Appearance and Progress of Multislice CT

Temporal, spatial, and contrast resolutions are essential factors that help us determine the quality of computed tomography (CT) images. To visualize the coronary arteries composed of rapidly moving small sized vessels, all these resolutions should be high. There had been many attempts to observe the coronary artery by helical CT, but both temporal and spatial resolutions were insufficient, and the attempts were rather investigative. The ultra-fast CT was anticipated very much, but contrast resolution was insufficient. The progressive development of multislice CT enabled the clinical application of coronary CT, to which the following 3 advancements contributed to 1) an increase in the number of detector rows, 2) an increase in the speed of gantry rotation, and 3) the development of an image reconstruction method exclusive for the heart.

1) Increase in the number of detector rows

Conventional helical CT was capable of acquiring only one image per rotation. The acquisition of several images per rotation was achieved by increasing the number of detector rows in the axial direction in multislice CT, which simultaneously realized an increased speed (improvement of temporal resolution) and acquisition of thin slices (improvement of spatial resolution). In 1998, 4-slice CT capable of simultaneously acquiring data from 4 slices appeared, and it could acquire 1–1.25-mm slices of the heart in 40 seconds. Sixteen-slice CT, capable of acquiring 0.5–0.625-mm slices of the heart in 20 seconds, appeared in 2002, and 64-slice CT, capable of acquiring 0.5–0.625-mm slices in 5–7 seconds, appeared in 2004.

2) Increased speed of gantry rotation

Faster gantry rotation is necessary to increase the temporal resolution of coronary CT. The gantry rotation speed of conventional helical CT was 1 second, but CT with a speed of 0.8 seconds appeared in 1996. The speed was improved to 0.5 seconds in 2001 in which 16-slice CT appeared, and a speed of 0.35 seconds (temporal resolution: 175 msec) was realized in 2004.

3) Development and progress of an image reconstruction method exclusive for the heart

Electrocardiographic gating is necessary to image the heart because it constantly beats. There are 2 methods to perform an electrocardiography-gated scan in multislice CT: 1) prospective gating, in which radiation is emitted only in a specific cardiac phase beforehand, and 2) retrospective gating, in which electrocardiographic and imaging information is simultaneously collected, and data on the target cardiac phase is extracted and reconstructed into an image.

On extraction of the target cardiac phase in retrospective gating, when the heart rate is 65 bpm or less and the R-R interval is long, an image can be prepared from data of a single heartbeat by collating with, for example, the
mid-diastolic phase (Fig. 1). However, when the heart rate is high, the R-R interval is short, if an image is reconstructed from data of a single heartbeat, resulting in poor image quality, for which a method to reconstruct an image by extracting and combining data of the same phase from several consecutive heartbeats was developed. This method is called multi-sector reconstruction (the name differs among manufacturers). This method increased temporal resolution and facilitated application for cases with a high heart rate.

**Current State and Problems of Coronary Arterial Examination Employing 64-row CT**

Current coronary CT is capable of providing information concerning the anatomical distribution of the coronary artery, diagnosis of coronary arterial stenosis, and coronary arterial wall evaluation.

Of these, the most firmly established usefulness is exhibited in identifying the anatomical distribution of the coronary arteries. Reportedly, abnormal origins of the coronary artery, single coronary artery, and coronary arteriovenous fistula are accurately visualized, compared to angiography (Fig. 2).\(^1\)\(^,\)\(^2\) It is very useful to perform percutaneous coronary intervention (PCI) if information on the abnormal origin of the coronary artery is available beforehand.

The diagnostic performance of the detection of coronary arterial stenosis is very high: both the sensitivity and specificity of 64-detector CT were between 90% and 95%, and the accuracy of detecting negativity was reported to be close to 100% (Table 1, Fig. 3).\(^3\)\(^-\)\(^6\) Thus, 64-detector CT has been employed to detect coronary arterial stenosis in patients suspected of having ischemic heart disease. For the analysis of stenosis, a new image
display method to display the distribution of lesions in a single image, an angiographic view, has been developed and effectively used for explaining the severity of disease to patients and designing treatment plans (Fig. 4). 

To consider the treatment policy and prognosis of ischemic heart disease patients, we judge the presence or absence of myocardial infarction as being more important than that of coronary artery stenosis. It was reported that abnormal perfusion was present on single-photon emission computed tomography (SPECT) in only about half of patients in whom significant stenosis was observed on coronary CT. In the deferral of percutaneous coronary intervention (DEFER) study, a pressure wire was inserted into intermediate stenosis lesions in which the significance of stenosis was unclear on coronary angiography. The fractional flow reserve (FFR), representing the functional severity of coronary stenosis, was calculated from the intracoronary pressure measurement, and the outcome of PCI was investigated. This study revealed that the FFR value is important for the outcome of PCI, rather than the degree of stenosis.

Although the diagnostic performance of coronary CT for the detection of morphological stenosis is high compared to coronary angiography, it does not necessarily predict functionally significant stenosis, i.e., ischemia. Evaluation of myocardial perfusion by loading a drug (adenosine

Table 1  Diagnostic performance of 64-slice CT for the detection of significant coronary stenosis (>50%)

| Per-segment | N  | Sensitivity (%) | Specificity (%) | PPV (%) | NPV (%) |
|-------------|----|----------------|-----------------|---------|---------|
| Leschka et al | 67 | 94             | 97              | 87      | 99      |
| Leber et al  | 55 | 76             | 97              | 75      | 97      |
| Raff et al   | 70 | 86             | 95              | 66      | 98      |
| Mollet et al | 51 | 99             | 95              | 76      | 99      |
| Ropers et al | 81 | 93             | 97              | 56      | 100     |
| Schuijf et al| 60 | 85             | 98              | 82      | 99      |
| Ong et al    | 134| 82             | 96              | 79      | 96      |
| Ehara et al  | 69 | 90             | 94              | 89      | 95      |
| Nikolaou et al| 72| 82             | 95              | 69      | 97      |
| Weustink et al| 77| 95             | 95              | 75      | 99      |
| Leber et al  | 88 | 94             | 99              | 81      | 99      |
| Total        | 824| 89             | 96              | 78      | 98      |

Schroeder et al. Eur Heart J 2008; 29: 531–56.6

N, number; PPV, positive predictive value; NPV, negative predictive value

Fig. 3  CT image of coronary arterial stenosis.

a) Curved MPR, b) Cross-sectional view: An eccentric plaque is present at the site marked with an arrow.

CT, computed tomography; MPR, multiplanar reconstruction
triphosphate (ATP) or adenosine) and myocardial staining in the early phase has recently become possible, and this CT perfusion has recently been investigated.11, 12)

As differences between myocardial blood flow information and morphological information of the coronary artery have been clarified, CT/SPECT fusion images have been increasingly used, in which evaluations of coronary arterial stenosis and the myocardial blood flow reserve estimated by SPECT were integrated (Fig. 5).13, 14) Myocardial SPECT is capable of collecting functional information, such as myocardial blood flow and metabolism, and extensive evidence concerning the diagnosis, judgment of treatment, prognosis, and course observation of ischemic heart disease has been accumulated. CT/SPECT fusion images share advantages of morphological and functional images, which is useful for the investigation of ischemic regions, evaluation of myocardial ischemia in each coronary arterial branch, and identification of the responsible blood vessel.

It was expected that CT provides information for coronary arterial wall evaluation, surpassing that provided by coronary angiography. The coronary arterial wall is evaluated based on the plaque properties and volume. Regarding the diagnosis of plaque properties, a study on comparison with intravascular ultrasound (IVUS) reported that CT values of 50 HU or lower and 50–120 HU indicated the dominance of lipids and fiber, respectively, and 120 or HU indicated calcification,15) which generated much expectation. However, the CT value of plaques varied due to the influence of the concentration in the coronary arterial lumen,16) and the prediction of unstable plaques based on the CT values became considered difficult. Later, a study reported that the risk of acute coronary syndrome (ACS) is high when the plaque is accompanied by all of the following 3 factors: a CT value of 30 HU or lower (low-density plaque), positive remodeling, and spotty calcification.17) A prospective study on whether or not the CT values of plaques serve as a predictor of vascular events is currently underway, and the results are anticipated. Regarding plaque volume evaluation, data showing a relatively strong correlation with IVUS have been reported,18) but further improvement of the accuracy may be necessary.

Problems of 64-slice CT are as follows: 1) poor image quality possibly from motion artifacts in patients with arrhythmia and a high heart rate, 2) incomplete presentation of the vascular lumen for the evaluation of stenosis when artifacts of calcification are present in many severely calcified lesions, 3) insufficient accuracy for routine use because of overestimated or underestimated plaque volumes,4) 4) dependence of CT values of plaques on those of the vascular lumens for diagnosing plaque properties, and 5) difficulty in the evaluation of stent lumen less than 3mm due to artifact. Coronary CT may be less useful than conventional coronary angiography for follow-up after PCT because the evaluation of thin stents is difficult. The improvement of spatial and temporal resolutions is expected to overcome these problems.

Fig. 4
a) Angiographic view, b) Coronary angiography.
Significant stenosis is observed in the right proximal coronary artery, showing a similar view to that on coronary angiography.
Positioning of Coronary CT in the Guidelines

There are several guidelines for the application of coronary CT. In Western countries, guidelines have been prepared since around 2006, and the clinical efficacy and validity of indications of cardiac CT and magnetic resonance (MR) have been discussed.6, 19–22) The guidelines for cardiac CT prepared by the Asian Society of Cardiovascular Imaging were established to correspond to the state in Asia.23) The Society of Cardiovascular Computed Tomography prepared guidelines concerning the test method and interpretation of images of cardiac CT, which did not include the indication or efficacy.24, 25)

In Japan, the Japan Circulation Society published the 2007–2008 joint study group report ‘Guidelines concerning noninvasive diagnostic methods of coronary arterial lesions’ in 2009,26) which contain most integrative contents, reviewing the following test methods and discussing their positions in the evaluation of coronary arterial lesions: 1) resting electrocardiography, 2) exercise electrocardiography, 3) echocardiography, 4) nuclear medical test of the heart, 5) coronary CT, and 6) cardiac MR. The positioning of coronary CT with regard to stable angina pectoris, acute coronary syndrome, and follow-up of PCI in these guidelines is introduced below.

1) Cases suspected to be stable angina pectoris

When patients with chest pain are first examined, the absence of unstable angina pectoris should be confirmed from the clinical symptoms. The possibility of coronary arterial disease is then assumed based on age, gender, and symptoms (Duke Database), and a decision on the diagnostic policy should be made. When the risk of coronary arterial disease is low, course observation is sufficient. When the risk is high, coronary angiography is applied. In cases other than these, noninvasive tests are performed, for which exercise electrocardiography is recommended because it is simple and cost-effective, and exercise tolerability and the prognosis can also be evaluated. Patients are classified into low-, intermediate-, and high-risk groups based on the findings (Fig. 6-1). When the patient cannot perform exercise or electrocardiographic diagnosis is impossible, cardiac CT or myocardial perfusion scintigraphy is directly performed (Fig. 6-2).

In the high-risk group, the possibility of having a coronary arterial disease is high, and it is difficult to rule out, even if no significant stenosis is detected by coronary CT. Thus, coronary angiography is immediately performed in many cases. Coronary CT may be useful to predict the no-reflow phenomenon and applicability of PCI in some cases even though they are being classified into the high-risk group.27, 28) For the low-risk group, the necessity of coronary CT is low because the prevalence of coronary arterial disease is low.

![CT/SPECT fusion image](image-url)

**Fig. 5** CT/SPECT fusion image.
SPECT images (a) were fused with cardiac CT images (b) to display a 3-dimensional image (c). The proximal circumflex branch shows 99% stenosis (c: white arrow), and reduced perfusion (→) in its distributed region can be readily perceived.
CT, computed tomography; SPECT, single-photon emission computed tomography
Fig. 6-1 Diagnostic tree of stable angina pectoris: When exercise is possible (for explanation, refer to the text).
Cited from Circulation Journal Vol.73. Supple. III, 2009, 1091–114.

Fig. 6-2 Diagnostic tree of stable angina pectoris: When exercise is not possible (for explanation, refer to the text).
Cited from Circulation Journal Vol.73. Supple. III, 2009, 1091–114.
For the intermediate-risk group or when judgment is impossible, myocardial perfusion scintigraphy or coronary CT is selected in consideration of the facility (such as sufficient experience in cardiac CT) and patient (such as iodine allergy and renal function) conditions. Since NVP of cardiac CT is high, when no significant stenosis is observed on cardiac CT, coronary arterial disease can be mostly ruled out, showing that coronary CT is sufficiently useful to examine this group. When coronary CT findings are normal, the probability of the presence of coronary arterial lesions is low, and course observation is sufficient. In contrast, when judgment by coronary CT is difficult (due to severe calcification and motion artifacts) or when a lesion indicating significant stenosis is present, it is important to investigate ischemia employing myocardial perfusion scintigraphy. Invasive coronary angiography is performed when severe ischemia requiring revascularization is predicted from the stenosis lesion.

2) Cases suspected to be acute coronary syndrome

Several studies reported a high diagnostic performance of 64-slice CT for acute coronary syndrome.29-34 The risk of acute coronary syndrome is stratified with clinical findings including the age and gender, past medical history, new electrocardiographic changes, and blood chemistry (myocardial markers, such as troponin). When the risk, i.e., the possibility of acute myocardial infarction, is judged to be high, these patients are first admitted to the intensive care unit, the performed coronary angiography and revascularization. For intermediate- and low-risk groups and cases in which acute coronary syndrome cannot be definitely diagnosed because of the absence of electrocardiographic and blood test abnormalities on admission, coronary CT early after arriving at the hospital has become considered useful for the early diagnosis or diagnosis by exclusion of acute coronary syndrome, by which invasive coronary angiography can be avoided. It is controversial for the low-risk group, but many physicians consider that coronary CT is useful for reliably ruling out acute coronary syndrome.

Invasive reperfusion therapy was established as acute-phase treatment of ST-segment elevated acute myocardial infarction, for which a rapid, accurate diagnosis is necessary, and not much time should be devoted to noninvasive imaging diagnosis. Coronary CT is not used as a rule because the decrease is definitely diagnosed by electrocardiography and echocardiography, followed by coronary angiography.

3) Follow-up after PCI

In Japan, coronary angiography is habitually performed 0.5–1 year after PCI at many facilities. The main purposes are 1) evaluation of the coronary arterial lumen at the treated site, and 2) evaluation of patency of the coronary artery stent.

Although there has been no report on the diagnostic CT results for coronary arterial lumens at sites treated with POBA, DCA, and rotablator, it may be appropriate to consider that the diagnostic performance of CT for these sites is similar to that for conventional significant coronary arterial stenosis lesions because no device is left in the site after treatment employing these techniques. Evaluation of rotablator-treated sites may be difficult due to residual calcification, even after treatment.

Generally, the stent lumen can be evaluated by coronary CT when the stent diameter is 3 mm or larger, but the appearance varies depending on the stent type and material, and various artifacts are likely to appear on CT of pulsating thin metal stents. In a study employing 64-slice CT, the lumen could be evaluated in about 60% of stents, and the sensitivity and specificity in the group in which the lumen could be evaluated were 86 and 98%, respectively.34 Evaluation was possible in 85% of stents with a diameter of 3 mm or larger, but only 26% of stents with a diameter smaller than 3 mm, for which CT is not indicated.39 Therefore, at present, the evaluation of stent patency by CT is limited.

4) Evaluation of bypass graft and its anastomosed site

CT is relatively useful for evaluation after coronary artery bypass grafting (Fig. 7). Evaluation items after grafting include graft patency and the presence or absence of stenosis of anastomosed sites and stenosis lesions in the native artery. In a meta-analysis of graft evaluations, the diagnostic sensitivity and specificity of occluded lesions were 97.6% and 98.5%, respectively, and evaluation was possible in 96% of grafts, while those of stenosis lesions were 88.7% and 97.4%, respectively, and evaluation was possible in 88% of grafts.35 In another meta-analysis, in which exclusion criteria was not set, the diagnostic performance of detecting graft patency (occlusion and stenosis) in 78%–100% of grafts were sensitivity, 97.6%; specificity, 96.7%; positive prediction rate, 92.7%; and negative prediction rate, 98.9%.36 These reports indicate that 64-slice CT is a useful modality for diagnosis of the patency of anastomosed regions entirely covering the graft.

Regarding evaluation of the native artery by CT, evaluation of the distal anastomosed site is difficult due to
the presence of a thin diameter in many cases. Moreover, many cases with complex lesions for which PCI is unsuccessful, complicating diabetes, multivessel lesions, and advanced atherosclerosis are included in CABG-treated cases, and these conditions make evaluation difficult. Ropers et al. reported that 9% of segments could not be evaluated, and the sensitivity and specificity were 86% and 76%, respectively, as the diagnostic performance for detecting significant stenosis lesions in the evaluable segment cases.\(^3\)\(^7\)\\

**Transition from Competition for Increasing the Number of Detector Rows to Radiation Dose Reduction**\\

After the appearance of 64-slice CT, competition for increasing the number of detector rows came to an end, and manufacturers began to compete to develop exposure-reducing techniques. Consciousness of exposure reduction is important. In addition to making efforts to avoid unnecessary tests, exposure in clinically significant tests should also be minimized. The exposure level in chest CT employed for conventional lung screening (non-electrocardiography-gated high-pitch helical scan) is about 7 mSv, whereas the attenuation level in cardiac CT employing the standard cardiac helical method (low-pitch electrocardiography-gated helical scan) reaches 13–15 mSv in men and 18–21 mSv in women.\(^3\)\(^8\) These are higher than in cardiac catheterization (3–6 mSv). The risk of X-ray attenuation-induced carcinogenesis in the mammary gland and lung is not negligible at these levels, and it is particularly problematic for young women, for which a dose-reducing acquisition method was developed (Fig. 8).

A method to reduce the radiation dose in systole, called ECG modulation, was initially developed (Fig. 8b).\(^3\)\(^9\) In this method, the systolic-phase radiation dose was decrease to about 20% compared with that of the

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**Fig. 7** CT images after CABG.\\
a) Volume-rendering image after CABG, b) Curved MPR image of RITA-LAD, c) Curved MPR image of LITA-4AV-4PD, d) Curved MPR image of GEA-4PD.\\
No stenosis or occlusion is present in any bypass.\\
CABG, coronary artery bypass graft; RITA-LAD, right internal thoracic artery-left anterior descending coronary artery; GEA-4PD, gastroepiploic artery-4 posterior descending artery
diastolic-phase, because the systolic phase data is not usually used; therefore, the dose of exposure was reduced by about 40%–59%. Later, a method involving X-ray irradiation only in mid-diastolic phase and data collection by repeating the axial scan (SnapShot Pulse method) was developed (Fig. 8c). The SnapShot Pulse method reduced the dose to about 1/3–1/4 because there is no irradiation in the cardiac phase excluding mid-diastolic phase.40) Application of this method is difficult for cases with a 70-bpm or higher heart rate, but stable, marked reduction of exposure is possible when the heart rate is 70-bpm or less. The active application of these methods by reducing the heart rate through the β-blocker administration is recommended.

In addition, a method called Adaptive Statistical Iterative Reconstruction (name varies between manufacturers) applying the concept of successive approximations has recently been developed, further promoting exposure reduction.41)

**POST-64-SLICE GENERATION CT**

After 2006, post-64-slice generation CT appeared, such as 320-row CT (Aquilion One, Toshiba), 256-row CT (Brilliance iCT, Philips), dual source CT (SOMATOM Definition, Siemens), and Gemstone CT (Discovery CT 750HD, GE). These aimed at increasing temporal and spatial resolutions; however, the new technique dual energy CT has now been introduced.

1) **Increase in temporal resolution and shortening of acquisition time**

Toshiba and Philips further increased the number of detector rows, but there was no extension of the previous attempt to increase the number of detector rows, and they were differently positioned, called area detector CT, to image the heart on a single rotation without helical acquisition. It is applicable for patients with arrhythmia and a high heart rate because the acquisition time is short, attracting attention. Since the entire heart is simultaneously imaged, it may be useful for CT perfusion. Toshiba performed an international joint study on CT perfusion, named Core 320, using Aquilion One. Brilliance iCT of Philips realized high-speed rotation (0.27 seconds) by adopting the air-bearing method.

Siemens achieved 83-msec temporal resolution by equipping 2 tubes with a rotation speed of 330 msec (SOMATOM Definition). A model with an increased rotation speed (280 msec) and temporal resolution (75 msec) has also been marketed (SOMATOM Definition Flash). In this model, the table movement speed was increased 12–30 times, and 2 pairs of X-ray tubes and detectors simultaneously collect data in 2 spiral tracks, through which high-pitch (pitch: 3:2) acquisition is possible. The entire heart is imaged within about 0.25 seconds, facilitating scan time and exposure reduction.

2) **IMPROVEMENT OF SPATIAL RESOLUTION**

The width of detector rows in the axial direction is 0.5–0.6 mm in current models of CT. Discovery CT 750HD, marketed by GE last year, is equipped with detectors in which the molecular structure of garnet was adopted for the scintillator. The response to X-rays was increased 100 times and afterglow was reduced to 1/4 in this garnet detector (Gemstone) compared to the previous detector. Using this detector, we can sample high-speed data, and, subsequently, the number of views can be increased to about 2.5 times of that on previous 64-row CT. The spatial resolution of the XY planes increases as the number of views increases. In our study, spatial resolution was increased by about 30%, and the diagnostic performance for stents with a 3-mm or smaller diameter was improved (Fig. 9).
3) Dual energy CT

In the dual energy method, images are acquired at 2 tube voltages (for example, 80 and 140 kV), not at the standard single tube voltage (for example, 120 kV). The CT value of substances varies depending on the tube voltage, and the rate of CT value change between the 2 tube voltages varies among substances. When CT value data at 2 tube voltages are available, the discrimination of substances, for example, iodine and calcification, is possible. Using the dual energy method, the separation of calcium (calcified plaque) from iodine (vascular lumen) is theoretically possible in blood vessels with difficulty in evaluating the stenosis rate due to severe calcification. If the stenosis rate of severely calcified lesions could be accurately determined employing the dual energy method, it would be very useful, leading to expansion of the indication of cardiac CT.

At present, dual source CT (Siemens) and garnet detector CT (GE) are capable of dual energy scanning, but only dual source CT is capable of electrocardiographic gating. It may be equipped with garnet detector CT (GE) in the coming year.

CONCLUSION

The progress of CT was outlined from the appearance of multislice CT, through to competition to increase the number of detector rows, dose reduction, and post 64-slice CT. We expect further progress in the reconstruction method, development of detectors, and reduction of exposure, facilitating that evaluation of diverse functions.

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Fig. 9 CT image of a stent with a diameter smaller than 3 mm.
Curved MPR image, CAG image.
a) The stent is imaged using a large number of views, and patency of the 2.5–3-mm stent lumen can be observed.
b) Patency was confirmed by CAG.
CT, computed tomography; MPR, multiplanar reconstruction; CAG, coronary angiography.
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