Advance of Cardiac Computed Tomography
— Functional Evaluation of the Cardiovascular System —

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The validity of X-ray CT in the functional diagnosis of several cardiovascular diseases was evaluated. CT was useful for assessing the amount and the characteristics of intrapericardial fluid, and it was also useful for the diagnosis of cardiac tamponade and constrictive pericarditis. A dynamic scan was found to be useful for determining the location, direction and the magnitude of intracardiac shunts, and for differentiating the true lumen from the false lumen in dissecting aortic aneurysms. As direct evidence of myocardial infarction, a filling defect in the infarcted area and late enhancement of the same area on delayed scan were noted. Regional wall motion abnormalities could be demonstrated by ECG gated CT, and other findings such as myocardial thinning, ventricular aneurysm and mural thrombi in the infarcted area were documented.

It has been only 12 years since X-ray computed tomography (CT) was introduced into clinical use, but the recent development of CT equipment has been remarkable. Today, it is becoming one of the essential diagnostic tools in the field of cardiovascular disease. The original CT scanner developed by Hounsfied took as long as 20 minutes for one slice, but 6 years later, the scan time shortened to 5–10 seconds per slice and, currently, newly developed machines take only 1.3 seconds. Spatial resolution and contrast resolution of the scanners are also remarkably improved. While those of the early scanners were around 10 mm and ±0.5% respectively, now they are around 0.7 mm and ±0.35%.

Initially, only plain scans were employed, but now several more sophisticated techniques such as enhanced CT, dynamic scan and ECG gated scan are available. Furthermore, an ultrafast CT

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>CASES WHICH HAVE UNDERGONE ENHANCED CT STUDIES IN OUR DEPARTMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>61</td>
</tr>
<tr>
<td>Myocardial infarction</td>
<td>147</td>
</tr>
<tr>
<td>Angina pectoris</td>
<td>24</td>
</tr>
<tr>
<td>Mitral valve disease</td>
<td>60</td>
</tr>
<tr>
<td>Aortic valve disease</td>
<td>26</td>
</tr>
<tr>
<td>Combined valve disease</td>
<td>16</td>
</tr>
<tr>
<td>Hypertrophic cardiomyopathy</td>
<td>43</td>
</tr>
<tr>
<td>Congestive cardiomyopathy</td>
<td>24</td>
</tr>
<tr>
<td>Hypertension</td>
<td>37</td>
</tr>
<tr>
<td>Atrial septal defect</td>
<td>37</td>
</tr>
<tr>
<td>Ventricular septal defect</td>
<td>12</td>
</tr>
<tr>
<td>Patent ductus arteriosus</td>
<td>4</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>2</td>
</tr>
<tr>
<td>Dextrocardia</td>
<td>6</td>
</tr>
<tr>
<td>Corrected transposition of</td>
<td>5</td>
</tr>
<tr>
<td>the great vessels</td>
<td>5</td>
</tr>
<tr>
<td>Double aortic arch</td>
<td>5</td>
</tr>
<tr>
<td>Pericardial effusion</td>
<td>20</td>
</tr>
<tr>
<td>Constrictive pericarditis</td>
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</tr>
<tr>
<td>Aortic aneurysm</td>
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<tr>
<td>Dissecting aortic aneurysm</td>
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<tr>
<td>Miscellaneous</td>
<td>72</td>
</tr>
<tr>
<td>Total</td>
<td>687</td>
</tr>
</tbody>
</table>

Key Words:
Cardiac CT
Cardiac function
Intracardiac shunt
Myocardial infarction
Dissecting aortic aneurysm

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702 Japanese Circulation Journal Vol. 49, July 1985
scanner which takes only 30–50 msec per slice has been developed recently. With these advances in the capacity of CT scanners, the applications CT have expanded from morphological diagnosis only to more comprehensive diagnoses including functional analysis of cardiac motion and blood flow. This study was undertaken to evaluate the validity of cardiac CT in the functional diagnosis of several cardiovascular diseases.

SUBJECTS AND METHODS

Table I summarizes the patients who have undergone enhanced CT study in our Department over the last five years. Of the patients, only those with pericardial disorders, congenital heart disease, ischemic heart disease and aortic aneurysm were included in this study.

The scanners used for this study included CT/T 8800 by GE and Somatom 2 by Siemens. Contrast enhancement was done with a bolus intravenous injection of 15–20 ml of 76% Urografin (methylglucamine diatrizoate) per slice. A dynamic scan was performed in approxi-

mately one third of the patients, and an ECG gated scan was performed in 12 patients with myocardial infarction.

RESULTS

1. Pericardial Disorders

Thickening and calcification of the pericardium, pericardial effusion and subepicardial fat were readily documented by plain CT scan. Normal pericardium can be seen as a thin,
smooth structure with a width of 1–2 mm by plain scan, but since its CT value is very similar to that of myocardium, it can seldom be clearly demonstrated in an individual without subepicardial fat. Left lateral and posterior portions of the pericardium are also difficult to visualize because of the cardiac motion. However, thickened pericardium could be easily recognized as a structure of greater thickness with higher CT values. It was noted that the thickness and the CT values of thickened pericardium were not even.

The CT values of pericardial fluid varied from 10 to 50 HU. Transudate had the lowest CT value, and bloody fluid the highest. The CT value of exudate was in between, and CT values were very useful for evaluating the intrapericardial fluid. Figure 1 shows an example of a carcinomatous pericardial effusion. By plain scan (upper panel), demonstration of the effusion was not too clear because of its high CT value (+44 HU) which was similar to that of myocardium. However, with contrast enhancement (lower panel), the pericardial effusion could be clearly differentiated from myocardium. The pericardial fluid of this patient was markedly bloody and included numerous malignant cells.

CT was also found to be useful for the diagnosis of cardiac tamponade and constrictive pericarditis. In the case of cardiac tamponade, massive pericardial effusion and a small heart were demonstrated. In constrictive pericarditis, marked generalized thickening of the pericardium.

Fig. 4. CT values curves in the right and left ventricle in a patient with Eisenmenger’s complex due to a ventricular septal defect. 2 = right ventricle, 3 = left ventricle.

Japanese Circulation Journal Vol. 49, July 1985
Fig. 5. CT images in a patient with anterior myocardial infarction.
Left: Nine days after infarction, a filling defect (FD) was demonstrated in the anterior wall of the left ventricle immediately after a bolus injection of contrast material. Middle: Twenty-two days after infarction, anterior wall thinning (arrows) was noted immediately after a bolus injection of contrast material, but a filling defect was not obvious. Right: Ten minutes after the injection, late enhancement of the myocardium (LE) appeared in the same region.
RV = right ventricle, RA = right atrium, LV = left ventricle, NM = normal myocardium

Fig. 6. End-systolic and end-diastolic CT images at ventricular level in a normal subject and a patient with extensive anterior wall infarction. The right panel reveals the changes of the left ventricular cross-sectional area and the changes of the anterior left ventricular wall thickness of the time scale.
Panel Discussion on Progress in Noninvasive Cardiac Diagnosis

was demonstrated and this was particularly prominent around the coronary sulcus and the interventricular sulcus. Marked calcification of the pericardium was noted in some cases. Marked dilatation of the superior and inferior vena cava was noted in many cases. We investigated 3 cases of cardiac tamponade and 7 cases of constrictive pericarditis and the CT studies were quite valuable in the management of all these patients.

2. Congenital Heart Disease

CT was diagnostic in 4 cases of patent ductus arteriosus, 2 cases of tetralogy of Fallot, 5 cases of corrected transposition of the great vessels, 5 cases of double aortic arch and 6 cases of dextrocardia in terms of anatomical assessment. However studies done in 37 patients with atrial sepal defect and 12 patients with ventricular sepal defect failed to document the defects precisely except for a few exceptional cases. Patent ductus arteriosus could be demonstrated as a structure connecting the upper thoracic descending aorta to the main pulmonary artery. Three of the 4 cases were also studied with dynamic scan, and left-to-right shunt was documented in all three patients. Figure 2 shows the images of one of those patients. The upper panel shows filling of the main pulmonary artery shortly after the bolus injection of contrast. The ductus adjacent to the pulmonary artery was minimally filled. The middle panel shows the image 6 seconds later. Visualization of the aorta and the ductus was noted. In patients with atrial sepal defect and ventricular sepal defect, it was very difficult to demonstrate the defects, although dynamic scan was found to be useful for determining the level, direction and degree of shunt. Figure 3 shows a comparison of CT values in both atrial cavities obtained by dynamic scan in a normal subject and in a patient with atrial sepal defect. In the normal subject, the CT value in the right atrium increased suddenly and subsequently gradually decreased along an exponential curve. In the left atrium, a similar change was observed with a certain time delay. The curves were very similar to a dye dilution curve. In the patient with atrial sepal defect, the fall in CT value in the right atrium was much slower and superimposed on the descending curve in the left atrium. This indicated the presence of a left-to-right shunt at the atrial level. Figure 4 shows CT value changes on a time scale in both ventricles of a patient with Eisenmenger’s complex due to a ventricular sepal defect. The rise in CT value in both ventricles was almost simultaneous and the following changes were very similar. This indicated the presence of a large right-to-left shunt.

3. Ischemic Heart Disease

Enhanced CT studies were done in 147 cases of myocardial infarction and 24 cases of angina pectoris. Among 36 cases of acute transmural myocardial infarction studied within one month of the attack, a filling defect in the infarcted area immediately following contrast injection was demonstrated in 27 cases (Fig. 5, left panel). The other 9 cases, in whom a filling defect was not clearly documented, included 6 patients with inferior wall infarction and 3 patients with relatively small infarctions. In 115 cases of transmural myocardial infarction in the chronic phase studied one month after the attack, filling defects could be documented in very few cases. Twenty-three patients were studied with a delayed scan 10–15 minutes after the injection of contrast. Late enhancement, accumulation of contrast in the infarcted myocardium, was demonstrated in both acute and chronic patients (Fig. 5, right panel). Seven of the 23 patients, who did not show clear late enhancement, had either inferior wall infarction or infarction with a very small area. In 12 patients, an ECG gated scan was performed with contrast enhancement and the ventricular wall motion was analyzed. A reduction in ventricular wall motion of the infarcted site, which was estimated by ECG, left ventriculography and/or myocardial imaging, was demonstrated in all patients. Figure 6 shows end-systolic and end-diastolic images at the ventricular level of a normal subject and a patient with extensive anterior wall infarction. The reduced motion of the anterior left ventricular wall was evident. The right panel reveals the changes in left ventricular cross-sectional area and in anterior left ventricular wall thickness on a time scale. These parameters were apparently reduced in patients with myocardial infarction.

Beside the abnormalities of functional CT parameters, several morphological abnormalities, such as thinning of the infarcted myocardium, left ventricular aneurysm and intraventricular thrombi, were noted in myocardial infarction patients. Left ventricular aneurysms were documented in 47 (37%) of 137 patients with transmural infarctions, and they were usually found in the anterior wall or in the apical portion. Left ventricular mural thrombi were revealed in

Japanese Circulation Journal Vol. 49, July 1985
26 (19%) of the 137, and the location of thrombi coincided with the infarction area. Intraaneurysmal thrombi were demonstrated in 21 cases.

Thus, cardiac CT was found to be valuable in the diagnosis of the infarction site, its extensiveness and its phase. However, studies performed in 10 patients with subendocardial infarction and 24 patients with angina pectoris failed to show any specific findings.

4. Aortic Aneurysm

Thirty-nine patients with aortic aneurysm and 53 patients with dissecting aortic aneurysm underwent enhanced CT studies. In all cases, CT alone was sufficient to determine the location and size of aneurysms and the presence of dissection. In dissecting aneurysms, the true lumen could not be differentiated from the false lumen by enhancement alone, but differentiation was possible in all 39 patients who also had a dynamic scan. Figure 7 shows an example of dynamic scan images in a patient with dissecting aneurysm, DeBakey's type I. The aorta was markedly dilated and two lumens divided by a intimal flap were demonstrated. The smaller lumen was obviously filled first and the filling of the larger lumen followed, and it remained longer. This indicated that the smaller lumen was the true lumen, and the larger lumen was the false lumen. Thrombi were seen in the false lumen.

DISCUSSION

Changes in CT values of a time scale can be very easily observed in any area of the cardiovascular system by most of the currently available CT scanners, and we have shown that analysis of those changes is very useful in the functional evaluation of many diseases. For instance, in the diagnosis of pericardial effusion, the CT value gives us information regarding the status of the tissue.1,2 Thus the applications of CT can be extended beyond the morphological assessment of the cardiovascular system.

The validity dynamic scans for diagnosis of
dissecting aneurysms or the patency of aorto-
coronary bypass grafts has been reported \(^3-^8\) but it has not been used extensively for the
evaluation of shunts. Our study has shown that
dynamic scans can be used to estimate the
location and the direction of shunts, and an
approximate shunt ratio can be obtained. However,
this method is not sensitive enough to detect a
small shunt and the quantification of shunts is
accurate enough by currently available systems \(^9\)
Further shortening of the scan time and further
advances in software are necessary for more
accurate assessment of shunts.

CT is only beginning to be used for the diag-
nosis of myocardial infarction \(^10-^11\) A filling
defect of the infarcted area immediately follow-
ing contrast injection, and late enhancement on
delayed scan 10–15 minutes later were most
characteristic. As the infarction gets older, the
filling defect becomes gradually unclear, but late
enhancement remains. This sequential change
was demonstrated in animal experiments by
Carlsson et al. \(^12,^13\) but clinical observations in
substantial numbers of patients have only been
done by us so far \(^11\) We found that both filling
defects and late enhancement were difficult to
demonstrate in inferior or posterior wall infarc-
tion, but they could be observed quite easily in
anterior or septal infarcts. CT was very valuable
for estimating the infarct site, extensiveness and
its phase. As far as the mechanism of those find-
ings is concerned, the filling defect is thought to
be due to a decrease in regional coronary blood
flow. The mechanism of late enhancement ap-
ppears to be rather complex. It should include
phenomena such as leakage of contrast into the
intercellular space due to vascular damage in the
infarcted area, entry of contrast into the myo-
cardial cells due to a damaged cell membrane and
delayed clearance of contrast due to impaired
regional coronary circulation \(^14\) Therefore, serial
observations of those findings would help in
assessing the healing process after myocardial
infarction. As mentioned above, inferior and
posterior wall infarcts are very difficult to assess
by CT. This is due primarily to the fact that the
scanning slices are not appropriate for evaluation
of those areas. Better resolution should be
available by changing the angulation of the
gantry.

Abnormalities of regional ventricular wall
motion can be accurately evaluated by ECG
gated CT \(^15\) Combining those findings with the
other abnormalities such as ventricular wall
thinning, ventricular aneurysm and intraventricu-
lar thrombi, a comprehensive diagnosis of myo-
cardial infarction is feasible using cardiac CT, and
it appears to have potential for wider clinical
application.

There have been a few previous reports regard-
ing the application of CT to the diagnosis of aortic
aneurysm \(^16,^17\) and our study reconfirmed the
validity of CT examination in this condition.
In patients with dissecting aortic aneurysm which
requires accurate diagnosis on an emergency
basis, dynamic scan CT can be performed quickly
without putting the patient under significant
stress \(^18,^19\) We found, it to be extremely valuable
in actual clinical cases.

The greatest disadvantage of cardiac CT
compared with other diagnostic methods is its
scanning time which is still too long. The newest
equipment still requires 1.3 seconds per slice and,
for the motion of the heart, this information col-
lection process remains much slower than the
other systems such as two-dimensional echo-
cardiography, cineangiography or digital sub-
traction angiography. And CT is inferior to the
other methods in terms of analyzing the sequen-
tial changes on a time scale. Even using the ECG
gated scan, we could only obtain images every
0.1–0.2 seconds. As shown in the present study,
even with the techniques currently available,
documentation of intracardiac shunts and dif-
ferentiation of the true lumen from the false
lumen in dissecting aneurysms are possible, but if
scanning time could be further shortened its
diagnostic capacity would increase remarkably.
Several new scanners, such as the Dynamic Spatial
Reconstructor, designed by Wood and his col-
leagues at Mayo Clinic \(^20\) and the Cardiovascular
Computed Tomographic Scanner, designed by
Boyd at UCSF \(^21\) are being developed. The ultra-
fast scanner developed by Boyd makes very fast
scanning possible and its scanning time is as short
as 30-50 msec per slice. With the development
of these ultrafast scanners, CT will have much
wider applications for hemodynamic assessment,
such as precise evaluation of regional wall motion,
cardiac output, segmental ejection fraction and
regional blood flow.

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Japanese Circulation Journal Vol. 49, July 1985


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