2 Electron Beam CT of the Heart

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INTRODUCTION

Electron beam tomography (EBT)* was developed by Douglas Boyd, PhD, and his associates at Imatron, starting in 1977; the first clinical installation was at University of California at San Francisco in 1984. The challenge was to design a CT scanner capable of imaging the heart without motion artifacts; this required data acquisition times of 100 ms or less. In order to study perfusion, covering most of the heart without moving the patient table was also necessary. Acquisition times of 100 ms or less required a design with no moving parts except for the patient table. The result is EBT, where an electron beam generates the X-ray views needed for CT by sweeping across fixed targets.

Since 1983, through several models, EBT has been continuously improved in spatial resolution, temporal resolution, and software capability, and has been distributed worldwide. In addition to the original anatomy, wall motion, and perfusion applications, applications such as measurement of coronary calcium, CT coronary angiography, lung studies, and standard CT radiological examinations have been developed and introduced.

Unless otherwise stated, this article quotes specifications for the e-Speed™ model.

TECHNOLOGY

EBT eliminates moving parts in the X-ray generation system by employing an electron beam that sweeps around a fixed tungsten-coated target to generate a fan of X-rays. The detector is mounted in a fixed position above the target ring, providing a fourth generation (fixed detector, moving beam) CT design. Sufficient data to reconstruct an image can then be acquired in one sweep of the beam around the target, which in the current model of the scanner (e-Speed) can be as short as 33 ms. The speed and position of the beam and data acquisition system are under computer control, allowing flexibility in the choice of temporal resolution, spatial resolution, and X-ray signal.

The schematic shown in Fig. 1 is representative of an EBT system. The electron source accelerates electrons at potentials of up to 140 kV, producing a 1000-mA beam. Under high vacuum, the beam expands down a beam pipe until it reaches a group of magnets used to control and shape the beam. Two dipoles deflect the beam onto one of four fixed targets and sweep it along that target. A solenoid and two quadrupoles focus the beam and ensure a proper elliptical shape aligned so that the minor diameter of the ellipse is in the scan direction. The tungsten targets form a 210° arc and are backed by a water-cooling system, allowing at least 20 s of continuous scanning at full power without reaching thermal limits. X-rays are generated as the electrons strike the tungsten and are collimated into a thin fan that irradiates the patient. The entire beam system, from electron source to target ring, is under vacuum and can be considered a very large, water-cooled, stationary X-ray tube.

Reconstruction of a cross-sectional image from CT data requires that at least one ray in every direction pass through each pixel; a ray connects a source point and a detector (180° plus the X-ray fan angle). Current EBT geometry meets this requirement with a 216° detector and a 210° target, providing a 47.5-cm central region for imaging.

X-rays from any of the four targets can reach the dual slice detector. If the targets are used in series, 76 mm of a patient can be seen without moving the patient. Brass collimation rings minimize the number of X-rays that could pass through the patient but not strike a detector. Collimation and detector size give dual 7-mm slices with any of the targets. For narrower slices, one target is used, and an additional collimator is employed to limit the X-ray beam to dual 1.5-, single 3-, or dual 3-mm slices as measured at the isocenter. This additional collimation is also prepatient, to give maximum dose utilization. During image reconstruction, the data for dual 1.5-mm slices can be combined to make a single 3-mm slice, and the data for dual 3-mm slices can be combined to make a single 6-mm slice.

As in any CT scanner, X-rays are detected and digitized by solid-state detectors. Special EBT challenges are the high data rates and short integration times necessary to acquire sufficient data for an image in 33 ms or less.

Reconstruction of these images requires that the data be corrected for beam hardening, beam and detector position, scattered X-rays, and incoming flux. The result is a cross-sectional CT image with very high temporal resolution and high spatial resolution.

A single sweep is the passage of the electron beam along a target from beginning to end (210°), producing sufficient data to reconstruct an image. Most sweeps used for imaging move at constant angular velocity. A reset lasting 4–6 ms, during which no X-rays are generated, brings the beam back to the

*Also referred to as EBCT in the published literature.

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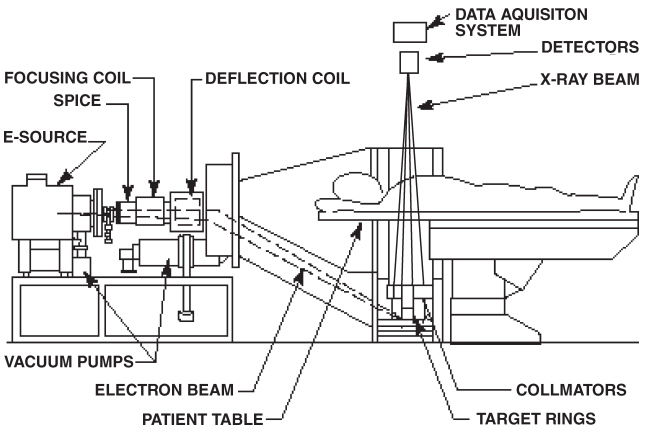

Fig. 1. Electron beam CT schematic.

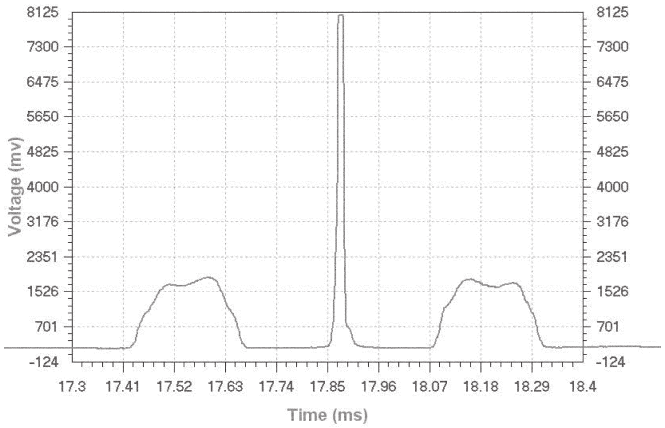

Fig. 2. Typical W wire signal.

starting position for the next sweep. If the next sweep does not immediately follow the preceding sweep, the beam is either turned off or deflected to a beam stop downstream of the deflection coils, where it continues to move until the next sweep is commanded. Because of its high power, the electron beam can never be allowed to stop on the target without damaging the target. Protections against such damage are built into the hardware and software controlling the scanner.

The geometry of the electron source requires the perveance, defined as $V^{1.5}/I$, to be a constant; there is only one mA value for a given kV setting. Thus, an e$^-$Speed with nominally 1000 mA at 140 kV has 895 mA at 130 kV.

EBT calibration and data correction involve scanning of air to get incoming flux, measurement of water to set the CT number of water to 0, and correction of beam hardening and scattering to ensure uniformity of CT numbers in imaging of an organ or object with constant density.

An additional EBT calibration is tuning, which is used to determine with high precision both the exact location of the beam with time, and the size, shape, and orientation of the beam spot. The beam condition at any given time is controlled by a sequence of coil currents vs time given to the magnets that steer and shape the beam.

An EBT scanner has a fifth target, located beyond those used for patient studies; a series of three-wire bundles in a W shape are located in front of this target. As the beam sweeps over this target and crosses one of the W wires, the location of the peak on the central wire gives the time of the beam with respect to data acquisition; the width of the peak on the central wire gives the beam spot width; the shape and similarity of the pulses from the angled side wires give the orientation of the elliptical beam spot and its length; the distance between the side peaks is related to the beam radius from isocenter. An example of a W wire signal is shown in Fig. 2.

The first part of tuning consists of adjusting the coil currents in time to give the desired parameters. Using equations that characterize the coil currents as a function of deflection angle, the tuned values are transferred to the sweep descriptions that will be used for scanning on the X-ray targets. The second part of tuning is a scan, with the transformed coil current values, of a phantom containing a set of pins. Analysis of the raw data from the pin scans gives the reconstruction system the location of the beam corresponding to the data as acquired, enabling interpolation of the raw data to the positions required by the reconstruction algorithm.

Control of the scanner requires numerous computers networked together, dealing with control of the beam, collimation, table, power supply, data acquisition, reconstruction, and operator interaction.

SCAN MODES

Standard sweep speeds with the e$^-$Speed are 33 ms, 50 ms, and 100 ms. Scan modes consist of different combinations of a series of sweeps on one or more targets, with patient-table motion or with no patient-table motion, and/or with an electrocardiogram (ECG) or timed trigger. If the patient table is not programmed to move while a sweep is being executed, the result is an axial scan mode. Axial scans, triggered from an ECG signal, are typical for cardiac studies. If the patient table moves while the X-rays are on, the result is a continuous volume scan, analogous to a spiral or helical scan with a mechanical CT. Continuous volume modes are typically used for CT angiographic studies of the great vessels, for example.

An external ECG monitor generates triggers at the R wave. Sweeps begin at a user-specified time after the R wave, which can be set either as a time interval in seconds or as a percentage of the RR interval. If triggering is based on percentages, the time is estimated from the previous seven heart RR intervals and thus adapts to changes in the heart rate. Extensive clinical studies *(1)* show, for an EBT scanner with its high temporal resolution, that the point in the RR interval with minimum motion is about 300 ms after the R wave, near the end of the T wave. Since the length of systole (starting at the R wave) tends to be more constant with heart-rate change than the length of diastole, triggering at the end of the T wave (end systole) seems to have fewer problems with irregular heart rates than does triggering by percentage of the RR interval.

EBT scanners use prospective triggering. Before the scan begins, a point (or points) in the heart cycle is chosen for the sweep to occur, and only those data are acquired and recon-

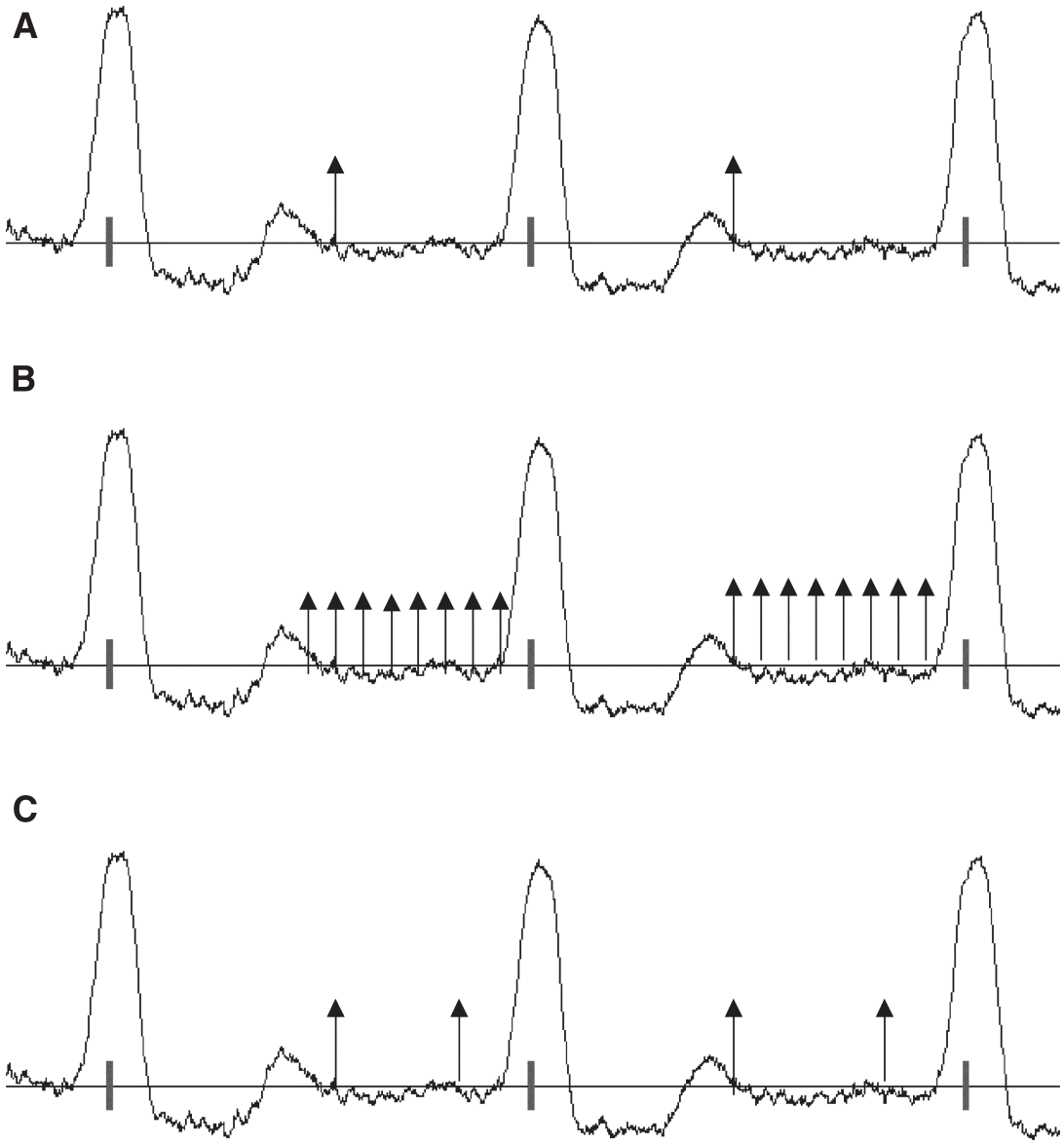

Fig. 3. (A) ECG trace—single trigger at end systole (represented by ↑). **(B)** ECG trace—triggering eight phases of the heart. (**C**) ECG trace—triggering at two positions within the heart cycle.

structed. Therefore, all exposure of the patient contributes to the study images; high temporal resolution and accurate triggering algorithms make this both feasible and efficient.

The simplest ECG-triggered scan mode has one sweep after the trigger at a prespecified time after the R wave; patient-table motion is after the sweep, so the patient table is at rest in the new position in time for the next scan. This is the scan mode used for a coronary calcium study or for an electron beam angiography (EBA) study (contrast in the arteries) with dual 1.5-mm, single 3-mm, or dual 3-mm collimation. Table increment is usually equal to the collimation, although smaller increments giving overlapping images are used in some cases.

Instead of just one sweep after the trigger, more than one sweep can be used, with each sweep immediately following its predecessor. The patient table moves to its next position after the set number of sweeps has been performed. This allows studies of the heart at multiple phases in the same study time as a single-phase study, and allows the clinician to appreciate changes in the heart over the heart cycle. Multiple phases is a cine mode including patient-table motion, and is used with all collimations. The high temporal resolution gives minimal motion artifact at any phase.

A further generalization of this mode allows the user to position sweeps at any point throughout the heart cycle. For example, this might be used to scan at approximately end systole and end diastole to obtain a measurement of ejection fraction.

Figure 3 shows a representative ECG trace with several possible triggering modes indicated.

For any ECG-triggered mode with patient-table motion, if the time required for the number of sweeps requested plus the patient-table motion is less than the RR interval, the table is positioned for the next location when the time to start the next

Table 1
Selected Specifications

Specification	*C150*	*C300 / C150 High Resolution*	*e⁻Speed*
Sweep speeds-thin slices	100 ms	100 ms	33, 50, and 100 ms
Sweep speeds-multitarget	50 ms	50 ms	33, 50, and 100 ms
Thin slice collimation	1.5, 3, and 6 mm	1.5, 3, and 6 mm	dual 1.5 mm, single 3 mm, dual 3 mm
Multitarget collimation	dual 7 mm	dual 7 mm	dual 7 mm
In-plane spatial resolution	7 line pairs (lp)/cm (100 ms)	9.5 lp/cm (100 ms)	10 lp/cm (50 ms) 13 + lp/cm (100 ms) 7 lp/cm (33 ms)
Power	83 kW (130 kV, 625 mA)	83 kW (130 kV, 625 mA)	140 kW (140 kV, 1000 mA) 116 kW (130 kV, 895 mA)
Trigger times (%RR)	40–80 (all) 0 (50 ms only)	40–80 (all) 0 (50 ms only)	0–99 (all)
Trigger times (seconds after R)	0.273–0.999	0.273–0.999	0.060–1.500

set of sweeps arrives; if the patient table is not in place for the next heart cycle, one heart cycle is skipped.

A multitarget cine study, typically covering the entire heart cycle, can also be performed. Sweeps every 33, 50, or 100 ms from the first target cover the time between first and second R waves; the second target is used to cover the third to fourth R-wave interval, the third target with the fifth to sixth R-wave interval, and the last target with the seventh to eighth R-wave interval. If more coverage is needed, the patient table is then moved 40 mm or more and additional scans taken.

A flow study is used to follow a bolus of contrast. One or more sweeps is taken each heart cycle without patient-table motion. If all four targets are used, then one sweep is taken on each of the targets during one heart cycle, allowing the measurement of perfusion over 76 mm of the body using the same contrast bolus. Some heart cycles are usually skipped to sample the bolus curve but minimize dose. This is the standard mode for the measurement of myocardial perfusion.

All of these modes can be triggered manually or by time instead of by ECG; however, cardiac studies are almost always ECG-triggered.

If the table moves while the beam sweeps continually, the result is a continuous volume scan, similar to a helical or spiral scan with a mechanical CT. Data can be acquired with any of the available collimations. Images are reconstructed at any location along the scan; the slice width in the image is determined from the collimation and the table travel corresponding to the sweeps included in the reconstruction. As an EBT scanner has a fixed mA for a given kV, in order to change the exposure in an image without changing the slice width, the speed of the patient table must also change. For example, in a study using 3-mm collimation and reconstructing a 3-mm slice, twice the exposure in the 3-mm slice requires the patient table to move half as fast.

A continuous volume scan is the normal scan mode for studying the noncardiac vessels, the lungs, abdomen, or any other organ not requiring ECG triggering. Of course, the axial modes described previously with a timed or manual trigger may also be used; however, the study time is longer than with continuous volume scanning but without patient-table motion during data acquisition.

A PreView™ (General Electric, formerly Imatron) (scout or localization scan) is created using a special sweep while the patient table moves continuously. The beam is swept very rapidly along the tuning target; near three o'clock and again near six o'clock, the beam moves onto the X-ray target for a short arc at the slower 50-ms speed. X-rays reaching the patient are generated only when the beam is on the X-ray target. A transmission image is synthesized from the source points along these arcs, giving views in both anterior/posterior and lateral directions. From these views the user not only can set the location in the patient direction to start and stop acquiring data, but also can set the center point and field of view for the reconstructed images in the studies to follow. Because PreView images are made from a number of source positions through a process of tomosynthesis, the plane of focus can be changed from the default value of the isocenter, or multiple planes can be computed and viewed. The depth of field is sufficiently large that isocenter is normally chosen.

IMAGE QUALITY

EBT is designed for high temporal resolution: 33, 50, or 100 ms in a single image without requiring data from more than one heart cycle. This temporal resolution is short enough that images can be acquired at any point in the heart cycle with no or almost no motion artifact.

Maximum in-plane resolution ranges from 7 line pairs (lp)/cm at 33 ms to 13 lp/cm at 100 ms. An extensive set of reconstruction kernels allow the optimization of resolution to the clinical study being performed. Narrowest slices are 1.5 mm. Because the arteries are typically moving from 20 to 100 mm/sec *(2)*, resolving the arteries clearly requires a high temporal resolution imaging system.

SPECIFICATIONS

As of this writing there are three EBT models in clinical use: C150, C300, and e⁻Speed. Some critical parameters such as sweep speed, slice width, and resolution are summarized in Table 1.

DOSE

As an EBT scanner irradiates a patient over a 210° arc (essentially from two o'clock to ten o'clock), dose near the surface of the patient is not uniform. For a patient lying supine, dose is a factor of five lower anterior than it is posterior. The result is that dose to the breast is minimized during a cardiac examination.

Prospective triggering also means that a patient receives only the dose necessary for the images desired for the study. The user can choose to acquire data over the entire heart cycle or over only a part of it, and the scanner acquires just those data.

Table 2 gives the CT dose index (CTDI) *(3)* information for a scan that would be typical of a calcium or coronary angiographic single-phase study for an EBT scanner, as well as an estimate of the effective dose (E) if the entire heart is covered. The 32-cm body CTDI is quoted with a 3-mm slice (or dual 1.5-mm with e-Speed) and a single sweep. The CTDI as defined is an estimate of the single-slice dose taking into account the tails of the dose profiles from the adjacent slices. E is estimated *(4)* by multiplying the CTDIvol (weighted CTDI adjusted for table speed) times the distance covered (which is the dose-length product) × 0.017.

Table 2
Dose Information

Parameter	*C150/C300*	*e-Speed*
CT dose index (CTDI) at A (center)	1.8 mGy	1.9 mGy
CTDI at B (12 o'clock)	1.2 mGy	1.2 mGy
CTDI at C (6 o'clock)	7.9 mGy	6.3 mGy
CTDI at D,E (3 or 9 o-clock)	5.6 mGy	5.1 mGy
CTDIw (weighted average)	3.7 mGy	3.6 mGy
Typical cardiac studies covering entire heart with one sweep each heart cycle:		
kV	130	140
mA	625	1000
Sweep time	100 ms	50 ms
Collimation	3 mm	3 mm
Table increment/heart cycle	3 mm	3 mm
Effective dose	0.7 mSv	0.7 mSv
Sweep time	100 ms	50 ms
Collimation	1.5 mm	dual 1.5 mm
Table increment/heart cycle	1.5 mm	3 mm
Effective dose	1.4 mSv	0.7 mSv

TYPICAL APPLICATIONS

Typical cardiac studies with EBT include coronary calcium *(5)*, EBA of the coronary arteries *(6,7)*, cardiac anatomy *(8)*, wall motion studies *(9)*, and perfusion studies *(10)*. EBT scanners are also excellent vehicles for CT angiography of the noncardiac vessels, as well as for lung studies *(11)* . The references given are to published studies as examples; no attempt has been made to make this a complete bibliography. Figure 4 is an example of an axial image showing coronary calcium; Fig. 5 shows a 3D volume rendering of an EBA study, and Fig. 6 shows a maximum intensity projection image of the same data set.

Studies of coronary calcium use an ECG-triggered axial mode with one phase/heart cycle. Most recently the preferred trigger point is near end systole, a time of minimum motion of the right coronary *(1)* with a 3-mm slice, 130 kV, and no contrast. Historically, most coronary calcium scanning has been done with triggering either near 80% or more recently near 40% of the RR interval. All EBT scanner models have a calcium scanning mode that matches slice width, reconstruction parameters, and kV to the early data on C100/C150, so that the Agatston *(12)* score for calcium is independent of EBT model; thus, historical data can be used for clinical comparison. Other scoring methods such as volume score *(13)* and mass score *(14)* have been proposed and implemented that may be more independent of the scan mode.

Coronary angiographic studies (electron beam angiography, or EBA) use ECG-triggered axial modes with one or more phase/heart cycle and intravenous contrast injection. If a single phase is used, then the scanner is triggered at the point of minimum motion; if multiple phases are being used, then the point of minimum motion is usually included as one of the phases.

In order to optimize the contrast, circulation time is determined before an EBA study, using a short bolus of contrast and a flow study looking at a given level. Typically a scan is triggered at the start of contrast injection (for a baseline value without contrast); some 6–10 heart cycles later a sequence of one sweep every other heart cycle begins through the expected peak of the contrast (18 s or so) followed by a sweep every 3 heart cycles or so to follow the contrast wash out. The circulation time (the time between injection and arrival at the coronary arteries) is then determined from the change in the CT number in the aorta or left ventricle with time. EBA data acquisition starts after a delay from the start of injection that is approximately equal to the circulation time. If the circulation time study uses all four targets and the dual 7-mm collimation, it becomes a perfusion study.

The length of the EBA injection should be approximately equal to the time required to complete the series, estimated from the distance to cover (which when divided by the table increment gives the number of heart cycles needed) and the starting heart rate. For most patients, the heart rate will increase during the study. Optimization of the contrast is very important; in addition to correct circulation time and injection duration, it may involve a saline chaser and variation of the contrast flow rate during the injection. The best studies come with the contrast signal uniform in time and the ratio of the average CT number of the contrasted vessels to the X-ray noise in the images as large as possible.

Most EBA studies are analyzed on a workstation making use of reformats, maximum intensity projections, and volume renderings to appreciate the details of the arteries. Multiple-phase EBAs make arterial motion obvious, although any individual phase can be analyzed. Clinical evaluation of the data frequently includes observing 2D and 3D renderings "beat" as the display cycles through the phases. With an appropriate choice of scan parameters, the study may cover a sufficient portion of the heart cycle to allow the estimation of ejection fraction. Valve motion can also be visualized.

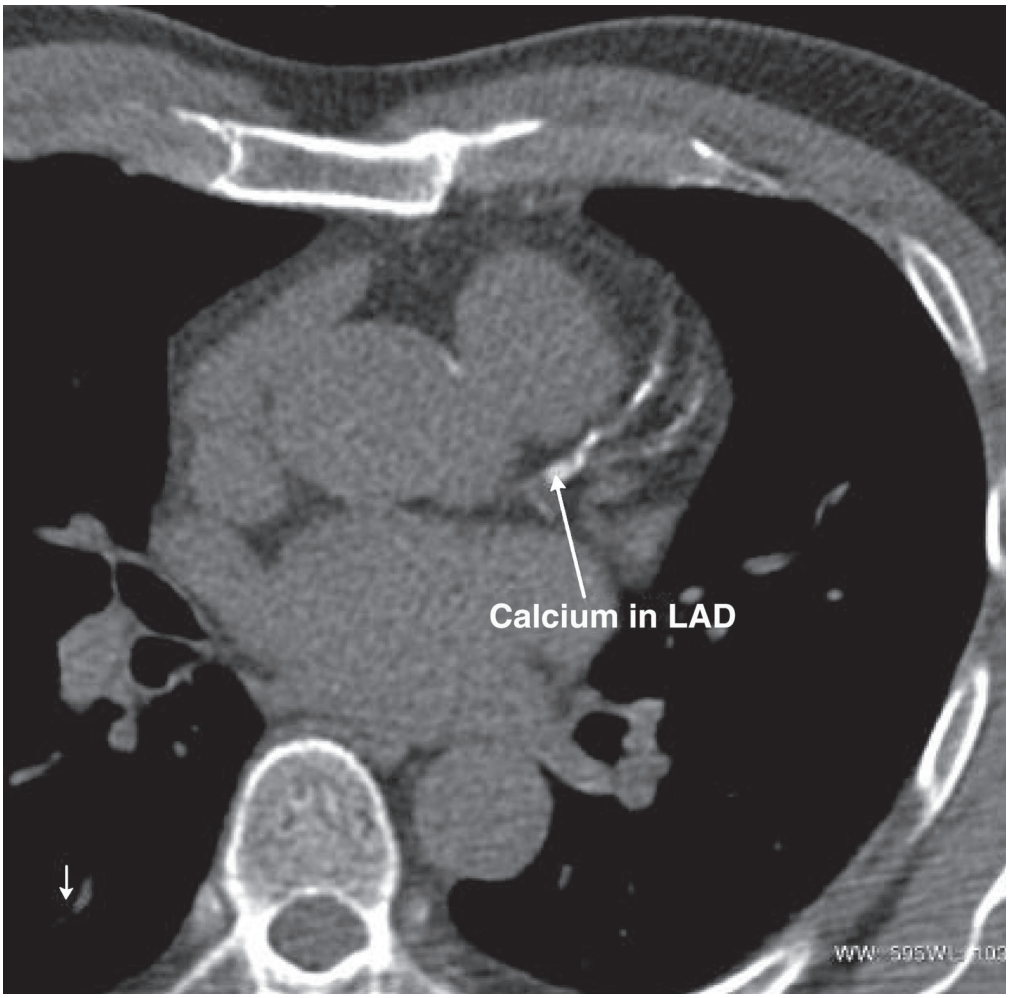

Fig. 4. Calcium example; 3-mm slice; 130 kV; 895 mA; 50 ms.

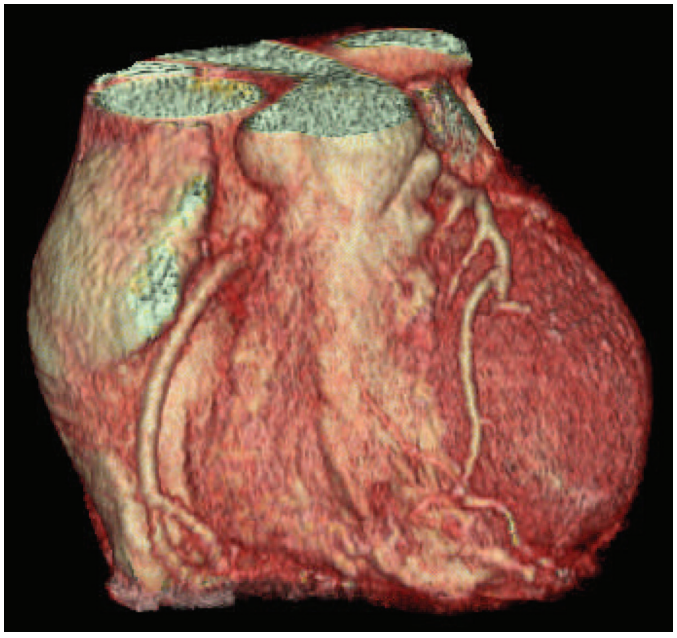

Fig. 5. Three-dimensional rendering of an electron beam angiography study; dual 1.5-mm slice; 140 kV; 1000 mA; 50 ms.

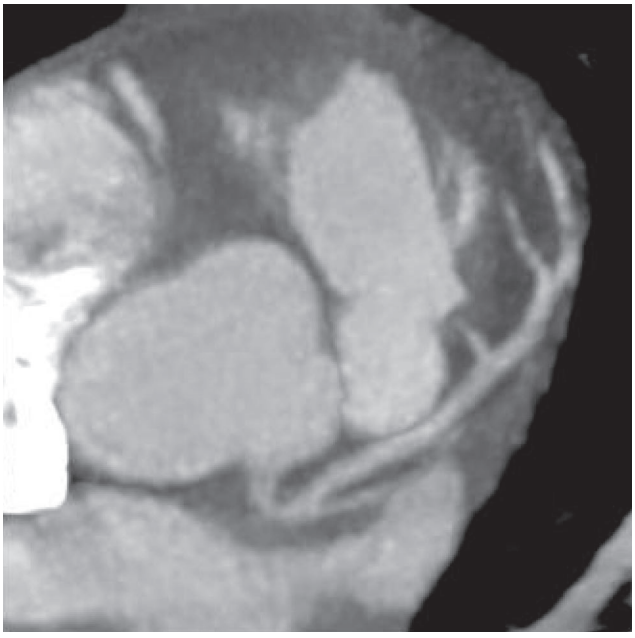

Fig. 6. Maximum intensity projection image of left anterior descending artery; same data set as Fig. 5.

Sufficient cardiac functional information is often gathered from a multiphase study. In addition, there are two ways to perform a dedicated wall-motion or function study. One is essentially an EBA using dual 7-mm collimation covering the entire heart cycle, with a 15-mm patient-table motion every other heart cycle. An alternative, avoiding patient-table motion, is to move the beam sequentially through the different targets instead of moving the patient table.

A perfusion study is a circulation time study with 76-mm coverage, using all four targets and the dual 7-mm collimation. This mode allows the measurement of perfusion throughout the myocardium using one bolus of contrast. There are three gaps of approx 5 mm each (between the targets) that are not fully illuminated.

A complete EBCT cardiac exam consists of a PreView for localization, a calcium study, a flow study used for both perfusion and circulation time determination, a multiphase EBA, and possibly a wall-motion study using residual contrast from the EBA.

The EBCT patient table can tilt 25° and slew ±25° (side to side in the horizontal plane). Tilt and slew allow the acquisition of wall-motion or perfusion data in approximately the short axis position (tilt 15°, slew –15° to –25°) or the long axis position (tilt 0°, slew +25°), approximating traditional cardiac views.

Continuous volume is the mode of choice to analyze the noncardiac vessels, yielding clear motion-free images. For example, using on the e$^-$Speed dual 1.5-mm collimation , 50-ms sweeps, and a 3-mm table increment, the patient table moves at 54 mm/s, allowing most areas of interest to be covered in 10 s or less.

FUTURE DIRECTIONS

EBCT scanners are designed for excellent cardiac imaging. There is no inherent limit on how fast an EBCT scanner can sweep the beam, as there are no moving parts, so sweep times can become even shorter, improving temporal resolution. Potential temporal resolution is limited only by available X-ray power (signal-to-noise in the images) and data acquisition speeds. Future directions are likely to include using a detector with smaller elements for thinner slices, as well as increasing the number of detectors in the patient direction for increased coverage with each sweep. As cardiac imaging continues to grow in clinical importance, EBT is an ideal modality for improved applications and efficient usage.

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