Working Paper 20-004

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 data[a]and using that capacity to improve tomographic X-ray images.

[a] 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.[6] 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.[7] 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.[8]

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,[9] 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:[10] 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,[11] 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**).[12]

Two of the larger and slightly later entrants acquired the technologies of two startups: [13] Pfizer, a pharmaceutical company seeking to diversify into medical imaging, acquired the rights to a CT scanner developed by Digital Information Science Corporation[14] (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.[15])

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.[16] 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.[17] Top models in 1977 were priced at $740,000, which was over twice the price of EMI's first model.[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. [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.[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.

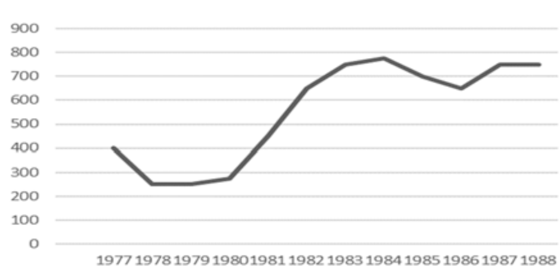
2. Broadening of Users and Uses (1980s)

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.[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. [22] (See **Exhibit 6**) EMI merged with Thorn Electrical Industries in 1979, and Thorn-EMI sold its CT division to GE the following year.[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.[24]

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.

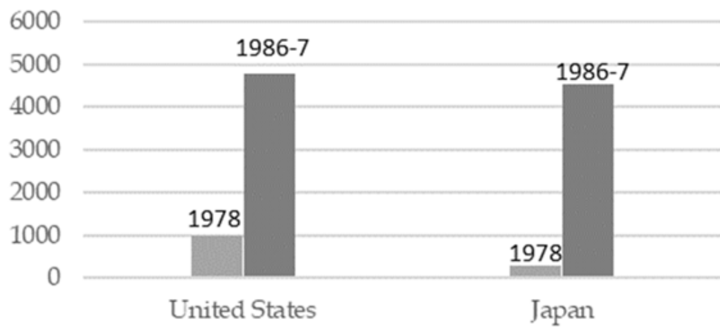
Scanning of the chest, abdomen, and pelvis increased as hospitals purchased more body scanners (sometimes to replace older head scanners). Some larger hospitals purchased second scanners as their first CTs were more intensively utilized, and smaller hospitals bought their first CTs.[25] Better computers 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. [26]

CT installations grew three times faster in Japan than in the US[27] **(Figure 2),** even though Japan had fewer radiologists per capita than any other OECD country.[28] 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).[29]

Other OECD countries remained well behind Japan and the US in CT adoption.[30] (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):

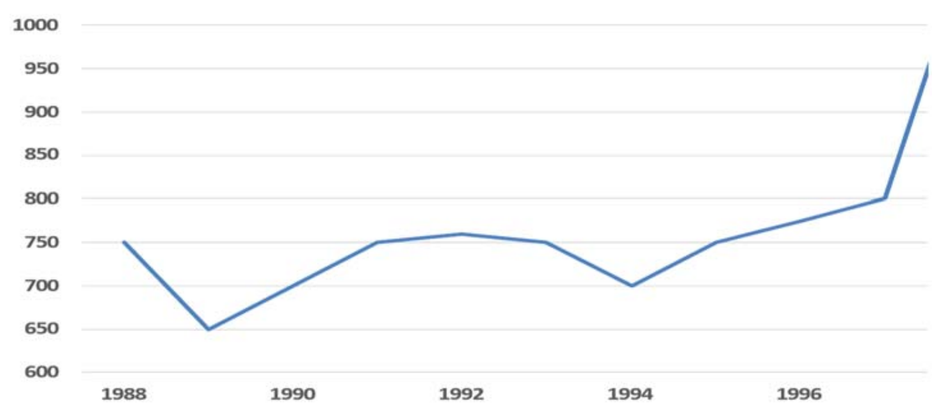
Before reading further, please write down (in less than ten words) what you found most significant or surprising in how the market for CTs evolved in the 1980s (and be prepared to explain why).

- ____

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]

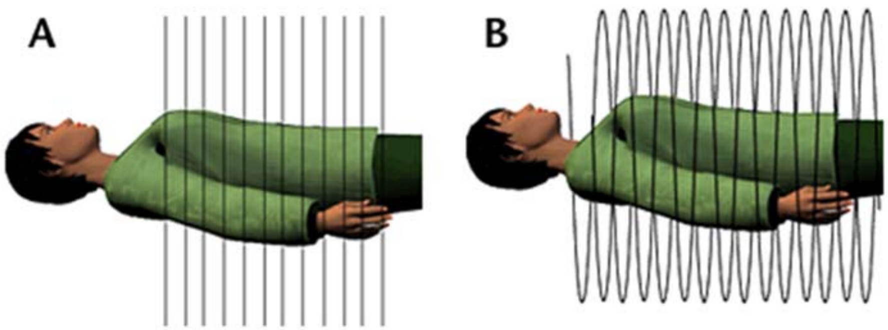
Figure 3 CT Sales in the US 1988-1997 (numbers of units sold)



Source: Bruce J. Hillman, *The Sorcerer's Apprentice: How Medical Imaging Is Changing Health Care* (Oxford; New York: Oxford University Press, 2011).

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



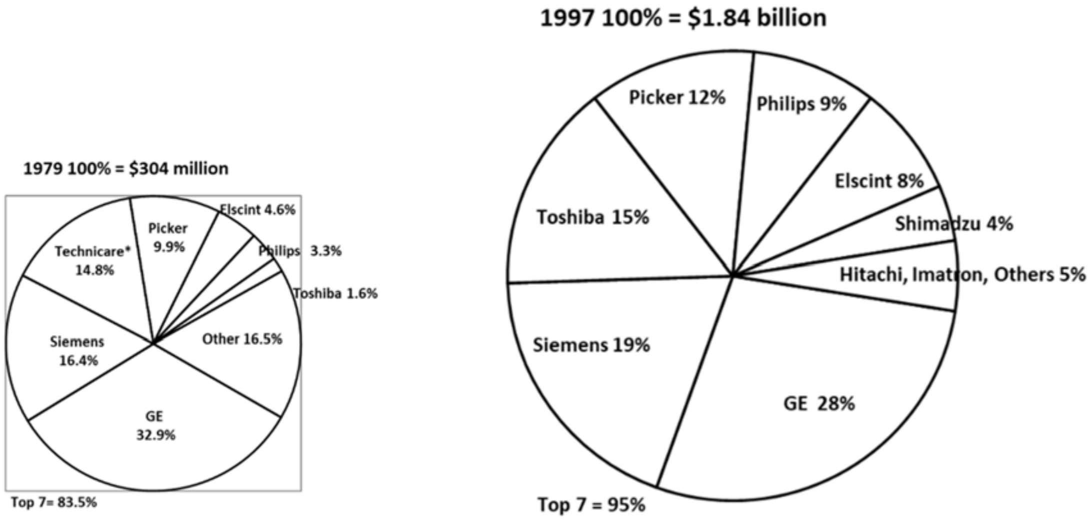
Source: Website of the National Cancer Institute, https://www.cancer.gov.

Competitors raced to produce CTs that combined spiral and multislice designs.[32] They eventually developed scanners that could acquire four times the image data, eight times faster than older CTs, thus reducing radiation exposures.[33] 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.[34]

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[35] (See **Exhibit 8)**. The market had become more concentrated as more producers with low shares exited or were acquired.[36] (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



Sources: "World X-ray and Computed Tomography Equipment Markets," Industry Research Report, January 7, 1999, Frost & Sullivan and The Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner: An Update: Background Paper*, OTA Background Papers; OTA-BP-H 8 (Washington, DC: The Office, 1981).

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.)

o See significant opportunities in the next five years.

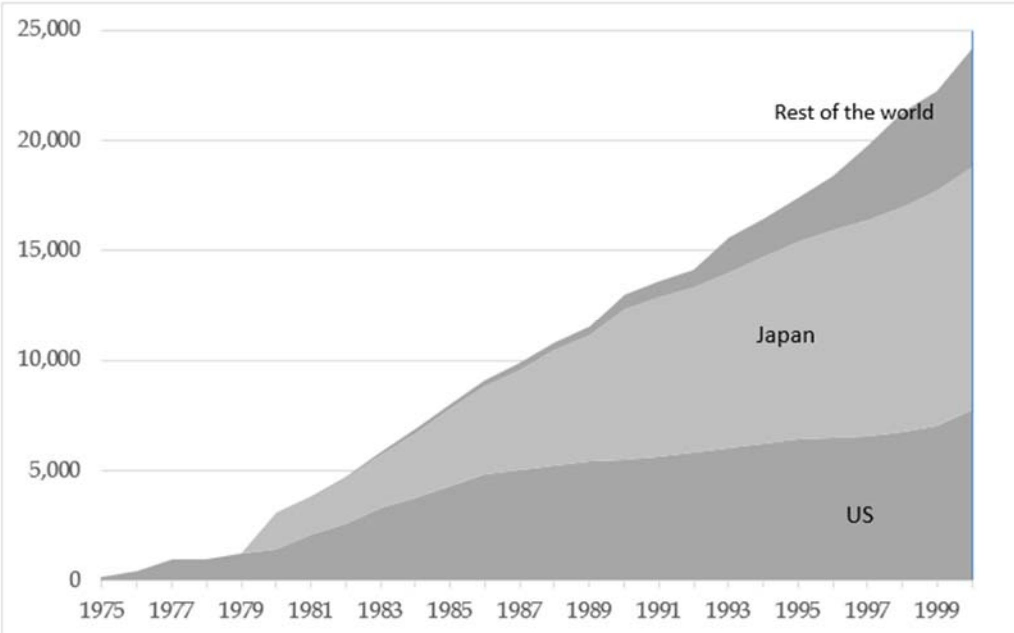
o See significant threats in the next five years.

o 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?

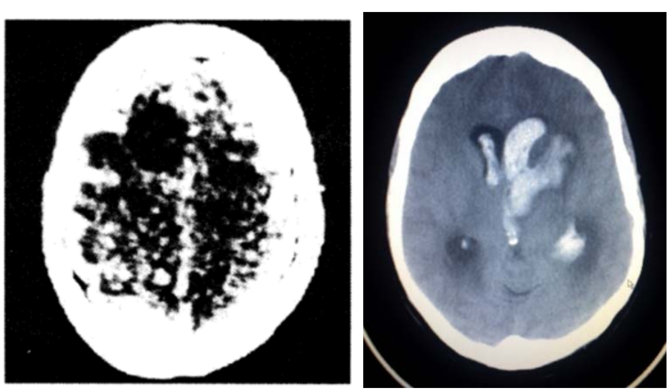
- ____

Exhibit 1 CT units installed in the US, Japan, and the rest of the world from 1975 to 2000.



Sources: "OECD Health Statistics 2015" https://www.oecd.org/health/health-systems/Focus-Health-Spending-2015.pdf, accessed November 2020.

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).



Source: Left image: Hounsfield, G. N. (1980), Computed medical imaging. Med. Phys., 7: 283-290. https://doi.org/10.1118/1.594709. Right image: "Intracerebral hemorrhage 2," Glitzy queen00, June 24, 2007, http://en.wikipedia.org/wiki/Image:Intracerebral_heamorrage_2.jpg on April 27, 2021.

Exhibit 3 Companies selling CTs, 1974-1978

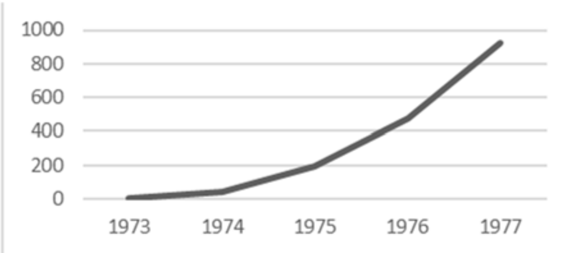
First Sold	Company (Origin)	Related Industries
1974	Technicare (US)	Diagnostic devices (Gamma cameras)
1974	Artronix (US)	Minicomputers
1975	General Electric (US)	Diagnostic devices (X-ray and mammography machines)
1975	Syntex (Mexico)	Pharmaceuticals
1976	American Science & Engineering (US)	Scientific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

Sources: Manuel Trajtenberg, *Economic Analysis of Product Innovation : The Case of CT Scanners*, Harvard Economic Studies; v. 160 (Cambridge, Mass: Harvard University Press, 1990) and William Gordon Mitchell, "Dynamic Commercialization: An Organizational Economic Analysis of Innovation in the Medical Diagnostic Imaging Industry" (Ph.D., University of California, Berkeley, 1988), http://search.proquest.com.ezp-prod1.hul.harvard.edu/docview/303668403/abstract?.

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)


Source: Left image: Richmond C. (2004). Sir Godfrey Hounsfield. BMJ: British Medical Journal, 329(7467), 687. Right image: Ledley, Fred "Robert Ledley with ACTA at Smithsonian" available at https://commons.wikimedia.org/wiki/ File: Robert_Ledley_with_ACTA_at_Smithsonian.jpg. CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0/deed.en.

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



Sources: The Office of Technology Assessment. Health Program, *Policy Implications of the Computed Tomography (CT) Scanner.*, OTA-H-56 (Washington: Congress of the United States, Office of Technology Assessment, 1978) and Steinberg, EP. "The status of MRI in 1986: rates of adoption in the United States and worldwide." AJR Am J Roentgenol. 1986 Sep;147(3):453-5. doi: 10.2214/ajr.147.3.453. PMID: 3488645.

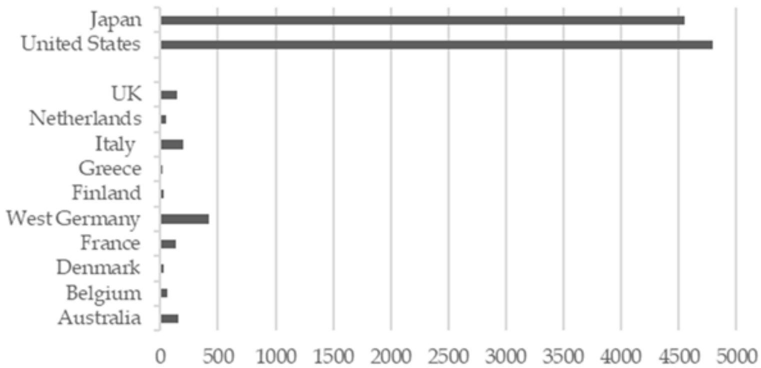
Exhibit 6 Exits from CT industry, 1978-1984.

Year of Exit	Company	Share of Installations at Exit
1978	Syntex	~ 2%
1978	Varian	~ 1%
1978	AS&E	> 1%
1978	Searle	~ 0%
1979	CGR	~ 0%
1979	Artronix	~ 2%
1981	Pfizer	~ 7%
1984	Omni Medical	> 1%

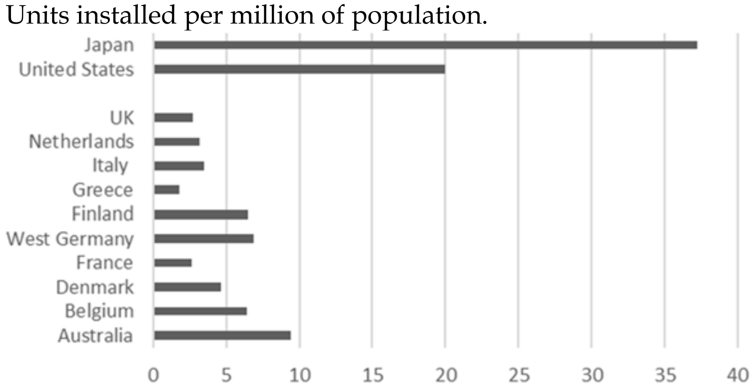
Sources: Manuel Trajtenberg, *Economic Analysis of Product Innovation : The Case of CT Scanners*, Harvard Economic Studies; v. 160 (Cambridge, Mass: Harvard University Press, 1990), William Gordon Mitchell, "Dynamic Commercialization: An Organizational Economic Analysis of Innovation in the Medical Diagnostic Imaging Industry" (Ph.D., University of California, Berkeley, 1988), http://search.proquest.com.ezp-prod1.hul.harvard.edu/docview/303668403/abstract?, and Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner : An Update : Background Paper*, OTA Background Papers ; OTA-BP-H 8 (Washington, DC: The Office, 1981).

Exhibit 7 CT adoption in OECD countries **in 1986**

Total Units Installed

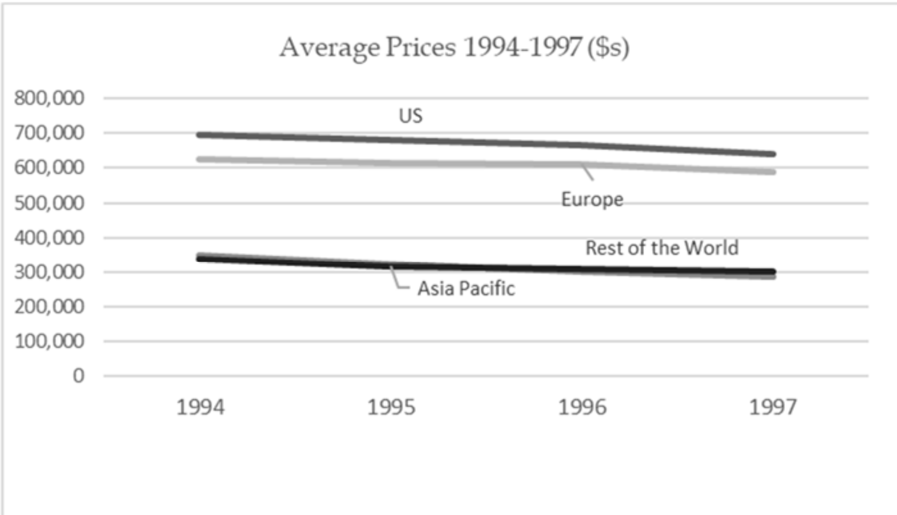


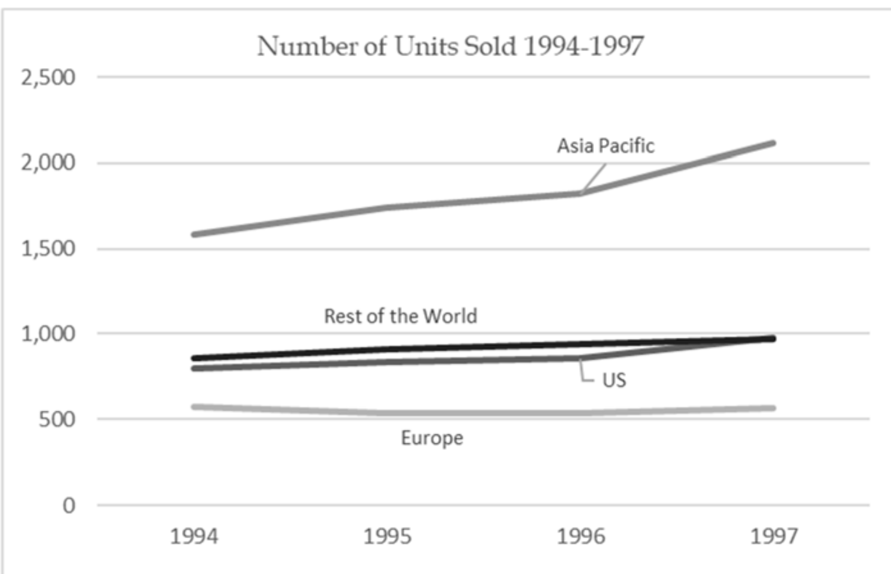
Units installed per million of population.



Sources: "OECD Health Statistics 2015" https://www.oecd.org/health/health-systems/Focus-Health-Spending-2015.pdf; Barbara Stocking and England, "EEC Workshop on Regulatory Mechanisms Concerning Expensive Health Technology" London, *Expensive Health Technologies : Regulatory and Administrative Mechanisms in Europe*, Commission of the European Communities Health Services Research Series. No. 5 (Oxford ; New York: Oxford University Press, 1988), and; Le Galès C, Lefaure C, Fagnani F, Héran F. "Contrasted diffusion and the use of CT scanner equipment in France." *European Journal of Radiology*. 1988 Nov;8(4):203-207..

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





Sources: "World X-ray and Computed Tomography Equipment Markets," Industry Research Report, January 7, 1999, Frost & Sullivan, Figures 10-05, 10-11, 10-17, and 10-22

Endnotes

[1] Table based on data available from Organization for Economic Cooperation and Development. Years missing in between years reported estimated based on previous and subsequent growth in installations. See: Organization for Economic Cooperation and Development. (2015). Health Statistics. Health Care Resources: Medical Technology [Table]. Accessed December 2015 from OECD iLibrary, http://eresources.library.nd.edu/resources/1680/15630.

[2] S. Webb, "Historical Experiments Predating Commercially Available Computed Tomography," *The British Journal of Radiology* 65, no. 777 (September 1992): 835–37, doi:10.1259/0007-1285-65-777-835; Steve Webb, *From the Watching of Shadows: The Origins of Radiological Tomography* (Bristol; New York: A Hilger, 1990).

[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.

[4] Allan M. Cormack - Nobel Lecture: Early Two-Dimensional Reconstruction and Recent Topics Stemming from It," accessed February 26, 2016, http://www.nobelprize.org/nobel_prizes/medicine/laureates/1979/cormack-lecture.html; Cormack, "Early Two-Dimensional Reconstruction and Recent Topics Stemming from It".

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

[6] Charles Susskind offers the most detailed account of EMI's development and launch of the CT scanner. Charles Süsskind, "The Invention of Computed Tomography," *History of Technology* 6 (1981): 39. See also: "Godfrey N. Hounsfield - Nobel Lecture: Computed Medical Imaging," accessed June 30, 2016, https://www.nobelprize.org/nobel_prizes/medicine/laureates/1979/hounsfield-lecture.html; "Godfrey N. Hounsfield - Biographical," accessed February 26, 2016, http://www.nobelprize.org/nobel_prizes/medicine/laureates/1979/hounsfield-bio.html; Kevles, *Naked to the Bone*; Blume, *Insight and Industry*; Riley E. Alexander and Richard B. Gunderman, "EMI and the First CT Scanner," *Journal of the American College of Radiology* 7, no. 10 (October 2010): 778–81, doi:10.1016/j.jacr.2010.06.003; Lawrence R. Goodman, "The Beatles, the Nobel Prize, and CT Scanning of the Chest," *Radiologic Clinics of North America*, Thoracic MDCT Comes of Age, 48, no. 1 (January 2010): 1–7, doi:10.1016/j.rcl.2009.09.008; Zeev V. Maizlin and Patrick M. Vos, "Do We Really Need to Thank the Beatles for the Financing of the Development of the Computed Tomography Scanner?:," *Journal of Computer Assisted Tomography* 36, no. 2 (2012): 161–64, doi:10.1097/RCT.0b013e318249416f; E C Beckmann, "CT Scanning the Early Days," *The British Journal of Radiology* 79, no. 937 (January 1, 2006): 5–8, doi:10.1259/bjr/29444122.

[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.

[8] Beckmann, "CT Scanning the Early Days," 6.

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

[10] Adoption statistics from: Manuel Trajtenberg, *Economic Analysis of Product Innovation : The Case of CT Scanners*, Harvard Economic Studies ; v. 160 (Cambridge, Mass: Harvard University Press, 1990); United States. Congress. Office of Technology

Assessment. Health Program, *Policy Implications of the Computed Tomography (CT) Scanner.*, OTA-H-56 (Washington: Congress of the United States, Office of Technology Assessment, 1978); Stanley Joel Reiser and Michael Anbar, *The Machine at the Bedside: Strategies for Using Technology in Patient Care* (Cambridge University Press, 1984); United States. Congress. Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner : An Update : Background Paper*, OTA Background Papers ; OTA-BP-H 8 (Washington, DC: The Office, 1981); William Gordon Mitchell, "Dynamic Commercialization: An Organizational Economic Analysis of Innovation in the Medical Diagnostic Imaging Industry" (Ph.D., University of California, Berkeley, 1988), http://search.proquest.com.ezp-prod1.hul.harvard.edu/docview/303668403/abstract?; For examples of the books that helped radiologists learn more about CT, see: Robert Steven Ledley, *Cross-Sectional Anatomy : An Atlas for Computerized Tomography* (Baltimore: Williams & Wilkins, 1977); Alvin C. Wyman, *Transverse Anatomy of the Human Thorax, Abdomen, and Pelvis : An Atlas of Anatomic, Radiologic Computed Tomographic, and Ultrasonic Correlation* (Boston: Little, Brown, 1978); Ralph J. Alfidi, *Computed Tomography of the Human Body : An Atlas of Normal Anatomy* (Saint Louis: Mosby, 1977).

[11] The pharmaceutical maker Syntex 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] Six entrants in this first wave—General Electric (GE), Siemens, Philips, Picker, Toshiba, and Elscint—would continue to dominate CT (although in some of these cases under different corporate parents) while the rest would exit. Trajtenberg includes an in-depth, year-by-year discussion of entrants. Trajtenberg, *Economic Analysis of Product Innovation*; See also: Mitchell, "Dynamic Commercialization"; Kevles, *Naked to the Bone*; Blume, *Insight and Industry*; "Encyclopedia of Cleveland History: TECHNICARE CORP.," accessed March 31, 2016, https://ech.case.edu/cgi/article.pl?id=TC1; A. B. Strong and R. A. A. Hurst, "EMI Patents on Computed Tomography; History of Legal Actions," *The British Journal of Radiology* 67, no. 795 (1994): 315–316; A. M. Cormack, "EMI Patent Litigation in the US," *The British Journal of Radiology* 67, no. 795 (1994): 316–17.

[13] Mitchell, "The Diagnostic Imaging Industry, 1896-1988," Chapter 5. "Guide to the Robert Ledley Papers NMAH.AC.1135," accessed February 29, 2016, http://amhistory.si.edu/archives/AC1135.html; Dean F. Sittig, Joan S. Ash, and Robert S. Ledley, "The Story Behind the Development of the First Whole-Body Computerized Tomography Scanner as Told by Robert S. Ledley," *Journal of the American Medical Informatics Association* 13, no. 5 (October 2006): 465–69; Robert S. Ledley, "Innovation and Creativeness in Scientific Research: My Experiences in Developing Computerized Axial Tomography," *Computers in Biology and Medicine* 4, no. 2 (1974): 133–136, doi:10.1016/0010-4825(74)90014-6; "Our History," *Pfizer: The World's Largest Research-Based Pharmaceutical Company*, accessed April 6, 2016, http://www.pfizer.co.uk/content/our-history.

[14]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.

[15] OmniMedical then acquired Neuroscan's intellectual property.

[16] Süsskind, "The Invention of Computed Tomography," 39-80; Banta, "Embracing or Rejecting Innovations: Clinical Diffusion of Health Care Technology," in Reiser and Anbar, *The Machine at the Bedside,* 73; See also: United States. Congress. Office of Technology Assessment. Health Program, *Policy Implications of the Computed Tomography (CT) Scanner*; Ulf Berggren, "CT Scanning and Ultrasonography: A Comparison of Two Lines of Development and Dissemination," *Research Policy*, Special Issue on Innovation in Medical Technology, 14, no. 4 (August 1985): 213–23, doi:10.1016/S0048-7333(85)80013-5.

[17] 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*.

[18] According to Tratjenberg, the average price of a head scanner was USD$354,000 and the average price for a body scanner was USD$573,000 in 1977. The next year, in 1978, the average price for head scanners dropped to USD$167,000. By 1982, the average cost of a head scanner had dropped to $150,000. The price of body scanners continued to rise after 1977; in 1978 the average body scanner was USD$620,000 and by 1982, the average price of a body scanner had climbed to USD$820,000. See Tratjenberg, Manuel, "The Welfare Analysis of Product Innovations, with an Application to Computed Tomography Scanners." *The Journal of Political Economy,* Vol. 97, No. 2 (Apr., 1989), pp. 455. See also note 14.

[19] Hospital categories used here are based on the American Hospital Association's statistics.

[20] In hearings before the Senate subcommittee, Carter's Secretary of Health, Education, and Welfare Joseph Califano stated, "We do not need a CT scanner in every hospital in this country. …Every child does not need a Rolls Royce; every teenager does not need a Cadillac; every hospital does not need a CT scanner." See: *Hospital Cost Containment Act of 1977 :hearings before the Subcommittee on Health and Scientific Research of the Committee on Human Resources, United States Senate, Ninety-Fifth Congress, First Session, on S. 1391 ...* (Washington :, 1977), http://hdl.handle.net/2027/pur1.32754076792617; Ted Bogue and Sidney M. Wolfe, "CAT Scanners: Is Fancier Technology Worth a Billion Dollars of Health Consumer's Money?," *Journal of Computed Tomography* 1, no. 1 (March 1977): 59–68, doi:10.1016/S0149-936X(77)80010-6.

[21] The 1974 law was the Health Planning and Resources Development Act. About 20 states had CON laws prior to the 1974 Act (authorized under a section of an earlier Social Security law). The federal CON mandate was repealed in 1987, after which 14 states eliminated their CON laws. United States. Congress. Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner*; Süsskind, "The Invention of Computed Tomography"; Trajtenberg, *Economic Analysis of Product Innovation*; Blume, *Insight and Industry,* Chapter 5; Kevles, *Naked to the Bone,* Chapter 7; Banta, "The Diffusion of the Computed

Tomography (CT) Scanner in the United States"; Steinberg, Sisk, and Locke, "X-Ray CT and Magnetic Resonance Imagers. Diffusion Patterns and Policy Issues"; Bruce J. Hillman, *The Sorcerer's Apprentice: How Medical Imaging Is Changing Health Care* (Oxford; New York: Oxford University Press, 2011); A. L. Hillman and J. S. Schwartz, "The Adoption and Diffusion of CT and MRI in the United States. A Comparative Analysis," *Medical Care* 23, no. 11 (November 1985): 1283–94; Jennie J. Kronenfeld, *The Changing Federal Role in U.S. Health Care Policy* (ABC-CLIO, 1997); "CON-Certificate of Need State Laws," accessed July 31, 2015, http://www.ncsl.org/research/health/con-certificate-of-need-state-laws.aspx.

[22] For year of entry and departure, see: Trajtenberg, *Economic Analysis of Product Innovation,* 52; As well as: Mitchell, "The Diagnostic Imaging Industry, 1896-1988," Chapter 5. For percentage of total scanners installed by May 1980, see: United States. Congress. Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner*; in some cases, the "final" market share as of 1980 listed in the OTA report is smaller than that recorded in the mid-1970s and listed in Trajtenberg. See also: Blume, *Insight and Industry,* Chapter 5; Süsskind, "The Invention of Computed Tomography"; Mitchell, "Dynamic Commercialization"; Walter L Robb, "Perspective on the First 10 Years of the CT Scanner Industry," *Academic Radiology* 10, no. 7 (July 2003): 756–60, doi:10.1016/S1076-6332(03)80121-6; M. L. Phillips and D. A. Durick, "Diffusion of an Innovation: Adoption of CT Scanners," *Radiologic Technology* 57, no. 2 (December 1985): 137–40; Berggren, "CT Scanning and Ultrasonography."

[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.

[25] R. G. Evens and R. G. Jost, "Computed Tomography Utilization and Charges in 1981," *Radiology* 145, no. 2 (November 1982): 427–29, doi:10.1148/radiology.145.2.7134447; E. P. Steinberg, G. F. Anderson, and D. M. Steinwachs, "Changes in CT Utilization between 1981 and 1984: Implications for Medicare Payment for MR Imaging under the Prospective Payment System," *Radiology* 165, no. 1 (October 1987): 279–81, doi:10.1148/radiology.165.1.3114824; The number of scanners installed in hospitals based on data published in: American Hospital Assn, *Hospital Statistics: Data from the American Hospital Association's Annual Survey*s; Number of scanners placed in private clinics based on estimates in: Trajtenberg, *Economic Analysis of Product Innovation,* 66-67; L. Souhrada, "Imaging Devices' Shifting Uses Affect Market," *Hospitals* 64, no. 21 (November 5, 1990): 28–31; F. Cerne, "Computed Tomography Alive and Well," *Hospitals* 62, no. 21 (November 5, 1988): 65–66, 69; "CT in the ER," accessed March 1, 2016, http://www.radiologytoday.net/archive/rt0711p16.shtml; Kevles, *Naked to the Bone,* Chapter 7, especially the discussion on 146-147, and 166-167.

[26] Mitchell, "The Diagnostic Imaging Industry, 1896-1988," Chapter 5. Geisler and Heller, *Management of Medical Technology,* Case 11; Kevles, *Naked to the Bone,* 166.

[27] Chart based on data published by: United States. Congress. Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner,* 15; and Mitchell, "Dynamic Commercialization"; and "OECD Health Statistics 2015 - OECD," accessed July 28, 2015, http://www.oecd.org/els/health-systems/health-data.htm; See also: Ryu Niki, "The Wide Distribution of CT Scanners in Japan," *Social Science & Medicine* 21, no. 10 (1985): 1131–37, doi:10.1016/0277-9536(85)90171-6.

[28] Masatoshi Matsumoto et al., "Geographic Distribution of Radiologists and Utilization of Teleradiology in Japan: A Longitudinal Analysis Based on National Census Data," ed. Toshiyuki Ojima, *PLOS ONE* 10, no. 9 (September 30, 2015): e0139723, doi:10.1371/journal.pone.0139723.

[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)."

[30] Chart data from Japan from 1987; all other figures from 1986. Australia (1987), Japan (1987), and US (1986) data from the PECD. West Germany (1985 and 1987) data from Stocking; see also Schenzler and Tuohy. France and density data for UK/England (1985) from Le Gales, et al, and Stocking. All other data from Stocking. (See following citations.) "OECD Health Statistics 2015 - OECD"; Barbara Stocking and England) EEC Workshop on Regulatory Mechanisms Concerning Expensive Health Technology : London, *Expensive Health Technologies : Regulatory and Administrative Mechanisms in Europe*, Commission of the European Communities Health Services Research Series ; No. 5 (Oxford ; New York: Oxford University Press, 1988); C. Le Galès et al., "Contrasted Diffusion and the Use of CT Scanner Equipment in France," *European Journal of Radiology* 8, no. 4 (1988): 203–7; Christoph Schenzler, "The Effect of Competition and Regulation on the Diffusion of Major Medical Technologies in German and United States Hospitals" (Ph.D., Vanderbilt University, 1998), http://search.proquest.com.ezp-prod1.hul.harvard.edu/docview/304457501/abstract; William Tuohy, "West Germany Can't Count on Citizenry at Census

Time," *Los Angeles Times*, March 2, 1987, http://articles.latimes.com/1987-03-02/news/mn-4300_1_census-time; For standing as of 1990, see: P. Lazaro and K. Fitch, "The Distribution of Big Ticket Medical Technologies in OECD Countries," *International Journal Of Technology Assessment In Health Care* 11, no. 3 (1995): 552–570.

[31] Chart based on data published in Hillman, *The Sorcerer's Apprentice*, 97.

[32] The combination increased patient throughput. Sources: Thomas, *The History of Radiology*, 112-115; James Brice, "Diagnostic Imaging at 30," *Diagnostic Imaging* 31, no. 11 (November 2009): 36–37,39,41,43; "New Breed of CT Creates MR-like Soft-Tissue Images | Diagnostic Imaging," January 10, 2008, http://www.diagnosticimaging.com/ge/new-breed-ct-creates-mr-soft-tissue-images-0; "Stanford 2008 Video - GE Unveils Ultrapremium CT | Diagnostic Imaging," May 15, 2008, http://www.diagnosticimaging.com/ge/stanford-2008-video-ge-unveils-ultrapremium-ct; "GE Turns CT Discussions from Slices to Volumes | Diagnostic Imaging," November 5, 2004, http://www.diagnosticimaging.com/ge/ge-turns-ct-discussions-slices-volumes; "GE Healthcare Unveils CT Scanner Sporting 64 Detector Rows | Diagnostic Imaging," April 7, 2004, http://www.diagnosticimaging.com/ge/ge-healthcare-unveils-ct-scanner-sporting-64-detector-rows; "Megaslice Scanners Trigger Second-Half Surge in CT Market | Diagnostic Imaging," July 18, 2005, http://www.diagnosticimaging.com/ct/megaslice-scanners-trigger-second-half-surge-ct-market; "Sixteen-Slice CTs Address Sweet Spot in U.S. Market | Diagnostic Imaging," September 12, 2005, http://www.diagnosticimaging.com/ct/sixteen-slice-cts-address-sweet-spot-us-market.

[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.

[34] Pediatric scanning increased during the period, as well, though not necessarily due to changes in the scanning technologies. "Nationwide Evaluation of X-ray Trends (NEXT) 2000 Survey," Conference of Radiation Control Program Directors, Inc., August 2007; "North American CT Imaging Market," Industry Research Report, 31 March 2009, Frost & Sullivan, accessed February 2016, slide 15; "World X-ray and Computed Tomography Equipment Markets," Industry Research Report, 7 January 1999, Frost & Sullivan, accessed February 2016, Figure 10-4. Mannudeep K. MD Kalra et al., "Multidetector Computed Tomography Technology: Current Status and Emerging Developments," *Journal of Computer Assisted Tomography Advances in Multi-Detector CT*, September 2003; "CT Outlook | Diagnostic Imaging," December 15, 2006, http://www.diagnosticimaging.com/articles/ct-outlook; Keith E. Kocher et al., "National Trends in Use of Computed Tomography in the Emergency Department," *Annals of Emergency Medicine* 58, no. 5 (November 2011): 452–462.e3, doi:10.1016/j.annemergmed.2011.05.020; Brian Casey, "CT the Surprise of the Show, Thanks to Multislice Scanners," *Diagnostic Imaging*, January 1999, IR28; James Brice, "Multidetector CT Generates 4-D Views of Occlusive Disease," *Diagnostic Imaging*, January 1999, IR40; Diego B. Nuñez, M. Stephen Ledbetter, and Lisa Farrell, "Dedicated CT Scanner in an

Emergency Department: Quantification of Factors That Contribute to Lack of Use," *American Journal of Roentgenology* 179, no. 4 (October 1, 2002): 859–62, doi:10.2214/ajr.179.4.1790859; A. F. MacNamara and P. A. Evans, "The Use of CT Scanning by Accident and Emergency Departments in the UK: Past, Present and Future," *Injury* 26, no. 10 (December 1995): 667–69, doi:10.1016/0020-1383(95)00147-6; Wayne T. Stockburger, "CT Imaging, Then and Now: A 30-Year Review of the Economics of Computed Tomography," *Radiology Management* 26, no. 6 (December 2004): 20–22, 24-27-30; "Heart Docs Embrace New Cardiac CT, MR Guidelines | Diagnostic Imaging," August 6, 2005, http://www.diagnosticimaging.com/ct/heart-docs-embrace-new-cardiac-ct-mr-guidelines; "CT Shines as Cardiac Triage Tool in the ER | Diagnostic Imaging," November 30, 2005, http://www.diagnosticimaging.com/ct/ct-shines-cardiac-triage-tool-er; "64-Slice CT Enters Clinical Practice Realm | Diagnostic Imaging," April 2, 2006, http://www.diagnosticimaging.com/ct/64-slice-ct-enters-clinical-practice-realm.

[35] Charts based on data published in "World X-ray and Computed Tomography Equipment Markets," Industry Research Report, 7 January 1999, Frost & Sullivan, accessed February 2016, Figures 10-05, 10-11, 10-17, and 10-22.

[36] Charts based on data collected and published by Frost & Sullivan and the OTA. See: "World X-ray and Computed Tomography Equipment Markets," Industry Research Report, 7 January 1999, Frost & Sullivan, accessed February 2016, Figures 10-27 and 10-34. and the United States. Congress. Office of Technology Assessment, *Policy Implications of the Computed Tomography (CT) Scanner*, 22.