Watershed Segmentation of Intervertebral Disk and Spinal Canal from MRI Images

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Abstract. A robust method to segment intervertebral disks and spinal canal in magnetic resonance images is required as part of a precise 3D reconstruction for computer assistance during diskectomy procedure with minimally invasive surgery approach. In this paper, an unsupervised segmentation technique for intervertebral disks and spinal canal from MRI data is presented. The proposed scheme uses a watershed transform and morphological operations to locate regions containing structures of interest. Results show that the method is robust enough to cope with variability of shapes and topologies characterizing MRI images of scoliotic patients.

1 Introduction

Benefits of minimally invasive surgery for disk resection are clear for scoliotic patient[1-3]. Unfortunately, enthusiasm for the adoption of this procedure has been sluggish by 3 main difficulties faced by the surgeons: the lost of depth perception, reduced field of view and the long training curve. An image guided surgery system that would integrate 3D preoperative data with the thoracoscopic video images would help to solve problems encountered by surgeons with minimally invasive surgery. An important part of this system is the precise preoperative 3D model of the patient anatomy. The structures of interest for scoliotic patients are the vertebral bodies, the intervertebral disks and the spinal canal.

MRI is a non invasive imaging modality that allows precise visualization of soft tissues while showing good delimitation of hard structure. Hence, MRI is a relevant choice of modality to obtain 3D reconstruction of the intervertebral disk and the spinal canal.

Magnetic resonance images are challenging because (1) non-uniformities of intensities over the same class of tissues or structures exist between patients, (2) shape and position of structures vary between patients due to the scoliotic deformity, (3) variation of relative intensity along the spine due to different structures surrounding the spine at different levels (intra patient variability). Also, as the ultimate goal of the segmentation process is to perform 3D reconstruction of the structures and as the final application will be used in a clinical context, the external constraints are (1) automatic

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segmentation (no user interaction), (2) segmentation should create closed contour that will be connected between successive sections for 3D reconstruction, otherwise it would necessitate an edge closing step which is often a complex task.

(a) (b) (c)

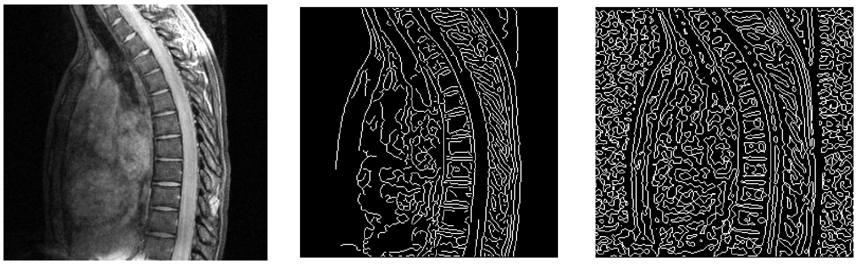

Fig. 1 . Results of segmentation obtained for (a) the original image with (b) Canny method, (c) Marr Hilldreth method

For MRI images of the spine where intervertebral disks and spinal canal have to be segmented, methods based on thresholding or top hat methods are not working since structures to segment do not have fixed size, orientation and intensity. Figure 1 shows examples of edge detection by Canny and Marr-Hildreth methods. For the Canny method, contours are not closed and for 3D reconstruction, it would necessitate an edge closing step which is often a complex task. The Marr-Hildreth can produce closed contours but the image is oversegmented as it contains edges of many structures besides the structures of interest.

Other segmentation techniques that are part of the active contour model category like the snakes introduced by Kass et al[4] or level sets, require a lot of fine tuning of parameters in order to obtain the type of segmentation needed. Also, results with this kind of methods are strongly dependant on the initialization phase so user interaction is often needed for this step.

Only few studies relate works on segmentation of MRI spine images[5-9]. None of these techniques are useful for our application because of the spinal deformity and the external constraints namely the unsupervised and closed contours requirements.

Hoad et al[7] and Coulon et al[5] respectively proposed a technique to segment vertebrae and spinal cord on MR images. For both cases, the initialisation phase needed a user interaction to manually locate the center of the spinal cord at every spine level[5] or to manually locate 4 points on each vertebral body[7]. Booth et al[9] developed an algorithm that can automatically detect the center of the spinal canal on the axial images based on a symmetry measure. With this information, they can apply an active contour algorithm to segment the spinal canal. The vertebral bodies are then segmented in the axial direction based on a radial edge detection scheme that produces open contours which is not adequate for the current application. Also, working in the axial direction only is not a good choice for the precise delimitation between the intervertebral disk and the vertebral body: saggital view gives much more information on the delimitation of these structures. On the other hand, Shi and Malik[10] proposed an unsupervised segmentation technique that could have been used for our application if the final application was not for scoliotic spines. Indeed, this technique does not require initialization and it looks for pairwise affinities between all pairs of pixels and admits combinations of different features such as brightness, position, windowed histogram, etc. Carballido-Gamio et al[8] have worked to alleviate the computational demand imposed by the normalized cuts technique but even with this work, the time to compute the segmentation is still too long. Also, this technique needed a selection of saggital slices where spinal canal can be clearly identified. For scoliotic patients, there is no saggital image that shows spinal canal from top down because of the 3D deformation of the spine. Peng et al[6] automatically found the best saggital slice to locate intervertebral disks but they use a Canny edge operator creating open contours.

Watershed has been used in combination with other techniques in cardiology on ultrasound images[11] and in neurology on MR images[12-14] and their results showed that the technique is able to cope with variation of topologies and shape but it was never used for spinal deformity.

The principle of watershed transform is based on the detection of ridges and valleys. The image is viewed as a topological image where intensity represents the altitude of the pixels. The image is flooded from its minimum and it allows the delimitation between the catchment basins and the ridges (watershed lines). Hence the catchment basins represent region of homogeneous intensity. But, as it is well known, the use of the watershed method on gradient image leads to oversegmentation problems[14-16] and the searched contours are lost in a bunch of irrelevant ones. Oversegmentation can be caused by too many minima due to noise or to other structures that should not appear in the gradient image. To overcome this problem it is possible to either remove irrelevant contour[12] or modify the gradient image[15].

Basic watershed method already uses the intensity information of the image (gradient image). Hence, to introduce shape information in the method and to get rid of the well known oversegmentation problem with the watershed technique, we have used the marker method based on morphological operators. This method allowed incorporation of a priori knowledge of the shape of the structure of interest by introducing internal markers (sets of connected pixels of the region of interest) and external markers that correspond to the background. The external markers represent the deepest valley lines surrounding every internal marker. The use of an atlas to automatically determine the markers as proposed by Grau et al[14] was not applicable in the case of intervertebral disk and vertebral body of scoliotic patient because of complex spinal curves (three dimensional deformation of the spine) specific to every scoliotic patient.

The objective of this paper is to present an unsupervised segmentation technique using watershed on magnetic resonance imaging and evaluating the capacity of the method to deal with different spinal deformities of scoliotic patients.

2 Proposed Approach

2.1 Image Acquisition System and Hardware

The magnetic resonance images were acquired at Sainte-Justine Hospital with a 1.5T Magnetom Avanto system from Siemens. The radiofrequency (RF) transmitting and receiving units consisted of a body coil. A 3D MEDIC (Multi Echo Data Image

Combination) sequence was used in saggital plane with a RT=23ms, ET=12ms, slice thickness of 1mm and a matrix of 256 X 256 leading to a voxel size of 1mm^3. The images were then transferred on a Pentium 4 3 GHz, 1 GB of RAM.

2.2 Segmentation Algorithm

The algorithm presented in this study is able to detect intervertebral disks and spinal canal. The preferred planes for the segmentation are not the same for both structures. The intervertebral disks have a cylindrical shape of approximately 20mm diameter with a height of 6mm and can be easily detected in the saggital or coronal plane. The spinal canal has a long cylindrical shape with a diameter of approximately 10mm with curvatures in 3D that depends on the severity of the scoliotic deformities so the axial plane is the preferred view to segment this structure.

Figure 2 shows that the algorithm needed a preprocessing step (described in section 2.2.1 - Preprocessing) allowing consistent contrast from slice to slice in the acquisition plane. Hence, image reconstruction in the other planes (axial and coronal) did not show any discontinuity.

The proposed method modifies the gradient image by using the internal and external markers to keep only the most significant and relevant contours for the structures of interest. Subsections 2.2.2 – Internal Markers and 2.2.3 – External Markers give details of how the marker, created with morphological operations, can locate intervertebral disks or spinal canal. Then, the watershed transformation was applied on the modified gradient image to give a segmentation of the disk for images in the saggital or coronal planes and the spinal canal for the images in the axial plane.

2.2.1 Preprocessing

As it is shown in figure 2, the first step of the proposed algorithm is a preprocessing procedure. In order to have the same contrast from slice to slice in the saggital plane, all the images of the volume go through a contrast stretching step which widens the dynamic range of the histogram based on a simple linear mapping.

$$I_{out} = \left(I_{in} - c\right)\left(\frac{b-a}{d-c}\right) + a \tag{1}$$

where I_{out} is the processed image, I_{in} the original image, a and b the minimum and maximum values of a normalized image respectively. c and d are chosen so that they represent the 2nd and 98th percentile of the histogram, meaning that 2% of the pixels in the histogram had a values lower than c and 2% of the histogram had values higher than d. This prevented outliers affecting the histogram mapping. The axial reconstruction based on this new volume was then obtained without any contrast irregularities. Once the axial reconstruction was completed, no more preprocessing was needed on these images.

For the saggital view, the spinal canal which appears very bright in the image was removed with a morphological operator called opening by reconstruction. A simple opening noted

$$\left(I \circ b\right) = \left(I \Theta b\right) \oplus b \tag{2}$$

was obtained by applying erosion Θ on an image with a structuring element b and then applying a dilation ⊕ on the resulting erosion. Opening by reconstruction is an iterative process (see Vincent et al[15] for details) defined as

$$\psi_{openrec}(I) = R_I(I \circ b \mid I) \tag{3}$$

which is representing the opening by reconstruction of I, using structuring element b. This morphological operator is often used to filter out all the connected components which can not contain the structuring elements while preserving the others entirely.

2.2.2 Internal Markers

After this preprocessing step, the structures of interest on the image *I* are the bright pixels. An opening by reconstruction was applied with a small structuring element. The structuring element used for the spinal canal was a disk of 8mm of diameter and a square of 2mm X 2mm for the intervertebral disk. The choice of the structuring element was made knowing that the intervertebral disk in the coronal or saggital plane can have different orientations depending on the severity of the spine deformity. Indeed to be able to keep the same structuring element regardless of the scoliotic severity, the structuring element should be invariant to the rotation and translation of the structure in the saggital or the coronal plane. This operation resulted in an image where the intervertebral disks and spinal canal had a smooth intensity (figure 3 a, e).

The markers are binary images, hence the intensity image (figure 3 a, e) was converted to a black and white image with thresholding (figure 3 b, f). The thresholding method used is the Otsu's method which can automatically find the threshold k that minimizes the within class variance and this turns out to be the same as maximizing the between class variance[17,18].

$$\max\left(\frac{\sigma_B^2}{\sigma_T^2}\right) \tag{4}$$

where σ^2_B is the between class variance and σ^2_T is the total variance that represents the sum of the between-class variances and the within-class variances.

2.2.3 External Markers

The external markers represent the background and were created with the help of the distance transform of the internal markers. The distance transform of a binary image is the distance from every pixel to the closest non-zero value pixel. The metric used was the Euclidean distance between 2 points u=(x1,y1) and v=(x2,y2)

$$d(x,y) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{5}$$

where *d* measured a straight line between 2 pixels. An example of a distance transform of an internal marker image is shown on figure 3 c, g. The watershed was applied on the distance transform which produced the external marker.

Combined binary marker Fm (figure 3 d, h) is then imposed as minima on the gradient image.

$$F^m = F^m_{\text{int}} \cup F^m_{ext} \tag{6}$$

This minima imposition eradicated the problem of oversegmentation that occurred with watershed directly applied on gradient image.

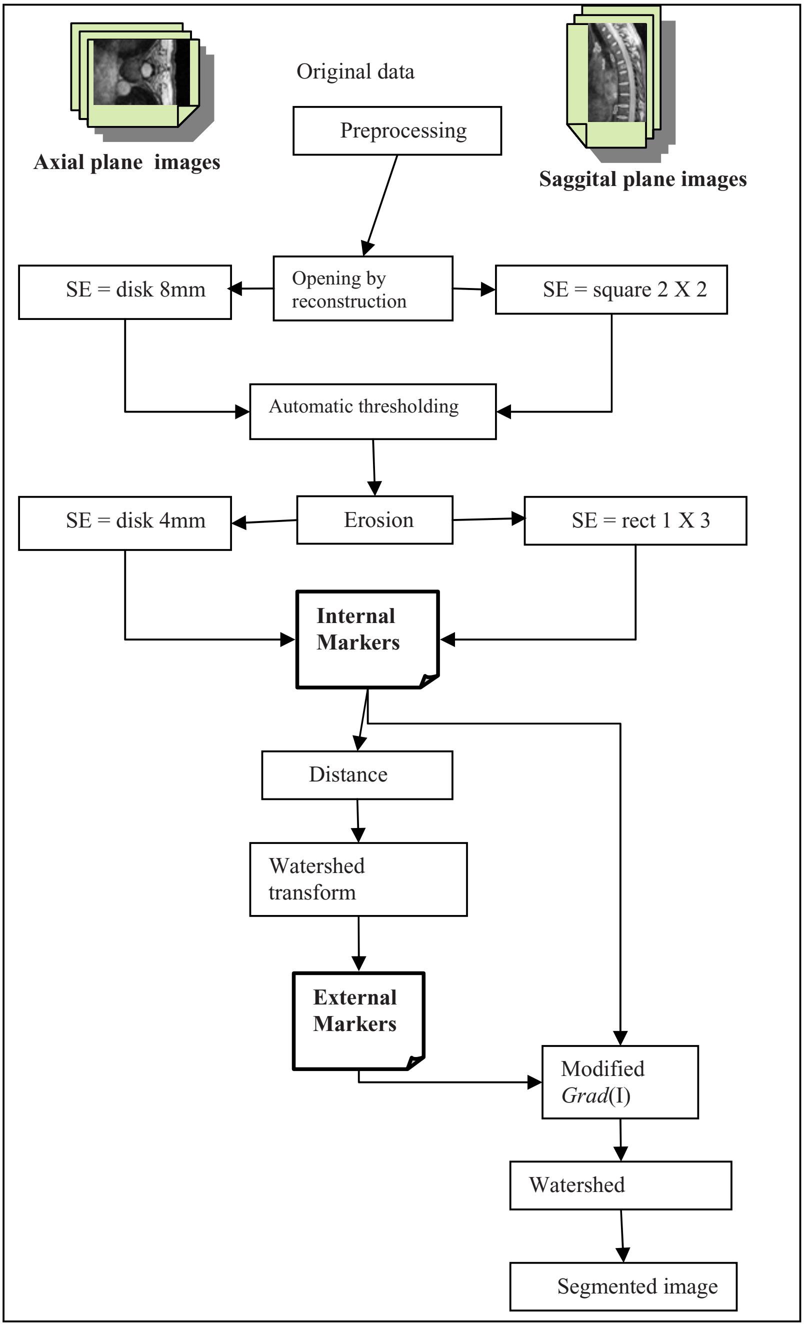

Fig. 2. Algorithm for automatic detection of internal and external markers and the final segmentation

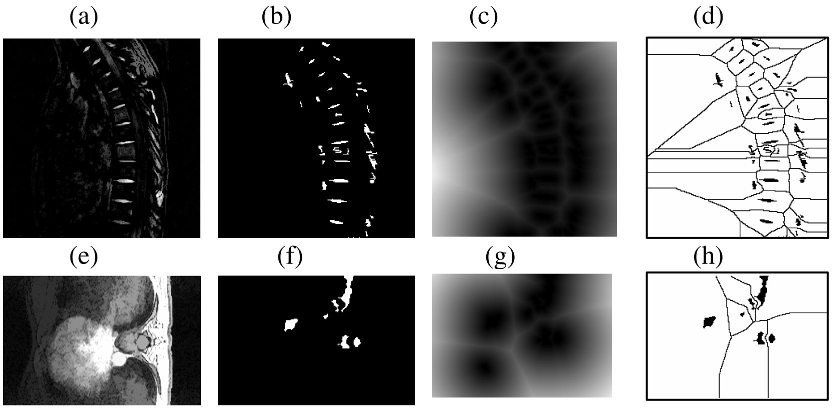

Fig. 3 . Creation of internal and external markers. (a) and (e) are the results of the opening by reconstruction with a structural element being a square and disk respectively. (b) and (f) are the results of the automatic threshold to create the internal markers in the saggital and axial planes. (c) and (g) the distance transform applied on the internal markers to obtain the external markers. (d) and (h) the internal and external markers used to impose minima on the gradient image.

3 Experimental Results and Discussion

For clinical purposes intervertebral disks and spinal canal have to be segmented on every image contained in the volume of interest. Intervertebral disks can easily be detected on the coronal or saggital views and the spinal canal on the axial view. The technique presented here is an unsupervised technique and do not need any initialization. All the segmented results were obtained using the algorithm directly on the magnetic resonance images acquired with the specified protocol. Our implementation using Matlab® on a Windows NT based system equipped with a 3 GHz processor took less than 2 seconds per frame. This is fast considering the complexity of the problematic of the current application and the use of a high level interpreted language like Matlab®.

Figure 4 a,b,c shows results for different types of scoliotic deformity severities and figure 4 d shows result for axial images. Taking the 4 results(a, b, c, d) independently, it shows that the proposed scheme does give satisfactory results in terms of its ability to detect intervertebral disk along the spine of one specific patient even with the relative intensity variation due to different structures surrounding the spine at different disk levels. Indeed, for the 4 cases all the disks and the spinal canal were detected and segmented. The comparison of the results of figure 4 (a), (b) and (c), illustrates that the marker-controlled watershed technique is able to deal with non-uniformities of intensities that exist over the same class of tissues or structures between patients because the algorithm is able to detect all the intervertebral disks. These results also illustrate that the proposed method can deal with the change of topology due to the scoliotic deformities of the spine. Figure 4 (d) illustrate the segmentation of the spinal canal on axial image and clearly demonstrate that the proposed technique is versatile and can detect many types of structures of interest. This new technique enables the use of prior information to automatically generate markers for specific structures. With proper internal and external markers used to modify the gradient images, watershed algorithm is able to detect specific structures on axial or saggital images.

The position of the plane of the image is a factor that does affect the quality of the detection of the intervertebral disk. Indeed, on the extremities of the disk in a saggital or a coronal plane, it is hard to find the delimitation between the disk and the surrounding tissue (figure 5). This can be bypassed by segmenting intervertebral disks in 2 orthogonal planes simultaneously. Hence regions that can hardly be segmented in one plane (saggital plane) correspond to regions that can easily be segmented in the other plane (coronal plane).

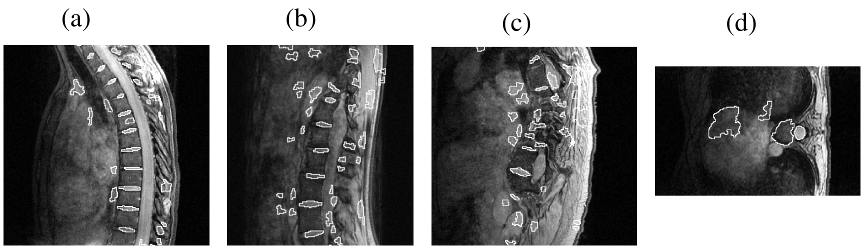

Fig. 4. Results for different severities of spine deformities. Saggital view of (a) normal spine, (b) moderate spine deformation, (c) important spine deformation, and (d) results in axial view for the spinal canal detection.

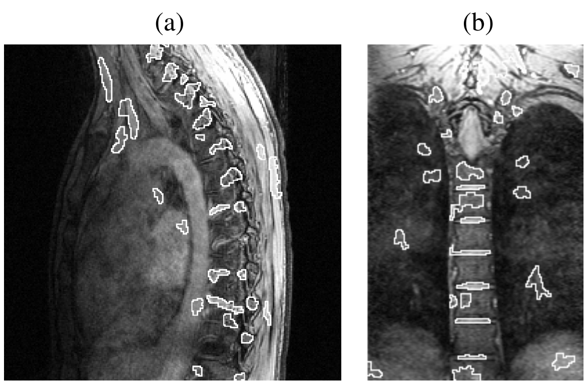

Fig. 5. Poor delimitation at the extremities of the disk in one direction (a) saggital, corresponds to good delimitation of the disk in the other orthogonal directions (b) coronal

Unfortunately, a persistent problem with our method is the oversegmentation. Our watershed based technique does segment regions that are not intervertebral disk or spinal canal. But since our segmentation technique leads to closed contours, it is easy to send the closed contours into an unsupervised pattern recognition algorithm to determine whether it is an intervertebral disk or not. Some preliminary work has been done with a non-parametric approach based on texture information and gives promising results.

A validation step based on the DICE similarity coefficient is being carried out. This method will quantitatively validate the segmentation method and we will be able to compare the results with manual segmentation done by radiologist.

4 Conclusion

As the ultimate goal of the segmentation process for the current application is to reconstruct in 3D the intervertebral disks and the spinal canal of scoliotic patients in a clinical environment, the robustness, the automatic aspect and the precision are the 3 fundamentals requirements of the segmentation process.

We developed a watershed based technique for segmentation of intervertebral disks and spinal canal from magnetic resonance images. A qualitative analysis of the results obtained with this technique compared favourably with other fast and unsupervised techniques such as Canny and Marr Hildreth edge detectors. The advantage of our approach lies in the fact that it is fast, unsupervised, produces closed contours, and is based not only on intensity information but also on prior knowledge of the shape to be detected. We also demonstrated the robustness of this novel method by assessing detection of intervertebral disks and spinal canal on MRI data coming from normal spine and highly deformed spine of scoliotic patients. Complementary works are being carried out to determine quantitatively the precision of this novel segmentation process. Furthermore, an extensive validation of the proposed approach by an expert on different classes of scoliotic deformities will be performed. Finally, further work is undertaken to integrate in the proposed method a learning step from a scoliotic patient's database to define shape descriptors of the anatomical structures of interest from their extracted boundaries.

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