Noninvasive Detection of Coronary Artery Bypass Graft Patency by Intravenous Electron Beam Computed Tomographic Angiography

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SUMMARY

This study evaluates the usefulness of intravenous electron beam computed tomographic angiography (EBA) for the detection of coronary artery bypass graft patency in 43 patients (33 men and 10 women, mean age, 65 years) who had coronary artery bypass graft surgery. EBA was performed a few days before selective bypass graft angiography (SGA). Forty axial cross-sections of angiographic images of the heart were acquired consecutively by an electrocardiographic trigger signal at 40% of the RR interval, which corresponds to the end-systolic phase. EBA data were reconstructed as a three-dimensional shaded surface display of the heart and bypass grafts. Detectability of the patency of bypass grafts was evaluated, taking selective angiographic images of the bypass grafts as a gold standard. One hundred and nine grafts (96%) out of 114 grafts were subjected to evaluation: 37 grafts were left internal mammary artery grafts (LIMA), 7 were right internal mammary artery grafts (RIMA), 6 were gastroepiploic artery grafts (GEA), 7 were free gastroepiploic artery grafts with venous drainage (free-GEA), 7 were radial artery grafts (RAG), and 45 were saphenous vein grafts (SVG). The sensitivity, specificity, positive predictive value, negative predictive value, and accuracy of EBA were 98%, 100%, 100%, 91%, and 98%, respectively. EBA sampled at the end-systolic period was determined to be useful for the detection of coronary artery bypass graft patency and occlusion. (Jpn Heart J 2003; 44: 811-822)

Key words: Electron beam computed tomography, Coronary artery bypass grafting, Angiography

POSTOPERATIVE angina occurs with a frequency of 30% in the first year after coronary artery bypass graft (CABG) surgery.¹⁾ It may result from either graft occlusion, or progression of the atherosclerotic lesion of the native coronary

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arteries.²⁾ Graft occlusion is reported to occur in 10-30% of grafts in the first 1-2 years, and in 45-55% by 10-12 years after surgery.²⁻⁵⁾ Therefore, detection of graft patency or occlusion is principally important in diagnosing postoperative angina in detail as well as predicting the clinical course of patients. The gold standard for evaluating graft patency in CABG patients is selective bypass graft angiography (SGA). However, angiography is an invasive and costly procedure with some risks⁶⁾. Therefore, noninvasive modalities such as exercise electrocardiography,⁷⁾ exercise thallium scintigraphy,⁸⁾ exercise radionuclide angiography,⁹⁾ Doppler echocardiography,¹⁰⁾ and magnetic resonance imaging¹¹⁻¹⁴⁾ have been developed, but they have been evaluated as having limited usefulness due to low diagnostic accuracy.

As an alternative to these procedures, electron beam computed tomography (EBCT) has been recently reported to be promising for the imaging of the coronary arteries because of its high spatial and temporal resolution and ability to trigger image acquisition with the use of electrocardiographic signals. A multicenter study using planar tomographic imaging with EBCT attained fairly good diagnostic accuracy (the sensitivity, specificity, and accuracy of detecting graft patency were 93.4%, 88.9%, and 92.1%, respectively).¹⁵⁾ For the purpose of obtaining more detailed information to understand the anatomy and status of graft patency,¹⁶⁻¹⁸⁾ recent advances in EBA technology have offered the challenge of constructing a three-dimensional image of the cardiac surface with coronary vessels. In this technology, a series of image data should be sampled at a specified trigger-time point of the cardiac cycle for several heart beats. However, it has not been established whether the time point should be chosen at the end-diastolic^{16,17)} or end-systolic phase.¹⁸⁾ EBA images scanned at the former phase of the cardiac cycle are apt to be distorted by movement of the coronary arteries associated with cardiac contraction. In this study, we adopted the latter phase by referring to the recent paper¹⁹⁾ by Mao, *et al.* We evaluated the diagnostic accuracy of EBA for determining the patency of 114 coronary artery bypass grafts including not only saphenous vein grafts (SVG) and left internal mammary artery grafts (LIMA), but also right internal mammary artery grafts (RIMA), gastroepiploic artery grafts (GEA), free gastroepiploic artery grafts with venous drainage (free-GEA),²⁰⁾ and free radial artery grafts (RAG). We discuss the usefulness and limitations of this method.

METHODS

The study population consisted of 43 patients who had undergone CABG surgery and subsequent SGA. The mean age ($\pm$ standard deviation) of the patients was 65 ± 8 years (range, 40 to 77); there were 33 men and 10 women. EBA was

performed a few days before SGA. The average time from surgery to angiography was 2.6 ± 0.7 years (range, 1 month to 11 years).

There were a total of 114 grafts: 38 were LIMA, 8 were RIMA, 6 were GEA, 7 were free-GEA, 7 were RAG, and 48 were SVG. There were no composite grafts and no sequential grafts. Table I shows the types of bypass grafts and the sites of the bypass graft anastomoses. The patients had neither atrial fibrillation nor any contraindications for the administration of a contrast agent. Informed consent was obtained from each patient.

EBA: EBCT was obtained with an Imatron C-150 ultrafast computed tomographic scanner (Imatron, South San Francisco, California). The patients were positioned head first, scanned in the supine position, and shifted a few centimeters to the right side to adjust the field of view. To achieve vasodilation, sublingual nitroglycerin (0.3 mg) was administered to all patients, who were then asked to hold their breath at near maximal lung capacity for each scan. To determine the position of the heart, five cross-sectional images of the chest (slice thickness, 3 mm, 7 mm gap between slices; field of view, 15 cm; acquisition time, 100 ms) were acquired with the scanner in the single-slice mode, and the position of the table was adjusted. For EBA, 40 axial cross-sectional images of the heart were acquired in the single-slice mode in 100 ms after an electrocardiographic trigger signal was generated at 40% of the RR interval (end-systolic phase). The matrix size was 512×512 and the field of view was 15 cm (pixel size, 0.29×0.29 mm). In-plane resolution was seven line pairs per centimeter.²¹⁾ The slice thickness was 3 mm with table increments of 2 mm, to provide an overlap for optimal resolution of the bypass grafts and coronary arteries. Since the EBA range was limited to 8 cm, it was difficult to detect both LIMA and GEA. Therefore, we detected not LIMA but GEA because the number of cases with GEA grafts was small. The contrast agent (Iopamidol, 370 mg iodine/mL) was injected at a rate of 2 mL/sec. The rate of the contrast agent was increased to 4 mL/sec for only 5 seconds after

Table I. Characteristics of Bypass Graft Anastomosis

Grafts	LIMA	RIMA	GEA	free-GEA	RAG	SVG	Total
Number	38	8	6	7	7	48	114
Anastomosis							
to LAD	31	5	1	0	0	3	40
to RCA	0	1	5	6	3	17	32
to LCx	3	0	0	1	4	20	28
to diagonal branch	3	2	0	0	0	8	13
to high lateral branch	1	0	0	0	0	0	1

a delay of 23 seconds because the injected contrast agent was diluted by increased venous return in deep breathing. Imaging was commenced 30 seconds after the beginning of injection, and injection was stopped at the 20th image. The radiation dose was estimated to be less than 11 mSv.^{22,23)} The images were transferred to a workstation (Allegro, ISG Technologies, Toronto, Canada), and three-dimensional angiography was reconstructed. The number and course of bypass grafts were known to the investigators, but postprocessing was performed in a blinded fashion without knowledge of the angiography or the clinical condition of the patients. These data were rendered as a shaded surface display. As a general rule, the left appendage was excluded on an individual basis to allow better assessment of the proximal left coronary artery. Surgical clips were involved in the vessel lumens. Other structures (eg, pulmonary vessels and chest wall) were removed. An EBCT density of 80-100 Hounsfield units was chosen as the lower threshold so as to exclude the nonenhanced cardiac structure. Three-dimensional reconstructions were rendered interactively from at least six angles. The patency of each bypass graft was assessed from at least two angles, and patency or total occlusion was reported. Occlusion of bypass grafts was diagnosed if the grafts did not appear in the 3-dimensional reconstructions. In cases in which diagnosis by EBA was difficult, axial images of EBCT were used as a reference.

Coronary angiography and SGA: In all patients, coronary angiography and SGA were obtained in the standard fashion with more than 2 orthogonal views of each coronary artery and graft. Information about the number, location, and type of bypass graft (eg, saphenous, mammary, radial, native, or free gastroepiploic) was obtained from the surgical reports for all patients. SGA was analyzed using visual assessment by two experienced cardiologists unaware of the EBCT findings. Each bypass graft was assessed and reported as patent or total occlusion.

Statistical analysis: The ability of the EBA to correlate with angiographically confirmed bypass patency was evaluated by calculating the sensitivity, specificity, positive and negative predictive values, and accuracy using 2×2 contingency tables. Sensitivity was calculated as truly patent grafts/(truly patent grafts + falsely occluded grafts). Specificity was calculated as truly occluded grafts/(truly occluded grafts + falsely patent grafts). Positive predictive value was calculated as truly patent grafts/(truly patent grafts + falsely patent grafts). Negative predictive value was calculated as truly occluded grafts/(truly occluded grafts + falsely occluded grafts). Accuracy was calculated as (truly patent grafts + truly occluded grafts) / (truly patent grafts + falsely patent grafts + truly occluded grafts + falsely occluded grafts). The results of SGA served as a standard of reference.

Figure 1. A 64-year-old male patient with a patent anastomosis LIMA to LAD, and a patent RAG to posterior lateral branch.

A: EBA image taken (left anterior oblique projection with cranial angulation) showing patency of LIMA to LAD and RAG to posterior lateral branch. **B:** SGA image in the left anterior oblique projection with cranial angulation showing a patent LIMA to LAD anastomosis. **C:** SGA image in the left anterior oblique projection showing a patent RAG to posterior lateral branch anastomosis. **D:** EBA image in the right anterior oblique projection showing a patent LIMA to LAD anastomosis, and a patent free-GEA to RCA. **E:** SGA image in the right anterior oblique projection showing a patent free-GEA to RCA anastomosis.

RESULTS

EBCT examination was completed successfully without complications in all 43 patients. The scans were performed during a single breath-hold of 35 to 65 seconds in duration. With instruction, 38 patients (88%) were able to hold their breath throughout the scan. A total of 106 to 136 mL of contrast medium was used per patient. Figure 1A shows an example of EBA which succeeded in the visualization of patency of a double bypass graft (LIMA to LAD, and RAG to posterior lateral branch) anastomosis. EBA visualization of the two bypass grafts was confirmed by SGA as shown in Figure 1B and Figure 1C. Figure 1D shows another EBA image aiming to visualize the patency of free-GEA with venous drainage to RCA. The EBA visualization is limited to a middle portion of the graft in comparison with that of SGA (Figure 1E). The EBA image does not cover the complete length of the graft due to the limited spatial coverage. Figure 2 is an example of an unsuccessful EBA image of GEA to RCA anastomosis, in which a stenotic lesion was visualized as indicated. The flow of the GEA graft to RCA, appeared to be satisfactory based on the density of contrast medium along the graft, however, the existence of stenosis (arrow in Figure 2A) could not be excluded from the graft image. On the other hand, this bypass graft was proved to be patent by SGA alone (Figure 2B). Figure 3A shows a case with occluded LIMA to LAD and patent SVG to diagonal branch anastomoses were proved by SGA (Figure 3B, 3C). EBA did not visualize the LIMA, and also did not detect the diagonal branch because this branch was too small in diameter to be visualized by EBA (Figure 3A).

Figure 2. A 55-year-old man with a patent GEA to RCA. **A:** EBA image in the right anterior oblique projection with cranial angulation visualizing a patent, but highly stenotic GEA (arrow) to RCA anastomosis. By referring to the axial images, we recognized that the stenotic image was produced by the patient's motion. **B:** SGA image in the left anterior oblique projection with cranial angulation visualizing a fully patent GEA to RCA anastomosis.

Figure 3. A 70-year-old man with an occluded LIMA to LAD and a patent SVG to diagonal branch. **A:** EBA image taken in the left anterior oblique projection with cranial angulation showing an occluded LIMA to LAD anastomosis, and a patent SVG to diagonal branch anastomosis. Great cardiac vein is indicated by arrow. The diagonal branch is not shown because of the narrow diameter. **B:** SGA image in the right anterior oblique projection showing an occluded LIMA. **C:** SGA image in the left anterior oblique projection with cranial angulation showing a patent SVG to diagonal branch anastomosis. Diagonal branch is indicated by arrow.

Overall accuracy for bypass graft patency: We excluded 5 grafts from evaluation because their images were out of the range of 40 EBCT frames. A total of 109 grafts (37 LIMA, 7 RIMA, 6 GEA, 7 free-GEA, 7 RAG, and 45 SVG) were evaluated for occlusion or patency. All 45 vein grafts (100%) and 62 of 64 arterial grafts (97%) were successfully visualized on EBA images. The overall rate of success in EBA visualization of the patent bypass grafts attained 98%.

Diagnostic accuracy of patency or occlusion in 109 grafts was calculated (Table II). Bypass graft angiography revealed 89 patent grafts, 87 of which were identified as patent on EBA. One LIMA to LAD was incorrectly judged as occluded by EBA because of its narrow diameter measured as 1.1 mm by quantitative coronary angiography (Figures 4A, B, C). One RAG to LCx was incorrectly judged as occluded by EBA due to poor image quality, probably because the patient was physically well built. As for the 10 grafts which were diagnosed as occluded by SGA, EBA succeeded in diagnosing all of the cases as occluded.

Table II Comparison of SGA Diagnosis and EBA Visualization of Graft Patency or Occlusion

grafts	SGA diagnosis	EBA visualization		SGA diagnosis	EBA visualization	
	patent	yes	no (%)*	occluded	yes	no (%)*
LIMA	29	28	1 (97)	8	8	0 (100)
RIMA	6	6	0 (100)	1	1	0 (-)
GEA	5	5	0 (100)	1	1	0 (-)
free-GEA		7	0 (100)		0	0 (-)
RAG	7	6	1 (83)	0	0	0 (-)
SVG	35	35	0 (100)	10	10	0 (100)

* percentage of successful EBA visualization of graft patency or occlusion proved by SGA.

Figure 4. A 60-year-old man with a patent LIMA to LAD and a patent SVG to circumflex artery. **A:** EBA image in the left anterior oblique projection with cranial angulation showing an occluded LIMA to LAD anastomosis, and a patent SVG to circumflex artery anastomosis. **B:** SGA image in the right anterior oblique projection showing a patent LIMA. **C:** SGA image in the left anterior oblique projection with cranial angulation showing a patent SVG to circumflex artery anastomosis.

Table III shows the sensitivity, specificity, positive predictive value, negative predictive value, and diagnostic accuracy of EBA in diagnosing patent and occluded bypass grafts, dividing them into arterial and vein grafts groups. The sensitivity and specificity were 96 and 100% in the former group, thus providing

Table III. Diagnostic Accuracy of Electron Beam Computed Tomographic Angiography (EBA) on Patent and Occluded Coronary Bypass Grafts

	Arterial grafts (n = 64)	SVG (n = 45)	all (n = 109)
Sensitivity (%)	96	100	98
Specificity (%)	100	100	100
Positive predictive value (%)	100	100	100
Negative predictive value (%)	83	100	91
Accuracy (%)	97	100	98

a positive predictive value, negative predictive value, and accuracy of 100%, 83%, and 97%, respectively, whereas all the values were 100% in the latter group.

Thus, the overall sensitivity, specificity, positive predictive value, negative predictive value, and accuracy were 98%, 100%, 100%, 91%, and 98%, respectively.

DISCUSSION

Although the patency of coronary artery grafts can be assessed by several noninvasive methods,^{7-14, 23)} it has been generally accepted that EBCT is one of the best ways to detect graft patency. However, in the early stage of these studies, EBCT was only used as a tool for time-density curves of bypass grafts rather than to produce two- or three-dimensional images of the lumen of a coronary artery bypass graft.^{15, 24, 25)}

Achenbach, *et al* showed that the assessment of bypass graft patency using three-dimensional images (EBA) obtained with EBCT yielded an accuracy of 100% in 25 patients with 56 bypass grafts.¹⁶⁾ Ha, *et al* found the sensitivity and specificity of EBA in revealing LIMA patency were 80% and 82.4%, and the sensitivity and specificity of EBA in revealing SVG patency were 91.7% and 91.1%, respectively.¹⁷⁾ They attributed the difference in accuracy to the fact that LIMA grafts are smaller in diameter and more likely to have a significant number of surgical clips, which can produce beam-hardening and stellate artifacts that obscure the images. Their EBA was scanned at a trigger point of 80% of the RR interval. Scanning with such a delay in the diastolic period aimed to minimize the motion of the ventricles. But the atria are contracting at that time point, causing motion artifacts in the right coronary artery and left circumflex arteries.²⁶⁾ Therefore, Mao, *et al* recommend a 40-50% R-R interval as an electrocardiographic trigger time to minimize cardiac artery motion.¹⁹⁾ Hoshi, *et al*¹⁸⁾ reported that EBA triggered at 45% of the RR interval succeeded in diagnosing 42 of 44 arterial grafts and all 47 venous grafts as patent (sensitivity: 95%, 100%), and all 7 venous

grafts as occlusive (specificity: 100%). As a result, the overall sensitivity and specificity were calculated to be 98% and 88%, respectively. Our study triggered at 40% of the RR interval showed good diagnostic accuracy of EBA in revealing LIMA and SVG patency; the sensitivity and specificity of EBA in revealing LIMA patency were 97% and 100%, and the sensitivity and specificity of EBA in revealing SVG patency were 100% and 100%, respectively.

For better graft patency over the long term, there has been routine use of multiple arterial grafts for CABG.²⁷⁾ As *in situ* arterial grafts, GEA is secondary to the internal mammary artery.²⁸⁾ Moreover, RAG²⁹⁾ and free-GEA²⁰⁾ have been applied clinically. We investigated 43 patients with 114 coronary artery bypass grafts including LIMA, RIMA, GEA, RAG, and free-GEA by EBA. Although 5 of the 114 bypass grafts had to be excluded from evaluation, graft patency and occlusion were diagnosed with 98% accuracy.

Limitations: EBA and our method have several limitations. The current EBCT scanner model has limited spatial coverage during a single breath-hold and during the first pass of the contrast agent. Our EBA protocol called for a slice thickness of 3 mm with table increments of 2 mm following previous reports of intravenous CT coronary angiography³⁰⁻³²⁾ for the detection of stenoses. But we could not evaluate 5 grafts because the EBA range was limited to 8 cm. Achenbach, *et al* used a slice thickness of 3 mm with table increments of 3 mm, and the scan area resulted in a 12 cm slab.¹⁶⁾ Their protocol may be better than ours from the standpoint of scan area rather than actual detection of stenoses. Other limitations include motion artifacts caused by cardiac motion, respiratory motion, and poor electrocardiographic gating. In our protocol, however, motion artifacts might be fewer than in other studies because scans were triggered at 40% of the RR interval (end-systolic phase) in comparison to their scans that were triggered at 80% (end-diastolic phase). It is desirable that EBA is performed in patients with sinus rhythm for reduction of motion artifacts. Moreover, a partial volume effect, exposure to ionizing radiation, potential reactions to contrast agent, and the need for cannulation of the vein also could be disadvantageous for some patients.

There were four bypass grafts with angiographically high-grade stenoses; three grafts were LIMA to LAD, and one was RIMA to LAD. The former three grafts with angiographically high-grade stenoses were diagnosed as patent without high-grade stenosis by EBA. These errors may be attributed to image interference caused by reflection from the metallic vessel clips. Since larger numbers of metallic vessel clips are attached to internal mammary artery grafts than other grafts, such interference may occur more easily in LIMA and RIMA grafts. But the error could be prevented using volume rendering as a postprocessing technique.

The latest generation of multislice spiral computed tomography scanners can reconstruct images with a data acquisition window of 250 ms.³³⁾ Achenbach, *et al* reported that multislice spiral computed tomography with retrospectively ECG gated image reconstruction permits coronary artery stenoses but its clinical use may presently be limited due to degraded image quality in a substantial number of cases, mainly due to rapid coronary motion.³⁴⁾ Multislice spiral computed tomographic angiography will be applicable for the detection of patency of CABG.

In conclusion, EBA triggered at 40% of the RR interval is clinically useful for noninvasive direct detection of coronary artery bypass graft patency because of its high accuracy.

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