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 Hounsfield 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 $\pm 0.5\%$ respectively, now they are around 0.7 mm and $\pm 0.35\%$.

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 I CASES WHICH HAVE UNDERGONE ENHANCED CT STUDIES IN OUR DEPARTMENT

<i>Normal</i>	61
<i>Myocardial infarction</i>	147
<i>Angina pectoris</i>	24
<i>Mitral valve disease</i>	60
<i>Aortic valve disease</i>	26
<i>Combined valve disease</i>	16
<i>Hypertrophic cardiomyopathy</i>	43
<i>Congestive cardiomyopathy</i>	24
<i>Hypertension</i>	37
<i>Atrial septal defect</i>	37
<i>Ventricular septal defect</i>	12
<i>Patent ductus arteriosus</i>	4
<i>Tetralogy of Fallot</i>	2
<i>Dextrocardia</i>	6
<i>Corrected transposition of the great vessels</i>	5
<i>Double aortic arch</i>	5
<i>Pericardial effusion</i>	20
<i>Constrictive pericarditis</i>	7
<i>Aortic aneurysm</i>	39
<i>Dissecting aortic aneurysm</i>	53
<i>Miscellaneous</i>	72
<i>Total</i>	687

Key Words:

Cardiac CT
Cardiac function
Intracardiac shunt
Myocardial infarction
Dissecting aortic aneurysm

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Fig.1. CT images before and after contrast enhancement in a patient with carcinomatous pericardial effusion (E).

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-

K. M. 34. f.
PDA
(dynamic scanning)

Fig.2. Images of dynamic CT scan in a patient with patent ductus arteriosus.

AA = ascending aorta, PA = pulmonary artery, DA = descending aorta, X = ductus arteriosus

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,

Fig.3. CT values curves in the left and right atrium in a normal subject (left panels) and in a patient with atrial septal defect (right panels).
1 and 2 = right atrium; 3 and 4 = left atrium

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 dia-

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

gnosis 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

T.S. 45 m Anterior infarction

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.

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 septal defect and 12 patients with ventricular septal 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 septal defect and ventricular septal 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 septal 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 septal 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 septal 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

Dissecting Aneurysm T.K. 67m

Fig.7. Dynamic scan at level of main pulmonary artery in a patient with a dissecting aneurysm. Scan interval 6 sec.

AA = ascending aorta, P = pulmonary artery, SVC = superior vena cava, LA = descending aorta, Tr = true lumen, F = false lumen

26 (19%) of the 137, and the location of thrombi coincided with the infarction area. Intra-aneurysmal 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 an 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 diagnosis of myocardial infarction.¹⁰⁻¹¹ A filling defect of the infarcted area immediately following 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 infarction, 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 findings is concerned, the filling defect is thought to be due to a decrease in regional coronary blood flow. The mechanism of late enhancement appears 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 myocardial 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 intraventricular thrombi, a comprehensive diagnosis of myocardial infarction is feasible using cardiac CT, and it appears to have potential for wider clinical application.

There have been a few previous reports regarding 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 collection process remains much slower than the other systems such as two-dimensional echocardiography, cineangiography or digital subtraction angiography. And CT is inferior to the other methods in terms of analyzing the sequential 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 differentiation 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 colleagues at Mayo Clinic,²⁰ and the Cardiovascular Computed Tomographic Scanner, designed by Boyd at UCSF,²¹ are being developed. The ultrafast 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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