DIAGNOSTIC CT IMAGING OF THE HEART AND AORTA IN HEALTH AND DISEASE

SHIGERU WATANABE, M.D.

Despite recent remarkable developments in computed tomography (CT) for many organs in the human body, its clinical application concerning the cardiovascular system has been slow. In this study, we investigated clinical applications of CT for the cardiovascular system.

We used conventional CT without ECG synchronization and ECG-synchronized CT. By the former, the size, the shape, and the arrangement of cardiovascular structures and the presence of pericardial effusion and calcifications were shown. For the latter, ECG gating method and data sorting method were used, and the cardiac border movement, the sequential changes of cross-sectional cardiac areas and the changing ratio were studied by both methods.

The cardiac CT was found to be a useful noninvasive method for observation of anatomical features in various cardiovascular diseases and for the analysis of cardiac motion — especially, dyssynergy such as hypokinesis, akinesis and paradoxical movement in myocardial infarctions.

X-RAY computed tomography (CT), introduced for brain scanning by Hounsfield in 1971, has developed remarkably in the field of diagnostic radiography. A whole body scanner was designed by Ledley in 1974. Its scanning time has been reduced from 5 minutes to 20 seconds as the improvement of the scanners. However, its application for the cardiovascular system was slow due to the problem of the cardiac motion, most data having been limited to still organs such as the brain or the abdominal viscera. There has been only limited information available regarding the CT of the heart in the past. For the last 4 years, we have been studying cardiac CT for various heart diseases using JEOL Dynamic Scanner developed by the Japanese Electron Optic Laboratory Co. It was shown that the detailed cardiac structure can be revealed by CT despite the cardiac motion and cardiac motion itself can be analyzed by dynamic cardiac CT. This report demonstrates the features of our study.

EQUIPMENT

As shown in Fig. 1, the equipment consists of 4 main elements, the X-ray generator, X-ray scanning unit, computer system and CT image display unit. An electron beam generated by the electron gun is focused on the target with the aid of electromagnetic lenses, so that a fine and high-intensity X-ray beam is obtained. The diameter of this X-ray microbeam is 0.4 mm near the X-ray generator. This system executed

Key Words:
Cardiac computed tomography (CT)
Conventional CT
ECG-synchronized CT
Cardiac structures
Cardiac area curve

(Received December 2, 1980; accepted April 16, 1981)
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linear X-ray scanning over a patient within an extremely short period of time by a flying spot of the electron beam on the target with an electronic scanning coil. Simultaneously with electronic linear scanning, angular scanning is performed by mechanical rotation of the X-ray generator and X-ray detector around the patient on the X-ray table.

The outline of technique is summarized in Table 1. The time required for the 230° ranges of angular scanning is 10 or 20 seconds. The X-ray photons which have passed through the object are detected by the NaI scintillation detector. By collecting the data about X-ray intensity measured for all points under observation in various directions, the cross-sectional tomographic image of the object is computed. The display matrices of this scanner are 160 × 160 and the size of a picture element cell (Pixel) is 2.7 × 2.7 mm. The radiation dose, which is one of the essential features, ranges only from 30–50 mRads per one slice, which is about 1/30–1/60 of the other conventional CT apparatus.

**METHODS AND MATERIALS**

Conventional CT without ECG synchronization and ECG-synchronized CT were obtained. The subjects were examined in the supine position during deep inspiration. For conventional CT, consecutive 8 to 10 slices were obtained from the 2nd to the 5th or 6th intercostal space every 1.5 cm. For ECG-synchronized CT, ECG gating method and data sorting method were used for scanning mainly at the level of midportion of left ventricle in full inspiration.

By ECG gating method, the gated cardiac images during 0.1 sec intervals at end-diastolic and end-systolic phases were obtained easily with synchronizing ECG and respiration (Fig. 2). Then the two pictures were superimposed and the cardiac borders were traced for analysis. By data sorting method, phasic CT images were reconstructed retrospectively by selecting appropriate data from a series of consecutive scans taken with simultaneous continuous ECG recordings. As shown in Fig. 3, each cardiac cycle during scanning is divided into ECG signals with one segment of 40 msec. Projection data with each ECG signal were accumulated in the computer. Ten scans at the same position were obtained, and after sufficient data were collected in the computer, a CT image was made by selecting appropriate data at a certain phase of
cardiac cycle. Due to the limited computer capacity used in our study, CT images every 40 msec interval could not be obtained. Therefore, sequential 3 ECG signals (120 msec) were used for reconstruction of a phasic image. Then the cardiac cross-sectional areas at each cardiac phase were calculated, and a cardiac area curve was obtained by plotting them consecutively. The cardiac cross-sectional images were divided into right anterior (which mainly consisted of the right ventricle), right posterior (mainly the right atrium), and left anterior and left posterior segments (the left ventricle for both). Cardiac area curves of each segment were also obtained for further analysis.

For investigation of conventional CT, 50 normal subjects (34.2 ± 7.5 years old) including 41 healthy volunteers and 181 cardiac patients

*Japanese Circulation Journal Vol. 45, September 1981*
Fig. 4. Eight scan levels of the heart. 
(1) aortic arch, (2) just beneath aortic arch, (3) pulmonary artery bifurcation, 
(4) supra-right atrium, (5) aortic root, (6) upper left ventricle, (7) mid left ventercle, (8) lower left ventricle. 
Conventionally, scans are viewed from feet of patient cephalad so that right side of body is on viewer’s left. 
AA = ascending aorta, DA = descending aorta, AR = aortic root, SVC = superior vena cava, PA = pulmonary artery, RVOT = right ventricular outflow tract, 
RA = right atrium, LA = left atrium, RV = right ventricle, LV = left ventricle, 
IVC = inferior vena cava

were examined. The cardiac pathology of these patients were as follows: mitral valvular disease (n = 35), aortic valvular disease (n = 25), congenital shunt lesions (n = 32), hypertension (n = 25), ischemic heart disease (n = 44), aortic aneurysm (n = 9) and pericardial effusion (n = 11).

For investigation of ECG-synchronized CT, 20 healthy volunteers (32.3 ± 7.0 years old) and 35 three weeks to 2 years postmyocardial infarction patients (52.0 ± 11.3 years old) were examined. Fourteen normals and 25 patients with myocardial infarction were studied by data sorting method.

RESULTS

1. Conventional CT
All images are shown as a cross-sectional slice of the chest looking upward from below the diaphragm.

Normal CT
CT images obtained every 1.5 cm from the 2nd to 6th intercostal space were classified into 8 levels based on the normal cross-sectional
TABLE II NORMAL VALUES OF CARDIAC STRUCTURES IN 50 NORMALS

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<tr>
<td><strong>Ascending aorta</strong></td>
<td>3.1 ± 0.5</td>
<td>3.0 ± 0.4</td>
<td>3.4 ± 0.4</td>
<td>(9.4 ± 1.9)</td>
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<tr>
<td><strong>Descending aorta</strong></td>
<td>2.4 ± 0.3</td>
<td>2.1 ± 0.3</td>
<td>1.9 ± 0.3</td>
<td>(2.6 ± 0.9)</td>
<td>1.8 ± 0.3</td>
<td>1.7 ± 0.3</td>
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<td><strong>Arch</strong></td>
<td>2.3 ± 0.3</td>
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<td><strong>Superior vena cava</strong></td>
<td>1.5 ± 0.3</td>
<td>1.6 ± 0.3</td>
<td>1.6 ± 0.3</td>
<td>2.6 ± 1.9</td>
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<td><strong>Inferior vena cava</strong></td>
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<td><strong>Main pulmonary artery</strong></td>
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<td>—</td>
<td>2.4 ± 0.3</td>
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<td><strong>Pulmonary artery</strong></td>
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<td>1.6 ± 0.3</td>
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<td><strong>Left atrium</strong></td>
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<td>—</td>
<td>6.7 ± 0.9</td>
<td>(14.6 ± 3.2)</td>
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<td><strong>Right atrium</strong></td>
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<td>—</td>
<td>—</td>
<td>1.9 ± 0.4</td>
<td>(6.6 ± 2.0)</td>
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<td><strong>Right ventricular</strong></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.6 ± 0.4</td>
<td>(12.1 ± 3.1)</td>
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<td><strong>outflow tract</strong></td>
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<td>—</td>
<td>10.7 ± 1.1</td>
<td>(73.4 ± 12.9)</td>
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*diameter (cm): transverse × anteroposterior  (area: cm²)*

anatomy (Fig. 4).

1. Aortic arch level: At this level, the aortic arch and the superior vena cava (SVC) are seen.

2. Level just beneath aortic arch: The ascending aorta (AA), the descending aorta (DA) and SVC are seen.

3. Level at pulmonary artery bifurcation: At this level, the main pulmonary artery is seen to the left of the AA and the bifurcation of the bilateral pulmonary artery (PA) is seen. The SVC and DA are also seen, the bifurcation of the trachea is also at this level.

4. Supra-right atrial level: The aorta was positioned at the center and the surrounding structures are seen. The right ventricular outflow tract (RVOT) or the main PA are seen to the left and anterior of the aorta, and the right atrial appendage or the upper portion of the right atrium (RA) can be seen to the right and anterior of the aorta.

5. Aortic root level: In the center of a cardiac shadow, the aortic root is seen. Occasionally it shows clover shape due to the sinuses of Valsalva. To the right and anterior of the aorta, the RVOT is seen, and the RA is seen to the right of the aorta. The left atrium (LA) appears posteriorly to the aorta. The left atrial appendage can be seen occasionally to the left of the LA as a triangular structure. The pulmonary veins draining into the LA can be seen in some cases.
This slice is the most important one for the assessment of the cardiac structures.

6. Upper left ventricular level: At this level, both atria and both ventricles are shown. The myocardium and the blood have very similar CT values, therefore, the inner structures of the heart cannot be seen clearly. However, by using the atrio-ventricular and interventricular grooves as a guideline, the anatomy of the atria and ventricles can be assessed.

7. Mid left ventricular level: At this level, the cardiac area is usually largest.

8. Lower left ventricular level: At this level, both ventricles and the RA are seen. The coronary sinus and the inferior vena cava can be seen occasionally.

The normal values of the areas and diameters of the each cardiovascular structure at the 8 levels are summarized in Table II. As seen in the table, most informations regarding to the cardiac structures could be obtained from pulmonary arterial bifurcation level which demonstrates the aorta, SVC and PA (Fig. 4-3), aortic root level which demonstrates the aortic root, RVOT, RA and LA (Fig. 4-5), and mid left ventricular level which is useful for the calculation of the cardiac areas (Fig. 4-7).

CT in Cardiovascular Diseases

The conventional cardiac CT can demonstrate the abnormalities of the position, the shape and the size of each cardiac structure and a presence of calcifications and pericardial effusion. CT abnormalities in each heart disease listed above
Fig. 6. CT images of the abnormalities of the shape and the size.
A left atrial enlargement in mitral stenosis (A), a right atrial enlargement in tricuspid regurgitation (B), a left ventricular aneurysm (arrow) following an anteroseptal myocardial infarction (C) and pulmonary arterial dilatation in atrial septal defect (D) are shown.
RA = right atrium, LA = left atrium, Ao = aortic root, RVOT = right ventricular outflow tract, RV = right ventricle, LV = left ventricle, AA = ascending aorta, DA = descending aorta, PA = pulmonary artery, SVC = superior vena cava

are shown below.

Fig. 5A is an example of a right aortic arch. The aorta was descending along the right of supine and the intracardiac anatomy was normal. Fig. 5B is an example of corrected transposition of the great vessels. The transposition of the pulmonary trunk and the aorta was clearly shown. Left atrial enlargement in mitral stenosis could be demonstrated (Fig. 6A). Fig. 6B shows right atrial enlargement in a patient with mitral stenosis and tricuspid regurgitation. Fig. 6C is an example of a left ventricular aneurysm following an anteroseptal myocardial infarction. The abnormal left anterior bulge corresponded to the aneurysm. In this case, the ventricular aneurysm was surgically resected, and the CT findings were found to correspond well to the operative findings. Fig. 6D shows an example of the dilatation of the pulmonary artery. This patient had a large left-to-right shunt through an atrial septal defect. Fig. 7A is an example of a thoracic aortic aneurysm in a patient with Behçet disease. An abnormal bump which was larger than the cardiac shadow was seen. A large filling defect which was due to a large thrombus was demonstrated by contrast enhancement (Fig. 7B). These findings were confirmed by an autopsy. Calcification is one of the most readily
Aneurysm of thoracic aorta (S.C. 56 f)

Fig. 7. An example of thoracic aortic aneurysm in Behçet disease. The larger aneurysm than cardiac shadow is shown (A) and intra-aneurysmal thrombus as a large filling defect is shown by contrast enhancement (B). DA = descending aorta, Th = thrombus, CE = contrast enhancement.

detected abnormalities by CT, and even very small or early calcifications which cannot be detected by plane chest X-rays could be detected. Fig. 8A is an example of aortic valvular calcification. The central density corresponded to the calcification of the valvar leaflets and the aortic ring. These findings were confirmed by an autopsy in this case also. Fig. 8B shows mitral valvular calcification. Fig. 8C is an example of aortitis syndrome with a diffuse calcification of the entire ascending aorta. Fig. 8D demonstrates partial calcifications of the pericardium secondary to tuberculous pericarditis. Fig. 9 shows a CT image of a patient with large tuberculous pericardial effusion. Moderate effusion is readily detected by CT, because the CT value of pericardial fluid is usually lower than the heart muscle.

II. ECG Synchronized CT

Image tracings of the midportion of the left ventricle at the end-diastolic and the end-systolic phases were obtained by both ECG gating method and data sorting method. Fig. 10 demonstrates examples of normal subjects. The solid lines represent the cardiac border at the end-diastole and the dotted lines at the end-systole. The heart movement did not appear circumferentially equal, the left posterior systolic movements were especially good, but right and anterior movement were relatively poor. The excursion of left posterior segment ranged from 5 to 10 mm. Fig. 11 demonstrates that the heart border was irregular and poor in each case compared to the normal. In 14 cases, paradoxical movement could be observed in the left heart border suggesting cardiac aneurysm. In the other cases, there was either hypokinesis or akinesis of the heart border at the left anterior or the posterior portion. These portions with abnormal motions roughly corresponded with the infarction sites estimated from ECG.

Sequential CT images were taken by the data sorting method. Fig. 3 shows a series of CT images in one cardiac cycle at the level of mid left ventricle in a normal subject. All CT images were synthesized by projection data at the same cardiac phase collected during 120 msec at every 40 msec. The cardiac cross-sectional area of each phasic image was calculated and a cardiac area curve was obtained by plotting them consecutively. Fig. 12 shows the changes of the cross-sectional total cardiac area and the 4 segmental areas, left anterior, left posterior, right anterior and right posterior areas, in the case shown in Fig. 3. The entire cardiac area curve was similar to the ventricular volume curve, and seemed to have several phases, such as an isovolumetric
contraction phase, ejection phase, isovolumetric relaxation phase, rapid and slow filling phase in one cardiac cycle. In the cardiac images at that level, the left posterior segment consists mainly of the left ventricle. So, the magnitude of the area curve is larger than the other 3 segmental area curves. In patients with myocardial infarctions, abnormal curves with a reduced amplitude were observed. Fig.14 was the cardiac area curve in an anteroseptal infarction which was shown in Fig.13, and there was a remarkable paradoxical change in the left anterior curve. By dividing the difference between the maximum and minimum cross-sectional cardiac areas by the maximum area, the changing ratio of the cross-sectional area was obtained. Fig.15 demonstrates a comparison of the changing ratio of the whole, the left anterior and the left posterior segment in normals and myocardial infarction. The changing ratios in normals were 10% for the whole, 9% in the left anterior segment and 18.5% in the left posterior segment. The changing ratios of anterior infarctions (n = 20) were significantly decreased to 4%, -0.8% and 15%, respectively. The minus changing ratio in the left anterior segment was due to paradoxical movement in 12 out of 20 cases. Three patients out of these 12 showed hyperkinetic movement at the posterior segment. In posterior infarctions (n = 3), the changing ratios in the whole and the left posterior segment decreased, but in inferior infarctions (n = 2) the cardiac motion of mid left ventricular level was not affected significantly.

**DISCUSSION**

The conventional diagnostic X-rays could show only 2 dimensional images of 3 dimensional objects. In a complex structure such as a human body, it was impossible in the past to
Pericardial Effusion (47y.o. f)

Fig.9. CT image of pericardial effusion in tuberculous pericarditis. Intrapericardial fluid is distinguished from the myocardium by distinction between their CT values.

obtain a detailed 3 dimensional image or to measure the X-ray absorption by human organs by the conventional radiography. But since the introduction of CT equipment, it has become easy to obtain horizontal tomographic images of the heart and the range of clinical diagnosis of cardiovascular disease has been greatly expanded. In conventional CT, a slice can be obtained within 10 to 20 seconds for which the patient can hold the breath easily. The image obtained by this method represents the mean image of the heart due to the cardiac motion. Naturally blurring of the image due to the cardiac motion is inevitable, however when it is compared with the images obtained with the ECG synchronization, the blurring is usually rather insignificant and the conventional CT image is usually similar to the image during the diastole when the cardiac volume is the largest. Therefore the conventional CT is useful for assessment of the cardiac structures and the relationships to the other organs, when it is taken at different levels within a short period of time.

Fig.10. Image tracings at the end-diastole and the end-systole by data sorting method and ECG gating method (*) in normal subjects.

*Japanese Circulation Journal Vol. 45, September 1984*
In our study, slices every 1.5 cm from the 2nd to the 6th intercostal space were taken. But there are differences of the cardiac level in each subject, therefore for the sake of analysis, we used the classification into the 8 levels described earlier, and the normal values of the each structure on thier levels were obtained. Our data were similar to the previously reported values by Guthaner et al.\textsuperscript{19}

Conventional CT images are useful in determining the size, the shape, and the arrangement of the heart and major blood vessels. The exact feature of an enlarged left atrium in a mitral disease was one of the most readily detectable abnormalities by this technique and the shape and the size of the right atrium and the right ventricle which were difficult to investigate by other diagnostic procedures were also easily observed. An abnormal large bulge in some patients with myocardial infarction suggested a cardiac aneurysm and that diagnosis was confirmed by ventriculography and surgical procedures in all the cases. It was possible to show the location, the size and the extent of aortic aneu-

*Japanese Circulation Journal  Vol. 45, September 1981*
rysms, and occasionally intraaneurysmal thrombi were found with contrast enhancement. Moreover, an evaluation of dissection of the thoracic aortic aneurysm by contrast enhanced CT has been reported. Diagnosis of a small calcification of the valve and arterial wall, which could not be recognized by plain chest X-ray, was now detected easily. Also, CT is useful for the detection of pericardial effusion. In presence of pericardial effusion, CT value of the inapercardial fluid is usually lower than that of the myocardium by 10 to 20. Pericardial effusion can be detected by echocardiography very easily too, but CT is superior to echocardiography for detection of localized pericardial effusion and for analysis of the type of the fluid. However the diagnosis of small pericardial effusion was rather difficult by CT because of the artifact by the cardiac motion and partial volume phenomenon. The distinction of the pericardial fat from fluid was easy due to the low CT value (−40) of the fat tissue. It can be used for evaluation of the intrapulmonary water volume quantitatively by looking at the lung fields, because the CT image is a map of X-ray absorption.

We feel CT can be used for assessment of the size, the age and the other characteristics of a myocardial infarction. A low CT value due to myocardial edema during an acute infarction and a high CT value due to a scar tissue secondary to an old infarction have been reported. By using contrast enhancement, a distinction of the ischemic area from the surrounding reactive hyperemic area was reported to be feasible. But these informations were based on animal experiments and such techniques have not been applied in the human thus far.

For scanning of rapidly mobile objects such as the heart, a high speed CT apparatus is being developed currently, but at the present time, an application of this apparatus is a stage of animal experiment. In our study, ECG gating method and data sorting method were used for obtaining stop action of cardiac CT images. These both methods need about 20 minutes to collect sufficient data. Only one phasic slice was obtained by the former method, but the latter method, which is similar to the “post data-acquisition correlation technique” by Harrell and the “prospective gating method” by Berninger, has an advantage of possibility of obtaining a series of CT images every 40 msec during a cardiac cycle. In this study, because of a difficulty of reconstructing the phasic image by only selective ECG signal (40 msec interval), the slight deficiencies of selective ECG signal were filled up by adjoining ECG signals. Therefore, the reconstructed image resulted in 120 msec interval. But this problem will be solved by increment of the computer capacity. For diagnosis of left ventricular wall motion disorders, various kymographies (i.e., plane roentgen kymography, electrokymography, radarkymography, etc.) and apexcardiogram have been used mainly for observation of cardiac border movement, and left ventriculography, echocardiography and radioisotope scanning are used clinically for analysis of inside movement. It is relatively easy to record cardiac border movement. Electrokymography, especially, is useful for detection of abnormal cardiac border movement in myocardial infarction, but there are difficulties with evaluation of cardiac motions of anteroposterior direction and quantitative assessment of the wall motion. By ECG synchronized CT, it is possible to analyse cardiac border movement and inside movement with contrast enhancement. The scanner which we used in this study had very low X-ray dosage in consideration of X-ray’s side effect against human body, so that the satisfactory examination could not be obtained always even with contrast enhancement. In the future we are planning to extend our research for further investigation of the cardiac inside movement by CT. However, there is good correlation between
A case of anteroseptal infarction (K.A. 46 m)

Fig. 13. A series of CT images during a cardiac cycle by data sorting method in an anteroseptal myocardial infarction (K.A. 46y. male).

echocardiography and CT, and CT makes up for some disadvantages of echocardiography. In addition, the abnormalities of cardiac border motion were coincident almost with the findings of left ventriculography in several cases who were catheterized.

One must be very cautious on defining the cardiac border on a CT image. We controlled the window level and window width very carefully on tracing cardiac border, so that the cardiac images at the end-systole and the end-diastole were displayed as clearly as possible. The cardiac areas were calculated with a computer software program by appointing the cardiac region of interest (ROI) and CT numbers range from a printed out pixel map of CT numbers. For determination of the boundary between the myocardium and the lumen opacified by contrast medium, the use of CT value on the pixel map of ROI has been reported to be reliable. It is ideal to obtain multiple scans at various left ventricular levels, but because of limited time for examination and of X-ray exposure, only representative level was scanned in this study. It was difficult to observe upper portion of the left ventricle as that posterior part often lies just next to left atrium very closely. Lower left ventricular level is largely influenced by long axial movement and pendal motion, and it often overlaps the diaphragm which is difficult to be distinguished from the heart muscle. We selected the midpoint of the left ventricle for scanning for two main reasons: an anterior or lateral myocardial infarction was most recognized on this level, and we presumed that long axial shortening movement of this level was almost negligible assuming that the heart muscle contracted toward the geometrical center of the left ventricular lumen. In inferior or small inferoposterior myocardial infarction the abnormality was im-

possible to be detected on the midportion of the left ventricle. In these lesions, long axial tomographic studies still need a device concerning posture and further improvement of the technique for a precise assessment.

In the group of myocardial infarctions who were tested by data sorting method, the abnormal motion of cardiac border, abnormality of cardiac area curve and diminution of changing ratio were shown in correspondence with infarcted site. Paradoxical movement, especially, were shown in 12 cases out of 20 anterior myocardial infarction patients. It was thought to be related to the fact that many anterior wall infarction patients had a persistent ST elevation on ECG or an abnormal protrusion of the left ventricle on chest X-rays following the attacks. Because of these findings, presence of a ventricular aneurysm was rather strongly suspected. Cardiac aneurysms were confirmed in 8 patients out of 12 by left ventriculograms or under operation of coronary bypass or aneurysmectomy. The other patients did not have any further investigation because of a good general condition, so presence of an aneurysm remained to be unconfirmed. This method found to be very useful for the noninvasive diagnosis of a myocardial aneurysm particularly.

There are several advantages of dynamic CT over the other noninvasive methods in analysis of cardiovascular motion. The method is believed to be more objective and more extensive than ultrasonic cardiocinography and radioisotope scanning. Although CT appears to be the best method available for the noninvasive assessment of external cardiac border motion and cardiac area, there are certain disadvantages with this technique. The time needed for a dynamic CT image is longer than the other methods and a dynamic CT can not evaluate the ventricular cavity and valvular motion.

Despite the very short history, the development of CT has been quite remarkable, and improvements of the computer software are still continuing. In the near future, the use of CT for the diagnosis and continuous assessment of various heart diseases, such as the diagnosis of the location and the age of a myocardial infarction and sequential assessments of the cardiac volume, cardiac output and ejection fraction, should be expected.

**Acknowledgement**

I wish to express my gratitude to Prof. Y. Inagaki.
and Assistant Prof. Y. Masuda, Dept. of Internal Medicine (III), Chiba University, for excellent guidance and encouragement, to Prof. N. Arimitsu, Dept. of Radiology, Chiba University and Prof. G. Uchiyama, Dept. of Radiology, Yamanashi University, for their pertinent advices.

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