FAST AND ROBUST MID-SAGITTAL PLANE LOCATION IN 3D MR IMAGES OF THE BRAIN

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Keywords: Mid-sagittal plane extraction, medical image analysis, medical image alignment, brain image segmentation.

Abstract: Extraction of the mid-sagittal plane (MSP) is an important step for brain image registration and asymmetry analysis. We present a fast MSP extraction method for 3D MR images, which is based on automatic segmentation of the brain and on heuristic maximization of cerebro-spinal fluid within the MSP. The method is shown to be robust to severe anatomical asymmetries between the hemispheres, caused by surgical procedures and lesions. The experiments used 64 MR images (36 pathological, 20 healthy, 8 synthetic) and the method found an acceptable approximation of the MSP in all images with a mean time of 60.0 seconds per image.

1 INTRODUCTION

The human brain is not perfectly symmetric (Davidson and Hugdahl, 1996; Crow, 1993; Geschwind and Levitsky, 1968). However, for the purpose of analysis, it is paramount to define and distinguish a *standard of asymmetry*, considered as normal for any given measurement, from abnormal asymmetry, which may be related to neurological diseases, cerebral malformations, surgical procedures or trauma. Several works sustain this claim. For example, accentuated asymmetries between left and right hippocampi have been found in patients with Schizophrenia (Wang et al., 2001; Csernansky et al., 1998; Styner and Gerig, 2000; Mackay et al., 2003; Highley et al., 2003; Barrick et al., 2005), Epilepsy (Hogan et al., 2000; Wu et al., 2005) and Alzheimer Disease (Csernansky et al., 2000; Liu et al., 2007).

The brain can be divided in two hemispheres, and the structures of one side should have their counterpart in the other side with similar shapes and approximate locations (Davidson and Hugdahl, 1996). These hemispheres have their boundaries limited by the longitudinal (median) fissure, being the corpus callosum their only interconnection.

The ideal separation surface between the hemisferes is not perfectly planar, but the mid-sagittal plane (MSP) can be used as a reference for asymmetry analysis, without significant loss in the relative comparison between normal and abnormal subjects. The MSP location is also important for image registration. Some works have used this operation as a first step for intra-subject registration, as it reduces the number of degrees of freedom (Ardekani et al., 1997; Kapouleas et al., 1991), and to bring different images into a same coordinate system (Liu et al., 2001), such as in the Talairach (Talairach and Tournoux, 1988) model.

However, there is no exact definition of the MSP and its determination by manual delineation is sensitive to different experts. Given that, a reasonable approach for evaluation seems to be visual inspection with error quantification, when we increase the asymmetry artificially and/or linearly transform the image.

The longitudinal fissure forms a gap between the hemispheres filled with cerebro-spinal fluid (CSF). We define the MSP as a large intersection between a plane and an *envelope* of the brain (a binary volume whose surface approximates the convex hull of the brain) that maximizes the amount of CSF. This definition leads to an automatic, robust and fast algorithm for MSP extraction.

The paper is organized as follows. In Section 2, we review existing works on automatic location of the mid-sagittal plane. In section 3, we present the proposed method. In section 4, we show experimental results and validation with simulated and real MR-T1 images. Section 5 states our conclusions.

2 RELATED WORKS

MSP extraction methods can be divided in two groups: (i) methods that define the MSP as a

P. G. Bergo F., C. S. Ruppert G., F. Pinto L. and X. Falcaõ A. (2008).
FAST AND ROBUST MID-SAGITTAL PLANE LOCATION IN 3D MR IMAGES OF THE BRAIN.
In *Proceedings of the First International Conference on Bio-inspired Systems and Signal Processing*, pages 92-99
DOI: 10.5220/0001066100920099

plane that maximizes a symmetry measure, extracted from both sides of the image (Junck et al., 1990; Minoshima et al., 1992; Sun and Sherrah, 1997; Ardekani et al., 1997; Smith and Jenkinson, 1999; Liu et al., 2001; Prima et al., 2002; Tuzikov et al., 2003; Teverovskiy and Liu, 2006), and (ii) methods that detect the longitudinal fissure to estimate the location of the MSP (Brummer, 1991; Guillemaud et al., 1996; Hu and Nowinski, 2003; Volkau et al., 2006). Table 1 summarizes these works, and extensive reviews can be found in (Hu and Nowinski, 2003), (Volkau et al., 2006), (Prima et al., 2002) and (Liu et al., 2001).

Methods in the first group address the problem by exploiting the hough symmetry of the brain. Basically, they consist in defining a symmetry measure and searching for the plane that maximizes this score. Methods in the second group find the MSP by detecting the longitudinal fissure. Even though the longitudinal fissure is not visible in some modalities, such as PET and SPECT, it clearly appears in MR images. Particularly, we prefer these methods because patients may have very asymmetric brains and we believe this would affect the symmetry measure and, consequently, the MSP detection.

The aforementioned approaches based on longitudinal fissure detection present some limitations that we are circumventing in the proposed method. In (Guillemaud et al., 1996), the MSP is found by using snakes and orthogonal regression for a set of points manually placed on each slice along the longitudinal fissure, thus requiring human intervention. Other method (Brummer, 1991) uses the Hough Transform to automatically detect straight lines on each slice (Brummer, 1991), but it does not perform well on pathological images. The method in (Hu and Nowinski, 2003) assumes local symmetry near the plane, which is not verified in many cases (see Figures 2, 5 and 8). Volkau et al. (Volkau et al., 2006) propose a method based on the Kullback and Leibler's measure for intensity histograms in consecutive candidate planes (image slices). The method presents excellent results under a few limitations related to rotation, search region of the plane, and pathological images.

3 METHODS

Our method is based on detection of the longitudinal fissure, which is clearly visible in MR images. Unlike some previous works, our approach is fully 3D, automatic, and applicable to images of patients with severe asymmetries.

We assume that the mid-sagittal plane is a plane that contains a maximal area of cerebro-spinal fluid (CSF), excluding ventricles and lesions. In MR T1 images, CSF appears as low intensity pixels, so the task is reduced to the search of a sagittal plane that minimizes the mean voxel intensity within a mask that disregards voxels from large CSF structures and voxels outside the brain.

The method is divided in two stages. First, we automatically segment the brain and morphologically remove thick CSF structures from it, obtaining a brain mask. The second stage is the location of the plane itself, searching for a plane that minimizes the mean voxel intensity within its intersection with the brain mask. Our method uses some morphological operations whose structuring elements are defined based on the image resolution. To keep the method description independent of image resolution, we use the notation S_r to denote a spherical structuring element of radius r *mm*.

3.1 Segmentation Stage

We use the tree pruning approach to segment the brain. Tree pruning (Falcão et al., 2004a; Miranda et al., 2006) is a segmentation method based on the Image Foresting Transform (Falcão et al., 2004b), which is a general tool for the design of fast image processing operators based on connectivity. In tree pruning, we interpret the image as a graph, and compute an optimum path forest from a set of seed voxels inside the object. A gradient-like image with high pixel intensities along object borders must be computed to provide the edge weights of the implicit graph. A combinatorial property of the forest is exploited to prune tree paths at the object's border, limiting the forest to the object being segmented.

To segment the brain (white matter (WM), gray matter (GM) and ventricles), we compute a suitable gradient image, a set of seed voxels inside the brain and apply the tree pruning algorithm. A more detailed description of this procedure is given in (Bergo et al., 2007). Note that any other brain segmentation method could be used for this purpose.

Gradient Computation. MR-T1 images of the brain contain two large clusters: the first with air, bone and CSF (lower intensities), and the second, with higher intensities, consists of GM, WM, skin, fat and muscles. Otsu's optimal threshold (Otsu, 1979) can separate these clusters (Figs. 1a and 1b), such that the GM/CSF border becomes part of the border between them. To enhance the GM/CSF border, we multiply each voxel intensity $I(p)$ by a weight $w(p)$ as follows:

Table 1: Summary of existing MSP methods.

Method	Based on	2D/3D	Application	Measure
(Brummer, 1991)	fissure	2D	MR	Edge Hough Transform
(Guillemaud et al., 1996)	fissure	2D	MR	Active contours
(Hu and Nowinski, 2003)	fissure	2D	MR, CT	Local symmetry of fissure
(Volkau et al., 2006)	fissure	3D	MR, CT	Kullback-Leibler's measure
(Junck et al., 1990)	symmetry	2D	PET, SPECT	Intensity cross correlation
(Minoshima et al., 1992)	symmetry	3D	PET	Stochastic sign change
(Ardekani et al., 1997)	symmetry	3D	MR, PET	Intensity cross correlation
(Sun and Sherrah, 1997)	symmetry	3D	MR, CT	Extended Gaussian image
(Smith and Jenkinson, 1999)	symmetry	3D	MR, CT, PET, SPECT	Ratio of intensity profiles
(Liu et al., 2001)	symmetry	2D	MR, CT	Edge cross correlation
(Prima et al., 2002)	symmetry	3D	MR, CT, PET, SPECT	Intensity cross correlation
(Tuzikov et al., 2003)	symmetry	3D	MR, CT, SPECT	Intensity cross correlation
(Teverovskiy and Liu, 2006)	symmetry	3D	MR	Edge cross correlation

$$w(p) = \begin{cases} 0 & I(p) \le m_1 \\ 2\left(\frac{I(p)-m_1}{m_2-m_1}\right)^2 & m_1 < I(p) \le \tau \\ 1-2\left(\frac{I(p)-m_2}{m_2-m_1}\right)^2 & \tau < I(p) \le m_2 \\ 2 & I(p) > m_2 \end{cases} \quad (1)$$

where τ is the Otsu's threshold, and m_1 and m_2 are the mean intensities of each cluster. We compute a 3D gradient at each voxel as the sum of its projections along 26 directions around the voxel, and then use its magnitude for tree pruning (Figure 1c).

Seed Selection. The brighter cluster contains many voxels outside the brain (Figure 1b). To obtain a set of seeds inside the brain, we apply a morphological erosion by S_5 on the binary image of the brighter cluster. This operation disconnects the brain from adjacent structures. We then select the largest connected component as the seed set (Figure 1d).

Morphological Closing. The brain object obtained by tree pruning (Figure 1e) might not include the entire longitudinal fissure, especially when the fissure is too thick. To ensure its inclusion, we apply a morphological closing by S_{20} to the binary brain image (Figure 1f).

Thick CSF Structure Removal. The last step of this phase is the removal of thick CSF structures (such as the ventricles, lesions and post-surgery cavities) from the brain object, to avoid the MSP from snapping to a dark structure other than the longitudinal fissure. We achieve this with a sequence of morphological operations: we start from a binary image obtained by thresholding at Otsu's optimal threshold (Figure 1b). We apply a morphological opening by

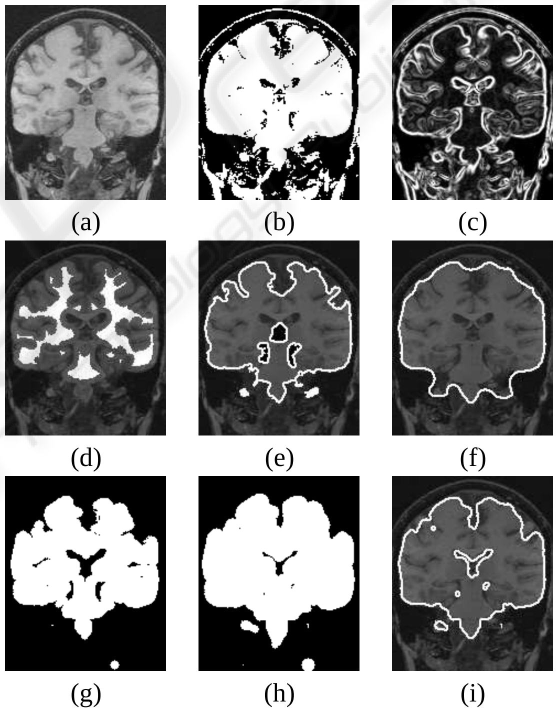


Figure 1: Sample slice of the intermediary steps in stage 1: (a) original coronal MR slice; (b) binary cluster mask obtained by thresholding; (c) gradient-like image used for tree pruning; (d) seed set used for tree pruning (white); (e) border of the brain object obtained by tree pruning (white); (f) border of the brain object after morphological closing; (g) CSF mask after opening; (h) CSF mask after dilation; (h) brain mask (intersection of (f) and (h)).

S_5 to connect the thick (> 5 *mm*) CSF structures (Figure 1g), and then dilate the result by S_2 to include a thin (2 *mm*) wall of the CSF structures (Figure 1h). This dilation ensures the reinclusion of the longitudinal fissure, in case it is removed by the opening. The binary intersection of this image with the brain object is then used as brain mask (Figure 1i) by the next stage of our method. Only voxels within this mask are considered by stage 2. Figures 2a and 2b show how the computed brain mask excludes the large cavity in a post-surgery image, and figures 2c and 2d show how the mask excludes most of the ventricles in patients with large ventricles.

3.2 Plane Location Stage

To obtain the CSF score of a plane, we compute the mean voxel intensity in the intersection between the plane and the brain mask (Figures 3a and 3b). The lower the score, the more likely the plane is to contain more CSF than white matter and gray matter. The plane with a sufficiently large brain mask intersection and minimal score is the most likely to be the mid-sagittal plane.

To find a starting candidate plane, we compute the score of all sagittal planes in 1 *mm* intervals (which leads to 140–180 planes in usual MR datasets), and select the plane with minimum score. Planes with intersection area lower than 10 000 mm^2 are not considered to avoid selecting planes tangent to the surface of the brain. Planes with small intersection areas may lead to low scores due to alignment with sulci and also due to partial volume effect between gray matter and CSF (Figures 3c and 3d).

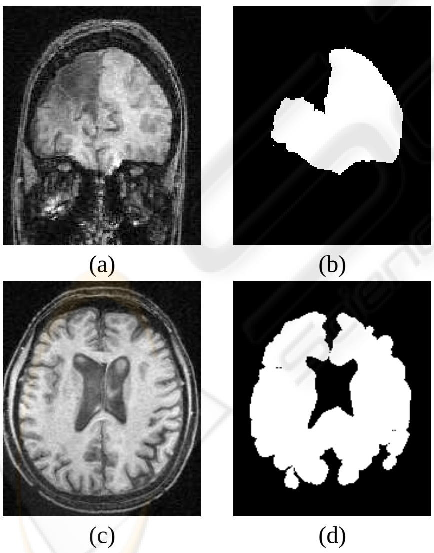


Figure 2: Examples of thick CSF structure removal: (a) coronal MR slice of a patient with post-surgical cavity; (b) brain mask of (a); (c) axial MR slice of a patient with large ventricles; (d) brain mask of (c).

Once the best candidate plane is found, we compute the CSF score for small transformations of the plane by a set of rotations and translations. If none of the transformations lead to a plane with lower CSF score, the current plane is the mid-sagittal plane and the algorithm stops. Otherwise, the transformed plane with lower CSF score is considered the current candidate, and the algorithm is repeated. The algorithm is finite, since each iteration reduces the CSF score, and the CSF score is limited by the voxel intensity domain.

We use a set of 42 candidate transforms at each iteration: translations on both directions of the X, Y and Z axes by 10 *mm*, 5 *mm* and 1 *mm* (18 translations) and rotations on both directions around the X, Y and Z axes by 10^o, 5^o, 1^o and 0.5^o (24 rotations). All rotations are about the central point of the initial candidate plane. There is no point in attempting rotations by less than 0.5^o, as this is close to the limit where planes fall over the same voxels for typical MR datasets, as discussed in Section 4.1.

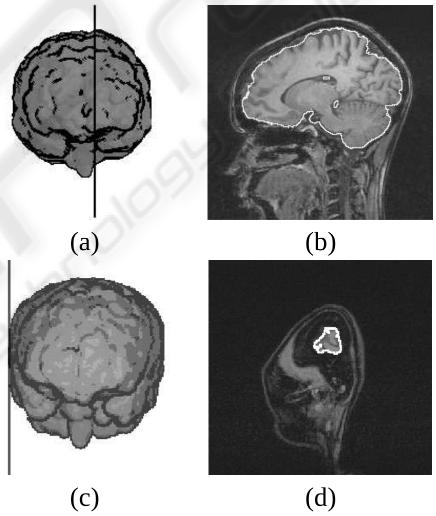


Figure 3: Plane intersection: (a–b) sample plane, brain mask and their intersection (white outline). (c–d) example of a plane tangent to the brain's surface and its small intersection area with the brain mask (delineated in white), overlaid on the original MR image.

4 EVALUATION AND DISCUSSION

4.1 Error Measurement

The discretization of $\mathbb{R}^3$ makes planes that differ by small angles to fall over the same voxels. Consider two planes A and B that differ by an angle Θ (Figure 4). The minimum angle that makes A and B differ by at least 1 voxel at a distance r from the rotation center is given by Equation 2.

$$\Theta = \arctan\left(\frac{1}{r}\right) \quad (2)$$

An MR dataset with 1 mm^3 voxels has a typical maximum dimension of 256 mm. For rotations about the center of the volume, the minimum angle that makes planes A and B differ by at least one voxel within the volume (point p_i in Figure 4) is approximately $\arctan\left(\frac{1}{128}\right) = 0.45^o$. For most MSP applications, we are only concerned about plane differences within the brain. The largest length within the brain is usually longitudinal, reaching up to 200 mm in adult brains. The minimum angle that makes planes A and B differ by at least one voxel within the brain (point p_b in Figure 4) is approximately $\arctan\left(\frac{1}{100}\right) = 0.57^o$.

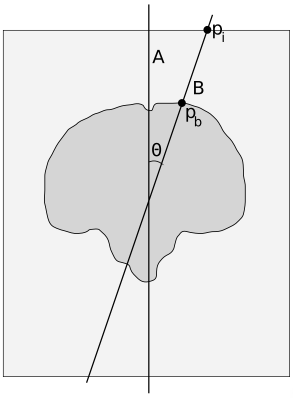


Figure 4: Error measurement in discrete space: points and angles.

Therefore, we can consider errors around 1^o excellent and equivalent results.

4.2 Experiments

We evaluated the method on 64 MR datasets divided in 3 groups: A control group with 20 datasets from subjects with no anomalies, a surgery group with 36 datasets from patients with significant structural variations due to brain surgery, and a phantom group with 8 synthetic datasets with varying levels of noise and inomogeneity, taken from the BrainWeb project (Collins et al., 1998).

All datasets in the control group and most datasets in the surgery group were acquired with a voxel size of $0.98 \times 0.98 \times 1.00$ mm^3. Some images in the surgery group were acquired with a voxel size of $0.98 \times 0.98 \times 1.50$ mm^3. The images in the phantom group were generated with an isotropic voxel size of 1.00 mm^3. All volumes in the control and surgery groups were interpolated to an isotropic voxel size of 0.98 mm^3 before applying the method.

For each of the 64 datasets, we generated 10 variations (tilted datasets) by applying 10 random transforms composed of translations and rotations of up to 12 mm and 12^o in all axes. The method was applied to the 704 datasets (64 untilted, 640 tilted), and visual inspection showed that the method correctly found acceptable approximations of the MSP in all of them. Figure 5 shows sample slices of some datasets and the computed MSPs.

For each tilted dataset, we applied the inverse transform to the computed mid-sagittal plane to project it on its respective untilted dataset space. Thus, for each untilted dataset we obtained 11 planes which should be similar. We measured the angle between all $\binom{11}{2} = 55$ distinct plane pairs. Table 2 shows the mean and standard deviation (σ) of these angles within each group. The low mean angles (column 3) and low standard deviations (column 4) show that the method is robust with regard to linear transformations of the input. The similar values obtained for the 3 groups indicate that the method performs equally well on healthy, pathological and synthetic data. The majority (94.9%) of the angles were less than 3^o, as shown in the histogram of Figure 6. Of $64 \times 55 = 3520$ computed angles, only 5 (0.1%) were above 6^o. The maximum measured angle was 6.9^o. Even in this case (Figure 7), both planes are acceptable in visual inspection, and the large angle between different two computations of the MSP can be related to the non-planarity of the fissure, which allows different planes to match with similar optimal scores. The lower mean angle in the phantom group (column 3, line 3 of Table 2) can be related to the absence of curved fissures in the synthetic datasets. Figure 8 shows some examples of non-planar fissures.

Table 2: Angles between computed MSPs.

Group	**Datasets**	**Angles**	
		Mean	σ
Control	20	1.33^o	0.85^o
Surgery	36	1.32^o	1.03^o
Phantom	8	0.85^o	0.69^o
Overall	64	1.26^o	0.95^o

All experiments were performed on a 2.0 GHz Athlon64 PC running Linux. The method took from 41 to 78 seconds to compute the MSP on each MR dataset (mean: 60.0 seconds). Most of the time was consumed computing the brain mask (stage 1). Stage 1 required from 39 to 69 seconds per dataset (mean: 54.8 seconds), while stage 2 required from 1.4 to 20 seconds (mean: 5.3 seconds). The number of iterations in stage 2 ranged from 0 to 30 (mean: 7.16 iterations).

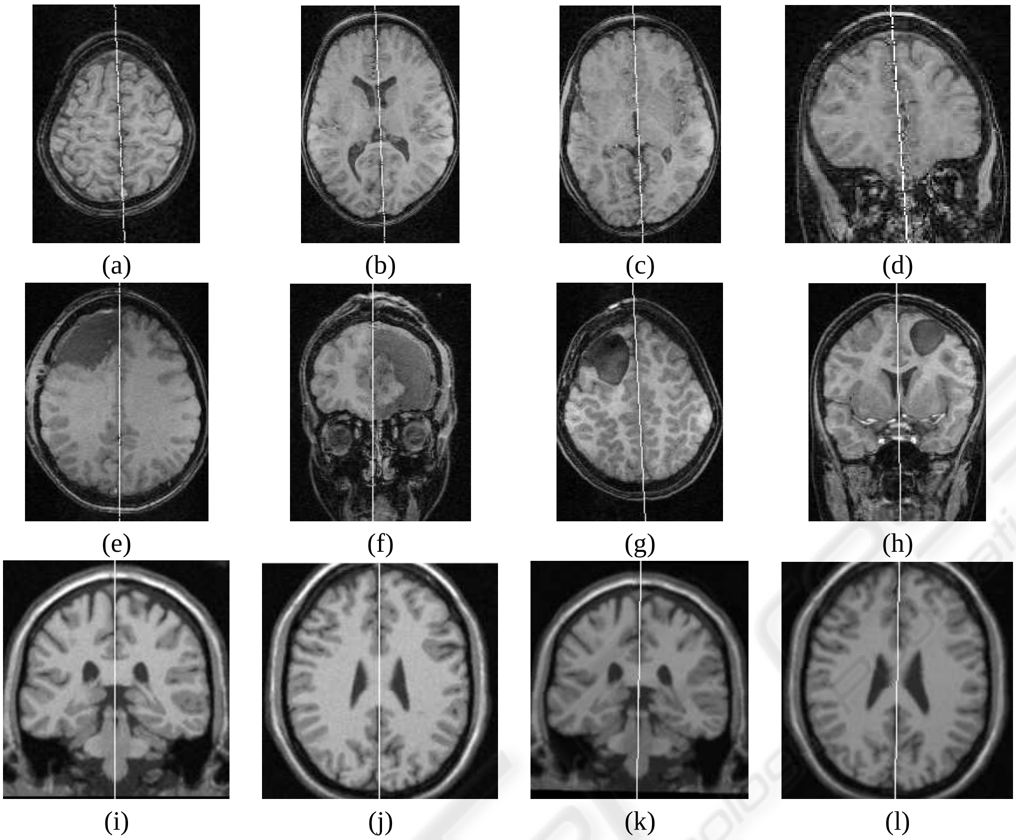


Figure 5: Examples of planes computed by the method: (a–d): sample slices from a control dataset; (e–f) sample slices from a surgery dataset; (g–h) sample slices from another surgery dataset; (i–j): sample slices from a phantom dataset; (k–l): sample slices from a tilted dataset obtained from the one in (i–j).

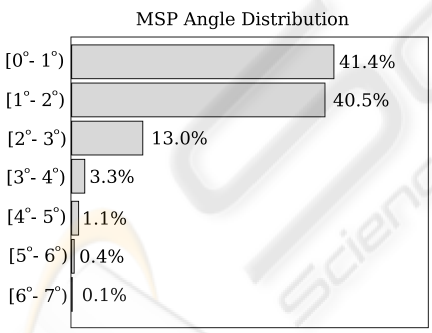


Figure 6: Distribution of the angles between computed mid-sagittal planes.

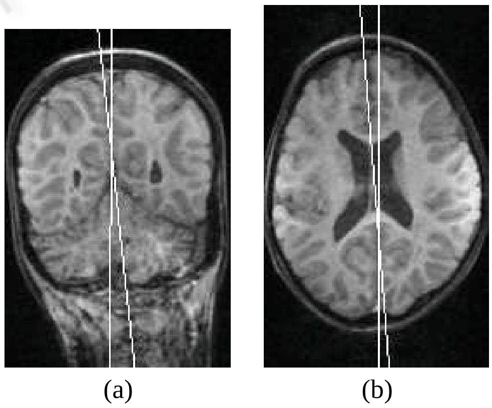
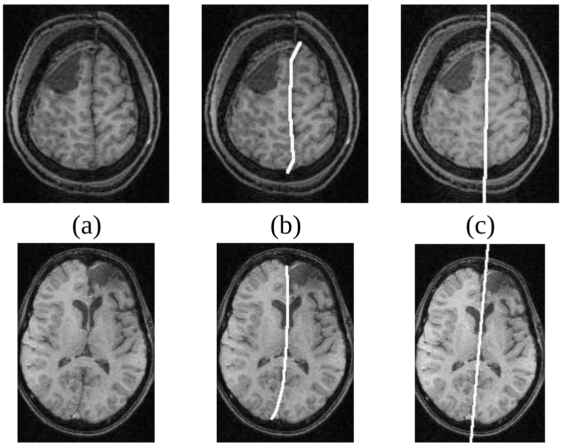


Figure 7: A coronal slice (a) and an axial slice (b) from the case with maximum angular error (6.9^o), with planes in white: The fissure was thick at the top of the head, and curved in the longitudinal direction, allowing the MSP to snap either to the frontal or posterior segments of the fissure, with some degree of freedom.

5 CONCLUSIONS AND FUTURE WORK

We presented a fast and robust method for extraction of the mid-sagittal plane from MR images of the brain. It is based on automatic segmentation of the brain and on a heuristic search based on maximization of CSF within the MSP. We evaluated the method on 64 MR datasets, including images from patients with large surgical cavities (Figure 2a and Figures 5e–h). The method succeeded on all datasets and performed



(a) (b) (c)

(d) (e) (f)

Figure 8: Non-planar fissures: (a) irregular fissure, (b) expert fissure delineation of (a) and (c) MSP computed by our method. (d) Curved fissure, (e) expert fissure delineation of (d) and (f) MSP computed by our method.

equally well on healthy and pathological cases. Rotations and translations of the datasets led to mean MSP variations around 1^o, which is not a significant error considering the discrete space of MR datasets. MSP variations over 3^o occurred only in cases where the longitudinal fissure was not planar, and multiple planes fitted different segments of the fissure with similar scores. The method required a mean time of 60 seconds to extract the MSP from each MR dataset on a common PC.

Previous fissure-based works were either evaluated on images of healthy patients, on images with small lesions (Volkau et al., 2006), or relied on local symmetry measurements (Hu and Nowinski, 2003). As future work, we intend to implement some of the previous works and compare their accuracy and performance with our method on the same datasets. Brain mask computation is responsible for most of the computing time. We also plan to evaluate how the computation of the brain mask on lower resolutions affect the accuracy and efficiency of the method.

ACKNOWLEDGEMENTS

The authors thank CAPES (Proc. 01P-05866/2007), CNPq (Proc. 302427/04-0), and FAPESP (Proc. 03/13424-1) for the financial support.

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