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Electron beam computed tomography: challenges and opportunities

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Abstract

In computed tomography (CT), a cross-sectional view is developed by measuring and analyzing the x-ray attenuation of a thin x-ray fan that rotates around the subject. There are two ways to make the x-ray fan. One is to physically rotate an x-ray tube around the subject. The other way is to scan an electron beam around a fixed tungsten anode ring that surrounds the subject. The medical application we address is to non-invasively determine risk of coronary disease in subjects who are symptom-free. Subjects lie still, holding their breath and drugs to lower heart rate are administered in order to reduce image blur. The advantage of electron beam CT imaging is speed. In addition to higher cost, the disadvantage is low x-ray source brightness so the scan speed is limited by signal strength. We explore the possible improvement of using electrostatic rather than magnetic beam deflection incorporating a new method that provides little or no deflection aberrations even at large deflection angles. Since shielding electrical fields is very easy, it is possible to operate a multitude of electron guns in close proximity - each scanning a short segment of the anode ring. By amplitude modulating each gun at a signature frequency, all guns could operate simultaneously and x-ray signals can be separated by the modulation frequency. This idea might allow speeding x-ray scan by perhaps 10-fold. This might allow a cardiac CT scan to be made on a subject who is at elevated heartbeat while on a treadmill. That is well known to accentuate heart malfunctions.

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1. Introduction

In comparison to most active areas of technology, charged particle optics is rather ancient. One way to date its origin is to consider that the first scanning cathode ray device was invented by the German scientist Karl Ferdinand Braun in 1897. In the intervening 109 years, there have been a multitude of scientific and commercial applications of charged particle optics. In fact there are so many that it is difficult for any one person to be aware of all the problems solved and unsolved and methods that have worked and those that did not. It may be helpful on occasion to explore some of the obscure applications in the hope that we may learn something that will prove useful in our

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current investigations. Before I get into my main topic of electron beam computed tomography (EBCT) as an example of a less well-known application of charged particle science, I want to mention how this project happened.

A few years ago I discovered a method for deflecting a wide charged particle stream into large angles using electric fields while introducing little or no deflection aberrations [1,2]. This was an unexpected finding since all the textbooks state that while electric field deflection is fast and useful for small angles, magnetic field deflection produces the lowest aberrations if the angles involved are more than ten or so degrees. In virtually every application of electrostatic deflection, beams are injected midway between the deflection plates to avoid the fringe fields as much as possible. The surprising result was that the best performance results when electron beams of diameter up to approximately 1/3 the gap between conventionally shaped oppositely charged conductive plates are injected offset approximately 1/3 of the way toward the attracting plate. The beam more or less follows equipotentials and, as is well known, the lines of force are perpendicular to these equipotentials and thus to the beam trajectory as well. From that perspective it seems logical that offset injection may be superior to centralized injection. With offset injection, deflection into large angles (at least 45 degrees) can be accomplished with little or no deflection aberration. That is, the beam could be focused as well after deflection as it would have been without deflection. This has been experimentally verified but only in a few cases. This innovation became a solution in search of a problem. It was at least 10 years too late to rejuvenate the cathode ray tube industry but there were several other interesting possibilities [3-5].

2. Computed tomography

Perhaps the most intriguing was the EBCT [6-8]. This is a type of computed tomography (CT) imaging device used to produce a cross section view of a human or animal or any other object as if someone sliced it open. In a CT, a thin rotating x-ray fan together with suitable detectors produces a continuous measurement of the x-ray attenuation of a thin slice of the body from all orientations. Reconstruction of the cross-section image is obtained with suitable algorithms. The image shows structure using local x-ray attenuation as contrast. Godfrey Hounsfield, a UK scientist, produced the first CT images in 1973. These took about 5 minutes of exposures using a mechanical device to move the x-ray source to provide exposure from different angles. The images were of head and neck areas since those were the only body parts that could remain motionless for that length of time. Hounsfield and Allan Cormack, a mathematician from Tufts in the US, shared the 1979 Nobel Prize for their innovative work in this field.

The major advantage of CT over plane film radiography is that in CT there is no confounding superposition of all structures in front of or behind the structure of interest. The visual clarity is striking. As one would imagine, there are many medical applications of CT imaging. Prominent is diagnosis of disease, measurement of disease status, and determining impending disease involving various organs and body parts.

The conventional method of CT is to rotate an x-ray tube around the subject to be imaged. Initially due to twisting cable problems, this was a slow back and forth rotation but eventually became a continuous rotation with 3 revolutions per second standard now. In an EBCT an electron beam is scanned around a fixed tungsten anode ring that surrounds the subject producing the radiation. With no moving parts, the EBCT is capable of scanning faster than conventional CT. Imatron, the only manufacturer of EBCT imagers, has sold about 150 machines with 20 Hz rotation or 50 msec scan speed. In comparison, there are thousands of conventional CT imagers in the field. The cost of EBCT and conventional CT is US $2M and US $1M respectively. Douglas Boyd of UCSF played a major role in developing the Imatron EBCT. A number of key patents were issued to Roy Rand. Fig. 1 shows a schematic drawing of the Imatron EBCT from US Patent 4,521,901.

They cannot scan much faster in EBCT due to limited x-ray source brightness, since the signal would be too weak and the image would be unacceptably noisy. General Electric purchased Imatron a few years ago and, while continuing to support existing devices, the product line is discontinued. Siemens is introducing a CT with two x-ray tubes offset 90 degrees apart and is reportedly speeding the rotation to 13 Hz. Detection of attenuated radiation and image reconstruction is essentially similar in mechanically rotating CT and in EBCT. The scan speed advantage of

EBCT is most useful in imaging organs that necessarily cannot be stopped even when holding the breath – particularly heart and to a lesser extent lung.

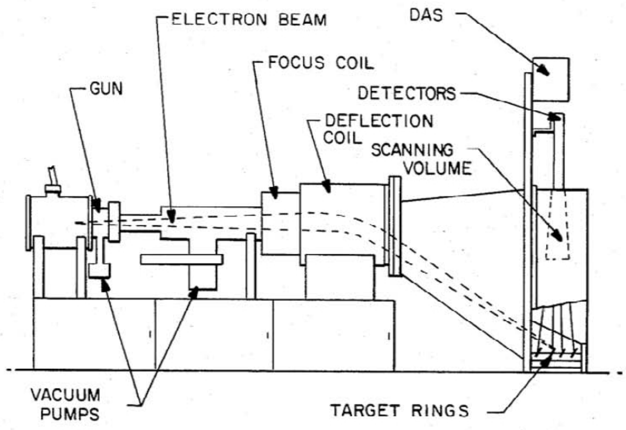

Fig. 1. Schematic drawing of the Imatron EBCT from US Patent 4,521,901

Of special interest is determining risk for cardiac (especially coronary artery) disease in asymptomatic individuals using non-invasive methods since that is where the EBCT may have some advantage over other CT devices. This is an important application since if individuals at high risk of coronary disease can be identified, there are several very effective ways to intervene such as changing life styles (by diet and exercise), medical (using statins to lower cholesterol such as Lipitor, the best selling drug in the US), placing mechanical stents in vessels that are partly closed to blood flow (termed stenosis), and coronary bypass surgery to replace diseased coronary vessels with healthy vessels usually from the person's legs. These are not the types of intervention that should done on anyone since, other than life style changes, there is high cost and some risk, but for those who are at high risk to have heart disease in the near future, it is a very acceptable risk/benefit trade-off.

Coronary disease is one of a number of cardiac diseases. In the US, of the $1 trillion yearly health expenditure, $366 or roughly 1/3 is spent caring for persons with advance cardiac disease. In the Western world, cardiac disease is the number one killer accounting for 38% of all deaths. Yearly 150,000 persons in the US have a fatal heart attack as their first sign of cardiac disease. Of these, 1/3 would not have been cited as having elevated cholesterol levels as presently classified [9].

3. Imaging studies to detect impending coronary artery disease

There are two separate pumps in the heart. The right pump sends oxygen depleted blood to the lungs for oxygenation and then the blood returns to the heart. The left side pump sends oxygenated blood to the full body via main arteries. The heart is the hardest working organ in the body and thus has very high needs of energizing blood. There is a tap off the left pumping circuit that directs blood through 3 coronary arteries directly to the heart. Each artery branches off several levels into progressively smaller vessels. The 3 major coronary arteries and their first few branches are of concern for coronary artery disease. The smallest capillaries are not a concern. Arteries of interest to us are 1 mm more or less in diameter.

The imaging difficulty for coronary applications stems from the motion of the heart during pumping which is roughly 1 beat per second. Some arteries move a full diameter during a pump cycle and the most active arteries move up to 5 diameters. During a heartbeat, much of the structure moves with simple harmonic motion. However other parts of the heart have much more complex motion with resulting higher harmonics. Valves for example are quiescent during most of the heartbeat but open and shut rapidly at key points in the cycle. In addition, valves do not simply close smoothly but they vibrate while closing. According to one physician I spoke with, this valve closing oscillation plays a role in pumping efficiency. CT is synchronized by electrocardiograms to be done at diastole where motion is minimized. The subject lies motionless on a cushioned support and the breath is held during exposure. Subjects are also often given drugs (beta blockers) to slow heart rate.

As stated, one of the main applications of EBCT is to non-invasively identify asymptomatic individuals who are at risk for future coronary artery disease. It is a challenging problem since, before symptoms appear, the disease can sometimes be very subtle. If there is say 50% or more occlusion of a vessel, that would be relatively obvious in imaging – especially if a high x-ray attenuating medium (called contrast or dye) such as iodine is added to the blood. However, sometimes serious artery disease can be caused by a 10-15% occluding plaque (atherosclerosis) that has a hard surface and can fracture or rupture. That will cause platelets to gather to stop the bleeding - a normal body defense mechanism. A problem that can occur is that a platelet clump can escape and produce a blood clot that may suddenly block an artery elsewhere producing a stroke or myocardial infarct (heart attack). Efforts to detect the presence of small deposits of plaque using biochemical tests of blood are ongoing but not yet successful.

The amount of calcification in coronary arteries as measured in an EBCT can be an indication of risk of coronary artery disease. The complete absence of calcification is said to be a very good indicator for no risk in the near term. However, many people, especially elderly ones, have extensive calcification in coronary arteries but do not develop coronary disease. Not everyone agrees that EBCT is better than conventional CT for cardiac disease prediction [9-11].

Iodine, when added to blood, is nontoxic. However, it must be cleared by the kidneys. In normal healthy persons who rarely have cardiac CT imaging, that is not a problem but for an elderly person, especially one who has had many imaging studies, that can overly stress the kidneys. Likewise, a small amount of radiation is acceptable in most cases for imaging purposes but we must remember that it can also cause disease.

The function of the heart is mechanical. That is, there are no biochemical processes that the heart performs to keep the body functioning. Therefore, it is reasonable to imagine that by viewing a high temporal and spatial resolution slow motion video of a beating heart over many full cycles and from any perspective, a cardiologist could determine how well the heart is functioning and also detect upcoming heart disease before there are symptoms. Perhaps computer analysis of localized motion of various features could also help. In addition, since some coronary problems are prominent only when the heart is most active, it would be particularly helpful if this could be done at elevated heartbeat while exercising on a treadmill or stationary bicycle.

So given this information, what is the greatest need in a tool for cardiac imaging including determination of risk of coronary disease? Improved spatial resolution would always be welcome but it seems the more important benefit would be from improved temporal resolution. An effective imaging tool to detect impending disease needs to see very subtle coronary stenosis that perhaps can be best identified by hypokinetic or hyperkinetic deviations of a short segment of a vessel while the heart pumps. In addition, there are dynamic structural aspects of the heart that are useful to cardiologists such as local muscle activity, wall thicknesses and volumes of pumping chambers through the full cycle. There are also other activities in pumping involving the detailed opening and closing of valves that are very useful to observe (currently done using ultrasound). It might be advantageous to sacrifice spatial resolution to reduce radiation especially if multiple images are needed to do kinetic studies.

4. Physics of Electron beam CT

X-rays are the result of bremsstrahlung that occurs when an energetic electron collides with a high atomic number atom. The photon is emitted in the original direction of electron motion. Multiple collisions resulting in photons emitted in all directions occur before the electron comes to rest. The spectrum of x-ray energy produced has a maximum corresponding to the full energy of the electron beam and also has a long tail extending to zero. The efficiency of conversion of kinetic energy into x-ray energy is proportional to atomic number of the substrate times the energy of the electron. For medical applications the beam energies are approximately 20 kV for mammography to 120 kV for chest views. Substrates are typically tungsten (Z=42) or molybdenum (Z=74). The resulting efficiency is a few tenths of a percent. In computed tomography for coronary imaging, the beam voltage is 100 – 120 kV and the current may be 600 to 800 mAmp to produce some tens of x-ray watts. Thermal destruction of the anode typically limits x-ray production.

The maximum range of an electron beam in matter expressed in gm/cm^2 is approximately half the energy in MeV. For tungsten, the density is 19.3 gm/cm^3 so the range of a 100 kV beam is approximately 25 microns. That means x-rays produced by an electron impacting the anode emanate from a plume beneath the landing point of 25 microns in size. For the 1 mm beam landing in the Imatron device, that adds very little to the x-ray source size but it perhaps puts a constraint on ultimate resolution.

As can be seen in Fig. 1, in the Imatron EBCT an electron beam is focused with a large magnetic lens and deflected with a magnetic field to scan a solid tungsten anode ring that encompasses 180 degrees plus the 30 degree fan or 210 degrees. The optical column is 1.5 – 2.0 m long. According to a scientist who used to work at Imatron, the beam landing is 1 mm by 8 mm. The larger dimension is in the direction of deflection and is the result of deflection aberration. The long dimension of the beam landing is along the fan axis so that, due to foreshortening, there is still approximately 1 mm size of beam landing. For comparison, Toshiba advertises an x-ray tube with 350 micron source size.

The Imatron device has a clever method to overcome Coulomb repulsion. They report in 1984 US patent 4,521,901 that leaking Nitrogen into their vacuum system to a few times 10^{-6} torr substantially reduces Coulomb repulsion.

5. Proposed method to increase temporal resolution of EBCT

CT and EBCT devices as described are very useful and no doubt have saved many lives. However there is apparently much room for improvement. One of the lessons from microcircuit lithography is that a parallel system in which many things are done at once (photon exposure) is usually superior to a serial system in which things are done one at a time (electron exposure) even if the serial system has inherent advantages. Perhaps we could use this philosophy in computed tomography. For example, we could divide the EBCT anode ring into a number of segments and have a dedicated electron gun and electrostatic deflection system for each segment. Electron guns using electrostatic deflection can be very effectively shielded from other guns in close proximity with simple conductive mesh shielding to eliminate cross-talk. The column lengths would be less than 50 cm instead of the 1.5 – 2 m for the Imatron EBCT. Alignment could be automated and the device could be modularized for ease in assembly and repair. Beam landing size roughly scales with the length of the electron optical column so there should be a significant gain in spatial resolution. That is always important but we will concentrate on improving temporal resolution where it appears the most gain is needed.

If we amplitude modulate each gun with a signature frequency, all segments can be scanned simultaneously instead of sequentially and the x-ray signals from the various fans will be identifiable and separable by the amplitude modulation. Otherwise, only one x-ray fan is operating at any one time and the remainder of the system is idle.

Orientation of the electron beam relative to the anode and the object to be imaged is probably well optimized in the Imatron device. It is unlikely that we need to make any changes in that configuration. There would be some engineering involved but it appears that a factor of 10 improvement in scan speed is achievable. Perhaps that will allow a sequence of CT cardiac images to be taken with 5 msec exposure while on a treadmill.

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