DEVELOPMENT OF THE BMI.7O7O AND BEYOND

Background

In 1976, EMI Medical still had the largest share of the x-ray computed tomography (CT) scanner market, but was being pressured by several companies that had newer designs The basic problem was that EMI's scanners used the original translate-rotate design, called "second generation" (the first generation had only one detector). This moved a line of detectors across the body, turned the x-ray tube and detectors through a small angle , and then repeated the process, taking 18 seconds to scan.

Many other companies designed scanners that avoided translate-rotate's stop-and-go motion. The strongest was General Electric, whose7800 model used continuous rotation of both the x-ray tube and an arc-shaped array of detectors. This geometry was called rotate-rotate or third generation. Though it claimed to scan in 4.8 seconds, it almost always was used at9.6 seconds. American Science and Engineering rotated the x-ray tube in five seconds inside a fixed ring of detectors, a geometry called rotate-stationary, or fourth generation.

The GE 7800 was subject to a weakness of third-generation design: light and dark rings that hid real variations in tissue density. It also had dark spaces at the edges of bone. These artifacts made its images hard to interpret, and so EMI's British management felt that the finer details and superior image quality of their 1010 head scanner and their 5005 body scanner would be more important in the market than GE's or AS&E's greater speed. But they forgot that, just as EMI had earlier improved its own image reconstruction software, GE could do so too. Knowing this, the engineering group at EMI Medical's American assembly plant at Norlhbrook (near Chicago) felt that action was needed. The British disagreed, as demand for their scanners was greater than the rate they were able to manufacture.

Why the 7070 Was Started

Soon, better GE software led to increasing loss of EMI Medical's US market, because American hospitals preferred the faster scans. The Northbrook engineers wanted to develop a faster scanner, but a major obstacle was that they did not know the Mathematical algorithms needed to reconstruct a cross-sectional“ slice ”image from the millions of individual x-ray readings-and the British management would not tell them! But late in 7976, one of the Americans reverse-engineered the British software, opening up the road to design. And by early I977, GE's increasing share of the US market finally persuaded the UK management to allow a team of engineers at Northbrook to start studies of new designs. This was strongly supported by EMI Medical America's president, Robert A. Hagglund.

The Early Design Efforts

The team set four goals: faster scans, better spatial resolution (the ability to see finer details), lower x-ray dose to the patients, and freedom from artifacts. Respectively, these meant simpler motion, narrower detectors, more efficient detectors, and avoidance of third generation.

But at first, UK management insisted on extending their tried-and-true second-generation geometry. This was attempted in two approaches. The simplest was to speed up the 5005's mechanism. The problem was vibration from the stop-and-go motions. Even though the Northbrook team took special care to balance all parts of a 5005 far better than its factory specifications, it was found that vibration increased roughly in proportion to the cube of the speed, and at a scan time of nine or ten seconds, almost tore the 5005 apart. The other approach was a paper study of increasing the angle covered in each translation, so fewer translations and rotations would be needed. The problems were that this would make the scanner undesirably large, and it would be difficult to make detectors and image reconstructing mathematics at the edges of a wider beam.

Abandoning second generation, the Northbrook team brainstormed new geometries with continuous motion. Some moved the detectors on tracks with complex curves, some had separate, different motions for the x-ray tube and the detectors, and some had more than one x-ray tube. Eventually, over thirty configurations were considered and rejected. The team concluded that fourth generation, inherently free from ring artifacts, was the only way to go, breaking away from all of EMI Medical's previous experience.

Problems and Solutions

However, in order for fourth generation's complete ring of stationary detectors not to block the x-ray beam, it had to be outside the orbit of the x-ray tube. And for higher resolution, a larger ring with smaller detectors meant a much larger number of expensive detectors. In addition to detector cost, every extra detector increased the amount of data, raising the cost of electronics and computer hardware and slowing down the time for the software to reconstruct the image.

Accordingly, the team began to ask if there was a way to put the detector ring inside the x-ray tube's orbit without interfering with the beam. This would make a more compact scanner, save cost, and reduce he number of detectors and the data load. The team examined putting the tube out of the plane of the detector ring, so that the moving x-ray beam would trace a very shallow cone, but realized that would cause a new kind of artifact. They looked at mounting the detectors in spring-loaded blocks, with a cam to move them out of the x-ray beam when the tube was behind them, but it was a mechanical nightmare. Then one of the team members invented the nutating detector ring. This tilted the ring by two degrees, so that the region near the x-ray tube was out of the beam, but the opposite part was in the beam that had passed through the patient. As the tube rotated, the position of the tilt also moved around, without rotating the detector ring. When the concept was first presented, at the 1977 RSNA convention, EMI's competitors speculated that the internal mechanism was an over-complex mess oflevers or cams; but it was much simpler - just two large ball bearings, set two degrees apart.

At the same time, the team reahzed that the combination of lower x-ray dose and higher resolution could not be achieved with the existing EMI detector concept. That used sodium iodide crystals as scintillators to convert x rays to light, and photomultiplier vacuum tubes (PMTs) to convert the light to electrical signals. While higher resolution might be obtained by using lead blocks to narrow the openings in front of the PMTs, the x rays from the patient would be wasted in the blocks, worsening the patient dose. It would again be necessary to break with previous EMI experience, by developing solid-state detectors that could be made smaller than PMTs, based on materials that had never been used before. As a scintillator, the team selected cadmium tungstate, with far greater x-ray stopping power than sodium iodide or the xenon gas detectors used by GE. The $CdWO_4$ crystals were epoxied to custom-made photodiodes.Each scintillator-photodiode “channel” was contiguous to the next, so that almost no x-rays were lost.In combination with the high stopping power of $CdWO_4$, the system had higher x-ray efficiency than any previous CT scanner, and therefore lower patient dose.

As tests went on, a new problem appeared: the photodiodes were weakening. At first, it was feared that they were damaged by radiation, but tests without scintillators showed good radiation resistance. Eventually, the problem was traced to minute amounts of sodium in the epoxy, and solved by using a more expensive sodium-free epoxy.

TransatlanticProblems

EMI Medical's UK management wanted to have a significant British content in the 7070. They directed two EMI subsidiaries, Pantak and SE Laboratories, to supply the x-ray power supply and the computer that would reconstruct the images. That computer, called an array processor or AP because of its array of many parallel computing elements, would have to have more than ten times the computing power of previous EMI processors, because the 7070 would be six times faster and have fifty percent better resolution. SE Labs would also supply the control console. Northbrook would supply the detectors, an expensive data acquisition system or DAS (between the detectors and the data processor),the gantry mechanism, and the patient couch. The latter was also a break from previous EMI practice, pioneering the use of a cantilevered carbon-fiber structure.

At first, the projected prices and specifications for the x-ray power supply and the AP were reasonable, but costs and delays began to escalate at the same time as specifications began to deteriorate. In the case of the x-ray power supply, Pantak was unable to provide the fast turn-on and turn-off times that were needed to keep the patient from being exposed while the scanning motion started and stopped. In the case of the AP, SE Labs' expected cost reached nearly three times the original estimates. Northbrook management found an American manufacturer that could meet the x-ray power supply specifications at a reasonable price, and began to negotiate with an American AP company.

These moves threatened EMI Medical with greatly reduced content from the UK. Already unhappy with the fact that Northbrook had broken from proven EMI designs, and worried that Northbrook was too inexperienced to do a good job, EMI's Central

Research Laboratory started a competing development called Topaz. It was based on third-generation geometry, but with an x-ray tube whose beam was scanned rapidly over a small distance in order to avoid ring artifacts. A number of UK middle managers pressed EMI top management to cancel the 7070 in favor of Topaz, citing the escalating costs and what they considered Northbrook's risky development. President Hagglund was fired, and several of EMI's top executives and scientists visited Northbrook in 1978 to review the 7070 project preparatory to closing it.

But in the review, it was reahzed that the AP from SE Labs had enough capacity to include the functions of the DAS. This not only saved a major piece of UK content, but also eliminated the costly separate DAS. The 7070 was saved, but at the cost of a nine–month delay while the design was converted to combine the AP and DAS. During this period, a large group of UK engineers was seconded to Northbrook, partly to give UK management more confidence, and parlly because they were underemployed in England asa result of diminishing sales for the old model 5005.

The End of the 7070 Story

The 7070 was an outstanding performer. It was the first successful solid-state scanner, the first to rotate in only three seconds, and the best in spatial resolution. The first unit was delivered to the Mallinckrodt Institute in St. Louis, and the doctors there were delighted to see anatomical details they had never seen before, and the fast scan enabled them to get unblurred images from patients who could not hold still for longer times. EMI booked over 80 orders within the next year!

Unfortunately, the nine-month delay proved to be its undoing. There were two factors. The worse one was EMI's financial situation. Development costs more than doubled because of continuing effort on the Topaz, because of the high costs of the UK engineers in Northbrook (who received hefty extra allowances for housing, cars, overseas bonuses, etc.), and because EMI was also working on the first MRI system for humans. At the same time, EMI income took a sudden drop from an unrelated event: the Beatles quit Capitol Records, a previously profitable EMI subsidiary. In fact, it had often been said that the Beatles paid for the original CT scanner development.

The other factor was that GE's new model. the 8800. came on the market in 1988 with better spatial resolution and reduced ring artifacts. While it was still not as fast or as accurate as the 7070, GE's marketing power, their heavy discounting, and their favorable position as incumbents for the conventional x-ray equipment in many hospitals made EMI realize that they would have to increase marketing costs and reduce profits with discounts. To save their finances. They merged with Thorn. a UK firm that was strong in consumer products.

Thorn did not want to stay in medical electronics. This included CT, MRI, and other EMI products such as ultrasound and therapy. Thorn attempted to sell all such activity as a block, but were unsuccessful. The MRI went to Picker, the ultrasound to Fisher, but there were no buyers for the 7070. Thorn tried to get out of the 80 orders, rejecting about 20 that had not yet paid deposits nor received written acknowledgements. For the

Remaining 60, EMI offered to pay those hospitals' costs of making new US government applications if they would cancel. (It was the time of the “ Capter cap ” , when hospitals had to get government approval for major purchases.)Thorn-EMI expected that most hospitals would accept cancellation, and a sales team from GE was waiting to fill the gap. But the majority insisted that they wanted the best scanner, and that EMI was legally obligated to deliver. In the end, Northbrook stayed open until a total of 43 of its 7070 scanners were shipped.

Even then, the 7070 story was not quite over. OmniMedical bought all of the parts inventory for the 7070, and managed to assemble and sell a few more units with their own AP and console, calling it the Quad-4.

The Torch is Passed

EMI Medical's demise came as a shock to Toshiba, a leading Japanese company that had been in x ray since the beginning of the twentieth century. Toshiba had been building scanners under EMI license, and had hoped to rely on EMI Medical to help it design future models. Toshiba learned that some of the Northbrook engineers and scientists were trying to form a new company, and Toshiba entered negotiations with this group, under the name Bio-lmaging Research, or BIR. As the result of a design analysis, BIR convinced Toshiba that it would be possible to make a scanner using the 7070's nutating principle to scan in only one second and have still better resolution.

BIR designed improved detectors, assembling them in modulesof i6 channels each,for easyassembly. This conceptprovedits worth when a loose bolt got into theprototype scannerduringrotation,destroying more than a quarterof the detector modules. Such a calamity would haveput any other scanner out of action for a week, but the prototype was repaired and running in less than a day.

Moreover, BIR proposed to do away with the cumbersome coils of high-voltage cable that connected the rotating x-ray tube to the external power supply. These cables meant that the gantry could not rotate continuously, but turned in one direction to wind up the cables, and then in the other direction to unwind them. Instead, BIR designed a high-voltage slip ring so that Toshiba's new model, the TCT-900, could rotate without stopping.

BIR wanted to create growth for the future, not just a single model. They built detectors with still higher resolution, putting 24 channels on modules that could be field retrofitted in place of the 16-channel modules. They tested the prototype scanner at two revolutions per second, a speed that did not reach the market until ten years later.

The TCT-900 was not only a technical and market success, selling more than 400units, but it s continuous rotation made possible the next advance in CT scanning: helical scan, where the patient couch advanced smoothly during scanning,giving three-dimensional views if the body without depending on separate slices.

CT Today and Tomorrow

EMI and Toshiba's influence on the CT market is substantial. All major manufacturers now offer sub-second scanning, continuous rotation, solid-state detectors, and helical scanning-features originated by the Northbrook team and Toshiba engineers. Even today's area detector arrays, giving eight or sixteen or more slices per rotation, had their origin in an early, two-slice EMI model.

What does the future hold for x-ray CT? Faster scanning, though except for non-mechanical scanning, centrifugal forces may set a limit. Somewhat better resolution, but that cannot get much better without unacceptable increases in patient dose. More slices, at least until the beam angle becomes so wide that it has a longer path through the patient or exceeds the reconstruction mathematics' ability.

There are other, more likely trends. Interventional scanning, where the scanner is shaped so that the patient need not be removed from the scanner for surgical procedures. Multi-sensor scanning, where CT is combined with positron emission tomography (PET)or single-photon emission CT (SPECT)to obtain information on physiological functions as well as anatomy. And perhaps most important, continually more sophisticated software, allowing simulated views from inside the heart or intestines, and including computer recognition of disease conditions.

“coutesy of John F.Moore and BIR,Inc.,Lincolnshire,Illinois”