



Automatic Extraction of the Aorta and The Measurement of Its Diameter

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Authors' contributions

This work was carried out in collaboration between all authors. Author NM designed the study, and wrote the first draft of the manuscript. Author YT performed the statistical analysis, and wrote the program. Author YC reviewed the method and investigated the data. Authors KN and ST checked the method and the results from the medical point of view. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Aims: The objective of this research is to extract the aorta and to measure its diameter for preoperative planning of heart surgeries such as Endo Vascular Aortic Repair (EVAR) or Aortic Valvular Replacement (AVR).

Study Design: Experimental Study.

Place and Duration of Study: Department of Knowledge Engineering and Graduate School of Engineering in Tokyo City University, and Department of Cardiovascular Surgery in Sakakibara Heart Institute, between April 2009 and August 2012.

Methodology: In order to extract the aorta correctly, the spine is removed first. Then, the diameter of the aorta is measured by considering the curvature of the aorta, especially the aortic arch. The novelty of the proposed method is as follows. 1) The spine that is almost parallel to the aorta is extracted and removed before the aorta extraction. 2) The aorta is traced by interpolating the image between the Computer Tomography (CT) sliced data to compensate the insufficient axial resolution. 3) The diameter of the aorta is measured by considering some planes, one of which is perpendicular to the center line of the aorta to lower the error due to the curvature.

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Results: The spine has been extracted and removed correctly and also the aorta has been extracted with the proposed method even if there is an aneurysm in the aorta. In addition, the diameter measured automatically is almost the same as that measured manually.

Conclusion: It has become possible to extract the aorta even if the spine overlaps with the aorta. In addition, the measured diameter of the aorta ranges from 20 to 30 [mm], which is almost the same as the average of normal persons' aorta. However, some parts of the heart were extracted as the aorta, and the diameter of the aortic arch was not correct. These are the issues for future works.

Keywords: Image processing; medical applications; cardiovascular surgery; aorta extraction.

1. INTRODUCTION

The aorta is the largest and the most important blood vessel and serves to convey the necessary nutrition to all parts of our body. In the presence of aortic valvular dysfunction, the blood does not flow correctly and surgeries such as Endo Vascular Aortic Repair (EVAR) or Aortic Valvular Replacement (AVR) are performed. Before the surgeries, preoperative planning is required and many algorithms have been developed for the simulation, which includes a blood flow simulation with an aortic model [1]. In order to simulate the blood flow in the aorta, an anatomic patient-specific model is necessary and it should be generated from Computer Tomography (CT) or Magnetic Resonance Imaging (MRI). For extracting long thin objects such as blood vessel or colon from image data, its center line is usually used. Then, an extraction algorithm called CEASAR (Centerline Extraction Algorithm that delivers Smooth, Accurate, and Robust results) was developed, which finds the center line by using Euclidian Distance from Boundary Field (DBF) [2]. In addition, another algorithm was invented, which searches medial lines of the aorta and the pulmonary artery that are imaged without contrast materials by using model matching method [3].

On the other hand, the perpendicular cross section of a blood vessel is circular so that the aorta was extracted by using circular Hough and Euclidean distance transforms, and also three branches of the aortic arch were detected, which were the innominate artery, the left subclavian artery and the left common carotid artery [4]. In addition, the abdominal aorta was extracted from non-contrasted MRI images by using circular Differential Structuring Element (DSE) and Dijkstra's shortest path algorithm [5]. The cross section of the aorta, however, is not a complete circle, but is deformed especially in the case of an aneurysmal dilation. Then, an automatic segmentation algorithm was developed for abdominal aortic aneurysm by using circularity measurement [6]. In addition, another method was invented, which segments the aorta or coronary arteries by extracting the contour of tubular objects [7].

However, there is a problem when some organs or bones overlap with the targeted arteries. In order to solve this issue, Successive Region Growing (SRG) algorithm was used by appointing a start point only in the aorta [8]. In addition, a new structural measure called HAI (Hole Area Index) was introduced, which represents a dense level within the area of interest, to distinguish bones and soft tissues from blood vessels [9]. The method using SRG is, however, sensitive to noise and artifact caused by insufficient axial resolution of the images, and the structural measure called HAI extracts some bones as false positives. As a result, osseous structures can frequently be included in the extracted data.

Therefore, we have developed an automatic extraction method of the aorta, which removes the spine first, and then extracts the aorta by interpolating the image data to compensate for insufficient axial resolution. In addition, we have developed a method to measure the diameter of the aorta automatically by considering the curvature of the aorta [10].

2. MATERIALS AND METHODS

2.1 Automatic Extraction and Removal of the Spine

The base image data for this research are obtained by CT without contrast materials and the image is formatted according to Digital Imaging and Communication in Medicine (DICOM). The target area is from the bottom up to the neck. Fig. 1 shows a three dimensional image based on the CT. There are 245 CT images in total and its resolution is 512×512 . The ratios of real length to a pixel and a slice are 0.7 [mm/pixel] and 2.0 [mm/slice], respectively. One pixel has 16 bits, and it is transformed to 8 bits by window level transformation to display the image with a normal device.

Fig. 2 shows a horizontal cross section image of the CT data shown in Fig. 1. There are some parts such as the heart, the spine and the rib around the aorta, which have almost the same density so that it is very difficult to extract only the aorta from the CT image by thresholding process for binarization. The spine in particular makes isolated extraction of the aorta difficult due to its juxtaposition to the aorta and its larger area than the aorta.



Fig. 1. Three dimensional image based on 245 CT data with the resolution of 512×512 . The spine as well as the aorta and the heart are clearly seen.

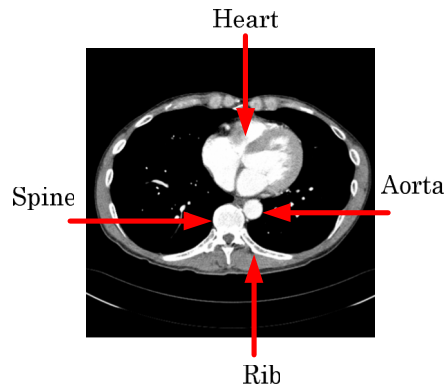


Fig. 2. A horizontal cross section image of Fig. 1. There are many organs in the image: the spine, the heart, the rib and the aorta.

Fig. 3 shows a simplified illustration of the aorta and the heart. The aorta is divided into three parts: the ascending aorta, the aortic arch, and the descending aorta. Although the descending aorta has almost straight line shape, the aortic arch is curved and the ascending aorta is connected with the heart. In addition, the aortic arch has three major branches: the brachiocephalic artery, the left common carotid artery, and the left subclavian artery. Given this curved nature of the aorta, the axial images can be difficult to be analyzed because they include complex portions of the aorta and do not simply show them connected on consecutive slices.

On the other hand, the spine is linear and has just one portion on CT image so that it can be easily extracted before the aorta extraction. Once a part of the spine is extracted on a slice of image, the spine can be traced by searching for another part which has almost the same area on the next sliced image. The spine, however, overlaps with the aorta on some slices of images so that the searched area might have larger one. Fig. 4 shows a simplified illustration of a vertical cross section of CT data. In Fig. 4, the part on slice # N has almost the same area as the part on slice # N-1. The area on slice # N+1, however, has larger area than that on slice # N since the spine overlaps with the aorta. The red solid lines in Fig.4 represent the larger area than that on slice # N. In this case, the method searches for another part that has almost the same area as the part on slice # N. In Fig. 4, the part on slice # N+2 has almost the same area as that on slice # N. Then, the parts on slice # N and # N+2 are interpolated and the area on slice # N+1 is estimated as the result of the interpolation. The red dotted lines in Fig. 4 represent the interpolation and the black solid line on slice # N+1 is extracted as the estimated area. Fig. 5 shows the extracted spine and Fig. 6 shows the human body CT data where the spine is removed. By comparing Fig. 6 with Fig. 1, it is clear that the spine is clearly removed.

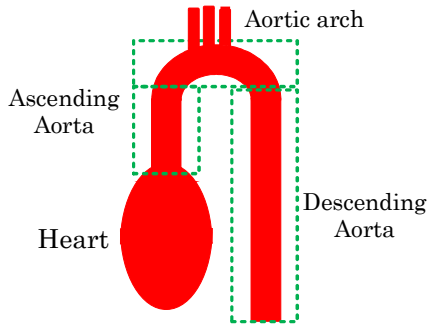


Fig. 3. Simplified illustration of the heart and the aorta that has three parts: the ascending aorta, the aortic arch and the descending aorta

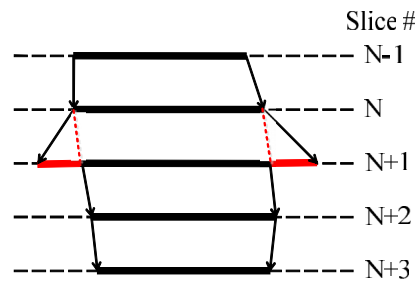


Fig. 4. Interpolation method between sliced images. If the target area on an image is extremely larger or smaller than that on the adjacent images, the estimated area is extracted by interpolation.



Fig. 5. Spine that has been clearly extracted by tracing and interpolation.



Fig. 6. Three dimensional CT image without the spine. The spine is clearly removed from Fig. 1.

2.2 Aorta Extraction

The above process removes the spine from all images so that the largest circular shape on the image is the aorta without the exception of the heart. Fig. 7 shows the piled up image of all the sliced data. In Fig. 7, there is a large circular shape object; however it is not the aorta but the heart and its density is not so high because the heart is located only on small amount of slices, while the aorta is imaged on large amount of slices. There are also some circular shaped objects above the heart, which are portions of the aortic arch. Some parts of the aortic arch have high density, but they do not have circular shapes. Then, by searching for a circular shaped object that has high density, the descending aorta can be specifically detected. Fig. 7, however, is the piled up image so that the number of the sliced image that has the circular area of the aorta cannot be specified. Then, by searching for the sliced image that has the same area as the detected aorta on the piled up image, the slice # can be specified, and it should be the starting sliced image to trace the aorta. Thus, the aorta is traced from the starting sliced image to superior and inferior.

The tracing method of the aorta is almost the same as that of the spine. The part that has similar area on the next sliced image can be traced. However, some organs overlap with the aorta and the candidate area of the tracing might have larger area. Fig. 8 shows three cases where the candidate area, which is the area of the detected aorta on the previous sliced image, overlaps with other organs. Fig. 8(a) shows the case where some parts of the candidate overlap with other organs: such as Organ A, Organ B and Organ C. In this case, the aorta can be estimated as the organ that has the maximum value of the intersection with the candidate, and Organ A is selected. On the other hand, Fig. 8(b) shows the case where the candidate is completely included by an organ, which is organ D in the figure. Fig. 8(c) shows another case where the candidate completely includes another organ, which is organ F in Fig. 8. In these cases, the candidate should not be estimated as the organ that has the maximum value of the intersection with the candidate because the organ might be the heart in the case of Fig. 8(b) or the organ might be a small object in Fig. 8(c). In these cases, not only the intersection area of the candidate and organs but also the difference area between them should be considered in the tracing process. If the organ area on the next sliced image is O , and the candidate area is CAN , the area to be traced should have the maximum value of the following equation.

$$Intersection(O, CAN) - Difference(O, CAN) \quad (1)$$

If the candidate area includes an organ and vice versa, the candidate has some value for both of $Intersection(O, CAN)$ and $Difference(O, CAN)$. Then, the value of Equation (1) becomes low. Thus, even if the heart includes the aorta and might be a candidate on the next sliced image, it is not selected as the result of the value of Equation (1). Thus, organ E and organ G are selected in Fig. 8(b) and Fig. 8(c), respectively. For example, suppose that the areas of the Candidate, Organ D and Organ E in Fig. 8(b) are 100, 200 and 100 pixels, respectively. In this case, $Intersection(D, CAN)$ is 100 because Organ D completely includes the Candidate. However, $Difference(D, CAN)$ is also 100. Then, Equation (1) becomes 0 for Organ D. On the contrary, $Intersection(E, CAN)$ and $Difference(E, CAN)$ might be 90 and 20. Note that there are two values for $Difference(E, CAN)$, one of which is the area of Organ E and the other is the area of the candidate that are not $Intersection(E, CAN)$. Then, Equation (1) becomes 70 for Organ E. Thus, Organ E is selected as the estimated aorta. In addition, if the candidate part has larger area than the detected one, some slices of images that are located ahead of the next are searched, and the part that has almost the same area as the detected one is found and selected as the candidate. Thus, the aorta area on the next sliced

image is estimated by interpolating between the detected area and the candidate on the sliced image ahead of the next.

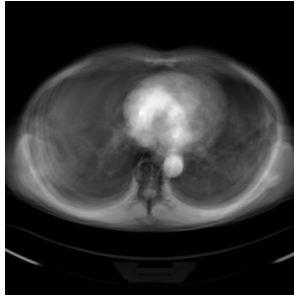


Fig. 7. Piled up image of CT data that have no spine.

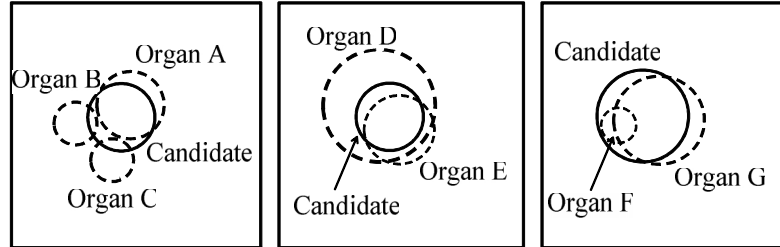


Fig. 8. Three cases where the candidate overlaps with other organs.

The most difficult part to be extracted is the aortic arch because of its curved course and non-circular shape. That is, the candidate area is translated and the shape is deformed. Then, even if the candidate area is not located near the previous one and the shape is not a circle, the candidate should be selected. However, when the area is much larger than that of the previous one, and the shape is far from a circle, the method decides that tracing reaches a part of the heart. In addition, the ratio of real length to a pixel is 0.7 [mm/pixel], while that to a slice is 2.0 [mm/slice] so that the change rate of the area of the aortic arch on a sliced image is larger than that of the descending aorta. Therefore, for the aortic arch extraction, even if the shape of the candidate area is not circle or the change rate of the area is larger, it should be traced.

After the aortic arch is extracted, the ascending aorta is traced from superior to inferior, whereas the descending aorta had already been traced from inferior to superior. In the process of tracing the ascending aorta, it reaches the heart and the change rate of the area becomes huge. Thus, in this process, if there are some candidates that have larger area on some images ahead of the next, it is judged that the process has reached the heart, and the tracing process ends. Finally, the aorta extraction algorithm is as follows:

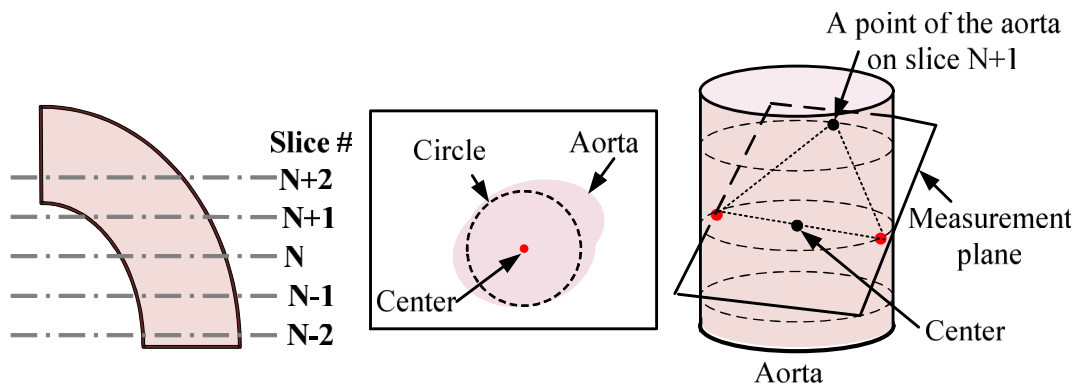
< Aorta Extraction Algorithm >

- 1) Specify one sliced image and decide the maximum circular object as the spine.
- 2) Trace the object that has almost the same area as the already decided one. If there is a sudden change of the area, estimate the area by interpolation with adjacent sliced images.
- 3) Remove the extracted spine.
- 4) Make the piled up image with all CT data.
- 5) Search the circular shape object that has high density, and decide it as the aorta, from which the aorta trace starts.
- 6) Trace the object that has the maximum value of Equation (1) with the same interpolation method as the spine tracing.
- 7) If there is no sliced data or there are some consecutive larger areas and the shape is far from a circle, stop the tracing. Otherwise go back to 6).

2.3 Automatic Measurement of the Aortic Diameter

Fig. 9 shows the concept how to define the center of the aorta and to measure its diameter, especially for the aortic arch. The ascending and descending portions of the aorta run almost straight; however, the aortic arch curves as shown in Fig. 9(a). This curve needs to be taken into account when measuring this section of the aorta. This means that the diameter should not be measured only on one sliced image, but should be measured by considering some planes which pass two different sliced images.

The first step in measuring the aortic diameter is to define the center of it. Then, in the measurement, the maximum circle inscribed in the estimated image of the aorta is extracted and its center is defined as a temporary center of the aorta as shown in Fig. 9(b). Next, a plane which passes the temporary center of the aorta and a point on the boundary of the aorta on the next sliced image is defined as shown in Fig. 9(c). When the estimated images of the aorta are projected onto the plane, the maximum circle inscribed in the projected aorta is defined and its center can be detected in the same way as the method mentioned above. Thus, some diameters which pass the center of the projected aorta are measured and the average is decided as the diameter of the aorta on the specified slice of # N.



(a) Shape of the aortic arch (b) Horizontal cross section (c) Measurement plane

Fig. 9. Measurement of the aortic diameter. (a) shows a part of the aortic arch that is curved so that the sliced image is not perpendicular to the center line of the aorta. Therefore, the center of the aorta cannot be defined. Then, a temporary center is defined as shown in (b) by using circularity measurement. Finally, a plane which has the maximum circle is selected from among some measurement planes, and the diameter is measured after the true center is decided.

3. RESULTS AND DISCUSSION

3.1 Result of the Aorta Extraction

Fig. 10 and Fig. 11 show some parts of the extracted aorta, which is displayed in red. In the figures, the alphabets correspond to each other. That is, A, B, C, and D in Fig. 11, which show the positions of the horizontal cross sections, correspond to the cross sections of A, B, C, and D in Fig. 10. E, F, G, and H in Fig. 11 also correspond to the positions of the vertical cross sections of E, F, G, and H. Fig. 10(d) shows a part of the descending aorta, the shape

of which is circular. Fig. 10(b) shows another part of the descending aorta and a part of the heart. The shapes of both areas are circular and the smaller one is the descending aorta. In addition, Fig. 10(a) shows the aortic arch so that the shape is not circular. Moreover, Fig. 10(c) shows another part of the descending aorta and the main part of the heart, the shape of which is far from a circle so that the tracing of the aorta ends at this sliced image.

On the other hand, Fig. 11(c) shows a vertical cross section which includes only the descending aorta that runs almost straight, while Fig. 10(d) shows only an upper part of the heart. Fig. 11(a) and Fig. 11 (b) show both of the aorta and the heart, and especially the aorta shape is clear in Fig. 11 (b).

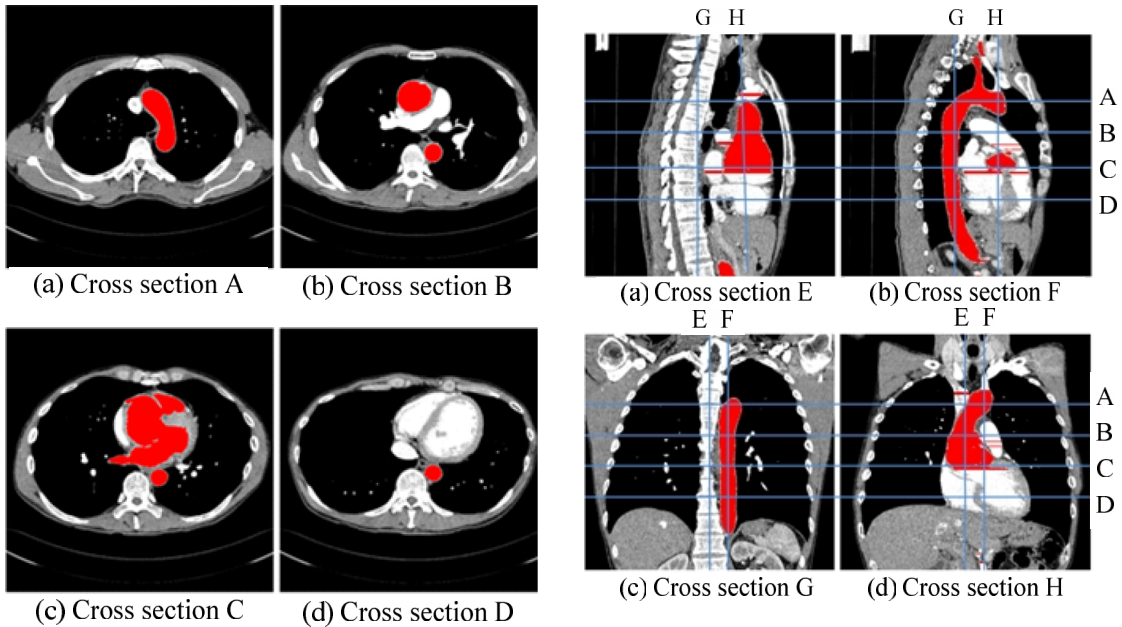


Fig. 10. Horizontal images of the extracted aorta. (a) is a part of the aortic arch, (b) has a part of the heart and the descending aorta, (c) has main part of the heart and a small part of the descending aorta, and (d) has only a part of the descending aorta.

Fig. 11. Vertical images of the extracted aorta. (a) has main part of the aorta and a small part of the heart, (b) has main part of the aorta and a small part of the heart. (c) has a straight part of the aorta, and (d) has main part of the heart.

3.2 Result of the Diameter Measurement

Fig. 12 and Fig. 13 show the positions and the result of the measurement, respectively. The circled numbers in the figures correspond to each other. There are 245 sliced images, and the number starts with 0 and ends with 244. The slice number 244 is a horizontal cross section, which is located around the bottom, and the smaller the number is, the upper the position is located. The number 0 is located around the neck, and there is not the main part of the aorta on the sliced image. The uppermost position that has the aorta is 71, and the image includes the aortic arch. Therefore, the slice #in Fig. 13 starts with 244 and is decreasing until 71, and then it is increasing up to 140, which includes a large part of the heart.

As shown in Fig. 13, the measured diameters of the aorta on the slices from # 244 to # 74, which corresponds to the descending aorta, are within the range between 20 and 30 [mm]. In addition, the result of the automatic measurement is almost the same as that of the manual one.

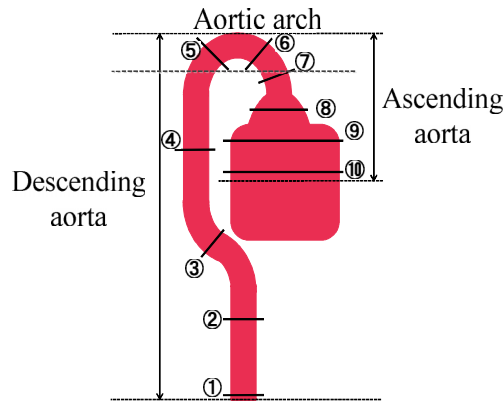


Fig. 12. Positions to measure the diameter of the aorta, which has three parts: the descending aorta, the aortic arch and the ascending aorta. The number corresponds to the one in Fig. 13.

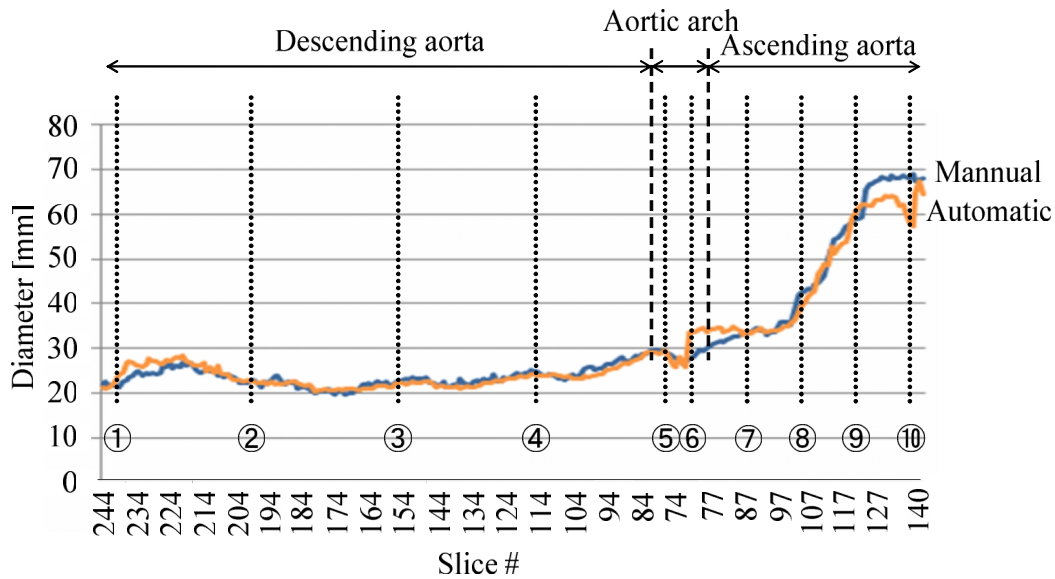


Fig. 13. Measurement results of the aortic diameter. The diameter measured automatically by the proposed method is almost the same as that manually. There are some differences at the aortic arch and a part of the heart.

3.3 Evaluation of the Method

The proposed method extracts and removes the spine before the aorta extraction. The spine is clearly extracted and removed from the original CT data shown in Fig. 5 and Fig. 6. Unless

the spine is removed, some spines are extracted during the aorta extraction as another paper indicates [9]. The reasons of this accuracy are three. The first is that the spine runs almost straight throughout the CT data. The second is that only one spine exists on one sliced image. The third is that the density of the spine is high and it has larger area. The extraction and removal were performed throughout the CT data that have 245 images and there is no error so that the method is accurate and repeatable. On the other hand, the aorta is extracted after removal of the spine. By removing the spine, it becomes much easier to extract the aorta compared to the method that treats the images with the spine. The most portions of the aorta including the aortic arch are extracted accurately as shown in Fig. 10 and Fig. 11 although some portions of the heart are extracted. This is the limitation of this method because the tracing ends when it reaches the part of the heart. The experiment was performed with a normal Personal Computer (PC) without Graphics Processing Unit (GPU). It took several minutes. The processing time depends on the specification of the PC used for the experiment. This result is fast enough to apply the method to patient-specific data although it could be faster with high performance PC with GPU.

For the measurement of the aortic diameter, the measured data are accurate except for the portions of the aortic arch and the upper portion of the heart as shown in Fig. 13. This reason is that the aortic arch is curved and the measured plane is not completely perpendicular to the center line of the aorta. However, this method defines the temporary center of the image of the aorta and tries to measure the diameter with some planes by considering adjacent slices. With this method, the diameter can be measured correctly for the aorta with aneurysms and the aorta overlapped by other organs, and the method is repeatable for extraction of the ascending and descending aorta. In addition, the measured diameters range from 20 [mm] to 30 [mm], and it is said that an average diameter of the thoracic aorta for normal persons is about from 20 to 25 [mm]. Then, it can be judged that the measured diameter of the aorta is accurate although that measured for the aortic arch and some portions of the heart has some errors. The average diameter measured automatically for the descending aorta, which ranges from #244 to #71, was 23.80 [mm], while that measured manually was 23.74 [mm]. Thus, the difference between them was only 0.06 [mm] and the accuracy of the proposed method has been proven. On the other hand, the difference for the whole data, which includes the descending aorta, the aortic arch, the ascending aorta, and some portions of the heart, was 0.28 [mm]. The reason that the difference for the whole data is larger than that for the descending aorta is that the measurement values include the aortic arch and some portions of the heart, which are very difficult parts to be measured. In addition, the standard deviation and the RMS (Root Mean Square) error for the whole data were 2.17 [mm] and 2.19 [mm], respectively. The measurements were performed for the whole data, which have 245 images, and most of the measurements were correct except for the aortic arch and some portions of the heart, which are corresponding to between #71 and #84 and between #123 and #137, respectively. Thus, there are 245 images in the whole, and 14 images, which are from #71 to #84, did not have correct results due to the curvature of the aortic arch and 15 images, which are from #123 to #137, also did not have correct results due to the extraction of some portions of the heart. Therefore, the repeatability precision of the method is $(245-14-15)/245=88\%$. The measurement was also performed by the same PC as that used for the aorta extraction. It took several minutes, while manually performed measurement took about an hour. The results measured manually by an engineer were checked by medical doctors.

4. CONCLUSION

In this paper, we have tried to extract the aorta that has three major parts. In the extraction, the center line is usually used; however, the method does not work well in situations of aortic aneurysmal dilatation. In addition, there are some organs that are falsely interpreted as part of the aorta, which is mainly the spine. Therefore, this method extracts the spine first to eliminate this error. As a result, the aorta is correctly extracted by tracing it on consecutive sliced images, and interpolating the area if there are sudden changes. On the other hand, in the measurement of the aortic diameter, a temporary center of the aorta is estimated on a slice of image, and a plane that passes the temporary center and a point on a different sliced image is considered. Although the results of the automatic and manual methods are almost the same, there are some differences, especially on the aortic arch. The main reasons of the difference are due to the curvature of the aortic arch and the low axial resolution of the sliced images. In addition, the ascending aorta is connected with the heart, the shape of which is not circular and the area is much larger than that of the ascending aorta. This is another reason that some of the results measured automatically and manually are different. One solution to increase the axial resolution is the reconstruction of the CT data by generating some intermediate image planes through interpolation. For measurement of the curved aorta, we have to investigate a method that can find a plane that is perpendicular to the center line of the aorta and measures the diameter by using the plane.

CONSENT

Not applicable.

ETHICAL APPROVAL

Not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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