xxvi) defining the connected region as a sum of the common boundary voxel set and the new regions.

12. A method according to claim 10 or 11 in which one of said regions of interest corresponds to a third ventricle, and said trimming step comprises the sub-steps of:

(xxvii) projecting the connected region onto a middle sagittal plane to obtain a projected image wherein each pixel in the projected image represents a number of voxels in the connected region along a project line leading to the pixel;

(xxviii) obtaining a threshold clustering values of the pixels in the projected image into two clusters; and

(xxix) removing voxels from the connected region corresponding to the pixels with values higher than the threshold.

13. A method according to any one of claims 10 to 12, wherein the trimming step comprises the sub-steps of:

(xxx) identifying a landmark in the image; and

(xxxi) removing voxels in the connected region which have a location postion relative to the landmark.

14. A method according to any one of claims 10 to 13 wherein the trimming step comprises the sub-steps of:

(xxxii) repeatedly locating an 8-neighbor connected region of pixels belonging to the connected region on each slice of the image until the area ratio of the voxels in a subsequent slice to the voxels in a current slice is greater than a predetermined threshold; and

(xxxiii) identifying the combination of the 8-neighbor connected regions as a C-shaped leakage component; and

(xxxiv) removing the C-shaped leakage component from the connected region.

15. A method according to any one of claims 10 to 13 wherein the trimming step comprises the sub-steps of:

(xxxv) identifying a first slice in the image with a maximum number of pixels in the connected region;

(xxxvi) calculating an increase in the number of pixels in the connected region for subsequent slices from the first slice;

(xxxvii) identifying a leakage slice having the greatest increase in the number of pixels in the connected region; and

(xxxviii) removing voxels from the connected region lying beyond the leakage slice.

16. A method according to claim any one of claims 10 to 13 wherein the trimming step comprises the sub-steps of:

(xxxix) identifying a first slice with a greater number of pixels in the connected region as compared to a previous slice; and

(xxxx) removing voxels from the connected region lying beyond the first slice.

17. A method of building a 3D surface model of a structure in an image, the method comprising the steps of:

segmenting the structure by a method according to claim 1;

constructing the 3D surface model of the segmented structure within a 3D space wherein the 3D surface model comprises a plurality of vertices; and

editing the 3D surface model by repeatedly:

(xxxxi) placing an amendment point on the 3D surface model at a location where a feature is omitted from the 3D surface model;

(xxxxii) calculating a distance from the amendment point to each vertex in the 3D surface model; and

(xxxxiii) for each vertex in the 3D surface model, if the distance from the amendment point to the vertex in the 3D surface model is less than a predetermined threshold, calculating a corresponding point of the vertex by positioning the corresponding point on a line joining the amendment point to the vertex such that the distance from the amendment point to the corresponding point is $\sin(\pi d(A,p_i)/2R)$ where $d(A,p_i)$ is the distance from the amendment point to the vertex p_i and R is the predetermined threshold.

18. A computer system having a processor arranged to perform a method according to any of claims 1 to 17

19. A computer program product, readable by a computer and containing instructions operable by a processor of a computer system to cause the processor to perform a method according to any of claims 1 to 17.