

Case Histories of Significant Medical Advances: Computed Tomography

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Computed Tomography

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Abstract: We describe 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) development of the first CT scanner (through the early-1970s); 2) rapid and enthusiastic adoption of CT scanning (until the late 1970s); 3) regulatory backlash against the perceived overuse of this expensive technology (in the 1980s); and 4) innovations that reignited growth (in the 1990s and 2000s).

Note: This case history, like the others in this series, 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 major 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 to the researchers. Limitations of space and information severely limit coverage of developments in emerging economies.

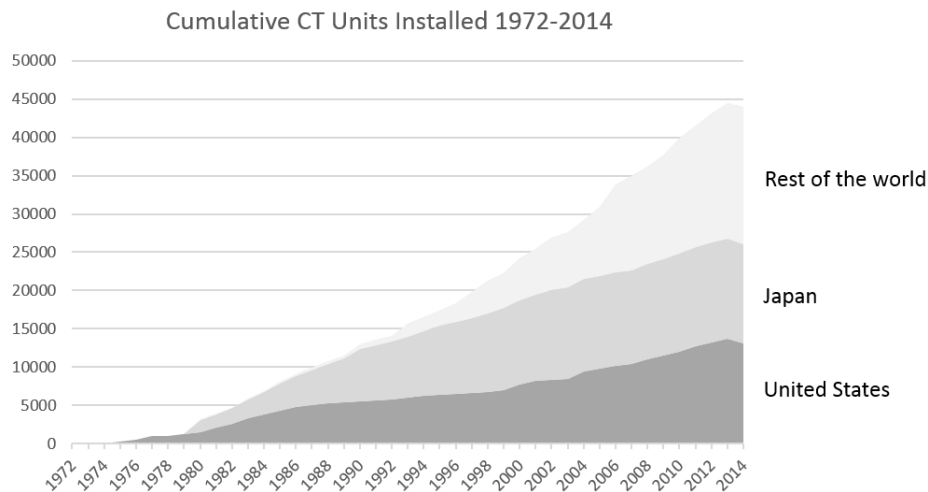
Acknowledgments: We would like to thank Kirby Vosburgh for helpful information and suggestions.

Computed Tomography

Computed tomography (CT) scanners have become ubiquitous since they were first offered for sale in 1972.¹ (See **Figure 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 industry has been global in its scope from the outset, but significant regional variations in use, prices, and competitive positions have also emerged. Japan has become the largest market both in terms of the number of scanners overall and the number of scanners per person.² (See **Exhibit 1**) Prices there are typically lower, but companies that dominate the Japanese market do not have equivalently large shares outside Japan.

Figure 1



Source: The Organization for Economic Cooperation and Development (OECD, 2015).

The next four sections of this case history describe: the development of the first CT scanner (through the early-1970s); rapid adoption (until the late 1970s); regulatory setbacks and recovery (in the 1980s); and the innovations (in the 1990s) that reignited growth. The concluding section summarizes developments after 2000.

1. Developing the First Scanner (1963-1971)

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.

To overcome these limitations, innovative physicians 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.³ 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).⁴

Physicist Allan Cormack first proposed a method to improve tomographic imaging in a 1963 article published in the *Journal of Applied Physics*.⁵ 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.⁶ Cormack's article generated no medical interest, however.

Instead, five years later, Godfrey Hounsfield, an engineer at the British entertainment giant EMI^a (who did not know of Cormack's paper) 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. There, he thought about using computers to recognize and display patterns of numerical data^b, and using that capacity to improve tomographic X-ray images. Hounsfield wrote up a proposal to build a scanner based on these ideas and, in 1968, the board that oversaw 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.⁷ 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.⁸ 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.⁹

2. Rapid Adoption (1972-1977)

The very next year, EMI started selling head scanners, targeting the U.S. 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. Large, prestigious teaching and research hospitals, such as Georgetown and Cleveland Clinic, were early buyers and set the stage for wider use:¹⁰ researchers and clinicians at these hospitals published journal articles and textbooks that taught other radiologists how to interpret CT images.^c

EMI's CT division became profitable in three years. Orders for the scanners, priced at USD\$310,000,¹¹ soon exceeded EMI's manufacturing capacity and in 1976 the company started building a plant to assemble CT scanners in the United States.

Rapid CT adoption attracted fourteen other companies. EMI, which had patented its technology, sued the newcomers for patent infringement but failed to block their entry. The entrants, based in France,

^a EMI stands for Electric & Musical Industries.

^b Hounsfield's prior service in the Royal Air Force during World War II, when he had worked with radar installations, influenced his 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.

^c Although (as mentioned) CT built on the technique of X-ray tomography, CT images were plotted on grid on a computer screen and looked quite different from traditional X-ray photographs. See, for example, **Exhibit 3** (which includes the first scan ever made on a live human).

Germany, Israel, Japan, Mexico,¹² the Netherlands, and the United States, already served health care markets -- some sold X-ray and other medical equipment, others sold pharmaceuticals (See **Table 1**). 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.¹³

Table 1 Entrants to emerging CT industry, 1974-1978

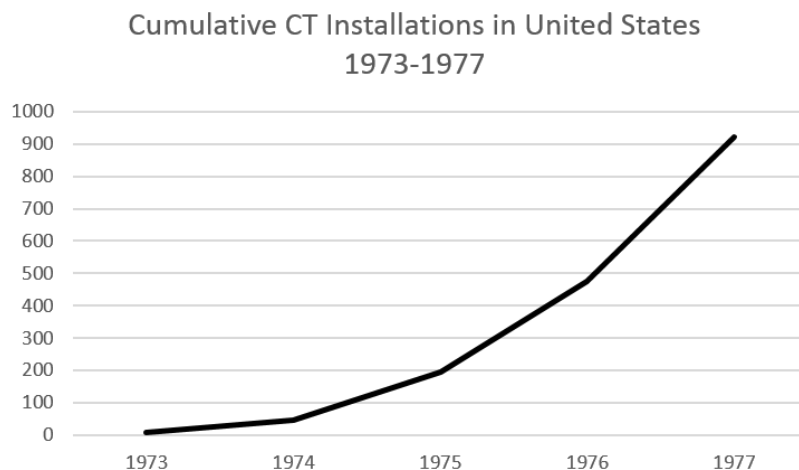
First Sold	Company (Origin)	Related Industries
1974	Technicare (US)	Diagnostic devices (Gamma cameras)
1974	Artronix (US)	Minicomputers
1975	General Electric (US)	Diagnostic devices (X-ray and mammography machines)
1975	Syntex (Mexico)	Pharmaceuticals
1976	American Science & Engineering (US)	Scientific 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: Trajtenberg (1990) and Mitchell (1988).

EMI and its rivals raced to improve the performance of CTs. The new CTs were larger: where EMI's 1972 machine could only accommodate heads, subsequent scanners could scan entire bodies. (See Exhibit 2) New CTs also had better X-ray detectors and rotated more quickly around patients. These improvements provided sharper images at a faster pace – but at higher prices.¹⁴ Top models in 1977 were priced at USD\$740,000, which was over twice the price of EMI's first model.¹⁵

Despite the higher prices, over 900 scanners were purchased and installed in the United States by 1977, mainly in large hospitals. (See **Figure 2**) Three-quarters of U.S. hospitals with over 500 beds and over half of hospitals with between 400-500 beds had at least one CT machine.¹⁶

Figure 2



Sources: The Office of Technology Assessment (1978) and Steinberg (1985).

As CT sales grew, EMI's dominance diminished. EMI's rivals secured forty-two percent of U.S. market by 1977.¹⁷ In whole body scanners, GE's sales actually surpassed EMI's, as the unexpected death of an EMI executive delayed the commissioning of the company's American CT assembly plant.

Two startups exited.¹⁸ In 1975, one, Digital Information Science Corporation,^d sold the rights to its scanner to Pfizer, a pharmaceutical company seeking to diversify into medical imaging,^e and the other, Neuroscan, licensed its scanner to GE (which already had a sizable X-ray business).^f

3. Regulatory Setbacks and Recovery (1978-1988)

Rapid adoption of expensive CT scanners provoked a backlash. Rising costs of health care had been an issue during the 1976 U.S. elections and 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.¹⁹

The backlash coincided with, and to a degree was reflected in, stricter enforcement of a law that had been passed in 1974 by the U.S. 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 1978.²⁰

These sales declines in the U.S. — which had accounted for two thirds of the worldwide CT market -- forced eight companies, all with single digit market shares, to exit.²¹ (See **Table 2**) EMI merged with Thorn Electrical Industries in 1979, and the following year, Thorn-EMI sold its CT division to GE.^g Seven players remained — Technicare, GE, Elscint, Siemens, Picker, Philips, and Toshiba — and GE led the market with almost thirty-three percent of 1979 sales.^h

Table 2 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: Trajtenberg (1990), Mitchell (1988), and the Office of Technology Assessment (1981).

^d Digital Information Science Corporation was formed by Robert Ledley, a Georgetown researcher who had designed the first full-body CT scanner (the "ACTA" — See **Exhibit 2**).

^e 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.

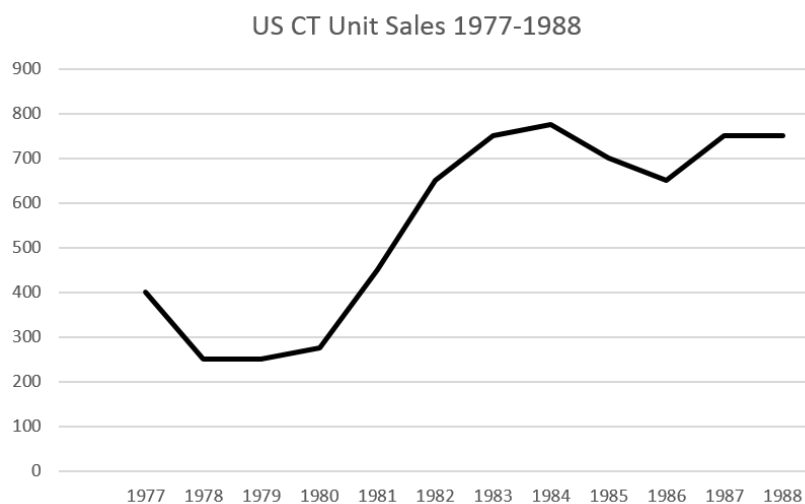
^f After GE introduced its own scanner in 1976, Neuroscan declared bankruptcy. OmniMedical then acquired Neuroscan's intellectual property.

^g 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.

^h GE gained additional share in 1986 when it bought Technicare (which had struggled with quality control issues) from parent company Johnson & Johnson.

U.S. sales recovered in the 1980s, however, as CT producers and their customers learned to navigate regulatory restrictions.²² (See **Figure 3**) In fact, the industry successfully lobbied to expand insurance reimbursement for CT scanning.ⁱ Later, as the federal government and insurance companies tried to restrict reimbursement,^j radiologists opened mobile and then freestanding imaging centers. The freestanding centers were exempt from reimbursement restrictions (and CON rules)^k and also offered imaging with MRI and ultrasound technologies that were emerging at the time.

Figure 3



Source: Hillman and Goldsmith (2010).

Leading producers also increased sales of CTs and found new sources of revenue by offering financing, service, support, and some lower-cost scanners (See box “GE’s CT offerings”). The broadened offerings were particularly helpful to the new freestanding imaging centers.

New uses and users contributed to the recovery. Scanning of the chest, abdomen, and pelvis increased as hospitals purchased more body scanners (sometimes to replace older head scanners). Better computers and software coupled with the use of contrast agents^l improved the quality of images and broadened use. Some larger hospitals purchased second scanners as their first CTs were more intensively utilized, and smaller hospitals bought their first CTs.²³

ⁱ When CT scanners were first introduced, they were not covered by private or public insurance. In order to receive reimbursement from a government-run public health insurance program, such as Medicare, companies had to show proof of the device’s effectiveness. EMI head scanners were the first to submit evidence of effectiveness and gain approval for reimbursement under this system. By the early 1980s, both Medicare and private insurance companies reimbursed for CT scans.

^j In 1983, Medicare began paying hospitals a fixed flat fee for each patient’s diagnosis, rather than reimbursing for each scan made. 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 were needed to make and confirm the diagnosis.

^k Freestanding imaging centers also had other advantages over hospitals: new constructions that could better accommodate large devices and the ability of physicians who invested in the centers to direct patients to their own facilities.

^l Contrast agents are compounds that are ingested or injected into body before a patient has an X-ray or a scan to improve the image produced. Such agents had long been used to improve X-rays; although researchers thought they would offer no advantage in CT scanning, studies later found that contrast agents did enhance the quality of a scan.

GE's CT offerings

GE drew on the resources and expertise from its other businesses (such as GE Capital, GE Information Services, GE Consulting Services, Employers Reinsurance) to offer a wide range of services to CT buyers. These included:

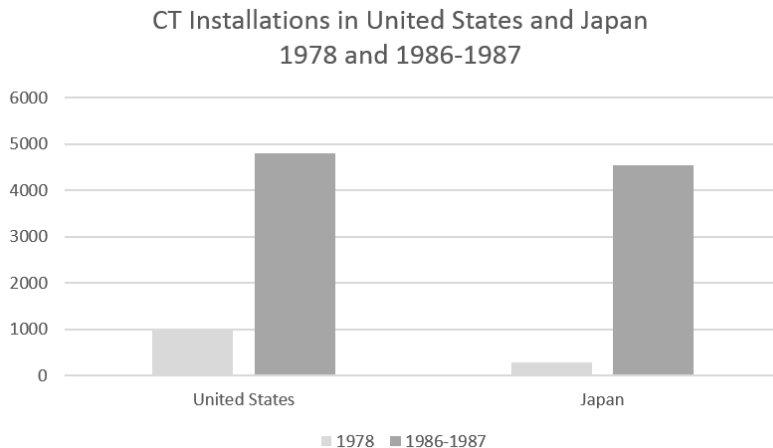
- Loans for freestanding imaging centers.
- Leases for equipment.
- Business insurance.
- Malpractice insurance.
- Office software and automation packages.
- Office systems design and consulting.
- Telephone and on-site technical and repair services (24-hours).
- Automated ordering systems for supplies and accessories.
- Construction services for freestanding imaging centers.

GE also widened its product line to include cheaper CTs produced by its Japanese joint venture, GE Yokogawa Medical Systems.

The recovery had attracted four entrants to the U.S. market, but their scanners did not have any novel features^m -- basic CT technology remained much as it was in 1980. 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.²⁴

While installations in the U.S. increased five-fold in the 1980s, CT sales grew three times faster in Japan, with installations in Japan increasing fifteen-fold²⁵ even though Japan had fewer radiologists per capita than any other OECD country.²⁶ (See **Figure 4**)

Figure 4



Sources: The Office of Technology Assessment (1981), Mitchell (1988), and the Organization for Economic Cooperation and Development (2015).

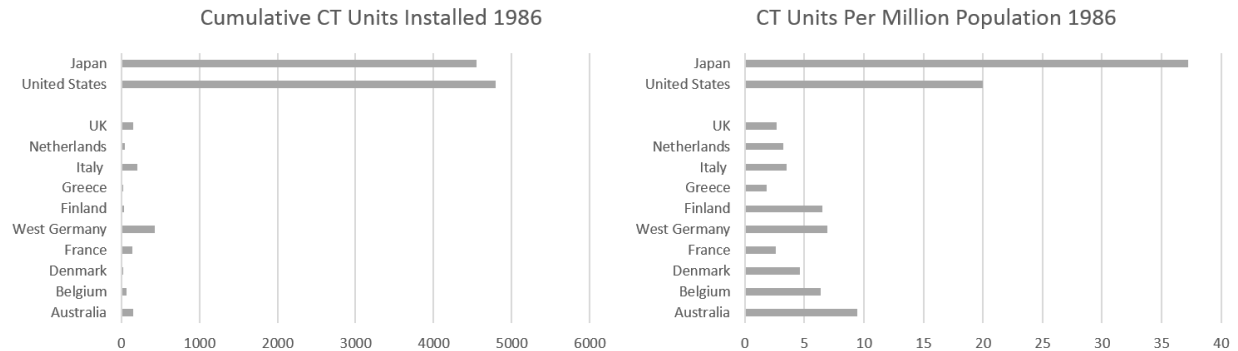
The seemingly anomalous demand in Japan is thought to reflect differences in regulations. Unlike the U.S., Japan had no CON-like restrictions on purchases. However, the government severely limited

^m The companies were Interad, Visiscan, Computer Medical Systems, and Meditech. All but Meditech soon exited.

reimbursementsⁿ prompting manufacturers to offer lower-cost machines. These less expensive CTs were especially popular among small, private facilities (including some that did not have a board certified radiologist on staff).²⁷

Other OECD countries remained well behind Japan and the U.S. in CT adoption.²⁸ (See **Figures 5 and 6**) 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, but many health facilities in those countries limited their purchases of CTs.

Figures 5 and 6

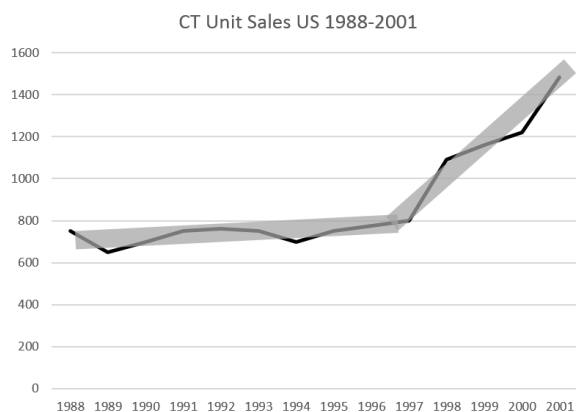


Sources: The Organization for Economic Cooperation and Development (2015), Stocking (1988), and Le Gales, et al (1988).

4. Innovations Reignite Growth (1989-2000)

CT sales in the United States had seemed to plateau beginning in the late 1980s, however, in the late 1990s they again accelerated as scanners with significantly advanced capabilities were introduced.²⁹ (See **Figure 7**)

Figure 7

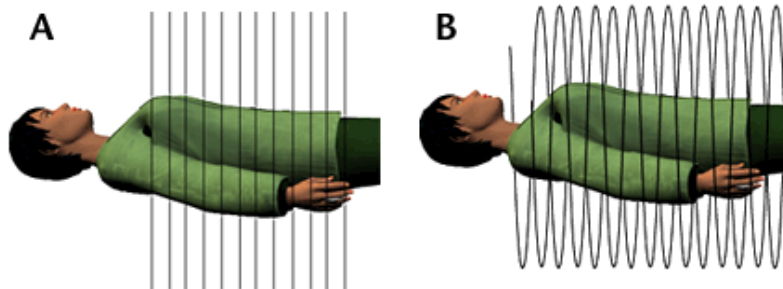


Source: Hillman and Goldsmith (2010).

ⁿ The Japanese government required all residents to buy health insurance (either through an employer or government-run program). The government also 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 U.S. at the time; in 1978, the difference in fees widened when the Japanese government cut the per-scan fee by more than half.

In 1988, the German company Siemens introduced spiral scanners that made one fast, corkscrew-shaped pass across the length of the patient. (See **Figure 8**) Up to that point, 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 multi-slice scanners that mounted X-ray sources and detectors in rows, imaging several slices at once. The spiral and multi-slice designs vastly improved the speed and clarity of CT scans, and reduced radiation exposure.³⁰ Competitors then raced to produce CTs that combined spiral and multi-slice features. The combination acquired four times the image data, eight times faster than older CTs, increasing patient throughput.³¹

Figure 8 X-ray path in conventional (A) and spiral (B) CT scans

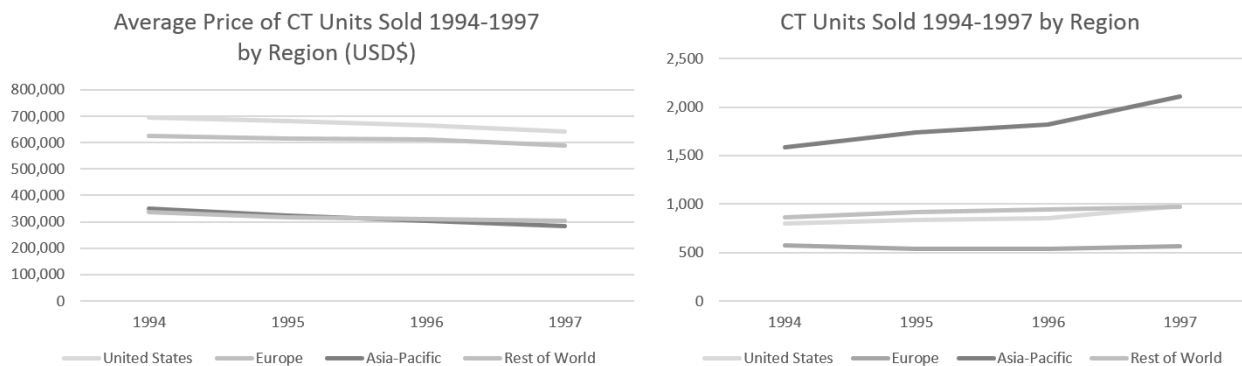


Source: The website of the National Cancer Institute (<https://www.cancer.gov>).

CT scans more than doubled in the U.S. between 1994 and 2000 as spiral, multi-slice combination scanners became widely available. The new scanners more accurately revealed internal bleeding, encouraging physicians to perform more trauma scans on the body and head. Physicians also used the CTs to detect problems within the heart and blood vessels, enabling new treatments – which in turn encouraged more scanning.³²

By 1997, worldwide CT sales were six times higher than in 1979. Growth in Asia – where CT prices were sharply lower than other regions – was even higher than in the U.S.³³ (See **Figures 9 and 10**).

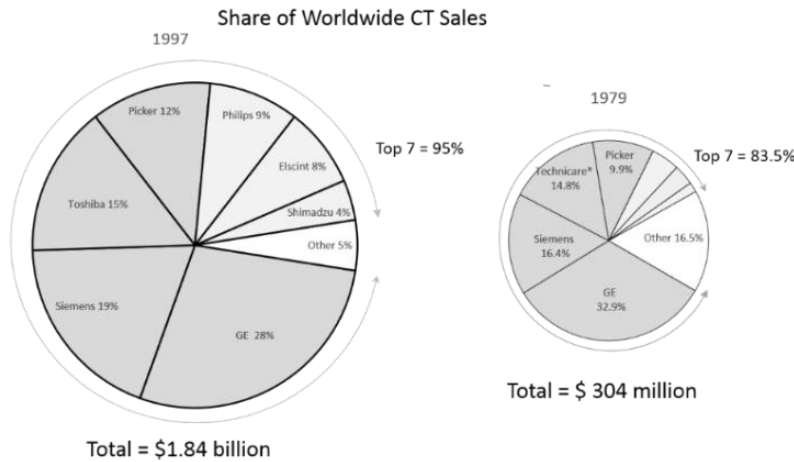
Figures 9 and 10



Source: Frost & Sullivan (1999).

The market became more concentrated, as many producers with low shares exited or were acquired.³⁴ (See **Figure 11**) GE remained the global market leader, but lost share to Siemens and Elscint, which had pioneered new technologies, and to Toshiba and Shimadzu, which had introduced lower-cost CTs.

Figure 11



Sources: Frost & Sullivan (1999) and the Office of Technology Assessment (1981).

5. Epilogue (after 2000)

In the early 2000s, the industry consolidated further as more CT companies were acquired.³⁵ Philips bought Picker International (which had itself acquired Elsint in 1998) in 2001. In 2000 and 2001, GE acquired two small producers: one was Imatron, which, as mentioned, had failed to make inroads with its cardiac scanners; the other was Sopha Medical, which had introduced a scanner designed for use with radioactive contrast agents^o in 1991.

Two entrants, Neusoft and NeuroLogica, introduced new CTs after 2000, focusing on emerging markets. Neusoft was a software company founded in China in 1988 that had started developing CTs in 1996. In 2002, it introduced low-cost machines for the Chinese market. NeuroLogica was founded in the U.S. in 2004, and, a year later, it introduced portable scanners for the U.S. market.³⁶

Only Samsung, the South Korean conglomerate, challenged established leaders in their home bases. The company acquired NeuroLogica's scanner business in 2013. Shortly thereafter, it announced its intention to invest \$1.1 billion in medical imaging by 2020.³⁷

CT sales continued to grow, defying predictions of obsolescence spurred by competition from MRI and digitized ultrasound scanning, which emerged in the late 1980s. MRI produced higher-quality images of soft tissues, while ultrasound equipment was portable and cheaper. Both MRI and ultrasound were safer than CT, because they did not expose patients to X-ray radiation. Indeed, MRI supplanted CT in scanning the central nervous system and joints. And, ultrasound dramatically increased in abdominal, pediatric, musculoskeletal, and emergency scanning.

Yet MRI and ultrasound growth did not always displace CT; and, technical and non-technical advances created new uses for CTs, notably in the imaging of hearts and lungs, emergency imaging, chronic cardiac care, and cancer screening.³⁸ Holistic environmental innovations, pioneered by Philips in 2003, also expanded pediatric use.³⁹ Philips' R&D deployed multidisciplinary teams to pioneer anxiety-reducing scanning facilities. The facilities featured calming colors, sounds, themes, and stories. (See **Figure 12**)

^o Contrast agents are compounds that are ingested or injected into body before a patient is scanned to improve the image produced. See Section 3.

Calmer children were less likely to require anesthesia before scanning and could be scanned more quickly, reducing radiation exposure.

Figure 12 Philips promotional images for pediatric CT systems

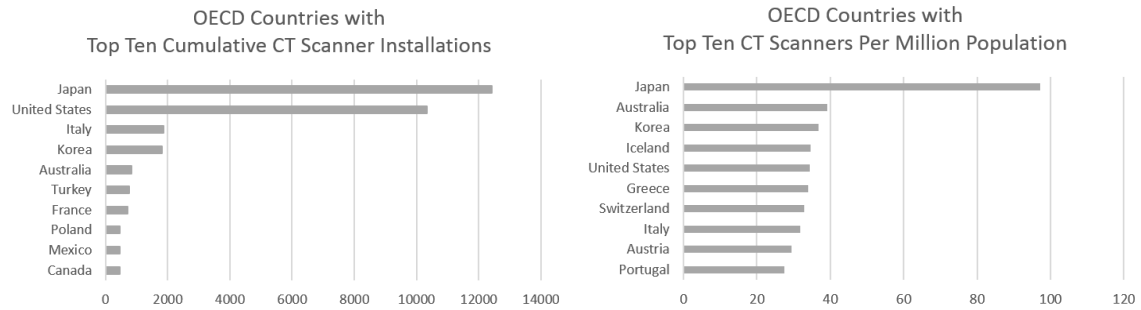


Source: Philips' corporate website.

CT market leaders continued to find opportunities to sell complementary products and services.⁴⁰ They developed or acquired software for managing images and computer-aided diagnostic systems, and collaborated with, and in some cases acquired, the makers of contrast agents (and related technologies).^P For instance, GE acquired Amersham, the world's largest maker of contrast agents, in 2004, and Siemens acquired German pharmaceutical maker Bayer's diagnostics division in 2007. Companies also offered consulting services, which designed, monitored, and analyzed diverse networks of specialized CTs within health care facilities.⁴¹

^P Contrast agents are compounds that are ingested or injected into body before a patient is scanned to improve the image produced. See Section 3.

Exhibit 1 OECD Countries with Top Ten Cumulative CT Scanner Installations and OECD Countries with Top Ten CT Scanners per Million Population



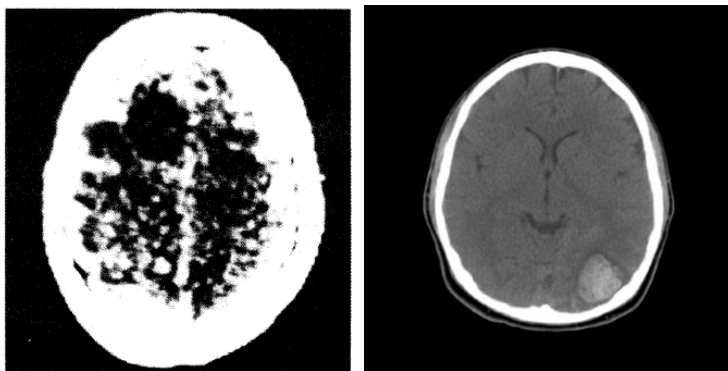
Source: The Organization for Economic Cooperation and Development (2015).

Exhibit 2 Godfrey Hounsfield posing with the first EMI head scanner (left) and Robert Ledley posing with his design for the first whole body scanner (right)



Sources: *BMJ* and *The New York Times*.

Exhibit 3 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 recent CT scan showing bleeding (light grey in the lower right) in the brain (right)



Sources: Hounsfield (1980) and the Aneurysm and AVM Foundation.

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 Tables based on data collected and published by 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>

³ 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: AHilger, 1990).

⁴ Physicians could "see" rough outlines of tumors via radio-nuclide 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 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".

⁶ Cormack also suggested in his article that the two-dimensional cross sections could easily be layered into three-dimensional reconstructions of a body.

⁷ 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.

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

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

¹² 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).

¹³ 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.

¹⁴ 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*.

¹⁵ According to Trajtenberg, 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 Trajtenberg, 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.

¹⁶ Hospital categories used here are based on the American Hospital Association's statistics.

¹⁷ 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.

¹⁸ 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>.

¹⁹ 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.

²⁰ 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>.

²¹ 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-

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²² Chart based on data published in Hillman, *The Sorcerer's Apprentice*, 97.

²³ 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 Surveys*; 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.

²⁴ Mitchell, "The Diagnostic Imaging Industry, 1896-1988," Chapter 5. Geisler and Heller, *Management of Medical Technology*, Case 11; Kevles, *Naked to the Bone*, 166.

²⁵ 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.

²⁶ 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.

²⁷ 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 cannot diagnose patients (i.e. examine the scanned image)."

²⁸ 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.

²⁹ Chart based on data published in Hillman, *The Sorcerer's Apprentice*, 97.

³⁰ 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.

³¹ 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>.

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