Coronary Artery Fly-Through Using Electron Beam Computed Tomography

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***Background*—**Virtual reality techniques have recently been introduced into clinical medicine. This study examines the possibility of coronary artery fly-through using a dataset obtained by noninvasive coronary angiography with contrast-enhanced electron-beam computed tomography.

***Methods and Results*—**Ten patients were examined, and 40 to 60 transaxial tomograms (thickness, 1.5 mm; in-plane pixel dimensions, ≈0.5×0.5 mm) were obtained after intravenous contrast injection. The datasets were processed on a graphics workstation using volume-rendering software. For fly-throughs, the contrast-enhanced lumen was made transparent and other tissue was made opaque. Then, key frames were selected in a path through the vessel, with software interpolation of frames between key frames. A typical movie contained 150 to 300 frames (10 to 15 key frames). Fly-throughs of coronary bypass grafts (n=3), left anterior descending arteries (LAD; n=6), and the intermediate branch (n=1) were reconstructed. Coronary calcifications were seen in 3 patients. The fly-through of the intermediate branch, the bypass grafts, and one of the LADs did not show any irregularities. In 2 cases, a stenosis was visible in the LAD; its presence was confirmed by conventional coronary angiography.

***Conclusions*—**Recent developments in fast-volume rendering using special-purpose hardware in combination with noninvasive coronary angiography with electron beam computed tomography have provided the possibility of performing coronary artery fly-throughs. **(*Circulation*. 2000;102:e6-e10.)**

Key Words: angiography ■ tomography, x-ray computed ■ computers ■ imaging

Coronary angiography is the standard way of visualizing the coronary arteries. However, this method is invasive and, in a few cases, the procedure is associated with complications and has a small risk of mortality. Therefore, noninvasive methods to visualize the coronary arteries are currently under investigation; these include MRI[1,2] and electron-beam computed tomography (EBT).[3,4] Coronary angiography depicts the coronary artery as a planar silhouette (lumenogram) and, therefore, only detects a stenosis if the plaque obstructs the lumen; it also provides no information on the vessel wall. Coronary artery fly-through is another way to provide a comprehensive delineation of the lumen and the impact of vessel wall disease on the lumen. Some examples of fly-throughs of the coronary arteries with calcifications and stenoses are shown in this article.

Methods

For this study, 10 patients were selected who had a noninvasive, contrast-enhanced EBT angiogram of adequate quality. The data acquisition was performed on an Evolution XP (Imatron) EBT scanner. The acquisition of the 3D dataset began with the injection of 120 to 180 mL of contrast medium at 3 to 4 mL/s through an antecubital vein. Scanning commenced just proximal to the left main coronary artery after an ECG trigger at 80% of the RR interval (diastasis). The tomogram (slice) thickness was set at 1.5 mm, and the table increment after each tomogram was set at 1.5 mm, which resulted in contiguous, nonoverlapping slices. A total of 40 to 60 transaxial tomograms were made during a single breath-hold. Breath-holding is necessary during data acquisition to avoid respiratory motion artifacts. Field-of-view size was generally set at 18 cm, with a matrix size of 512×512 pixels; this yielded a pixel size of 0.35×0.35 mm. The acquired data were then transferred to a special-purpose graphic workstation (Indigo2, Silicon Graphics, Inc) running VoxelView software (Vital Images) for volume rendering and processing.[5–8]

The volume dataset consisted of voxels (3D pixels), each of which had a certain value that was based on the tissue density value measured by the EBT scanner. Using these voxel values, several types of renderings can be performed. One of the possibilities is to construct a fly-through movie. A fly-through is similar in some ways to a flight-simulator. The surroundings in a flight-simulator are all virtually stored in a large computer database, and the image shown to the pilot is based on the position and direction of the virtual airplane in the virtual surroundings. By a fast and smooth replacement of the image of the virtual surroundings, the illusion of flying is created. In the case of a coronary artery fly-through, the surroundings are the scanned

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Figures I through III can be found at http://circ.ahajournals.org/cgi/content/full/102/1/DC1

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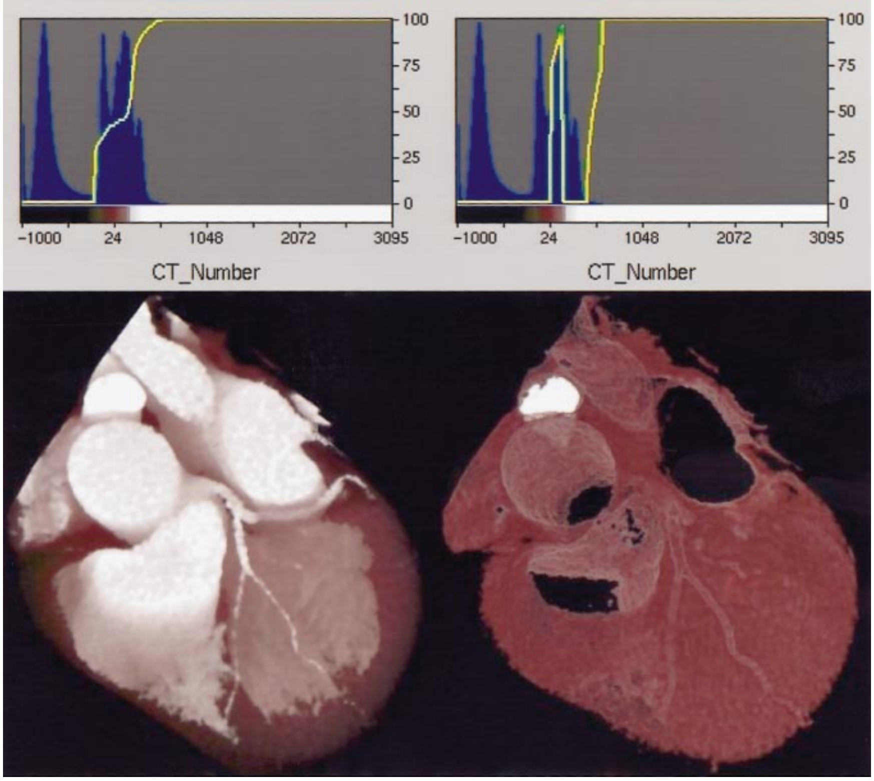

Figure 1. Top, these graphs contain 2 types of information. The histogram shows the distribution of the voxel values. The *x* axis represents the voxel value, and the *y* axis, the number of voxels with this value. The line graph shows the opacity value assigned to a certain voxel value. The *x* axis again represents the voxel value, and now the *y* axis shows the opacity percentage (low value is transparent; high value is opaque). The images on the bottom demonstrate the effect of a change in opacity setting. The bottom left image shows the typical opacity setting used to depict the contrast-rich blood in the lumen of the vessel (maximum opacification), which is not necessarily an optimal setting for the depiction of the coronary arteries. In this case, the soft tissue and fat (with a lower voxel value) are transparent, and the contrast-enhanced blood (with a higher voxel value) is fully opaque. On the bottom right, the opacity for the soft tissue and fat is high (small peak in the yellow curve), and the voxel values corresponding to contrast-enhanced blood are fully transparent. As can be appreciated from the image shown, this type of setting hollows out the vessels, which enables flying through.

data, and the airplane can be thought of as a camera mounted on the tip of a catheter. The images shown are based on the position and direction of this catheter in the coronary artery. By displaying images at consecutive positions along a certain path through the coronary (the flight path), the illusion of moving through this artery is created.

To make a fly-through movie like this, the vessels must be "hollowed out" by assigning voxels representing contrast-media–rich blood an opacity of zero (full transparency) (Figure 1). Next, the viewpoint is moved inside the aorta or coronary artery; this will be the first key frame. After this, a number of viewpoints can be selected, which are positioned along the flight path as key frames for the movie (typically 10 to 15 key frames are selected). These key frames and the desired number of frames to be interpolated between the key frames are fed into the VoxelAnimator software, which is used to render the movie. From this information, the software interpolates a curve through the defined key frames and renders the requested number of new frames between the key frames along this curve, which results in a 150- to 300-frame movie.

Results

The 3D EBT datasets of 39 patients were evaluated, with special attention paid to interslice correlation quality, lack of artifacts, and slice image quality. The best 10 datasets were selected for coronary artery fly-throughs. From these 10 patients, fly-through movies of coronary artery bypass grafts (n=3), the left anterior descending artery (LAD; n=6), and the intermediate branch (n=1) were constructed. Typical examples from a bypass (Figure 2 and Figure I [Figures I to III can be found online at http://circ.ahajournals.org/cgi/content/full/102/1/DC1]) and from the LAD (Figures 3 and 4 and Figures II and III) are shown. Coronary calcifications were visible in 3 patients (eg, Figure 4 and Figure III), and a significant stenosis, which was confirmed by conventional diagnostic coronary angiography, was depicted in 2 patients (eg, Figure 3 and Figure II).

Discussion

EBT coronary angiography has emerged as a potentially viable technique for noninvasive visualization of coronary arteries and coronary bypass grafts.[3,4] However, although the technique is reasonably robust, only 81% of the major coronary artery branches could be visualized with sufficient quality to assess patency, the presence of a severe stenosis, or total occlusion.[4] For the reconstruction of fly-through movies, the image quality of the 3D datasets must be perfect. Even small irregularities may hamper the successful construction of a coronary artery fly-through. Aquisition problems include the following. (1) Problems with breath-holding may reduce the continuation of a coronary artery from one slice to another. (2) Arrhythmia, or even a single premature complex, may lead to images that are triggered at a slightly different time in the heart cycle, resulting in a displacement of 1 to 2 mm of a single slice with respect to the other slices. This creates a discontinuation of the coronary arteries in 3D reconstructions. (3) Vessels with a diameter $<$1.75 mm (area, 5$\times$5 pixels) will not provide a smooth coronary fly-through. (4) Movement artifacts of the right coronary artery during the 100-ms image acquisition time hamper the construction of a fly-through movie of this artery.

In addition to these acquisition problems, the reconstruction of a coronary artery fly-through is very time-consuming; therefore, only the best quality datasets with a large vessel diameter were selected to undergo this proce-

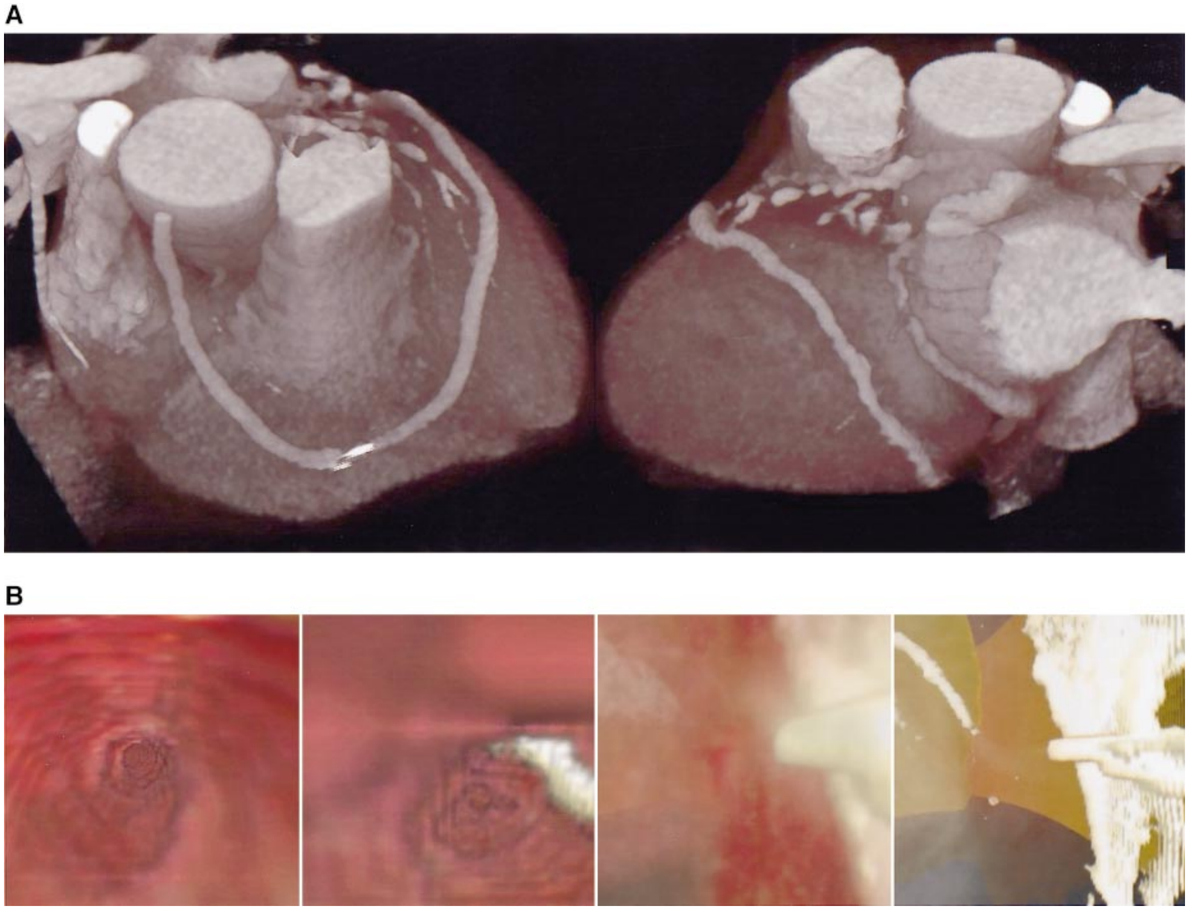

Figure 2. A, Volume renderings of a patient with a coronary artery bypass graft. The left image shows the artifact introduced by the segmentation of the sternum and sternal wires as a bright white portion of the bypass graft. Evaluating the patency of the graft at this particular point is difficult. B, When flying through the vessel, it is clear from the first 2 images that the graft is patent. However, a possible calcified region shows up in the second image. By setting the opacity curves slightly differently (third and fourth images), the walls disappear and it becomes clear that this is not a calcified plaque, but an artifact from the sternum and the sternal wires. The actual fly-through is shown in Figure I.

dure. For these reasons, a high-quality coronary artery fly-through was reconstructed in only 25% of the eligible patients. Much of the difficulties stated here can be overcome in the future by improvements in the spatial and temporal resolution of the EBT scanner. An update of the scanner is already available with a higher spatial resolution; this will increase the image quality and provide the possibility to display and fly-through smaller vessels. A reduction of slice acquisition time to below 100 ms will decrease the artifacts introduced by the movement of the right coronary artery. New scanning techniques that allow the acquisition of >1 slice during each heartbeat will shorten total scanning time and, thus, reduce the artifacts introduced by arrhythmias and breath-holding problems. Furthermore, the rapid development of both special-purpose rendering hardware and software will provide faster and more interactive ways to reconstruct fly-through movies.

Fly-through movies of venous bypass grafts are relatively easy to make because the vessel diameter is relatively large, and the cardiac motion of these vessels is limited. However, surgical clips or sternal wires may sometimes degrade the images because of the bright artifacts they cause (Figure 2 and Figure I). Calcifications of the vessel wall, which have a very high voxel value, are retained in the fly-throughs and are visible as white blobs floating in the artery (Figure 4 and Figure III).

These preliminary findings demonstrate the feasibility and potential of this method in coronary artery or bypass graft fly-through movies. The technique of coronary artery fly-through cannot be considered an alternative to traditional coronary angioscopy because it does not provide any information about the color of the lumen or its contents, such as plaque and thrombus. Coronary artery fly-through is an alternative way to evaluate noninvasive coronary angiography, and it has several advantages. (1) It provides a delineation of the "true" 3 dimensions of the vessel lumen, unlike diagnostic angiography (lumenography), which is limited by foreshortening and overlapping structures. (2) Fly-throughs may eliminate the time-consuming segmentation of overlapping, obscuring anatomical structures (left atrium, coronary sinus) that is needed to visualize the coronary arteries from the outside. (3) Fly-throughs may provide a more comprehensive delineation of bifurcation lesions or anastomoses of grafts on native vessels, which are sometimes difficult to asses, even with routine diagnostic angiography. Finally, fly-throughs may be helpful in assessing the remaining coronary lumen of a

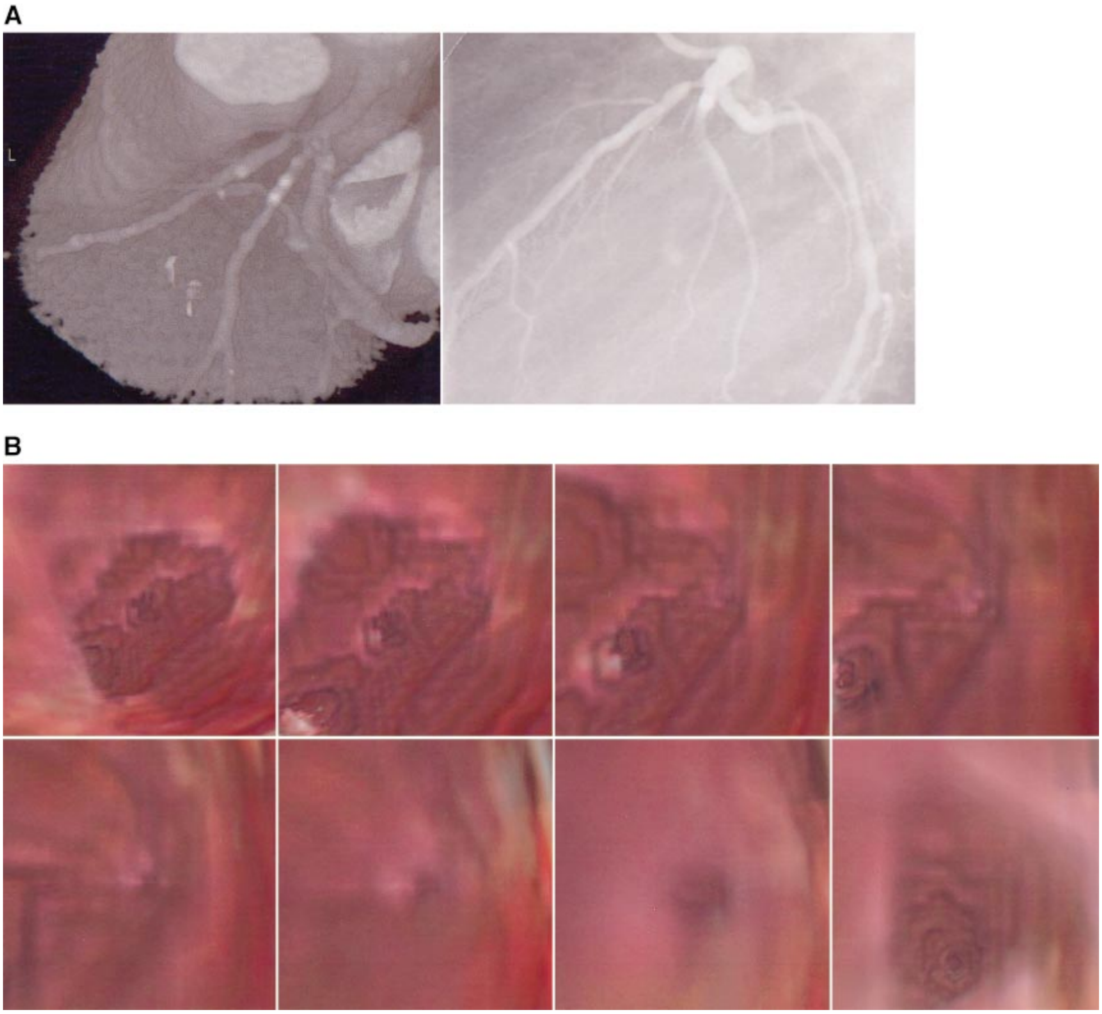

Figure 3. A, The left image shows a 3D volume rendering of the coronary arteries. The stenosis can be seen in the proximal part of the LAD right after the left main. This stenosis was confirmed using conventional coronary angiography shown on the right. B, Some interesting frames from the fly-through. The trifurcation through the lumen is approached in frames 1 through 6, and movement is toward the stenosed origin of the LAD. Frame 7 shows the stenosis in close-up and, in frame 8, the stenosis has been crossed and the remaining part of the LAD is seen. The actual fly-through is shown in Figure II.

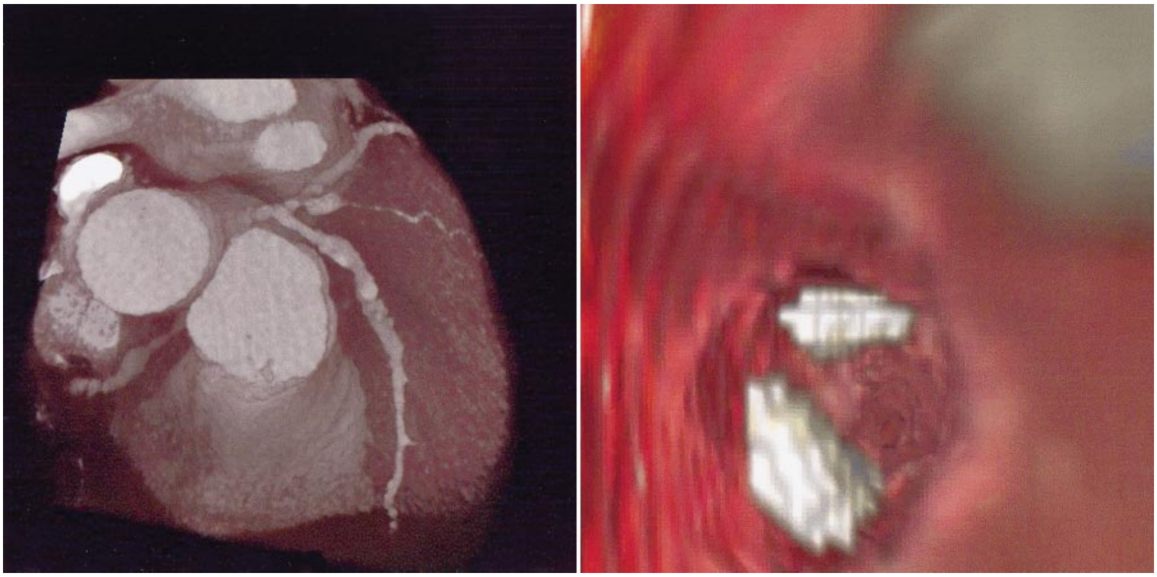

Figure 4. When flying through a calcified LAD, the calcifications show up as white blobs floating inside the vessel. In this case, 3 big calcifications were passed on the fly-through of the LAD. The actual fly-through is shown in Figure III.

heavily calcified coronary plaque or stented segment, which may be invisible with traditional EBT-derived 3D rendering techniques.

Conclusions

A fly-through of coronary arteries and venous bypass grafts is feasible in clinical practice and may represent a future diagnostic technique that will allow comprehensive 3D delineation of the vessel lumen.

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