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Vol: 4958 **Iss:**

Month/Year: 2003

Pages: 294-302

Article Author:

Article Title: Zhu, Fuping; Medical image segmentation using level set and watershed transform

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Medical image segmentation using level set and watershed transform

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ABSTRACT

One of the most popular level set algorithms is the so-called fast marching method. In this paper, a medical image segmentation algorithm is proposed based on the combination of fast marching method and watershed transformation. First, the original image is smoothed using nonlinear diffusion filter, then the smoothed image is over-segmented by the watershed algorithm. Last, the image is segmented automatically using the modified fast marching method. Due to introducing over-segmentation, the arrival time the seeded point to the boundary of region should be calculated. For other pixels inside the region of the seeded point, the arrival time is not calculated because of the region homogeneity. So the algorithm's speed improves greatly. Moreover, the speed function is redefined based on the statistical similarity degree of the nearby regions. We also extend our algorithm to 3D circumstance and segment medical image series. Experiments show that the algorithm can fast and accurately obtain segmentation results of medical images.

Keywords: Level Set, Fast Marching Method, Image Segmentation, Medical Image, Watershed Transform

1. INTRODUCTION

Image segmentation plays an essential role in medical image processing. Accurate extraction of clinical information from medical images promises reliability for clinical applications and it is the basis of 3-D model reconstruction. Image segmentation is a very difficult problem in practice. Due to the importance and difficulty of image segmentation, it has attracted great effort of many investigators since the seventies last century.

Currently, the numerous existing approaches of image segmentation may be classified into two main categories: boundary-based and region-based. Edge detection is the earliest of the boundary-based methods, based on local gradients [1]. Active contours [2], have been introduced for segmenting deformable objects, by defining the internal and external functional and minimizing the functional whose local maximum is located at the object boundary. But, active contours are relatively noise sensitive, and their results depend on the initialization and they are not sufficiently topologically adaptive. In the region-based approaches, techniques, such as seeded region growing [3] or split-and merge were firstly introduced. Region growing methods generally require the desired regions to be homogeneous with respect to certain prespecified features. Research on region-based segmentation methods has focused on either the design of feature measures and growing criteria or algorithm efficiency and accuracy.

Level set method, developed by Osher and Sethian[4], based on the theory and numeric of weak solutions to surface propagation, has been used in the formulation of several region or boundary based approaches for image segmentation and offers highly robust and accurate techniques for tracking interfaces moving under complex motions. The main idea of level set method is to represent a curve as the zero level set of a higher dimensional function; the motion of the curve is then embedded within the motion of the higher dimensional surface. Since the proposal of level set method, many researchers have succeeded in applying level set method to image processing and computer vision. For example, Sethian[4] used level set to filter the noise of images; Malladi[5] utilized it to segment image, especially medical image segmentation and reconstruction. Bertalmio[6] applied level set method in image restoration; Masouri[7] exploited level set to track motion objects; Parogios and Deriche[8] used level set method to carry out texture segmentation and segment motion objects; Samson[9] applied level set method in the field of image classification.

In this paper, a medical image segmentation method is proposed based on the combination of fast marching level set method and watershed transformation. First, the original image is smoothed using nonlinear diffusion filter to eliminate the image noise; then the smoothed image is over-segmented by the watershed algorithm; last, the image is segmented automatically using the modified fast marching method. Owing to introducing over-segmentation, we only need to calculate the arrival time that is the seeded point to the boundary of region. For other pixel points inside the region of the seeded point, the arrival time is not calculated. So the algorithm speed improves greatly. Moreover, the speed

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function is defined again based on the statistical similarity degree of the adjacent regions, and we also extend the modified fast marching into three dimension.

The organization of this paper is as follows. Section 2 briefly introduces watershed transformation. Section 3 presents level set method. Section 4 gives the details of modified fast marching method. We make some experiments in Section 5, followed by the conclusion and discussion in Section 6.

2. WATERSHED ALGORITHM

In gray scale mathematical morphology, the watershed algorithm, originally proposed by Digabel and Lantuejoul [10] and later improved by Beucher and Lantuejoul [11], is the method of choice for image segmentation. The watershed algorithm can be classified as a region-based segmentation approach.

The intuitive idea underlying this method comes from geography: it regards the gradient magnitude image as a landscape where the intensity values correspond to the elevation. Areas where a rain drop would drain to the same minimum are denoted as catchment basins, and the lines separating adjacent catchment basins are called watersheds.

Steps of watershed algorithm are as follows:

1. Smooth the original image using nonlinear diffusion filter;
2. Compute the gradient map of smoothed image;
3. Compute the maximum value (MAX) of gradient map;
4. Select appropriate drowning threshold DT=MAX*1/n;
5. For each pixel in 2-D image, we consider it's 8-neighbor. If the value of current pixel and its neighbor is smaller DT, we merge current pixel with its neighbor;
6. Merge the small regions (e.g. the pixel number of region<10).

From above, we know the output of watershed algorithm is an over-segmentation of original image, and it is very important to select drowning threshold DT, which finally determines the region number of over-segmentation. Figure 1 gives an example of the over-segmentation of one slice by the watershed algorithm under the condition of different threshold DT.

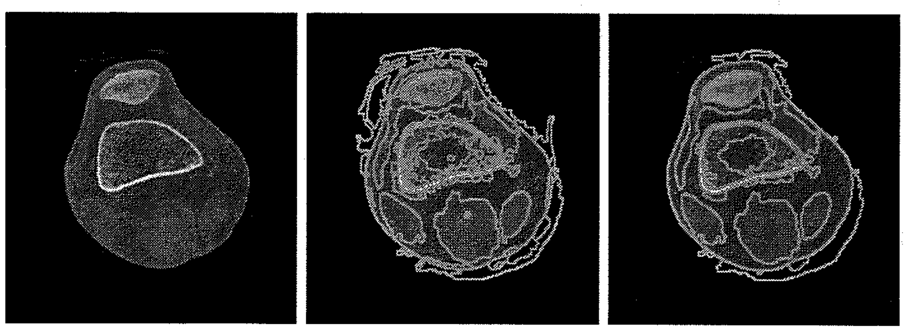

Figure 1 Over-segmentation of the knee by watershed algorithm

3. LEVEL SET METHOD

The basic idea of level set method is to represent a closed curve on the plane as the zero level set of a higher dimensional function. The motion of the curve is then embedded within the motion of the higher dimensional surface. Although the transformation makes the problem complex in the form, level set method offers several advantages. The most advantage is that its zero level set can change topology, and form sharp corners.

The basic equation that level set function satisfies is as follows:

$$\Phi_t + F|\nabla\Phi| = 0 \qquad (1)$$

Where Φ is level set function:

$$\Phi(x, t = 0) = \pm d \qquad (2)$$

Where d is the distance from x to Γ(t=0), and the plus (minus) sign is chosen if the point x is outside (inside) the initial hypersurface Γ(t=0).

The zero level set of Φ is the object contour curve. That is:

$$\Gamma(t) = \{x \mid \Phi(x,t) = 0\} \qquad (3)$$

Where F is the speed in the normal direction and control the motion of the curve. In general there are two components that the speed F has: one is derived from the image data (such as gradient information), the other is derived from the curve itself (such as curvature of the curve).

One of the most popular level set algorithms is the so-called fast marching method. Now we briefly discuss the fast marching method introduced in [13]. Detailed description about fast marching method refers to [13]. Let Γ be the initial position of a hypersurface and F be its speed in the normal direction. In the level set method, one views Γ as the zero level set of a higher dimensional function Φ. Then, by chain rule, an evolution equation for the moving hypersurface can be produced like equation (1).

Now consider the special case of a surface moving with speed F>0 (the case where F is everywhere negative is also allowed). We then have a monotonically advancing front whose level set equation is of the following form:

$$|\nabla T|F = 1 \tag{4}$$

This simply says that the gradient of arrival time is inversely proportional to the speed of the surface. Broadly speaking, there are two ways of approximating the position of the moving surface; iteration towards the solution by numerically approximating the derivatives in equation (1) or explicit construction of the solution function T from equation (4). Fast marching method depends on the latter approach.

Equation (4) is one form of the Eikonal equations. Sethian proved that it is equivalence to solve the following quadratic equation in order to get the arrival time T of the equation (4). The detailed approximating scheme refers to [12][13].

$$\begin{bmatrix} \max(D_{ij}^{-x}T,0)^2 + \min(D_{ij}^{+x}T,0)^2 + \\ \max(D_{ij}^{-y}T,0)^2 + \min(D_{ij}^{+y}T,0)^2 \end{bmatrix}^{1/2} = 1/F_{i,j} \tag{5}$$

Where D^- and D^+ are backward and forward difference operators.

The steps of the traditional fast marching method are as follows:

1. Initializing step:

1) Alive points: Let A be the set of all grid points $\{i_A, j_A\}$ the represents the initial curve. In our algorithm, Alive points are the seeded points users assign to. See Figure 2;

2) Narrowband points: Let Narrowband points be the set of all grid points neighbors of A. In our algorithm, those are the 4-nearest points of the seeded points. Set T(x, y)= 1/F(x, y) . See Figure 2;

3) Faraway points: Let Faraway points be the set of all others grid points {x,y}. Set T(x, y)= TIME_MAX , See Figure 2;

2. Marching forwards:

1) Begin loop: Let (i_{min}, j_{min}) be the point in Narrowband with the smallest value for T;

2) Add the point (i_{min}, j_{min}) to A; remove it from Narrowband;

3) Tag as neighbors any points (i_{min}-1, j_{min}), (i_{min}+1, j_{min}), (i_{min}, j_{min}-1), (i_{min}, j_{min}+1) that are either in Narrowband or Faraway. If the neighbor is in Faraway, remove it from that list and add it to the set Narrowband;

4) Recompute the values of T at all neighbors according to equation (5), selecting the largest possible solution to the quadratic equation;

5) Return to top of Loop.

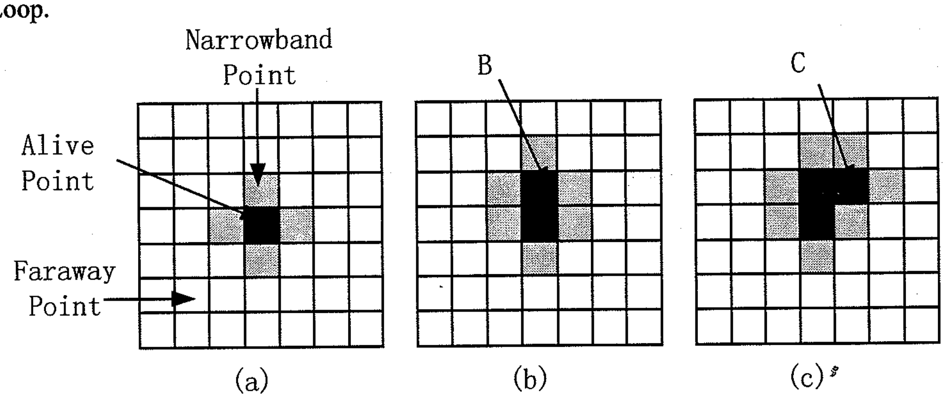

Figure 2 Alive, Narrowband and Faraway points

Figure 2 (a) is the initialization procedure of fast marching method. The black grid point is the alive point. The gray grid points are narrowband points, and the white grid points are faraway points. Figure 2 (b) and Figure 2 (c) is the marching procedure of fast marching method. In Figure 2 (b) and (c), B and C are regarded as another two alive points.

4. MODIFIED FAST MARCHING METHOD

From the steps of traditional fast marching method, we know that all the pixels should be visited under the worst condition. Certainly, this depends on the definition of the speed function and the parameter value. In [14], R.Malladi defined the following speed function

$$F(x,y) = e^{-\alpha\left|\nabla G_{\sigma} * I(x,y)\right|} \qquad (6)$$

Where $I(x, y)$ is the original image, ∇ is the gradient operator, $G_{\sigma} * I(x,y)$ is a Gaussian smooth operator for the original image, $0<\alpha<1$ is a weighting constants.

From equation (6), we can know the speed function $F(x, y)$ only depends on the edge information of the image, that is the gradient information. Because the speed function does not make full use of the global information of the image, for the blurred edge in the image, it is difficult to get good segmentation results. Figure 3 is an example.

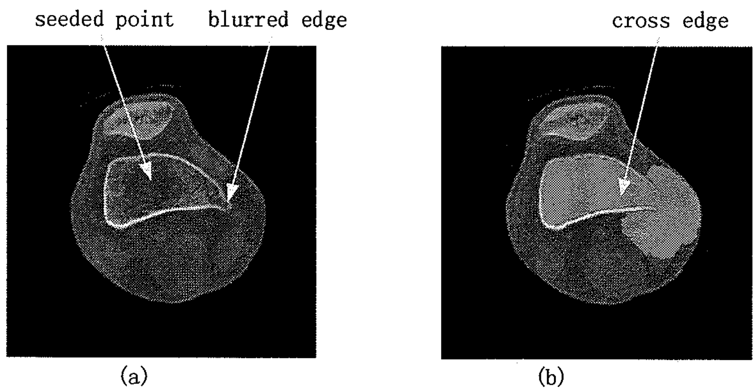

Figure 3 Traditional fast marching method crosses the blurred edge

Figure 3(a) is an original image of knee. Those places that the green arrow points to are the seeded points and the blurred edges; Figure 3(b) is the segmentation result that crosses boundary in the blurred edge. Certainly this relies on the definition of the speed function and the parameter value. The key of fast marching method is the definition of speed function. Due to the speed function only depending on the gradient information (edge information), not the global information of the image region, it is necessary to make mistakes in segmenting the blurred image boundary.

In general, it is well known that the image is composed of many small regions. Each region is of homogeneity, such as the contiguous intensity value, the similar texture structure. It is crucial for the final segmentation result to make full use of the region information. So, we introduce watershed transform to over-segment the original image into many small regions.

The merit of introducing watershed transform lies in three aspects. Firstly, for fast marching method, let the seeded point be in the interior of the small region, we only need to calculate the arrival time of the seeded point to the boundary pixels. For the other pixels of the interior of the small region, due to the homogeneity with the seeded point, it is not necessary to calculate the arrival time of the seeded point to these pixels. So the algorithm's speed improves greatly. Secondly, the segmentation accuracy can be improved since the final segmentation results are bounded to be potential boundaries of objects. Finally, the statistical similarity degree of the nearby regions is a good reference of speed function of fast marching method.

The data structure for representing partitions segmented by watershed algorithm is the region adjacency graph (RAG) [15]. The RAG of a n-partition is defined as an undirected graph, G=(V, E), where V={1, 2, 3 … , n} is the set of nodes and $E \subset V \times V$ is the set of edges. Each region is represented by a graph node and between two regions (nodes) $I, j \in V$ exists the edge (I, j) if the regions are region. Figure 4 is an example of six –partition of an image and the corresponding RAG.

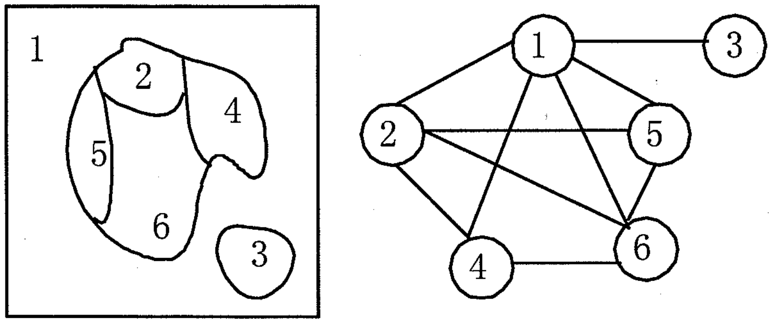

Figure 4 Six-partition of an image (left), and the corresponding RAG (right)

Let the over-segmentation regions be R_1, R_2, R_3, …, R_n, n is the number of the over-segmentation region. Let the statistical feature of the region R_i be: $\{SF_{i,j}|\ 1\leq i\leq n,\ 1\leq j\leq m\}$. Where m is the number of features in the set, $SF_{i,1}$ is the mean gray value of the region and $SF_{i,2}$ is the variance of the region. The number of features used can be decided according to the character of the image. For example, if some objects in the image have apparent textures, texture features can be included in the feature set of the region. In our experiment, only $SF_{i,1}$ and $SF_{i,2}$ are used.

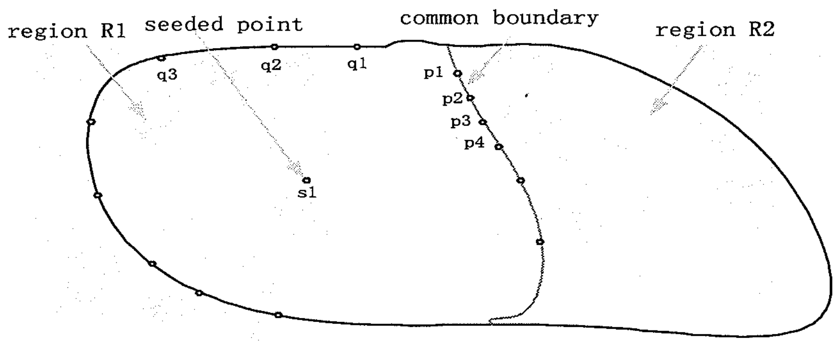

Figure 5 the nearby regions R_1 and R_2 of Watershed transformation

Figure 5 shows the nearby regions R_1 and R_2, after the image is watershed transformed. The seeded point (Alive point) locates in the region R_1. The red line in Figure 5 is the common boundary of the region R_1 and R_2. p_1, p_2 and p_3 are the pixels of the common boundary, while q_1, q_2 and q_3 are the pixels of the other boundary of the region R_1.

When the seeded point s_1 arrive at the common boundary of the region R_1 and R_2, we can calculate the statistical features $SF_{1,j}$ and $SF_{2,j}$ of the region R_1 and R_2, and calculate the similarity degree between the region R_1 and R_2 as the following equation:

$$Sm_{i,j}=\frac{1}{m}\sum_{k=1}^{m}\left|SF_{i,m}-SF_{j,m}\right| \qquad (7)$$

Where $Sm_{i,j}$ is the similarity degree between the region R_1 and R_2, m is the number of the statistical feature of the region R_i and R_j, $SF_{i,m}$ is the statistical feature of the region R_i, $SF_{j,m}$ is the statistical feature of the region R_j.

We can define the speed function of the common boundary pixels of the region R_i and R_j, after getting the similarity degree between the region R_1 and R_2:

$$F_{i,j}=e^{-\beta\left|Sm_{i,j}\right|} \qquad (8)$$

Where β is positive parameter. ($0\leq\beta\leq1$)

In summary, the steps of modified fast marching method are as follows:

1. Initializing step:

1) Alive points: Let the seeded point and the interior pixels of the region where the seeded point locates be the alive points, T(x, y)=0;

2) Narrowband points: Let the boundary pixels of the region where the seeded point locate be the narrowband points, T(x, y)= 1/*F*(x, y), where *F(x, y)* is computed according to Equation (8);

3) Faraway points: Let the set of all others grid points {x,y} be faraway points, T(x, y)= TIME_MAX;

2. Marching forwards:

1) Begin loop: Let (i, j) be the point in Narrowband with the smallest value for T, and the regions that the point (i, j) locates in be R_i and R_j;

2) Mark the point (i, j) to alive point, remove it from Narrowband, calculate the similarity degree between the region R_i and R_j;

3) Mark all of boundary points of the point (i, j) that are either in Narrowband or Faraway. If the boundary point is in Faraway, remove it from the Faraway and add it to the Narrowband;

4) Recompute the values of T of all boundary points of the point (i, j) according to equation (5);

5) Return to top of Loop.

5. EXPERIMENT RESULTS

We have experimented our modified fast marching algorithm in the 3DMED(http://www.3dmed.net/) medical image processing system developed by ourselves. The segmentation results of the 2D medical images are shown in Figure 7 and Figure 8. In 3D circumstance, the directions of fast marching method are separately front, back, left, right, top, and down. Figure 6 is an example of marching direction. The 3D segmentation results of medical image series slices are shown in Figure 9 and Figure 10.

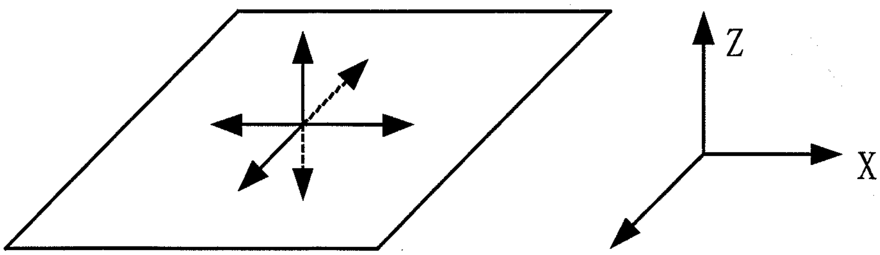

Figure 6 Marching direction of 3D fast marching method

6. CONCLUSION AND DISCUSSION

In this paper, a medical image segmentation method is proposed based on the combination of fast marching method and watershed transformation. First, the original image is smoothed using nonlinear diffusion filter to eliminate the image noise and enhance the image edge. Then the smoothed image is over-segmented by the watershed algorithm. The speed function is defined again based on the statistical similarity degree of the regions to replace the speed function of traditional fast marching method, which depends on the gradient information of the image. Experiments show our algorithm can segment medical images of the blurred boundary and intensity inhomogeneity. Future research will focused on the further improvement of the speed function of fast marching method to improve the reliability of the segmentation.

7. ACKNOWLEDGMENTS

This paper is supported by the National Science Fund for Distinguished Young Scholars of China under Grant No. 60225008, the Special Project of National Grand Fundamental Research 973 Program of China under Grant No. 2002CCA03900, the National Natural Science Foundation of China under Grant Nos. 79990580, 69931010, 60172057, 60071002, 60072007, 30270403; the National High Technology Development Program of China under Grant No. 2001AA144120

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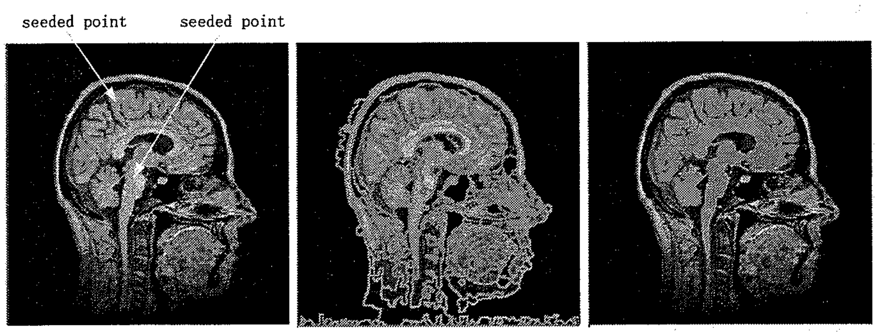
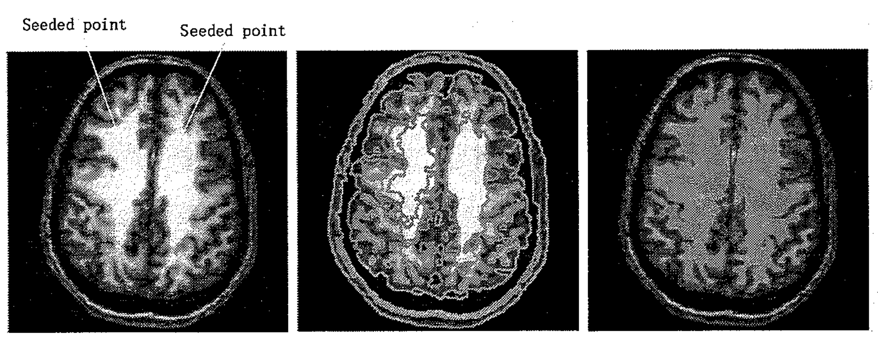


(a) the original image (b) over-segmentation (c) final segmentation

Figure 7 brain MR image: segmentation of the gyrus



(a) Original image (b) Over-segmentation (c) final segmentation

Figure 8 brain MR image: segmentation of the brain white matter

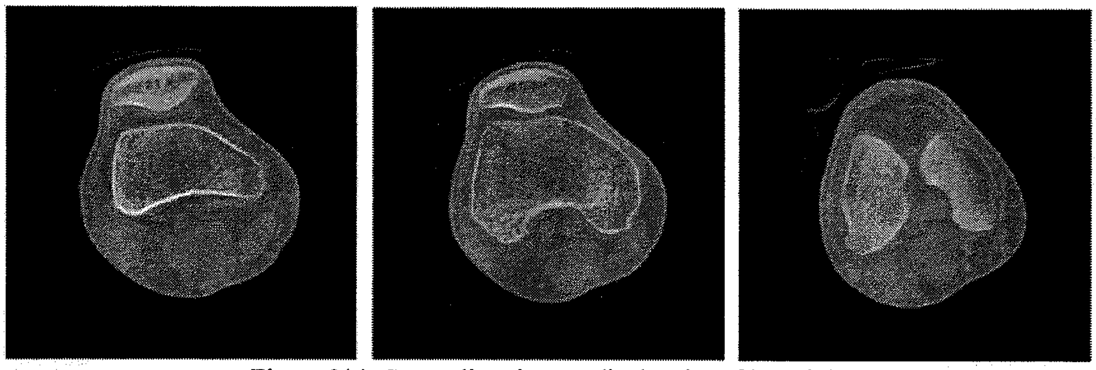


Figure 9(a). Some slices in a medical series of knee joint

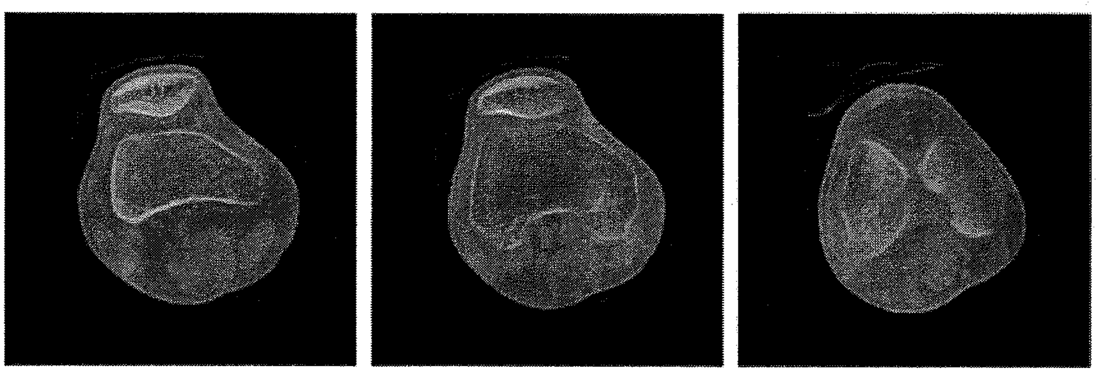


Figure 9(b). Segmentation result of the slices in 9(a)

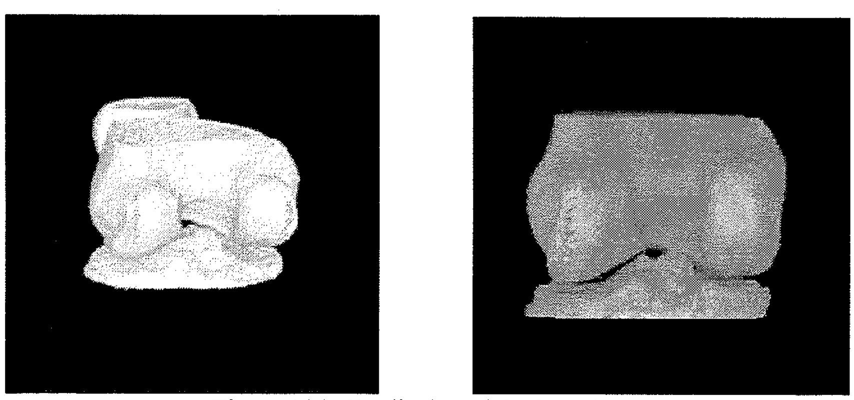


Figure 9(c). 3D display of the knee joint

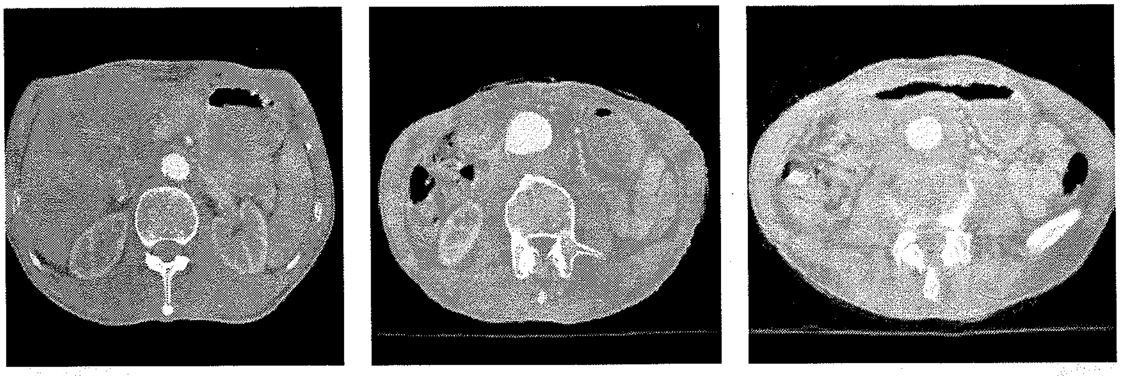


Figure 10(a). Some slices in a medical series of the abdominal region

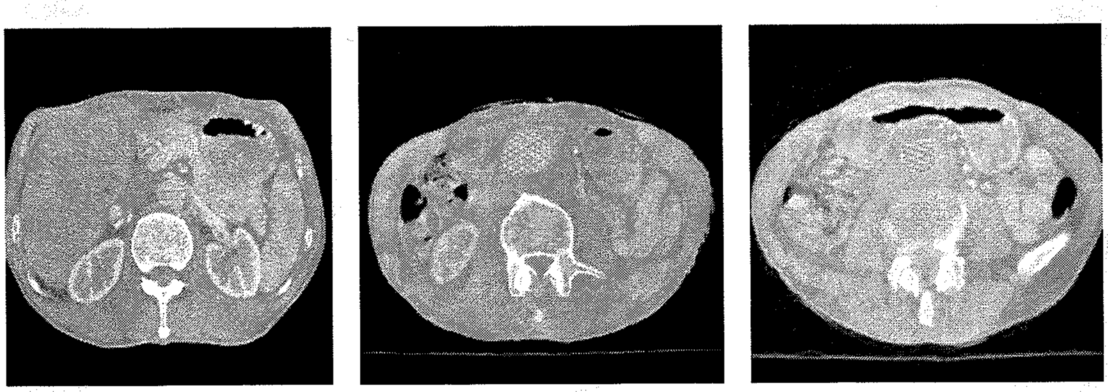


Figure 10(b). Segmentation result of the aorta

Figure 10(c). 3D Display of aortic aneurysm of abdominal region