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CASE HISTORIES OF TRANSFORMATIONAL ADVANCES

Computed Tomography (CT) - Beyond Traditional X-Rays

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Abstract: This case history describes how Computed Tomography (CT) scanners - that combine X-rays and computers to image soft tissues of the brain and other organs -- have become a widely used diagnostic tool. Specifically, we chronicle the 1) initial development of CT technology and markets (in the 1960s and 1970s), 2) broadening of uses and users (in the 1980s), and 3) introduction and adoption of combination scanners (in the 1990s).

Note: Like the other histories in this series, this advance is included in a list compiled by Victor Fuchs and Harold Sox (2001) of technologies produced (or significantly advanced) between 1975 and 2000 that internists in the United States said had had a significant impact on patient care. The case histories focus on advances in the 20th century (i.e., before this millennium) in the United States, Europe, and Japan -- to the degree information was available. Limitations of space and information severely limit coverage of developments in emerging economies.

Acknowledgments: We thank Kirby Vosburgh for helpful information and suggestions.
Computed Tomography (CT)  
-Beyond Traditional X-Rays

Computed tomography (CT) scanners have become ubiquitous, particularly in Japan and the US, since they were first offered for sale in 1972.¹ (Exhibit 1). Combining X-rays and computing technology, CTs allow physicians to “see” tumors and other conditions that do not appear clearly (or at all) in traditional X-rays. And technological advances have broadened potential applications—for instance, in supporting complex radiological treatments. CT scanning has, therefore, become routine even though the equipment remains expensive to buy, operate, and maintain.

The three main sections of this case history describe 1) the initial development of CT technology and markets (in the 1960s and 1970s), 2) the broadening of uses and users (in the 1980s), and 3) the introduction and adoption of combination scanners (in the 1990s).

1. Initial Development (1960s-1970s)

X-rays revolutionized medical diagnostics after they were introduced in 1895 because they allowed physicians to look inside bodies without cutting open patients. But X-rays had limitations. Two-dimensional projections gave prominence to bones. This obscured tumors and other soft tissues in shadows and made it difficult to locate the position of problems (such as bullets) lodged behind bones.

Innovative physicians then developed “tomographic” techniques between the 1910s and 1960s that created images of specific cross-sections or “slices” of the body by beaming X-rays from multiple angles around the patient.² But, tomography exposed patients to large doses of radiation. And, like traditional X-rays, tomographic X-rays could not clearly differentiate between adjacent soft tissues—for instance, between tumors and healthy tissues inside skulls (although they could better locate the position of hard objects such as bullets).³

Physicist Allan Cormack first proposed a method to improve tomographic imaging in a 1963 article published in the Journal of Applied Physics.⁴ Rather than use X-rays to make photographs (the traditional method), Cormack suggested that physicians measure X-rays after they passed through a body to see how much radiation had been absorbed. He also provided mathematical formulas for constructing images of specific cross-sections using the measurements.⁵ Cormack’s article generated no medical interest, however.

Instead, five years later, Godfrey Hounsfield, an engineer at the British entertainment giant EMI (abbreviated from Electrical and Musical Industries), envisioned a device that would work much like Cormack had described. Hounsfield had worked on EMI’s early computer, the EMIDEC 1100. When EMI terminated its computer project, Hounsfield moved to the company’s Central Research Laboratory. Without knowing of Cormack’s paper, Hounsfield thought about using computers to recognize and display patterns of numerical data⁶ and using that capacity to improve tomographic X-ray images.

¹ Hounsfield’s prior service in the Royal Air Force during World War II, when he had worked with radar installations, influenced his

This case history does not present original research or new thesis. Instead, it summarizes historical developments and includes questions to stimulate reflection and discussion.
Hounsfield wrote up a proposal to build a scanner based on these ideas. In 1968, the board overseeing EMI’s Central Research Laboratory approved Hounsfield’s proposal, enabling him to build an experimental prototype (although EMI did not then sell any medical products).

After Hounsfield’s team had built a rudimentary but functioning device, EMI sought and received funding from the British Department of Health and Social Services to continue developing prototypes that were refined on animal and human cadavers. The Department also helped Hounsfield, who had been struggling to establish relationships with physicians, find a medical collaborator: Dr. James Ambrose, a neurologist at a small hospital outside London. By October 1971, Hounsfield’s team had a head scanner ready for testing at Dr. Ambrose’s hospital on a woman whose symptoms suggested a brain tumor. The test scan supported the diagnosis; the surgeon who then operated on the patient observed that the tumor he removed “looked exactly” like the image seen in the scan.

The following year, EMI started selling head scanners, targeting the US market. The company hired eight sales representatives and sent Hounsfield to lecture to neurologists in New York and to an annual meeting of radiologists in Chicago. EMI was also able to secure reimbursement for CT procedures from Medicare, the government-run public health insurance program, after demonstrating the effectiveness of its head scanner. (Initially, Medicare – and private insurers -- had declined to cover the new procedures.)

EMI’s CT division became profitable in three years. Orders for the scanners, priced at $310,000, soon exceeded EMI’s manufacturing capacity. In 1976, the company started building a plant to assemble CT scanners in the United States.

Large, prestigious teaching and research hospitals, such as Georgetown and Cleveland Clinic, were early buyers and set the stage for broader use: researchers and clinicians at these hospitals published journal articles and textbooks that taught other radiologists how to interpret CT images, which were plotted on computer displays and looked quite different from traditional X-ray photographs. (See, for example, Exhibit 2, which includes the first scan ever made on a live human).

The CT market soon attracted fourteen other companies. EMI sued the newcomers for infringing its patents but failed to block their entry. The entrants, based in France, Germany, Israel, Japan, Mexico, the Netherlands, and the United States, already served healthcare markets -- some sold X-ray and other medical equipment, while others sold pharmaceuticals (See Exhibit 3).

Two of the larger and slightly later entrants acquired the technologies of two startups: Pfizer, a pharmaceutical company seeking to diversify into medical imaging, acquired the rights to a CT scanner developed by Digital Information Science Corporation (a company started by George Ledley, a Georgetown researcher). Similarly, GE, which already had a sizable X-ray business, licensed a scanner from Neuroscan. (After GE introduced its own scanner in 1976, Neuroscan declared bankruptcy.)

EMI and its rivals introduced larger CTs. Where EMI’s 1972 machine could only accommodate heads, subsequent scanners (pioneered by Digital Information Science’s Ledley) could scan entire bodies (Exhibit 4). New CTs also had better X-ray detectors and rotated more quickly around patients, providing sharper images at a faster pace.

New entrants and their products reduced EMI’s dominance. By 1977, EMI’s rivals secured forty-two percent of the US market. In whole body scanners, GE’s sales surpassed EMI’s, as the unexpected death

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thinking. Like X-Rays, radar relies on the interaction of high-frequency electromagnetic waves with objects of interest; however, unlike traditional X-rays, radar also creates images of the objects on electronic displays.
of an EMI executive delayed the commissioning of the company’s American CT assembly plant. Meanwhile, new products offered better performance—but at higher prices.\textsuperscript{17} Top models in 1977 were priced at $740,000, which was over twice the price of EMI’s first model.\textsuperscript{18} Yet over 900 scanners were purchased and installed in the United States by 1977, mainly in large hospitals (See Exhibit 5). Three-quarters of US hospitals with over 500 beds and over half of hospitals with between 400-500 beds had at least one CT machine.\textsuperscript{19}

Hospitals’ purchases of CTs, in turn, increased concerns about wasteful capital expenditures. Rising healthcare costs had been an issue during the 1976 US elections. In 1977, a member of the new Carter administration’s cabinet singled out CT for criticism. The consumer activist Ralph Nader’s advocacy group, Public Citizen, also questioned the cost-effectiveness and safety of CT.\textsuperscript{20}

Questions (for reflection and discussion):

Before reading further, please write down (in less than ten words) how the top management of EMI should respond to the challenges and opportunities in CTs.

- ____________________________________________

Please also think about—and be prepared to talk about—what you found to be the most significant or striking in the development of CTs.

2. Broadening of Users and Uses (1980s)

The backlash against purchases of expensive CT scanners encouraged stricter enforcement of a law passed in 1974 by the US Congress requiring hospitals to obtain a “Certificate of Need” (CON) before making large capital investments. In March 1978, the federal government issued guidelines for CT CONs: new CTs could not be approved unless existing CTs in the area where the new CTs would be used were performing at least 2,500 scans per year. The guidelines helped trigger a thirty-three percent decline in sales in 1978.\textsuperscript{21}

Declining sales in the US—which had accounted for two-thirds of the worldwide CT market—forced eight companies with low market shares to exit.\textsuperscript{22} (See Exhibit 6) EMI merged with Thorn Electrical Industries in 1979, and Thorn-EMI sold its CT division to GE the following year.\textsuperscript{23} Seven players remained—Technicare (acquired by Johnson & Johnson in 1978), GE, Elscint, Siemens, Picker, Philips, and Toshiba. GE led the market with almost thirty-three percent of 1979 sales.

US sales stabilized in 1979 and yearly sales then increased five-fold in the 1980s (See Figure 1) as producers who had survived the slowdown learned to navigate regulatory restrictions.\textsuperscript{24}

\textbf{Figure 1}  Annual CT sales in the United States 1977-1988 (number of units sold)

Source: Hillman (2011)
Producers and their customers even successfully lobbied for expanded insurance reimbursement for CT scanning. As mentioned, when EMI first introduced its scanners in the early 1970s, insurers did not pay for the procedures. By the early 1980s, both Medicare and private insurance companies reimbursed for CT scans. Insurers then tried to restrict reimbursements. In 1983, the Federal government’s Medicare program began paying hospitals a fixed fee for each patient’s diagnosis. For example, if a patient was diagnosed with a brain tumor at a hospital, the hospital would be paid a flat fee no matter how many CT scans had been made for the diagnosis.

Equipment producers then helped radiologists open mobile and freestanding imaging centers. The freestanding centers were exempt from reimbursement restrictions (and CON rules). The centers also offered imaging with MRI and ultrasound technologies that were emerging at the time. Unlike in older hospitals, their newly constructed facilities could be designed to accommodate new equipment. And physicians who invested in the centers could send patients to their centers. Leading producers supported the new freestanding imaging centers -- and found new sources of revenue -- by offering financing, service, support, and some lower-cost scanners.

Scanning of the chest, abdomen, and pelvis increased as hospitals purchased more body scanners (sometimes to replace older head scanners). Some larger hospitals purchased second scanners as their first CTs were more intensively utilized, and smaller hospitals bought their first CTs. Better computers and software, along with the use of contrast agents, improved the quality of images and broadened use. The improvements, however, were more incremental than radical. Contrast agents ingested or injected into patients’ bodies, for instance, had long been used to improve traditional X-rays. Initially, researchers did not believe contrast agents would help in CT scanning, but the agents were later used in CTs after studies showed they did enhance image quality.

Imatron, founded in 1983 by radiologist Douglas Boyd, did introduce a high-speed cardiac scanner in 1984, which it sold through larger companies. However, after a decade, only about seventy-five of Imatron’s scanners had been installed. The other entrants who started selling CTs in the US market in the 1980s -- Interad, Visiscan, Computer Medical Systems, and Meditech -- did not offer novel features, and all but Meditech soon exited. Meanwhile, GE increased its share in 1986 after acquiring Johnson and Johnson’s Technicare subsidiary (which had struggled with quality control problems) and by offering a wide range of products and other services (such as financing) to its customers.

CT installations grew three times faster in Japan than in the US (Figure 2), even though Japan had fewer radiologists per capita than any other OECD country. However, Japan had no CON-like restrictions on purchases. But, the government required everyone to buy health insurance (either through an employer or government-run program) and set the fee schedule for all health care providers. From 1973 to 1978, the fee for a CT scan was set at less than half the cost of a typical scan in the US at the time; in 1978, the difference in fees widened when the Japanese government cut the per-scan fee by more than half. The low reimbursements encouraged manufacturers to offer low-cost machines that were especially popular among small facilities (including some that did not have a board-certified radiologist on staff). Other OECD countries remained well behind Japan and the US in CT adoption. (See Exhibit 7) Regulators in six European countries -- Belgium, France, Greece, Italy, the Netherlands, and the United Kingdom -- restricted the number, geographic distribution, and use of scanners. Other countries, such as Denmark and Germany, had no explicit restrictions. Nevertheless, many health facilities in those countries limited their purchases of CTs.
Figure 2  CT installations in the United States and Japan 1978 vs 1986-87

Sources: Office of Technology Assessment (1981), Mitchell (1988), and OECD Health Statistics 2015

Questions (for reflection and discussion):
Before reading further, please write down (in less than ten words) what you found most significant or surprising in how the market for CTs evolved in the 1980s (and be prepared to explain why).

3. Combination Scanners (developed in the 1990s)

CT sales in the United States had stagnated after 1988, but in the mid-1990s, they again accelerated (See Figure 3) after the introduction of ‘combination’ scanners.31

Figure 3  CT Sales in the US 1988-1997 (numbers of units sold)

In 1988, the German company Siemens had introduced spiral scanners that made one fast, corkscrew-shaped pass across the length of the patient. (See Figure 4) Until then, X-ray beams had circled around and then moved across the patient, “slice-by-slice,” as it were. In 1992, the Israeli company Elscint introduced multislice scanners that also increased scanning speeds: these devices mounted X-ray sources and detectors in rows, imaging several slices at once. (According to some competitors, Elscint’s pioneering CTs increased speed but reduced image quality; this limited their clinical value and commercial attractiveness.)

Figure 4: X-ray path in conventional (A) and spiral (B) CT scans

Competitors raced to produce CTs that combined spiral and multislice designs. They eventually developed scanners that could acquire four times the image data, eight times faster than older CTs, thus reducing radiation exposures. The new scanners also supported more diagnostic applications; for example, because they more accurately revealed internal bleeding, they could be used to perform more trauma scans on the body and heads. They could also detect more problems within the heart and blood vessels. Improved diagnostic scanning was expected to enable new treatments—which in turn could encourage more scanning.

By 1997, worldwide CT sales were six times higher than in 1979. Growth in Asia—where CT prices were sharply lower than in other regions—was even higher than in the US (See Exhibit 8). The market had become more concentrated as more producers with low shares exited or were acquired. (See Figure 5). The leading competitors cross-licensed each other’s technologies (at annually renegotiated net fees). They all operated globally but typically had larger shares of their home markets.

GE remained the global market leader. It had established a strong presence in Japan through a joint venture that it had started in 1982 with the Yokogawa Electric Corporation. GE had also formed marketing and sales joint ventures in emerging economies such as India. GE’s CT business produced more than 100% of the cash flow of its medical devices division (which included MRIs and ultrasound). But, GE had lost share to Siemens and Elscint, which had pioneered new technologies, and to Toshiba and Shimadzu, which had introduced lower-cost CTs.
Figure 5  Market shares of worldwide CT sales – 1979 vs 1997

![Pie chart showing market shares of worldwide CT sales for 1979 and 1997, with GE leading in 1997 at 28%]


Questions (for reflection and discussion):
Looking forward from 1997, do you see significant opportunities or threats in CTs for GE? (Pick one or more options from the list below and be prepared to explain why.)
- See significant opportunities in the next five years.
- See significant threats in the next five years.
- Do not see significant opportunities OR threats in the next five years.

And (in less than ten words): If you had been appointed head of GE’s CT business in 1995, what would you have done to defend or expand GE’s position in CTs?
- ____________________________________________________
**Exhibit 1**  CT units installed in the US, Japan, and the rest of the world from 1975 to 2000.

![Graph showing CT units installed in the US, Japan, and the rest of the world from 1975 to 2000.](image)


**Exhibit 2**  The first CT scan ever made on a live human in 1971 showing a tumor (a black shadow in the upper left) in the brain (left) vs. a 2007 CT scan showing bleeding in the brain (right).

![CT scans](image)

Exhibit 3  Companies selling CTs, 1974-1978

<table>
<thead>
<tr>
<th>First Sold</th>
<th>Company (Origin)</th>
<th>Related Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>Technicare (US)</td>
<td>Diagnostic devices (Gamma cameras)</td>
</tr>
<tr>
<td>1974</td>
<td>Artronix (US)</td>
<td>Minicomputers</td>
</tr>
<tr>
<td>1975</td>
<td>General Electric (US)</td>
<td>Diagnostic devices (X-ray and mammography machines)</td>
</tr>
<tr>
<td>1975</td>
<td>Syntex (Mexico)</td>
<td>Pharmaceuticals</td>
</tr>
<tr>
<td>1976</td>
<td>American Science &amp; Engineering (US)</td>
<td>Scientific instruments, airport X-ray scanners</td>
</tr>
<tr>
<td>1976</td>
<td>Varian (US)</td>
<td>Lab equipment and diagnostic devices (Gamma cameras)</td>
</tr>
<tr>
<td>1976</td>
<td>Elscint (Israel)</td>
<td>Diagnostic devices (Gamma cameras)</td>
</tr>
<tr>
<td>1976</td>
<td>Searle (US)</td>
<td>Pharmaceuticals</td>
</tr>
<tr>
<td>1976</td>
<td>Siemens (Germany)</td>
<td>Diagnostic devices (X-ray, ultrasound, and mammography machines)</td>
</tr>
<tr>
<td>1977</td>
<td>Picker (US)</td>
<td>Diagnostic devices (X-ray machines and gamma cameras)</td>
</tr>
<tr>
<td>1977</td>
<td>Philips (Netherlands)</td>
<td>Diagnostic devices (X-ray machines)</td>
</tr>
<tr>
<td>1977</td>
<td>CGR (France)</td>
<td>Diagnostic devices (X-ray machines)</td>
</tr>
<tr>
<td>1977</td>
<td>Omni Medical (US)</td>
<td>Medical equipment</td>
</tr>
<tr>
<td>1978</td>
<td>Toshiba (Japan)</td>
<td>Diagnostic devices (X-ray and ultrasound machines)</td>
</tr>
</tbody>
</table>


Exhibit 4  Godfrey Hounsfield posing with the first EMI head scanner (left) and Robert Ledley posing with his design for the first whole body scanner (right)

Exhibit 5  Cumulative CT Installations in the United States, 1973-1977


<table>
<thead>
<tr>
<th>Year of Exit</th>
<th>Company</th>
<th>Share of Installations at Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>Syntex</td>
<td>~ 2%</td>
</tr>
<tr>
<td>1978</td>
<td>Varian</td>
<td>~ 1%</td>
</tr>
<tr>
<td>1978</td>
<td>AS&amp;E</td>
<td>&gt; 1%</td>
</tr>
<tr>
<td>1978</td>
<td>Searle</td>
<td>~ 0%</td>
</tr>
<tr>
<td>1979</td>
<td>CGR</td>
<td>~ 0%</td>
</tr>
<tr>
<td>1979</td>
<td>Artronix</td>
<td>~ 2%</td>
</tr>
<tr>
<td>1981</td>
<td>Pfizer</td>
<td>~ 7%</td>
</tr>
<tr>
<td>1984</td>
<td>Omni Medical</td>
<td>&gt; 1%</td>
</tr>
</tbody>
</table>

Exhibit 7  CT adoption in OECD countries in 1986

Total Units Installed

Units installed per million of population.

Exhibit 8  Prices and Sales of CTs by Region (1994-1997)

Endnotes


3 Physicians could “see” rough outlines of tumors via radionuclide scanning or ultrasound at the time, but neither procedure showed the brain, so the tumor appeared to float in empty space. Cerebral arteriography and pneumo-encephalography revealed the blood and other fluids in the brain, but, as Dr. James Ambrose, who helped run EMI’s clinical trials, put it: “If I were a patient, I think I would be scared to death at the mere thought of having any of the last two mentioned investigations performed on me. …What we have required for a long time now is a system that would enable us to look at the structures of the brain without causing the patient fear or discomfort.” According to radiologist Ron Evans, who helped introduce computing to radiology in the 1970s, “[Pneumo-encephalography] is the study that is at the very top of my list of studies that I wouldn’t want done to myself.” xrayctscanner, The Scanner Story (Part 1 of 2 of Documentary Covering Early CT Development), 2011, https://www.youtube.com/watch?v=u_R47LDdlZM.


5 Cormack also suggested in his article that the two-dimensional cross sections could easily be layered into three-dimensional reconstructions of a body.


7 According to Beckmann, the DHSS’s advising radiologist, Evan Lennon, found Hounsfield “confusing but was reluctant to dismiss him,” even though “other eminent radiologists had already dismissed [Hounsfield] as a crank.” Lennon set up Hounsfield’s first meeting with Ambrose, at which “the conversation was difficult,” in part because Hounsfield focused on the technology and potential of the machine. However, after Hounsfield scanned a sample of brain tissue for Ambrose to inspect a few days later, Ambrose was convinced that the project had clinical merit. See Beckmann, “CT Scanning the Early Days,” 6; See also: Süsskind, “The Invention of Computed Tomography,” 52-59.


9 Prices in USD$ from Trajtenberg, Economic Analysis of Product Innovation, 92.

The pharmaceutical manufacturer Syntax was founded in 1944 in Mexico City, Mexico. It initially produced therapeutic steroids and synthesized an early birth control pill. In 1994, the company was acquired by Roche, a Swiss healthcare company. See Soto Laveaga, Gabriela. Jungle Laboratories: Mexican Peasants, National Projects and the Making of the Pill. (Duke University, 2009).


12 For prices of each company’s scanners from 1973-1982, see Trajtenberg, Economic Analysis of Product Innovation, 92-101; There was a single scanner, the Artronix head scanner, priced below EMI’s scanners, at $270,000. The rest were priced above EMI’s offerings when introduced. Artronix never became a major rival; it sold 31 scanners before going out of business in 1978. Pricing is also discussed in: Süsskind, “The Invention of Computed Tomography”; Kevles, Naked to the Bone; Blume, Insight and Industry.

13 Besides acquiring Digital Information Science Corp. in 1975, Pfizer began funding University of California, San Francisco’s magnetic resonance imaging (MRI) lab in 1976. These efforts to expand into imaging turned out to be unsuccessful, however, and Pfizer exited the field in 1981.

14 OmniMedical then acquired Neuroscan’s intellectual property.


23 The British government would not approve the sale of Thorn-EMI’s MRI business to GE, and Thorn-EMI subsequently sold its MRI business to GEC, a British electronics manufacturer that was expanding into medical imaging, in 1981.

24 Chart based on data published in Hillman, The Sorcerer’s Apprentice, 97.


29 Niki, “The Wide Distribution of CT Scanners in Japan.” According to sources in the Japanese government, “Small, private facilities can introduce CT, [but] only physicians, dentists, and clinical radiologists can use CT, because a license is required. Small, private facilities that own CT, may be operated without physician, dentist, or radiologist. However, it is illegal for these facilities’ staff to use CT. [Instead,] an external physician, dentist, or radiologist may visit these facilities, and then use CT. [In other words,] while facilities may own CT without radiologist legally, they cannot legally use CT without licensed physician, dentist, or radiologist. [In addition,] all physicians, dentists, and radiologists can radiate radiation to film (i.e., use CT), but only a radiologist can diagnose patients (i.e., examine the scanned image).”


31 Chart based on data published in Hillman, The Sorcerer’s Apprentice, 97.


33 Although the faster speed helped to reduce radiation dose for individual scans, some researchers have argued that increases in use and frequency of scans have increased patients’ radiation exposure overall.

