

Focal Cortical Dysplasia Segmentation in 3D Magnetic Resonance Images of the Human Brain

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***Abstract.** In this work we present an image processing pipeline for automatic segmentation of focal cortical dysplasia lesions in 3D magnetic resonance images of the human brain. Dysplasia lesions are a common cause of refractory epilepsy, especially in children, and their treatment often involve surgical intervention. To achieve this pipeline we developed several new image processing techniques, procedures and algorithms, which led to an automatic FCD segmentation method that is more accurate than the state-of-the-art and that, unlike the state-of-the-art, is applicable to MR images of children.*

1. Introduction

Focal cortical dysplasia (FCD) is a malformation of the brain cortex commonly associated to refractory cases of epilepsy, where drug-based treatment does not eliminate the seizures [Montenegro et al. 2002]. FCDs are characterized by microscopic abnormalities of the gray matter tissue, which lead to subtle macroscopic variations in the tissue appearance in magnetic resonance images [Taylor et al. 1971, Bastos et al. 1999]. Detection and localization of FCD lesions are fundamental for treatment planning. These tasks are often difficult, tedious and subjective due to the subtlety of the lesion appearance and to the large amount of data in a typical 3D MR image.

In this work we present a method for automatic detection and segmentation of FCD lesions in 3D magnetic resonance images of the human brain. The method combines new image segmentation techniques, automates a previously interactive technique (curvilinear reformatting [Bastos et al. 1999]) and uses classification by supervised learning [Duda et al. 2000] to detect and segment lesions with a 100% rate of detection and 76.9% coverage of the lesions [Bergo et al. 2008a]. This result is slightly better than the state-of-the-art [Colliot et al. 2006].

2. Related Works

The most common FCD diagnosis method in clinical practice is the straightforward visual inspection of MR images by specialists. The reported detection rate for this technique is 50% [Montenegro et al. 2002]. Techniques such as multiplanar reconstruction (MPR) and curvilinear reformatting (CR) increase the detection rate to 100% [Montenegro et al. 2002]. Curvilinear reformatting [Bastos et al. 1999] consists of visualizing 3D MR images as curved surfaces that follow the shape of the brain. This technique improves the visibility of FCD lesions over MPR [Montenegro et al. 2002] and can be computed automatically without human interaction [Bergo and Falcão 2006].

Several recent works presented automatic FCD detection methods, with detection rates varying from 53% to 85% [Kassubek et al. 2002, Antel et al. 2003, Srivastava et al. 2005, Colliot et al. 2006]. Most of these works focus on detection rather than segmentation. To our knowledge, Colliot et al. [Colliot et al. 2006] is the only work that reports segmentation accuracy rate, with a coverage of 73% of the lesional voxels. Some of these works [Kassubek et al. 2002, Antel et al. 2003, Colliot et al. 2006] rely on template-based segmentation techniques of the GM, which are often unreliable for children and patients who underwent brain surgery [Collins et al. 1998, Cuadra et al. 2004].

3. Contributions

The main contribution of this work is an automated procedure for segmentation of FCD lesions in 3D magnetic resonance images of the brain. The procedure attempts to mimic the effective CR-assisted visual inspection technique used by specialists [Montenegro et al. 2002]. The procedure consists of 4 steps: brain segmentation, mid-sagittal plane location, curvilinear reformatting computation, and feature extraction and classification. All steps involve original contributions, detailed in [Bergo 2008]¹ The next sections provide an overview of the contributions in each of these steps.

3.1. Brain Segmentation

FCD lesions are often diagnosed in childhood [Colombo et al. 2003, Ruggieri et al. 2004], and it is also desirable to segment these lesions on images from patients who underwent surgical treatment, to detect, locate and evaluate FCD lesions that were not removed. Many FCD detection/segmentation methods in the literature rely on template-based brain segmentation techniques [Kassubek et al. 2002, Antel et al. 2003, Colliot et al. 2006], which are not reliable for images of children or surgical patients [Cuadra et al. 2004].

To circumvent this limitation, we developed a graph-based automatic brain segmentation procedure that reliably segments brains from 3D MR images regardless of patient age or anatomical variations. The main contribution in this point was the tree pruning segmentation technique. Tree pruning exploits the Image Foresting Transform (IFT) framework [Falcão et al. 2004b] to automatically detect object borders based on graph connectivity properties. An interactive version of this idea was first presented in [Falcão et al. 2004a]; Improvements and automation were presented in [Miranda et al. 2006]; and an extensive description of the methods, including preprocessing for brain segmentation and evaluation of the method in 8 synthetic MR volumes and 20 real MR volumes, was presented in [Bergo et al. 2007]. Brain segmentation by tree pruning provided an average of 97.6% accuracy in comparison to expert delineations, and a desktop PC can automatically segment a typical MR brain image in about 25 seconds. These results are much better (both in accuracy and performance) than what is achieved with the popular SPM2 [Frackowiak et al. 2003] template-based segmentation software, used by many works in the literature. Figure 1 shows an example of brain segmentation obtained by tree pruning.

¹Available online at: <http://libdigi.unicamp.br/document/?code=vtls000439611> and <http://www.liv.ic.unicamp.br/~bergo/bergo-phd.pdf>.

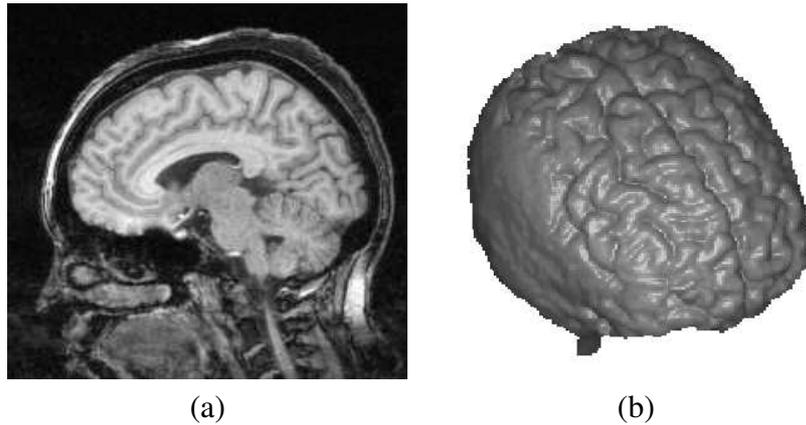


Figure 1. Automatic brain segmentation: (a) A 2D slice of a 3D MR image of the brain. A typical 3D MR image has from 120 to 200 slices. (b) 3D rendition of the brain segmentation obtained by automatic tree pruning.

3.2. Mid-Sagittal Plane Location

A key idea in our approach to FCD segmentation is to exploit the texture asymmetry of FCD lesions. Blurring and intensity shifts are typical signs of FCD lesions, but these features can also be caused by acquisition artifacts, such as partial volume, patient movement and magnetic field ramps. What specialists do when they visually search for lesions is look for asymmetric textures, since there are no records of FCD lesions occurring in both brain hemispheres within the same patient. In order to mimic this behavior, we need to locate a symmetry surface so that we can find a symmetric correspondent to each voxel in the brain. The inter-hemisphere fissure is a liquid-filled region between the brain hemispheres (Figure 2). It can be roughly approximated by a plane and it serves well as symmetry surface.

There is a wide selection of MSP computation methods in the literature, but many of them are not reliable for brains of post-surgery patients, or are too slow and take several minutes to locate the MSP. We developed a new MSP location technique that uses brain segmentation obtained by tree pruning [Bergo et al. 2007] as a starting point and reliably locates the MSP, using an heuristic search algorithm, in about 5 seconds on a desktop PC. This method has been shown to be very reliable for images of patients with surgical cavities. The method has been evaluated on 64 MR images, including 36 images of patients with surgical cavities, and was shown to be accurate to within 1.5 degrees of rotation and 1.5 mm of translation. The method was first presented in [Bergo et al. 2008b]. The evaluation was later extended to compare the automatically-located MSPs with specialist delineations, and published in [Bergo et al. 2009].

3.3. Automatic Curvilinear Reformatting

Curvilinear reformatting (CR) was originally proposed by [Bastos et al. 1999]. This technique allows specialists to visualize MR images of the brain as surfaces that follow the curvature of the brain, and that minimize partial volume effects and make FCD lesions more evident (Figure 3). This technique has been shown to greatly improve the detection rate of FCD lesions by visual inspection [Montenegro et al. 2002]. But the CR computation was an interactive process where the operator had to manually delineate the

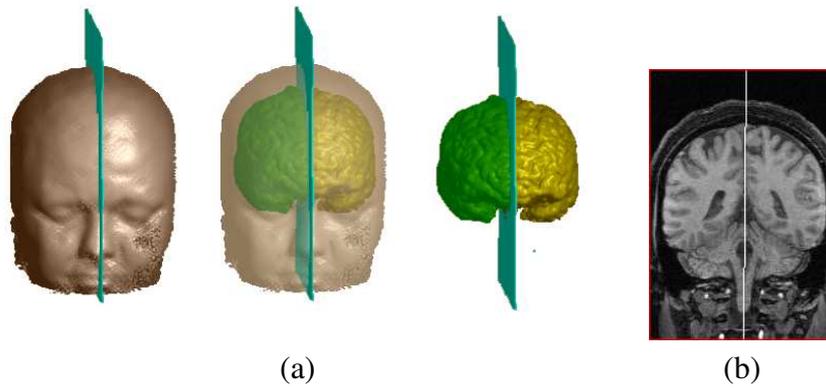


Figure 2. Brain hemispheres and mid-sagittal plane: (a) mid-sagittal plane shown in 3D renditions of an MR volume with segmented skin and brain. (b) automatically-located mid-sagittal plane shown in a 2D slice of an MR volume.

brain curvature on several MR slices, compromising the technique’s repeatability. We have shown that CR can be computed and displayed automatically with an Euclidian distance transform from a surface called *brain envelope* that closely follows the surface of the segmented brain object. The brain envelope can be computed from the brain segmentation using trivial mathematical morphology operations, and the EDT can be efficiently computed using an IFT [Falcão et al. 2004b]. These results have been presented in [Bergo and Falcão 2006].

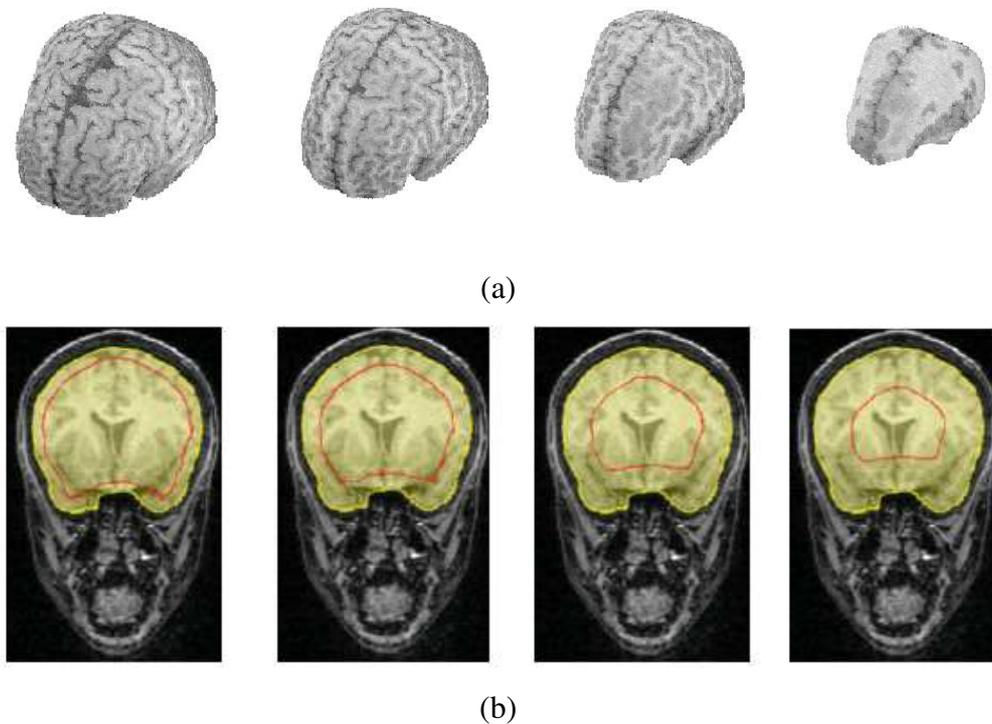


Figure 3. (a) Curvilinear reformatting visualizations for an MR volume, at 4 distinct depths. (b) The curvilinear surfaces of (a), plotted on regular 2D MR slices.

3.4. Feature Extraction and Classification

In this step we extract features from 2D texture patches that are tangent to the CR surfaces. For each voxel, we extract features from a pair of texture patches: one centered at the voxel and one centered at the symmetric voxel on the opposing hemisphere. By doing this, each feature vector stores information about the texture surroundings of the voxel and also about the similarity between the symmetric region in the opposing hemisphere. The key contribution in this step is adding symmetry information to the feature vector, something that was not tried in previously published FCD segmentation methods. To perform segmentation, we use a pattern classifier based on supervised learning. A specialist manually delineated FCD lesions in MR images of epilepsy patients. These delineations were used to train a Reduced Coulomb Energy network (RCE) [Duda et al. 2000], which was then used to classify voxels between as lesional or not. An evaluation of the complete procedure was presented in [Bergo et al. 2008a]. In this article we used datasets from 5 patients for experimental evaluation, obtaining a detection rate of 100% and average voxel coverage of the lesions of 76.9%. This coverage was better than the 73% reported by [Colliot et al. 2006]. Unlike [Colliot et al. 2006], our procedure does not use template-based segmentation techniques (unreliable for children) and 2 of the patient datasets in our evaluation were from children. Figure 4 shows sample slices comparing the specialist delineations to the automatic lesion segmentations obtained by our method.

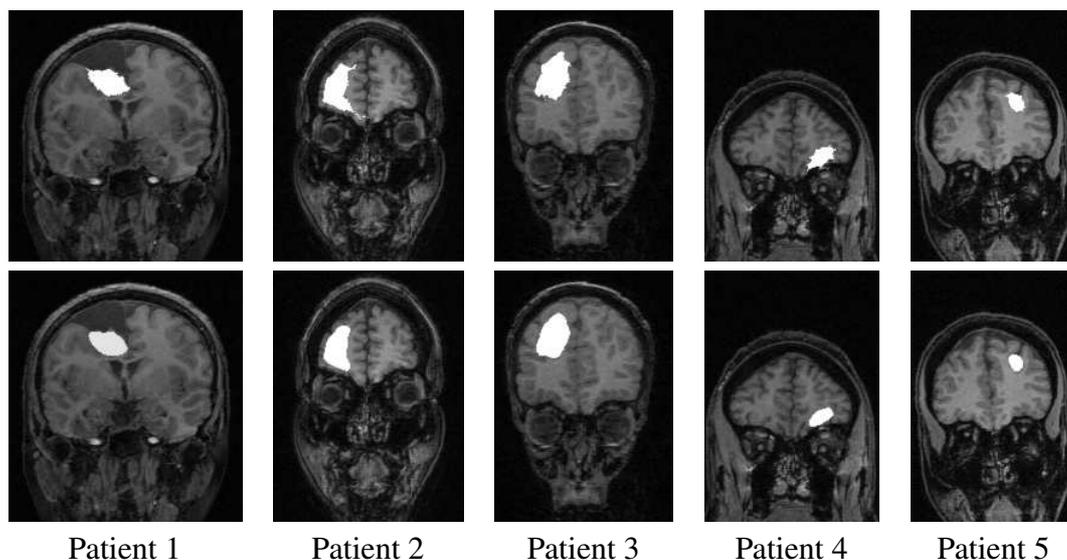


Figure 4. Ground truth and segmentation results for the 5 patients. The first row shows the ground truth provided by an specialist. The second row shows the final automatic segmentation result. Patients 1 and 3 are children, and patient 1 has a visible anatomical deformity (top left).

4. Conclusions

In this doctorate work we have presented several original contributions related to image processing and medical image analysis: tree pruning, a new image processing technique that is fast, does not require background markers and is very tolerant to variations in image background [Bergo et al. 2007]; a mid-sagittal plane location for MR images of the brain that is fast, accurate and works well regardless of patient age and anatomical

variations [Bergo et al. 2008b, Bergo et al. 2009]; an automatic technique to compute the curvilinear reformatting of MR images of the brain [Bergo and Falcão 2006]; a procedure for feature extraction and classification that mimics the behavior of medical specialists to precisely determine the location and extent of focal cortical lesions in MR images of the brain [Bergo et al. 2008a].

Treatment of epilepsy patients with FCD lesions often involve surgical removal of the lesions, and MRI is the only imaging technique that can reveal these lesions. The FCD segmentation procedure developed during this work provided better quantitative results than the state-of-the-art, and it is also more widely applicable, since we have chosen techniques that perform well on images of children and of patients with anatomical variations.

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