

An Extraction Method of Coronary Artery and Left Ventricle from Heart CT Images based on Hough Transformation and Region Growing

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Abstract— In this paper, we propose a method to automatically extract the ascending aorta, the coronary artery and the left ventricle from a cardiac CT image with a contrast medium. In this method, the outline of the ascending aorta is extracted by Hough transformation and the coronary artery is automatically extracted from the ascending aorta by the region growing method. Furthermore, using the extracted position information of the coronary artery and the region information inside the left ventricle, automatic extraction of the left ventricular boundary was performed. We applied this method to the CT images of 14 cases and confirmed its effectiveness.

Keywords: Heart CT Image, Region Growing, Hough Transformation, Volume Rendering

I. INTRODUCTION

Currently, heart disease is the third leading cause of death among Japanese, close to 15.5% of the deaths of all causes. Many of these cases of heart disease are ischemic heart diseases such as angina pectoris and myocardial infarction. The main cause of ischemic heart disease is myocardial ischemia caused by stenosis of coronary arteries due to arteriosclerosis, plaque or the like. Ischemic myocardium causes necrosis and functional deterioration due to poor nutrition and lack of oxygen and causes serious defects in cardiac function.

In recent years, due to the performance improvement of multislice CT, cardiac CT examination has been actively performed for diagnosis of heart disease. Cardiac CT examination is minimally invasive, the burden on patients is small, and the reliability of examination is high [1]. However, with the increase in the number of cardiac CT images produced for an examination, the burden on doctors who interpret CT images has increased, and improvement in the efficiency of interpretation is required. In the diagnosis of ischemic heart disease, it is important to identify the blood

vessels responsible for sending blood to the ischemic part [2]. In order to identify the responsible blood vessel from the cardiac CT image, it is necessary to observe the stenosis of and plaque in the coronary artery. However, it is difficult to observe the connection and the stenosis of the coronary artery in a slice image of a heart CT. Also, in volume rendering display of cardiac CT images, other bodily structures such as ribs and left atrium appendages hinder observation of the coronary arteries, making observation difficult.

In this paper, we propose a method to automatically extract the ascending aorta, coronary artery and left ventricle from cardiac CT images in order to improve efficiency and quantify the reading of cardiac CT images. Coronary arteries extracted by this method can be used for detection of stenosis of and plaque in coronary arteries, quantitative observation, superimposition with ultrasonic images and SPECT images, and auxiliary information for cardiac segmentation. In this paper, we describe related research in Section 2. Section 3 describes the algorithm of the proposed method and its implementation method. In Section 4, we evaluate our method, show the extraction results, and examine them. Section 5 summarizes this paper and describes remaining issues and future developments.

II. RELATED STUDIES

Research on image processing of cardiac CT images has been widely conducted.

Shinozaki used an average heart shape, aligned with pixel information and an atlas with boundary information, and performed automatic segmentation of the heart. In the method by Shinozaki et al., the cardiac part is stably segmented from a 2-dimensional cardiac CT image by repeating the feedback of

the alignment of the boundary information and the pixel information with each other [3].

Komatsu performed automatic extraction of a lung and heart region from CT images using three-dimensional region growing and template matching. Threshold processing and extraction of the lung region by the three-dimensional region growing method and extraction of a cardiac region which is difficult to extract depending on the concentration value was performed by the template matching method [4].

Hua performed a model-based detection based on a machine learning algorithm and deleted the part that hinders the observation of the coronary artery from the cardiac CT image. Combining the global shape model based on the machine learning algorithm with the local intensity based region expanding method, the part obstructing the observation of the coronary artery is deleted. In the method of Hua et al., we succeeded in deleting the part that hinders the observation of the coronary artery from the cardiac CT image when performing 3-dimensional visualization [5].

In the above method, deletion of the part that disturbs the observation of the coronary artery and extraction of the heart region are performed but coronary artery extraction is not performed.

III. PROPOSED METHOD

A. Overall Flow

In this method, coronary artery extraction and left ventricle approximation are performed. First the air part and the pulmonary artery are removed. Next, Hough transformation is applied to all the axial slice images to specify the vessel position of the ascending aorta. Since the ascending aorta forms a circle in the axial sectional CT image, it is possible to specify the position by the Hough transform. Next, the ascending aorta and the coronary artery are extracted by performing region growing from the ascending aorta. For the seed point of the region growing, the center coordinates of the circular part of the ascending aorta specified by the Hough transformation are used. Since the coronary artery is connected to the ascending aorta, by performing the region growing method from the ascending aorta, a part of the coronary artery is extracted at the same time. Since the extracted ascending aorta and the coronary artery are one object, the coronary artery part is specified from the extracted object. Because the end of the coronary artery has a value close to the pixel value of the heart surface, it is difficult to extract by the normal region growing method. Therefore, by

extending the region with enhanced detection intensity with respect to the advancing direction of the coronary artery, a more accurate coronary artery end portion is extracted. The approximation of the left ventricle is done by inflating the contrast agent part inside the left ventricle. On this occasion, based on the positional information of the coronary artery and the analysis result of the image by the discriminant analysis method, a region which does not expand beyond that is determined.

B. Deleting pulmonary veins and pulmonary arteries

First, erroneous detection by Hough transform is prevented, and the pulmonary artery part and air part are deleted to prevent an extraction region from reaching the pulmonary artery when region growing is performed. Pulmonary artery deletion is performed by combining the discriminant analysis method and morphological processing.

Second, the discriminant analysis method is used to extract the air portion. The air portion is between the minimum value of the luminance value of the image and the calculated threshold value after discriminant analysis. The air part also includes the air part inside the lung. Since the pulmonary vein and pulmonary artery are thin tubular shapes, it is possible to obtain a region inside the lung where the pulmonary vein and pulmonary artery are deleted by closing the air part. The pulmonary vein and pulmonary artery are deleted by subtracting the region inside the lung from which the pulmonary vein and pulmonary artery are deleted from the original image of the three-dimensional cardiac CT.

Fig. 1 shows the volume rendering image of the cardiac CT image before deleting the pulmonary vein and pulmonary artery[6]. Fig. 2 shows the volume rendering image of the cardiac CT image from which this pulmonary artery was deleted[6].

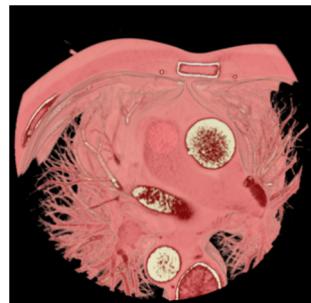


Fig. 1. Before deleting



Fig. 2 . After deleting

C. Identification of the position of the ascending aorta by Hough transformation

The circular section is extracted from the axial slice image of the heart CT by Hough transformation, and the position of the ascending aorta is specified. Since the ascending aorta has a substantially circular shape on the axial cross section, the position can be identified by Hough transformation. Before performing Hough transformation, noise is eliminated by applying a Gaussian filter to the axial slice image in order to reduce false detection. After removal of noise, the Canny edge detection method is applied to perform edge detection.

Hough transformation is applied to each of the axial cross-section slice images for which edge detection has been performed to extract circular portions. The information acquired by the Hough transformation is the center coordinates (x, y, z) of the circle and the radius r of the circle. Also, the luminance value of the center coordinates of the circle is determined from the original cardiac CT image. The circle acquired by Hough transformation is divided into the ascending aorta, the descending aorta, the backbone portion and other vascular portions. Fig. 3 shows an axial cross-sectional image and a volume rendering image showing the circular portion extracted by the Hough transformation[6]. In the axial cross-sectional image of Fig. 3, a white circle portion is a circular portion extracted by Hough transformation. The larger circle radius is the ascending aorta and the smaller one is the descending aorta.

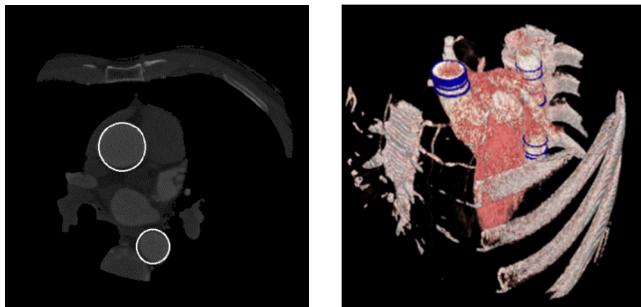


Fig. 3. Axial section image and volume rendering image after Hough transformation

D. Extraction of ascending aorta and coronary arteries

In this study, coronary arteries are extracted by performing region growing from the ascending aorta. The ascending aorta is connected to the coronary artery, and it is possible to extract the coronary artery by performing region growing.

In order to expand the region, the seed point is determined. The seed point uses the center coordinates of the circle extracted by the Hough transformation. First, it is necessary to

select a circle that becomes the seed point of the region growing method from the circle extracted by Hough transformation. The circle acquired by Hough transformation is divided into the ascending aorta, the descending aorta, the backbone portion and other vascular portions. The circle that becomes the seed point must be the circle of the ascending aorta. To select a circle, the radius of the circle, the luminance value of the center coordinates, and the center coordinates of the circle are used.

First, the circles of the backbone portion and other blood vessel portions are deleted from candidates of the ascending aorta. The luminance value of the center coordinate of the circle is used for deletion. A circle with a small luminance value at its center is not the ascending aorta portion, so it is deleted from the ascending aorta candidate. Next, the circle of the descending aorta portion is deleted. The descending aorta has a smaller blood vessel radius than the ascending aorta. The circle of the descending aorta is deleted from candidates of the ascending aorta by deleting the extracted circle with a small radius. After removing the circles other than the ascending aorta from these candidates and sorting the circle's depth information, the center coordinates of the circle with the median are taken as the seed point of the region growing method. Coronary arteries and ascending aorta are high brightness values in the cardiac CT image, due to the contrast medium effect. First, the standard deviation is calculated in the region of the high brightness values. Next, the global threshold value of the region growing method is determined by the standard deviation. The global threshold shows the difference in brightness between the seed point and the pixel to be expanded. We don't use the local threshold value, which is the difference between pixels to be expanded.

The discriminant analysis utilizes Otsu's adaptive thresholding method. The Otsu's method finds an optimum threshold value in a statistical manner from the histogram of CT image. The histogram is divided into two classes. The within-class variance σ_w^2 and the between-class variance σ_B^2 are calculated for the two classes. Here, w_1 , m_1 , and σ_1^2 are the number of pixels of class 1, the average density value, and the variance value, and w_2 , m_2 , σ_2^2 are the number of pixels of class 2, the average density value, and the variance value.

$$\sigma_w^2 = \frac{w_1\sigma_1^2 + w_2\sigma_2^2}{w_1 + w_2} \quad (1)$$

$$\sigma_B^2 = \frac{2w_1w_2(m_1 - m_2)^2}{(w_1 + w_2)^2} \quad (2)$$

The degree of separation S is calculated using intra-class variance and inter-class variance. The above calculations are

performed with all density values, and a threshold value that maximizes the degree of separation is adopted.

$$S = \frac{\sigma_w^2}{\sigma_B^2} \quad (3)$$

Fig. 4 shows the results of the discriminant analysis, and the horizontal axis represents the luminance value and the vertical axis represents the accumulated number of pixels. The discriminant analysis is performed three times to determine the threshold of region expansion. The first discrimination analysis is performed on all the pixels included in the image to identify the air portion. The air portion is between the minimum value of the CT image and the luminance value calculated by the discriminant analysis for all the pixels (first blue line from the left in Fig. 4).

The second discriminant analysis is performed on the pixel between the calculated luminance value (the first blue line from the left in Fig. 4) and the maximum value of the luminance value of the CT image, and we can obtain the luminance value (the second blue line from the left in Fig. 4). Between the luminance value (the first line from the left in Fig. 4) calculated from the discriminant analysis for all the pixels and the luminance value as the result of the second discriminant analysis (the second line from the left in Fig. 4) is the luminance value of fat and meat. The third discriminant analysis is performed between the luminance value (the second blue line from the left in Fig. 4) as the result of the second discriminant analysis and the maximum value of the luminance value of the image to obtain the luminance value (the third blue line from the left in Fig. 4). The distance between the luminance value (the second line from the left in Fig. 4) as a result of the second discriminant analysis and the result of the third discrimination analysis (the third line from the left in Fig. 4) is the approximate luminance value of the contrast medium.

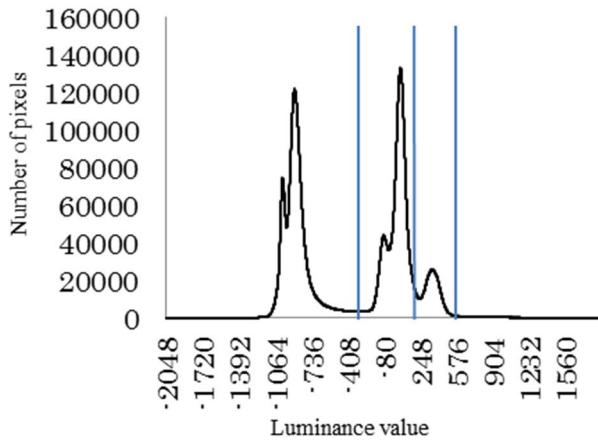


Fig. 4. Histogram and results of discriminant analysis

The luminance value between the result of the second discriminant analysis and the result of the third discriminant analysis is an approximate luminance value of the contrast agent portion. The standard deviation within the range of the brightness value of the contrast agent part is calculated and it is used as the threshold of the brightness difference between the seed point and the extending pixel (GLOBAL threshold). Here, the threshold of luminance difference between pixels to be extended (LOCAL threshold) is not used. Fig. 5 shows a volume rendering image of a cardiac CT image obtained by extracting the ascending aorta and the coronary artery by the region growing method[6].

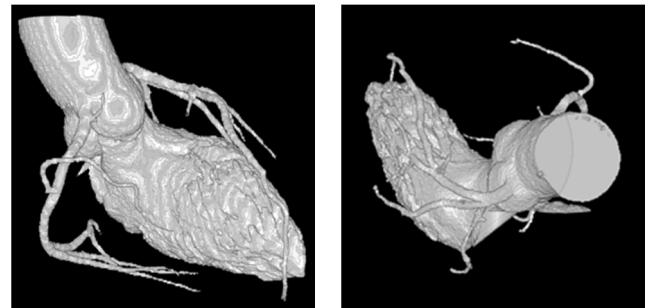


Fig. 5. Extraction result by region growing

E. Identification of coronary arteries

Region growing is performed for the image (Fig. 5) in which the ascending aorta and the coronary artery appear to specify the coronary artery. The Euclidean distance is found for the pixel extracted with the ascending aorta and the coronary artery (Fig. 5) and the seed point extracted by Hough transformation. Using the fact that the coronary artery is positioned so as to cover the heart, we select multiple voxels based on the Euclidean distance information and use them as a seed point of region growing to identify coronary arteries.

In order to prevent the coronary artery from being in close contact with other cardiac structures or to prevent the extraction area from reaching the ascending aorta, the mask image is saved in a search of an area not to be expanded in advance. The mask image is created by performing an opening process on the image of the ascending aorta and the coronary artery (Fig. 5). In this way, a mask image as shown in Fig. 6 is obtained[6]. The created mask image is regarded as an area not to be expanded, and the region growing is performed again to identify the coronary artery. Fig. 7 shows an image obtained by specifying a coronary artery[6].

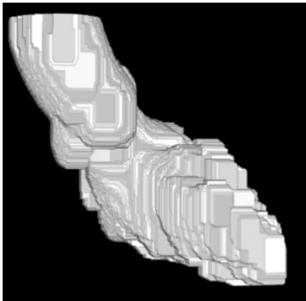


Fig. 6. Mask image

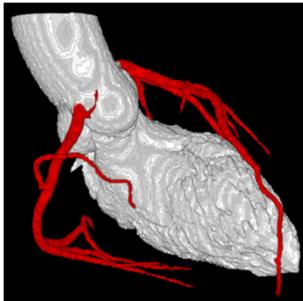


Fig. 7. Coronary artery specific result

F. Extraction of coronary artery periphery

The luminance value is low at the end of the coronary artery where the penetration rate of the contrast medium is low. At the coronary artery periphery, the difference in luminance from the myocardial part is small. For these reasons, it is difficult to set an appropriate threshold value of the region growing method in the normal region growing method. In order to extract the coronary artery periphery while preventing spreading to the myocardium, the detection strength of the region growing is strengthened in the direction in which the coronary artery is spreading, and the region growing taking coronary artery direction information into consideration is performed.

In order to determine the spreading direction of the coronary artery, thinning processing is first performed on the image of the coronary artery. An image of the coronary artery after thinning is shown in Fig.8.

In acquiring direction information from the thinned image, the end point is first specified from the thinned image. The n^{th} voxel connected to the end point from the thinned image is found and the unit vector from the continuous voxel to the end point is found. A vector obtained by adding all n unit vectors is set as a direction information vector D representing the spreading direction of the coronary artery at the end point. The direction information vector D is obtained for all the end points. The equation for obtaining the direction information vector is shown in equation (4). In equation (4), x_0 , y_0 , z_0 represent the coordinates of the end points, and x_i , y_i , z_i represent the coordinates of the voxels connected to the end points. N represents the number of consecutive voxels and d represents the Euclidean distance from the voxel connected to the end point.

$$\vec{D} = \sum_{i=1}^n \left(\frac{(x_0 - x_i)}{d}, \frac{(y_0 - y_i)}{d}, \frac{(z_0 - z_i)}{d} \right) \quad (4)$$

In the region growing method considering the direction information of the coronary artery, the end point is set as the seed point. In the region extension method considering the direction information of the coronary artery, the threshold

value (GLOBAL threshold) of the luminance difference between the seed point and the pixel to be extended is taken as the standard deviation t of the luminance value of the already extracted coronary artery. The formula for calculating the standard deviation t is shown in equation (5). In equation (5), m_i represents the luminance value of a voxel of the coronary artery. \bar{m} represents the mean value of the brightness values of voxels of the coronary arteries and n represents the number of voxels of the coronary arteries.

$$t = \sqrt{\frac{1}{n} \sum_{i=1}^n (m_i - \bar{m})^2} \quad (5)$$

In consideration of the direction information of the coronary artery, a threshold value (LOCAL threshold value) of the luminance difference between the pixels to be extended is dynamically set from the direction information vector in order to set the threshold value. First, we obtain the vector S from the seed point to the candidate point to be expanded by the region extension method. Next, the cosine similarity c between the direction information vector D and the vector S from the seed point to the candidate point is obtained, and the value obtained by multiplying the standard deviation t of the luminance value of the coronary artery by the cosine similarity c is extended. Expression (6) shows an equation for obtaining the cosine similarity c between the direction information vector D and the vector S from the seed point to the candidate point. Expression (7) shows an expression for obtaining the threshold value (LOCAL threshold value) p of the luminance difference between pixels to be expanded.

$$c = \frac{\vec{D} \cdot \vec{S}}{|\vec{D}| |\vec{S}|} \quad (6)$$

$$p = c \cdot t \quad (7)$$

Fig. 9 shows an image obtained by extracting the end portion of the coronary artery by the region growing method considering the direction information of the coronary artery[6].



Fig. 8. Thinned image



Fig. 9. Periphery extraction result

G. Left ventricular approximation

After extracting the coronary artery, the left ventricle is approximated from the position information of the coronary artery. First, the contrast agent part is identified inside the left ventricle. The left ventricle is anatomically between the Valsalva sinus and the direction of travel of the coronary arteries. The position of the Valsalva sinus can be specified from the boundary between the coronary artery and the ascending aorta. From the travel information of the coronary artery already extracted and the position information of the Valsalva sinus, the contrast agent part inside the left ventricle is specified.

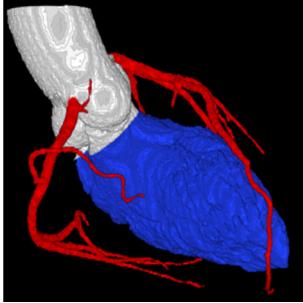


Fig. 10. Identification results of contrast medium approximation result

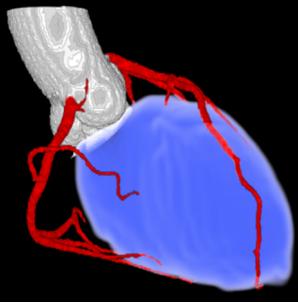


Fig. 11. Left ventricular approximation result

Approximation of the left ventricle is performed by expanding the identified contrast agent portion inside the left ventricle. At this time, based on the analysis result of the discriminant analysis, a region which does not spread further is obtained. The dilation process is repeated until the coronary artery and the part performing the dilation process overlap, and the dilation process is terminated at the time of overlapping. Fig. 10 shows an image displayed inside the left ventricle. Fig. 11 shows an image obtained by dilating the contrast medium portion inside the left ventricle and approximating the left ventricle[6].

IV. EVALUATION

A. Experimental environment

Automatic extraction of the coronary artery and approximation of the left ventricle were performed by this method for 14 cases of cardiac CT images. The cardiac CT image is obtained by imaging using a contrast medium. In this research, we used the C and C++ programming languages, and we used the Microsoft .NET Framework 4.5 as the development environment. Experiments were conducted with an Intel® Core™ i7-4790 Processor 3.6 GHz CPU, Windows 8.1 OS, and 8 GB main memory. Volume Extractor 3.0 was

also used for displaying volume rendering images of the experiment results.

B. Experiment results

Table 1 shows the image size and the time taken for extraction. The extraction time was 10.3 seconds to 17.3 seconds, and the larger the image size, the longer the extraction time. However, there were cases where the extraction time varied even though the image size was the same. Such a case depends on the shape of the heart.

Table 1. Image size and processing time

	Image size	Extraction time (seconds)
Case 1	512×512×256	11.1
Case 2	512×512×256	11.2
Case 3	512×512×320	14.2
Case 4	512×512×280	11.9
Case 5	512×512×280	12.0
Case 6	512×512×280	12.7
Case 7	512×512×280	13.1
Case 8	512×512×240	11.2
Case 9	512×512×240	11.3
Case 10	512×512×414	16.8
Case 11	512×512×441	17.3
Case 12	512×512×240	10.3
Case 13	512×512×263	12.1
Case 14	512×512×280	13.4

We conducted the questionnaire survey on whether the results of coronary artery extraction are useful for diagnosis or practical at clinical level. The survey was conducted for two doctors in the field of cardiovascular internal medicine.

Table 2 shows items of the coronary artery questionnaire and the score, which show the evaluation criteria.

Table 2. Coronary artery questionnaire item and score

It is not practical because it has failed to extract either the right coronary artery, the left anterior descending coronary artery, or the circumflex of the left coronary artery	1
Right coronary artery, left anterior descending coronary artery and left coronary artery circumflex branch are extracted, but extraction of each coronary artery branch is insufficient	2
Right coronary artery, left anterior descending coronary artery, left coronary artery circumflex branch are extracted, each branch of the coronary artery is extracted at the minimum, and it can withstand practical use	3
Right coronary artery, left anterior descending coronary artery, left coronary artery circumflex branch are extracted, and each branch of the coronary artery is extracted and it is useful for diagnosis	4
Right coronary artery, left anterior descending coronary artery and left coronary artery circumflex branch are extracted, extraction of each branch of the coronary artery is sufficient and it is very useful for diagnosis	5

The results of doctor evaluation for each case of the questionnaire concerning the extraction of the coronary artery are shown in Table 3. In case 10, it was judged that extraction of each coronary artery branch was insufficient from two experts. In case 10, extraction of the atrioventricular node branch, posterior descending branch, left anterior descending branch and the like was insufficient. Case 4 was judged to be very useful for diagnosis.

Table 3. Questionnaire results on coronary arteries and score

	Score given by expert 1	Score given by expert 2
Case 1	3	3
Case 2	3	3
Case 3	4	5
Case 4	5	5
Case 5	4	3
Case 6	3	5
Case 7	4	3
Case 8	3	3
Case 9	3	3
Case 10	2	2
Case 11	2	3
Case 12	4	5
Case 13	3	5
Case 14	3	2

Next, a questionnaire on the approximation result of the left ventricle is shown. Table 4 shows questionnaire items for approximation of the left ventricle. In Table 4, the left shows the evaluation criteria and the right shows the score.

Table 4. Left ventricle questionnaire item and score

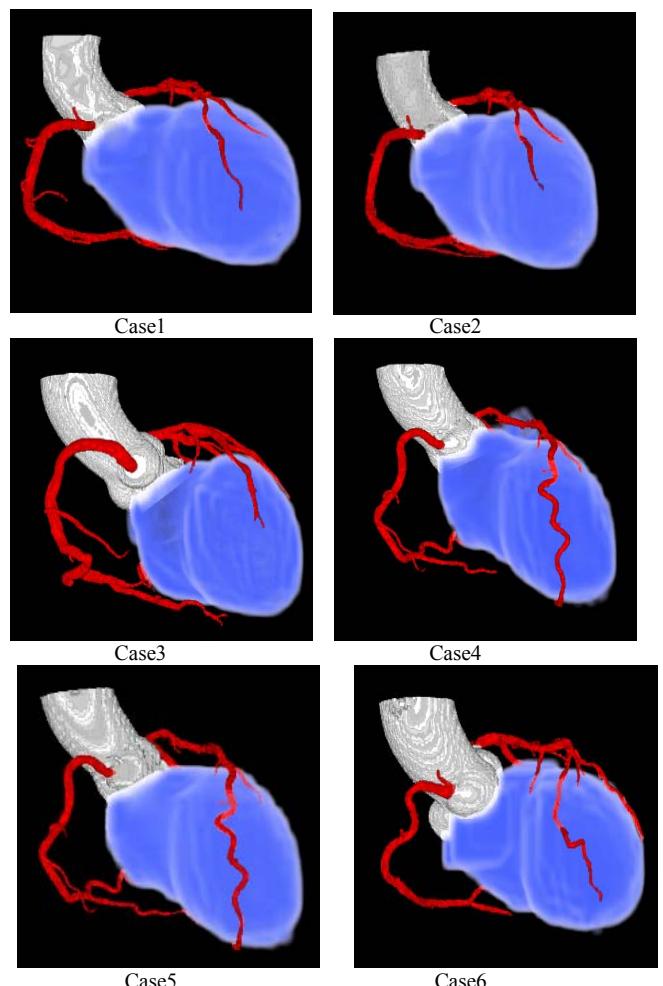
Approximation result of the left ventricle was enlarged	1
Approximation result of the left ventricle was contracted	2
There is a problem with the shape of the left ventricular approximation result	3
Succeeded in approximating left ventricle	4

Table 5 shows the results of expert evaluation on each case of the questionnaire concerning the approximation of the left ventricle. In case 13, it was judged that the approximation result of the left ventricle was contracted from the two experts. The result of the left ventricular approximation is away from the ascending aorta.

Table 5. Questionnaire results on left ventricle

	Score given by expert 1	Score given by expert 2
Case 1	4	4
Case 2	4	4
Case 3	4	4
Case 4	4	4
Case 5	4	4
Case 6	3	4
Case 7	3	4
Case 8	4	4
Case 9	4	4
Case 10	3	4
Case 11	4	4
Case 12	4	4
Case 13	2	2
Case 14	3	4

The results of applying this method to each case are shown in Fig. 12.



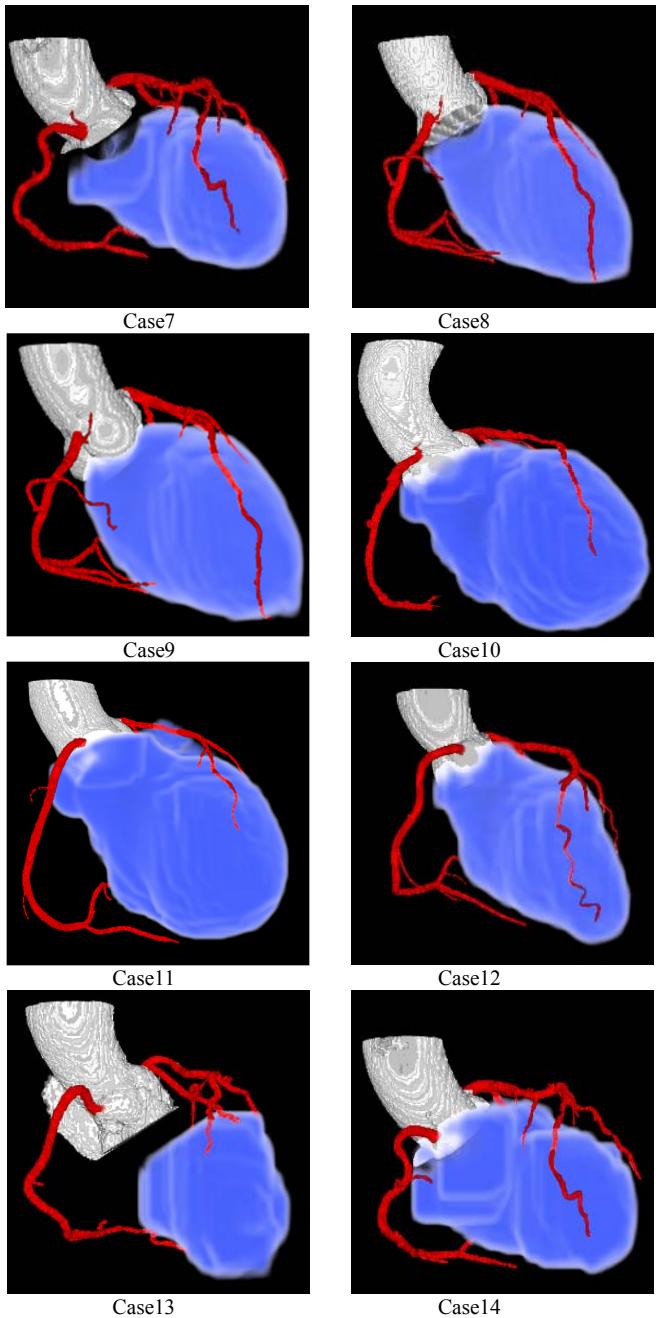


Fig. 12. Results image of our method

C. Discussion

For case 10, in which coronary artery extraction was not performed sufficiently, the contrast medium permeability was lower than other images and the contrast was weak. Therefore, coronary arteries were not sufficiently extracted when the region was expanded. In case 13 in which the approximation of the left ventricle was unsuccessful, it could be considered that it failed at the stage of identifying the contrast agent portion in the left ventricle. Since only the part near the tip of the left ventricle was selected at the stage of specifying the

contrast agent part, it was excessively separated from the ascending aorta and contracted from the actual left ventricle.

V. CONCLUSION

In this paper, we proposed a method to automatically extract an upper ascending artery, coronary artery and left ventricle from a contrast medium containing a cardiac CT image. It is difficult to set an appropriate threshold value of the region growing method in the usual region growing method, and it is difficult to extract the periphery part of the coronary artery. In order to solve this problem, we proposed a region growing method considering the direction information of the coronary arteries which strengthens the detection strength of the region growing in the direction in which the coronary artery is spreading. Also, using the position information of the extracted coronary artery, approximation of the left ventricle was performed.

This method was applied to 14 cases of clinical cardiac CT images and its effectiveness was confirmed. The extraction time was 10.3 seconds to 17.3 seconds, and it was confirmed that extraction was possible at a practical level.

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