Dynamic Cardiopulmonary Imaging by X-ray CT: A View to the Future

Douglas P. Boyd, Ph.D.
Imatron Inc., 389 Oyster Point Blvd. So. San Francisco, CA 94080

ABSTRACT

Electron Beam Tomography offers a fast method to acquire large numbers of X-ray CT slices. Scanning is performed by sweeping an electron beam over a curved tungsten ring that encompasses the body and serves as a high speed X-ray source. This technology is now in use in more than 100 hospital and clinics and has enabled a number of important new diagnostic applications, especially for 3D imaging of organs and structures that are moving. This paper will describe recent results in chest imaging applications, coronary artery imaging, and 4D-imaging of cardiopulmonary structures. The technology is under continuous development and will lead to future machines with higher 3D and 4D resolution and speed.

Keywords: Electron Beam Tomography, EBT, Electron Beam Computed Tomography, EBCT, Ultrafast CT

1. INTRODUCTION

X-ray CT offers a unique capability for 3 and 4-dimensional imaging of the cardiopulmonary system at rest and in motion. The latest mechanical CT scanners use a helical (spiral) technique to acquire cross section slice images of the body at speeds of up to 3 per second. The best temporal resolution is less than this (~600 msec) due to the requirement of spiral interpolation. Although the improvements in speed and coverage of the newest Helical CT scanners have been introduced, Helical CT speed is still insufficient to overcome motion artifacts introduced by cardiac motion when imaging in the chest.

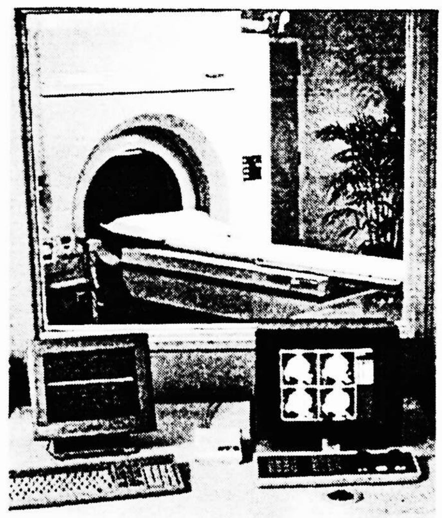

Figure 1. Photograph of a hospital EBT scanner facility.

In recent years a new technique of fast X-ray CT scanning known as Electron Beam Tomography (EBT) has been developed[1]. EBT produces an X-ray CT scan without mechanical motion using a scanning electron beam. In the high-resolution mode of EBT temporal resolution is 100 msec and speed is 9 scans/sec to a maximum of 140 scans in 15 seconds. In a lower resolution mode dual-slices are acquired in 50 msec at a rate of 34 slices/second to a maximum of 160 slices in 5 seconds. The higher speed of EBT scanning has enabled a number of new applications in the cardiopulmonary system that are not feasible with slower scanners. The EBT technique is scalable to even faster speeds using future area detector array technology. Some examples of the present unique applications of EBT are described below:

2. HIGH RESOLUTION CHEST IMAGING USING CONTINUOUS VOLUME SCANNING.

Using continuous 100msec scanning, it is possible to scan the entire chest in with 140 slices in a single breath holding interval of 15 seconds. Alternatively, using an overlap scan technique, 140 overlapped 0.2 sec scans can be obtained in 30 seconds, if even higher detail is required. With 3mm collimation and 3mm steps, 42 cm of the chest and upper abdomen are covered. Recently a new double-density detector has been introduced which increases the static spatial resolution of EBT scanning from ~7 lp/cm to ~10 lp/cm. The fast 100 msec scan speed helps preserve the full 10 lp/cm resolution even in the presence of cardiac and respiratory motion of lung tissues. The result is superior diagnostic image quality of even the smallest structures in the lung as compared to slower scanners.

3. SCREENING FOR CORONARY CALCIFICATION USING ECG TRIGGERING

It was found that the coronary arteries could be imaged even without contrast media if 100msec EBT scanning is combined with ECG triggering. In this mode the ECG triggers slices and the patient is moved at increments for each successive

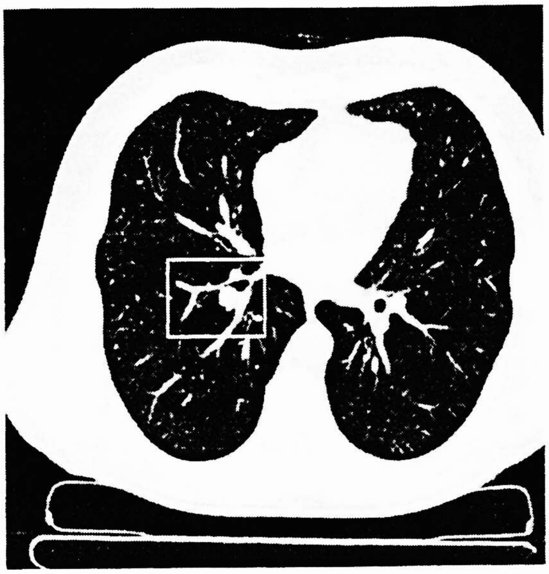

Figure 2. Example of a high-resolution chest scan obtained using 100msec exposure.

Figure 3. 5X magnification of a small region in the CT image at the left.

heart beat. Typically, 40 slices are scanned at 3mm steps over 40 heartbeats. The resulting images reveal the presence of calcified deposits in the walls of coronary arteries for patients who have atherosclerosis. Atherosclerosis is a progressive disease that develops over decades and eventually results in symptoms of coronary artery disease, heart attack and death. Coronary artery disease remains the number one killer in the United States even though promising new statin drugs and life style changes have been found to be effective in preventing the progression of atherosclerosis.

Scores of clinical research papers[2,3] have documented the effectiveness of coronary artery screening in detecting early atherosclerotic disease and in tracking its progression or regression. It now seems likely that coronary artery screening, combined with the newest therapies for those who need treatment, can have an enormous impact on the successful prevention of heart disease for future generations.

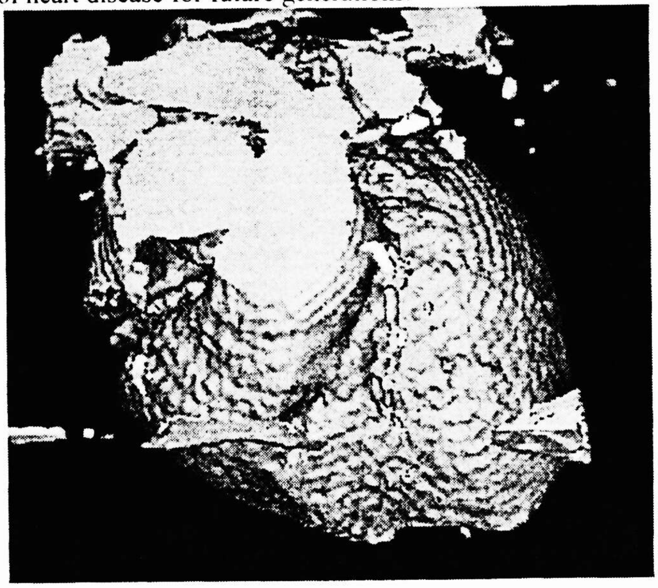

Figure 4. 3D shaded surface reconstruction of a heart without contrast media showing calcium deposits in the circumflex, branch of the right, and the left anterior descending coronary arteries.

Figure 5. A large calcification partially blocking the left anterior artery (left) and a smaller deposit distally in the first diagonal (right). This is an endoscopic reconstruction of a single frame from a coronary artery fly-through movie.

4. 3-DIMENSIONAL CORONARY ANGIOGRAPHY

For the past 20 years the clinical treatment for those who have symptomatic coronary artery disease has been based on the findings of invasive coronary angiography as performed in a catheterization laboratory. This sophisticated test involves risk, discomfort, and hospitalization. In coronary angiography a dye is injected into the blood which enables fluoroscopic images to be acquired of the lumen of the artery. For patients with severe coronary disease, narrowing (stenosis) of the lumen is found which limits the ability of blood to flow at normal rates. The stenosis may be treated by interventional techniques including angioplasty, stenting, or bypass surgery.

Although EBT scanning does not yet approach the full resolution obtained in the cath lab, the images at the present time are sufficient for imaging the proximal regions of the major coronaries to a distance of 8 cm or so from the aorta. Since EBT scanning is simpler and less invasive, it can be used for many applications that would be inappropriate for angiography. EBT can be used as a follow-up method to check the status of bypass grafts, the integrity of dilated arteries, the status of stents, etc. Further, it may be used for categories of patients who need a study but have contraindications for angiography[4,5,6].

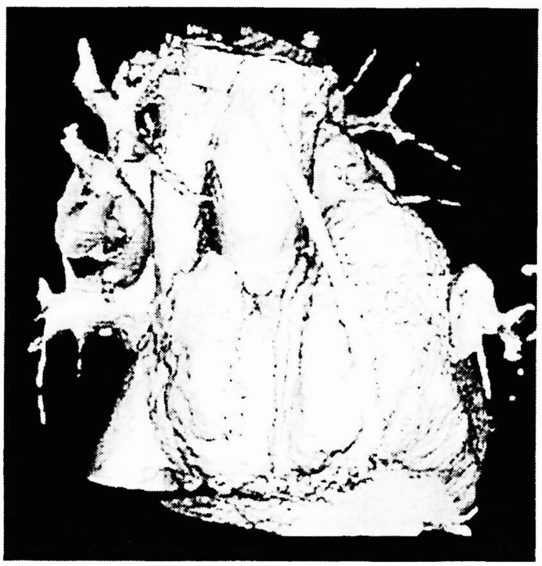

Figure 6. EBT CT coronary angiogram using intravenous contrast media. The native right coronary artery (center, lower half) shows evidence of multiple stenotic segments. The right bypass graft (center) has a normal, healthy appearance and is patent.

Figure 7. Using a cut-plane it is feasible to examine the anatomy of the proximal bypass anastomosis from inside the ascending aorta.

5. 4-DIMENSIONAL IMAGING OF CARDIAC MOTION AND FLOW.

Using the multi-slice 50 msec scanning mode of EBT, it is possible to perform motion studies of wall motion and of blood flow. For motion studies the cine mode is used to acquire continuous images of a pair of adjacent slices at 17/sec over a heart beat. The EBT scanner has 4 X-ray source rings (target rings), and the beam can be switched instantaneously from one the next. An 8-level cine is performed in four steps on 4 consecutive heartbeats. Typically 10-16 cine scans are acquired on each of the rings for a total of 80-128 images. Using table incrementation, up to 12 levels can be scanned in the cine mode up to a maximum of 160 images.

The images may then be combined and reconstructed in a workstation to reveal a 3D representation of a beating heart. Using an interactive cut-plane, the interior structures of the heart in motion can be examined by a physician who may inspect wall thickening and wall motion for patterns indicating ischemia or infarction. Cardiac valve motion may also be observed in this fashion.

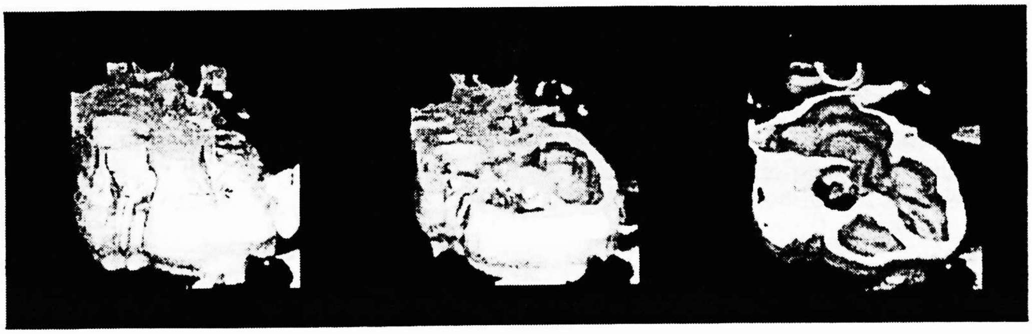

Figure 8. Three frames from a 4-dimensional study of the beating heart. By moving a cut plane into the beating heart a physician can observe wall motion patterns interactively at all points within the volume[7].

To study blood flow, the EBT scanner is equipped with a flow mode that captures 8 slices of the heart in approximately 200 msec. These 8-slice scans are repeated at intervals of 1-2 heartbeats during the time that a bolus of contrast media is flowing through the heart. The iodinated contrast media is usually injected at a rate of 4-8 ml/sec into a vein in the arm. The appearance of contrast media in the four cardiac chambers is easily viewed. Calculations of time-density changes can be used to estimate cardiac output. The myocardial tissue also experiences enhancement from wash-in and wash-out of contrast media but at a concentration of only about 10% of the intensity in the cardiac chambers giving information that is used to estimate perfursion..

Again a series of 8-level flow images may be reconstructed into a 4-D image of the heart consisting of a series of 3-D images over time. Again the physician may observe both vascular blood flow and tissue perfusion by interactive rotation of the heart and manipulation of a cut-plane.

6. FUTURE DEVELOPMENTS

The full potential of dynamic X-ray CT imaging will not be realized until it becomes economically and technically feasible to acquire large numbers of slices (say 128 or more) simultaneously. This will require the introduction of a future area detector along with new data acquisition technology that would be 2 orders of magnitude faster than present technology. In addition, current studies at 50 and 100 msec still exhibit motion artifact, indicating that ultimately an exposure speed in the range of 30 msec, close to that used in angiography, will be necessary.

Further, when it becomes feasible to acquire all of the slices of a volume simultaneously, the need to reconstruct cross section slices will be less evident. Rather, real-time reconstruction of fully 3D images with transparency will be needed. The technology for real-time 3D reconstruction is already under development, and a preliminary version of CT fluoroscopy, the RTR-2000, is already undergoing clinical testing at hospitals in Japan, the U.S. and Europe. The computation requirements for real-time 3D reconstruction in the 30msec range will be also two orders of magnitude higher than the performance of the present RTR-2000 system[8]. Fortunately, Moore's law of chip speed lessens the technical burden of developing advanced designs to meet these requirements. With luck and appropriate funding, such machines could be developed within the next five years or so.

7. REFERENCES

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7. 3D and 4D reconstructions in Figs. 4-8 were performed using workstations from AccuImage Diagnostic Corp., 400 Oyster Point Blvd, Suite 114, So. San Francisco, CA 94080; www.accuimage.com.
8. RTR-2000 system developed by Terarecon Inc., 280 South Utah Ave., Suite 100, So. San Francisco, CA 94080.