Working Paper 20-003

Case Histories of Transformational Advances

Ultrasound Imaging – Cheap, Versatile, and Safe

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Abstract: This case history describes how efforts on multiple fronts, including advocacy, training, and technological development, made ultrasound the second most commonly used diagnostic imaging technology (after X-rays). Specifically, we chronicle 1) ultrasound's development and introduction in the 1950s and 1960s, 2) widespread adoption in the 1970s, and 3) innovations that sustained growth in the 1980s and 1990s.

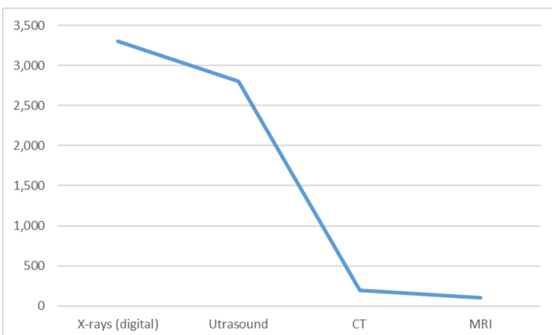
Note: Like the other histories in this series, this advance is included in a list compiled by Victor Fuchs and Harold Sox (2001) of technologies produced (or significantly advanced) between 1975 and 2000 that internists in the United States said had had a significant impact on patient care. The case 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 to the researchers. Limitations of space and information severely limit coverage of developments in emerging economies.

Acknowledgments: Kirby Vosburgh and Kai Thomenius provided helpful information and suggestions for which we are grateful.

Ultrasound Imaging – Cheap, Versatile, and Safe

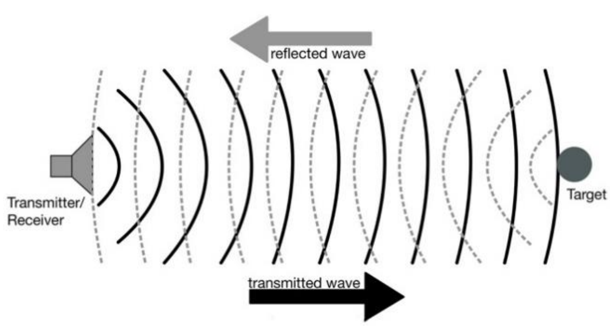
Ultrasound scanners, which first moved from development labs into medical practice in the 1960s, now produce billions of diagnostic images each year. (See **Figure 1**). Unlike X-rays, which date back to the 1890s and create images from the electromagnetic waves absorbed by bones and other tissues inside a patient's body, ultrasound relies on reflections or "echoes" of sound waves. (See **Figure 2**). The computerized processing of the echoes produces images of soft tissues and blood flows that X-rays picture poorly. Moreover, X-rays pose radiation risks, whereas physicians consider directing even high-frequency (hence "ultra") sound waves at patients harmless. This makes ultrasound a safer, as well as more effective, choice for scanning brains, hearts, veins and arteries, abdominal organs, and fetuses. [1]

Figure 1 Imaging Procedures Worldwide in 2011 (millions of procedures)



Source: Szabo (2013).

Figure 2 How ultrasound works.

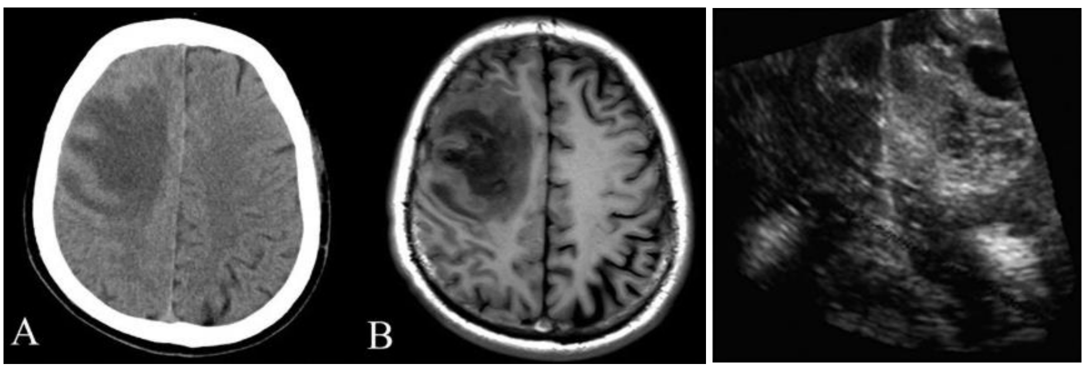


This case history does not present original research or new thesis. Instead, it summarizes historical developments and includes questions to stimulate reflection and discussion.

Computed Tomography (CT), introduced in the early 1970s, and Magnetic Resonance Imaging (MRI), introduced in the mid-1980s, offer sharper images of soft tissues (See **Figure 3**), but both require expensive, room-sized equipment; and CT is based on X-rays, so it exposes patients to radiation. In contrast, ultrasound units can be as small as a smartphone and cost less than one-eighth the cost of a CT or MRI.[2] Therefore, ultrasound dominates soft-tissue imaging in the many cases where the sharpness of CT and MRI is not crucial.

Ultrasound did not immediately leap into widespread use. At first, only some devices produced images. Many merely depicted measurements as electrocardiogram (EKG[3]) -like plots (or, in common medical terminology, "traces"). The images that were produced by the more advanced units were grainy and initially required immersing patients in water tanks. The following sections describe how these and other limitations were overcome. Specifically, they cover: 1) ultrasound's development and introduction in the 1950s and 1960s; 2) clinical adoption in the 1970s; 3) continued growth in the 1980s; and 4) new product introductions in the 1990s.

Figure 3 Recent examples of brain scans made with CT (left), MRI (middle), and ultrasound (right)



Source: Left image: Huang et al. (2018), Right image: Mercier et al. (2012)

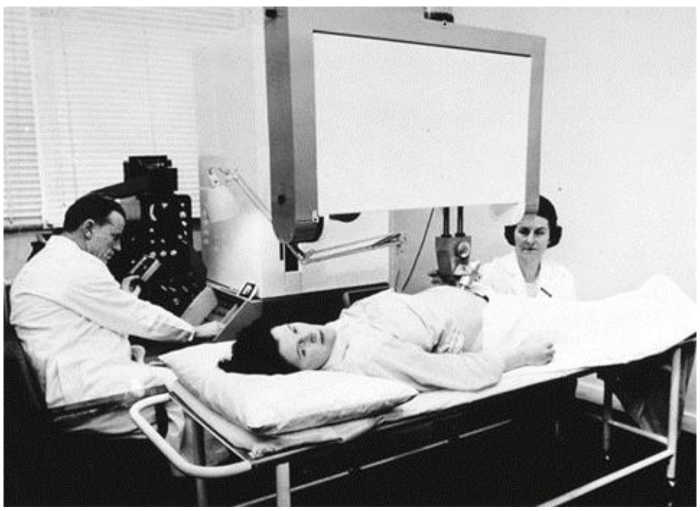
1. First Devices Developed (1950s and 1960s)

Ultrasound grew out of efforts to adapt SONAR (SOund Navigation And Ranging) technology for medical diagnosis. SONAR was first developed in World War I to hunt submarines. By the 1940s, the technology had been adapted for industrial use to detect flaws in metal structures. Medical researchers in France and Germany proposed using echoes from sound waves to picture abdominal organs and the heart in the 1940s but could not implement these proposals in any practical device.[4] However, by the 1950s, several groups of university-based physicians, engineers, and physicists had developed working diagnostic devices.

Two research teams in the United States and one in Sweden led the field. (See **Exhibit 1**) In 1953, the American teams – one led by a surgeon at the University of Minnesota, the other by a radiologist and a kidney specialist at the University of Colorado – demonstrated devices that offered crude cross-sectional images showing "slices" through the body[5] that could detect thyroid, breast, liver, and kidney cancers that were not visible on traditional X-rays.[6] The Swedish researchers, led by a cardiologist at the University of Lund, demonstrated a device that plotted measurements ("traces") from which physicians could detect faulty heart valves, offering an alternative to more invasive methods (such as inserting catheters through arteries into the heart.)[7]

By 1958, researchers at five other universities had developed prototypes that expanded ultrasound's diagnostic capabilities beyond cancer and heart disease. (See **Exhibit 2**) For instance, researchers at the University of Illinois, led by ophthalmologists, developed a device to locate eyeball injuries; researchers at the University of Lund, led by a neurologist, developed a device to locate bleeding in the brain; and researchers at the University of Glasgow, led by an obstetrician, developed a device to detect problems with pregnancies.[8] The prototypes were all built from military or industrial equipment, and they were all large – some up to eight feet tall. Each used a hand-controlled probe fitted with a transducer to transmit high-frequency sound waves and receive echoes.[9] (**See Figure 4**)

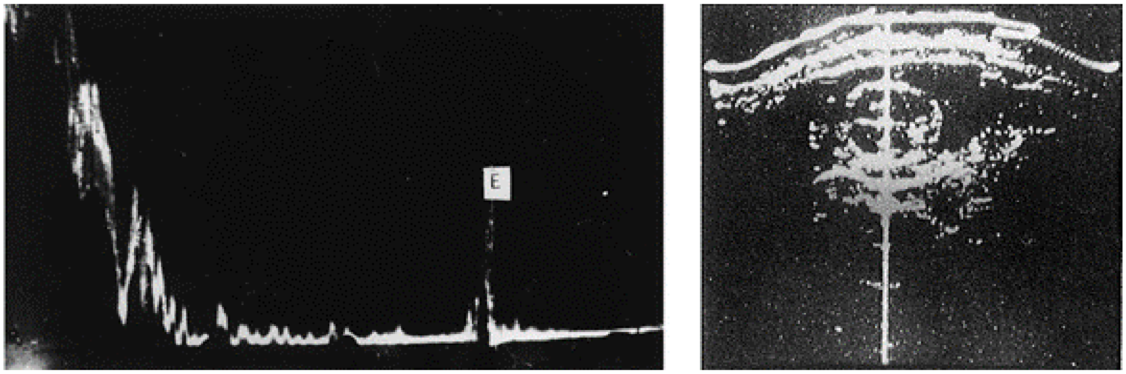
Figure 4 Ultrasound device scanning a fetus in 1960. Note the size of the unit and the operator on the right who guides the probe attached below a large rectangular arm.



Source: Campbell (2013)

By 1960, ultrasound progressed beyond prototypes, and soon, several devices were being sold for clinical use. The most basic version, used mainly to examine eyes and brains, measured distances. The measurements helped physicians check whether eyeballs or brains had been displaced from their normal positions.[10] A second type, used mainly to examine defective heart valves, plotted traces of their movements on monitors.[11] (See **Figure 5** for an example of an ultrasound trace) A third type, used to examine blood flow, including flow in the blood vessels of fetuses, also plotted traces on monitors from which doctors could determine the motion of the blood. (Beginning in the late 1970s, these devices produced a "whooshing" sound to signal blood flow.)[12] The fourth type, used mainly to examine fetuses and abdominal organs (such as the liver), produced cross-sectional images that could help diagnose cancers, cysts, and obstetrical conditions.[13] (See **Figure 5** for an example of an early cross-sectional ultrasound image).

Figure 5 The first trace made by an echocardiograph, an ultrasound device for detecting faulty heart valves, taken in 1953 (left), and a 1964 cross-sectional ultrasound image of a fetus's head (right)



Source: Edler and Lindström (2004) and Kevles (1998)

Units producing cross-sectional images were the most expensive, commanding prices of up to $24,000, while measurement-producing units sold for about $180. (By comparison, X-ray equipment at the time cost between a few hundred to a few thousand dollars.)[14]

Fifteen of the twenty-one companies that started selling these units in the 1960s secured help from university researchers (including those who had developed pioneering prototypes earlier, see **Exhibits 1 and 2**); the other six entered without such assistance thanks to easily available technologies that were not protected by strong patents, and components that could be purchased off the shelf and assembled in low volumes. Notably, different entrants designed their products for different applications[15], limiting direct competition.[16]

Eighteen of the twenty-one entrants had existing businesses in a variety of industries. Three –Toshiba (Japan), Siemens (Germany), and Picker (US) -- were diversified multinational companies whose "portfolios" included large X-ray businesses.[a] All three sold ultrasound devices outside their home markets. Two of the three, Toshiba and Siemens, would later emerge as world leaders in ultrasound.[17]

Fifteen companies that started selling ultrasound in the 1960s did not sell X-ray equipment but rather came from computing, communications, defense, pharmaceuticals, and scientific instrumentation.[18] Two of these fifteen companies, Aloka and NEC Corporation, were based in Japan; the rest were headquartered in Europe and the United States. Six sold ultrasound devices outside their home markets, including the Japanese company Aloka and Hewlett Packard (HP), one of the first Silicon Valley-based high-tech companies. Both Aloka and HP would later become world leaders in ultrasound.[19]

[a] Two other diversified multinationals who were also significant X-ray producers, General Electric (GE, U.S.) and Philips (The Netherlands), did not enter ultrasound in the 1960s but would enter in the 1970s.

Only three of the 1960s entrants – Sonicaid (UK), Physionics Engineering (US), and Unirad (US) -- were startups. Although these companies started on a small scale, one of them (Physionics) had international ambitions and sold outside its domestic market.[20]

Throughout the 1960s, researchers in the US, Europe, and Japan expanded the range of ultrasound's potential uses. For instance, Mayo Clinic (Rochester, MN, US) cardiologists used ultrasound to locate tumors inside the heart, Queen Charlotte's Maternity Hospital (London, UK) obstetricians located abnormalities in placentas, and Nagoya City University Medical School (Nagoya, Japan) radiologists diagnosed injuries to forearms and legs.[21]

Nevertheless, several factors limited ultrasound's actual diagnostic use and sales. Image-producing devices required operators to precisely guide probes across the area under inspection[22] and even advanced units produced grainy or blurry images with "speckles" or dots. (See, for example, the image on the right in **Figure 5**) Yet few device producers or medical schools provided the training necessary to make or read the images. Some obstetricians had concerns (later shown to be unfounded) that the sound waves produced by ultrasound devices could damage fetuses. And the size and weight of the devices made installation difficult.[23] Thus, at the end of the 1960s, more than a decade after they had been introduced, sales of ultrasound devices in the United States amounted to less than $5 million per year. According to industry experts, sales in Europe and Japan were even smaller.[24] Nonetheless, only about four companies had exited by the end of the decade.[25]

Questions (for reflection and discussion):

Before reading further, please write down (in less than ten words) which decision, event, or condition you found the most significant in speeding or slowing the development of ultrasound devices in the 1960s.

• ____

Be prepared to explain in class why you found this significant.

Also, think about what might speed up or slow the use of ultrasound devices in the future.

2. Adoption in the 1970s

Two physician-professors enthusiastically promoted the use of ultrasound in the 1970s. One, Scottish obstetrician Ian Donald, was internationally known for leading the development of obstetrical scanners at Glasgow University in the 1950s. Already in his sixties, Donald tirelessly lectured and wrote about ultrasound and helped launch the first university class on diagnostic ultrasound in obstetrics and gynecology. The course drew many physicians from throughout the United Kingdom, the United States, Canada, New Zealand, and South Africa. It served as a model for classes offered at other academic institutions. The other physician, Harvey Feigenbaum, a thirty-three-year-old cardiologist at Indiana University, had been the lead author of a groundbreaking article on using ultrasound to detect accumulations of fluid around the heart. Like Donald, Feigenbaum lectured, taught, and published widely on ultrasound's diagnostic capabilities,[26] highlighting its superiority over existing invasive methods in cardiology (that required inserting catheters into the heart, as mentioned).[27]

Other medical researchers published textbooks that explained the operation of ultrasound units and interpretation of ultrasound images through "atlases" that showed, for instance, what ultrasound scans of healthy organs looked like. New professional associations formed by technicians (who operated ultrasound devices) and physicians (who interpreted results) helped disseminate this knowledge through courses and seminars. And research encouraged by Donald assuaged concerns about damage to fetuses.[28]

Technological advances made the interpretation of ultrasound images easier. Replacing monochromatic oscilloscopes with television screens that displayed "grayscale" images (images in multiple shades of gray) reduced blurring. Blurring was also reduced by using digital instead of analog components in probes and to render images. These advances were first introduced in devices for obstetrical and abdominal scanning and shortly thereafter in devices used for cardiovascular applications. [29]

Additionally, the cardiovascular devices produced these grayscale images in a rapid sequence (at the rate of thirty or more a second) to create movies of beating hearts. The movies enabled physicians to better diagnose conditions such as diseased heart valves.[30] The movie-producing capabilities were then incorporated into devices used for obstetrical and pediatric applications. The devices reduced the problem of images of fetuses and of children's abdominal organs being blurred by the natural movement of fetuses and the fidgeting of young patients.[31]

Using multiple (instead of single) transducers that transmitted and received sound waves reduced the maneuvering of probes that ultrasound operators needed to perform to scan patients. As with grayscale imaging, multi-transducer probes were first developed for obstetrical and abdominal applications. The probes were then incorporated into scanners used for cardiovascular applications to produce panoramic movies that allowed cardiologists to see far more of the organ's beating action – and more easily understand what they were seeing.[32]

Advances such as grayscale imaging that improved the sharpness of images enabled entirely new diagnostic applications for ultrasound. These included replacing surgical techniques previously used to diagnose conditions such as enlarged lymph nodes and X-rays to diagnose gallbladder problems taken with the help of contrast agents (chemicals visible in X-ray images injected into patients).[33]

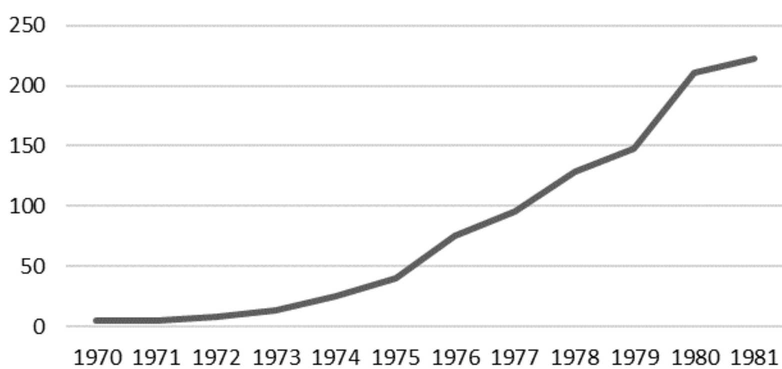
In addition to advances in ultrasound components themselves, developers harnessed new technologies from outside the ultrasound industry (as shown in **Exhibit 4**). For instance, movies of beating hearts were stored on videocassette recorders that had been recently developed, mainly for the entertainment industry.[34]

Companies that introduced an advance for its "first" application often did not adapt the advance for its "next" use (even though, by then, many companies had products that spanned several applications). For instance, Rohe Scientific Corporation, a subsidiary of an aerospace company, introduced grayscale images in devices for obstetrical and abdominal applications in 1973. However, it did not introduce grayscale imaging for cardiovascular applications, even though the company sold ultrasound devices for this application. Instead, Varian, which, like Hewlett Packard, was an early Silicon Valley startup (founded in 1948) producing a range of high-tech instruments, introduced grayscale imaging for cardiovascular applications in 1977. Similarly, Organon Teknika, a diagnostic device company, introduced a movie-producing device for cardiovascular applications in 1972 but lagged in applying the technology to devices for other applications. Three years later, a division of Grumman Aerospace introduced a movie-producing device for obstetrical applications, and two years after that, Mediscan, a startup, introduced a movie-producing device for abdominal applications.[35]

The National Science Foundation (NSF) launched a program in 1974 to keep American companies from falling behind in ultrasound technology.[36] Although a report by Arthur D. Little, a leading technology consulting firm, suggested the NSF's program was ineffective (See **Exhibit 5**), American companies were often the first to introduce many of the 1970s advances described above. At the same time, companies based in Europe and Japan, which were only a little behind, soon caught up.[37]

Ultrasound sales grew particularly strongly in the United States in the 1970s: devices sold increased over 40-fold (**See Figure 6**), and procedures increased over 30-fold between 1970 and 1980. The range of prices concurrently widened: prices of premium devices (that now offered grayscale and moving images) quadrupled, while prices of some more basic designs declined.[38] Sales in Europe and Japan continued to lag the US sales, as they had in the 1960s.

Figure 6 Ultrasound Sales in the United States ($ millions)



Sources: Mitchell,(1988) and Frost & Sullivan. (1982).

Hospitals accounted for much of the 30-fold increase in use in the US, performing six million ultrasound procedures in 1980 compared to fewer than 200,000 procedures in 1970. Unlike X-rays, CTs, and, later, MRIs, where radiologists performed most procedures, radiologists performed only about a quarter of the ultrasound procedures in hospitals in 1980. Rather, cardiologists, obstetricians, and gynecologists (who, as mentioned, had previously made pioneering contributions to developing and popularizing ultrasound) accounted for almost two-thirds of hospital procedures, using equipment purchased by and located in their departments. For instance, by the end of the 1970s, over half of cardiology departments and almost a tenth of obstetrics and gynecology departments in American hospitals had their own ultrasound scanners.[39]

Radiologists also did not participate in the 1.3 million (or so) ultrasound procedures performed outside hospitals in 1980 by physicians in solo or small group practices.[40] Previously, such physicians had outsourced much of their diagnostic testing, by, for example, sending blood samples to laboratories or their patients to radiologists for X-rays. Ultrasound scanning in their own offices provided more convenience to patients – and revenue to the physicians.

Even so, many general practitioners and specialists (particularly outside cardiology and obstetrics) did refer patients to radiologists for ultrasound scanning. Radiologists thus dominated abdominal scanning in the US, performing two million such procedures in 1980. And companies like Picker, which already sold X-ray units, focused their ultrasound marketing, sales, and technical support efforts on radiologists.[41]

Rapid growth in the 1970s attracted at least eighty entrants to the US market (some of whom also started selling ultrasound in Europe). (See **Exhibit 6**) Entrants included twelve multinational companies with significant diagnostic device businesses. Among the twelve were long-time producers of X-rays: General Electric (GE, US), Philips (The Netherlands), Compagnie Générale de Radiographie (CGR, France), and Hitachi (Japan), who would also enter the CT business in the same decade. GE, Philips, and Hitachi would then become major players, in some cases through acquiring small companies and startups.

Other entrants, mainly based in North America, included twenty large pharmaceutical, defense, computer, communications, and consumer products companies, including G.D. Searle, Colgate-Palmolive, and Honeywell; twenty small companies producing other diagnostic devices;[42] and twenty startups.[43]

These entrants acquired their technological and marketing capabilities from a variety of sources, including universities, a government research institute, agreements to resell and rebrand devices made by Japanese companies, and the acquisition of 1960s vintage companies.[44]

Few of the 1970s entrants had noteworthy commercial success in the US market, however. Three 1960s-vintage companies accounted for nearly sixty percent of ultrasound sales in the US through the mid-1970s. Only two 1970s entrants – Rohe Scientific, which (as mentioned) had pioneered grayscale imaging, and Kontron, a division of a Swiss pharmaceutical maker Hoffmann-La Roche – had more than single-digit shares of ultrasound sales (each had about ten percent). Later in the decade, however, one 1970s entrant, Washington-based Advanced Technology Laboratories[45] (ATL), took the lead (with a twenty-one percent share), offering a unit that combined two previously separate devices: one that monitored blood flow and another that produced grayscale movies.[b] (See Exhibit 7) Meanwhile, twenty-six other companies exited, some only a few years after starting to sell ultrasound; at least nine sold out to other companies, and the rest closed down their businesses.[46]

Ultrasound sales in Europe and Japan, as mentioned, had been relatively low in the 1960s accelerated in the late 1970s. Producers cut prices[c] and, in Europe, started marketing to obstetricians, gynecologists, and cardiologists; previously, they had mainly targeted radiologists. (Companies in Japan already marketed to these specialists.) Lower prices and broader marketing helped produce over a five-fold increase in sales of ultrasound equipment in Europe between 1976 and 1980. Increased European sales, which totaled about $134 million in 1980, reduced – but did not close -- the gap with the US, which had sales of about $210 million that year. Sales in Japan also grew rapidly, quadrupling between 1976 and 1980. However, Japan lagged well behind Europe, with revenues totaling just $61 million.[47]

Entrances and exits were also lower outside the United States. In Japan, only three large industrial companies- National (Matsushita), Hitachi, and Shimadzu - started selling ultrasounds in the 1970s. The three entrants could not take away much market share from two 1960s vintage companies (Toshiba and Aloka) that accounted for eighty percent of sales in the late 1970s. There were no recorded exits, although

[b] As ATL gained market share, three 1960s vintage companies lost share: Unirad – one of the few 1960s ultrasound startups -- and the subsidiaries of Picker and Smith-Kline (see **Exhibit 7**).

[c] Prices remained higher than U.S. prices, however – ultrasound devices cost up to two times more in Europe and about one-and-a-half times more in Japan.

NEC, a third 1960s entrant, had apparently stopped being a significant producer by the end of the 1960s. (See **Exhibit 7**).

Entrants to the European ultrasound market in the 1970s included thirty of the eighty companies that had entered the US market and ten other companies that only sold in Europe. As in the US and Japan, few 1970s entrants had commercial success in Europe: 1960s-vintage companies, led by Germany's Siemens, accounted for up to seventy-six percent of sales in the 1970s. Just two 1970s entrants – Japan's Hitachi (which had not had much success in its domestic market) and the US market leader ATL -- were able to accumulate double-digit shares. Moreover, except for Siemens,[d] none of the companies with double-digit shares at the end of the 1970s were based in Europe.[48] (See **Exhibit 7**) Despite the many with low sales, only six left the ultrasound business.

By the early 1980s, the market for ultrasound, particularly in the US, appeared to be saturated. Almost all hospitals with over one hundred beds had multiple ultrasound devices in several departments. Many solo practitioners and small groups of physicians in private practice had also installed ultrasounds in their offices. Medical Products Marketing Services, a market research company, predicted revenue declines of fifteen to forty percent.[49]

Questions (for reflection and discussion):

Before reading any further, please write down (in less than ten words) which decision, event, or condition you found the most significant in increasing the use of ultrasound in the 1970s.

- ____

Be prepared to explain why you found this significant.

And think about what would have to happen for rapid growth in the ultrasound market to resume in the 1980s.

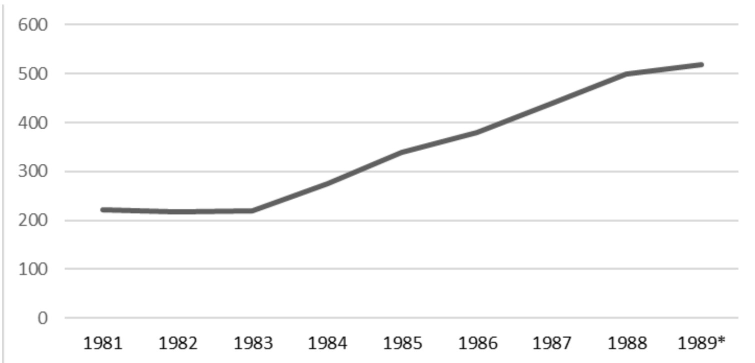
3. Growth in the 1980s

Soon after *BusinessWeek* observed, in 1983, that "the [ultrasound] market is nearly saturated, and sales have started to slip," growth in the US market resumed.[50] (**See Figure 7**)

"Computed sonography," which, like CT scanners, used computers to process images, was one factor in the return to growth.[51] Acuson, a Silicon Valley-based startup, became the first to sell such a device in 1983. (See box titled "Acuson's Path to Product Launch"). In addition to computerized processing, Acuson's pioneering device used more sensitive probes to construct images that were two to six times sharper than the images produced by previous scanners. (See **Figure 8**) In addition, Acuson hired its own sales force, unlike many other small entrants and startups that relied on distributors and focused its marketing on radiologists.[52]

[d] Philips, which would later become a market leader, had revenues that were still in single digits at the end of 1970s.

Figure 7 Ultrasound Sales in the United States in the 1980s



Source: Coste (1989)

* Partial year estimate for 1989

In 1985, just two years after it had started selling its devices, Acuson had become the market leader[e] with a twenty-seven percent share of US ultrasound sales.[53] Acuson benefited from the quick popularity of computed sonography – and a somewhat surprising absence of competition. Acuson did not have much intellectual property protection against imitators[54] , and other companies had also been trying to develop computed sonography in the early 1980s.[55] For instance, shortly after it entered ultrasound in 1979, GE launched a computed sonography program alongside its CT development. Yet, no one offered a competing device until ATL, which (as mentioned) had jumped into market leadership with its pioneering devices in the 1970s,[56] began selling its own "computed" ultrasound devices in 1987.[57]

Meanwhile, other ultrasound producers introduced improved cardiovascular scanners. Japan's Aloka offered scanners that produced color instead of grayscale movies of blood flowing through hearts (both in the US and Japan in 1984). Within a year, another Japanese producer, Toshiba, had also introduced a scanner with this capability, and in the next few years, several other ultrasound producers from the US, Europe, Japan, and Israel followed.[58] As competition to sell the improved cardiovascular scanners increased, their clinical use grew: in just five years, cardiovascular ultrasound procedures in the US nearly tripled.[59]

Acuson's Path to Product Launch

Acuson was founded in 1979 by Samuel Maslak and Robert Younge, who had worked for Hewlett-Packard (HP). HP started making ultrasound fetal heart monitors in 1967 and hired Maslak in 1974 out of the Massachusetts Institute of Technology to lead the development of probes with electronic components instead of mechanical parts. Younge had no experience with ultrasound, but Maslak considered him a "gifted" electrical engineer.

"Hewlett Packard had been very pioneering in their willingness to invest in a sophisticated ultrasound system… [and] they were quite pleased with the new architecture that had been developed," Maslak later

[e] By 1985, the 1960s-vintage companies that had long dominated the U.S. market had faded. Along with Acuson, two other 1970s-vintage companies -- 1977 startup Diasonics and 1974 entrant ATL – accounted for sixty percent share of sales revenues that year.

recalled. "But I think [their] view was that this architecture would serve for many years." In addition, Maslak observed, that by the late 1970s, HP prioritized computers over all their other businesses, including scientific instruments, which had been HP's core business at its founding. "Then further down in their priority [list] were medical electronics, and then still further down in their priority list was ultrasound," Maslak added. By contrast, "my sole priority was ultrasound."

For two years, Maslak and Younge supported Acuson with savings, second mortgages on their homes, and occasional consulting. One consulting job led to an angel investor, whose $100,000 investment enabled them to hire another former HP engineer, Amin Hanafy, who specialized in ultrasound transducers.

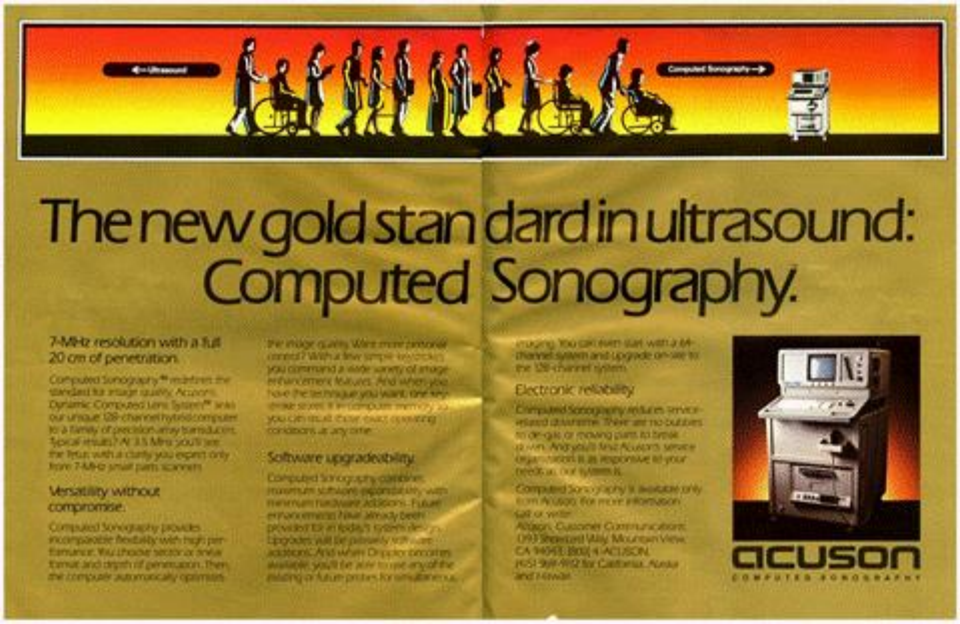
In January 1982, Acuson raised $2.5 million, half from the angel investor and half from a top venture capital (VC) firm. To find the firm, the partners ranked local VCs based in Silicon Valley, intending to pitch down the list until they were successful. The first four VCs to get their business plan immediately offered more money than Acuson solicited. Acuson chose Kleiner Perkins Caufield Byers.

Ten months later, in October of 1982, Acuson had a working prototype -- but they had spent more than they had expected. To advance to the next stage of their plan, which called for testing their device with top radiologists and preparing for manufacturing, they secured a loan from Kleiner Perkins. After the device earned glowing reviews in tests, Acuson began to sell and ship units in 1983. Two years later, they topped the US market. In 1986, the company went public.

Source: Smithsonian Institution's Videohistory Program (1997)

Ultrasound development and sales in the 1980s benefitted from a favorable regulatory decision. US Food and Drug Administration (FDA) rules, which could have slowed the development of new ultrasound devices and increased the costs, did not. The 1976 Medical Device Regulation Act had given the FDA authority to require clinical trials for new devices – previously, the FDA only had such authority over new drug introductions. Devices that the FDA decided were not "substantially equivalent" to existing devices had to undergo clinical trials to demonstrate safety and effectiveness. For instance, the FDA exempted CT devices introduced in the 1980s from trials because they were deemed substantially equivalent to a device that (as mentioned) had been sold before 1976. With MRIs, which appeared after 1976, the FDA did require trials, raising the cost and increasing the time for launching the devices.

Figure 8 1983 advertisement for Acuson's "Computed Sonography"



Source: *Journal of Ultrasound in Medicine*, Volume Two, Number Seven, July 1983, page 10.

The FDA had initially classified all new ultrasound devices as substantially equivalent to existing ultrasound devices and thus exempt from clinical trials. However, in 1984, the FDA qualified this exemption after research on lab animals suggested that ultrasound might harm fetuses, and an FDA review showed that some new ultrasound devices produced higher-powered sound waves than earlier devices. That year, the FDA set power limits; if a new device exceeded the limits, it was no longer considered substantially equivalent and, therefore, subject to clinical trial requirements. As it happened, these limits were set above the power of all existing units, and no new device that exceeded the limits was introduced. Later, large-scale studies found no harmful effects on human fetuses, dissipating concerns about ultrasound (that had been raised by research on animals).[60]

Meanwhile, cost-containment rules introduced to limit procurement of expensive CT and MRI units had the unintended effect of stimulating ultrasound purchases. (See box titled "How CONs Stimulated Demand for Ultrasound in the United States.")

Fewer companies started selling ultrasound in the 1980s than in the 1970s, particularly in the second half of the decade. Compared to the more than eighty entrants in the 1970s, less than sixty started selling ultrasound devices to American buyers in the 1980s, and only about twenty of the 1980s entrants (mainly startups) came in after 1984. The slowing rate of entry – even as sales of ultrasound devices picked up – may have reflected the disappointing performance of previous entrants. Acuson's success after it entered the industry in 1982 (like ATL's in the previous decade) was exceptional; barriers to securing significant share, if not entry, apparently remained high: one survey of companies selling ultrasound in the US conducted in 1985 and 1986 found two-thirds of companies selling less than $5 million in ultrasound equipment per year. Many were presumed to be operating at a loss. A third of companies reported that they remained in ultrasound to develop new technology; another third reported that they remained to offer a broad range of imaging and other medical equipment.[61]

Disappointing sales may also explain increased exits from the US market in the 1980s: thirty-four companies stopped selling ultrasound in just the first four years of the 1980s, whereas twenty-six companies exited in all of the 1970s. Exits during the rest of the decade did slow, however, possibly because ultrasound sales rebounded. Only ten companies – mainly large diagnostic device, industrial, and pharmaceutical companies that failed to gain significant share -- exited in the last six years of the 1980s.[62]

How CONs Stimulated Demand for Ultrasound in the United States

The launch of CT scanners in 1972 catalyzed rules to limit purchases of expensive diagnostic equipment by hospitals. The popularity and high cost of CTs – more than $700,000 per unit – raised concerns among public officials and consumer groups about hospitals' unnecessary purchases.

In 1974, Congress passed rules that required hospitals to obtain a Certificate of Need (CON) to purchase expensive equipment. In the late 1970s, regulators introduced specific standards for minimum usage of existing CTs before new purchases could be made in a region.

The new CON standards triggered a steep decline in CT sales. Shortly thereafter, MRIs were introduced at a cost of $800,000 to $2 million per unit. They, too, were covered by CON rules that restrained hospitals' purchases.

Ultrasound cost considerably less than CT and MRI and was therefore not covered by CON rules. However, ultrasound became the unintended beneficiary of the CON rules restraining hospitals' purchases of CTs and MRIs in the following way: radiologists opened imaging centers exempt from CON rules because they weren't affiliated with hospitals. These new imaging centers bought ultrasound to round out their diagnostic capabilities.

By the end of the 1980s, around half of all imaging centers in the US had installed ultrasound devices. These purchases helped ultrasound post the largest share (thirty percent) of all imaging device revenues in the US in 1990. Imaging centers then grew by almost forty percent, and the number of ultrasound units in centers more than tripled.

Ultrasound sales in Japan and Europe remained below US sales in the 1980s. Cardiovascular devices whose new features (such as color movie production) had increased usage in the US were successfully sold in Europe and Japan, often by the same companies. However, computed sonography (sold only by Acuson until the late 1980s), which significantly contributed to the revival of ultrasound sales in the US, did not sell as well in Japan and Europe.[63]

Nonetheless, both Japan and Europe attracted more entrants in the 1980s than they had in the 1970s. In Japan, about six domestic companies and Acuson started selling ultrasound. The Japanese entrants included three large industrial conglomerates, one maker of marine products, and a small medical equipment manufacturer. Europe saw an even greater increase: About fifty-three companies entered in the 1980s -- over a dozen more than in the 1970s. And unlike in Japan, the newcomers included several small companies and startups, some of which were based outside of Europe.[64]

The more numerous entrants in the 1980s did not seem to take away much market share from the 1960s- and 1970s-vintage producers. In Japan, Toshiba and Aloka continued to dominate.[65] In Europe, Siemens did lose its top position, even its home market of Germany, but not to 1980s entrants. Rather, Japan's Toshiba and Aloka and the 1977 US startup Diasonics held the greatest shares of sales revenues in France and Germany, the two largest markets in Europe.[66] Yet, many companies that could not secure significant sales did not exit. In Japan, none left, and in Europe, only ten exited, making the market "overcrowded."[67]

Questions (for reflection and discussion):

Please write down (in less than ten words) which decision, event, or condition you found the most surprising or significant in the section you just read.

- ____

Be prepared to explain why you found this surprising or significant.

4. New Product Introductions (in the 1990s)

New ultrasound scanners enabled physicians to monitor the progress of heart operations. The new systems used narrow tubes fitted with small ultrasound probes that patients swallowed to produce scans of the heart from inside the chest. (See **Figure 9**) This and other such advances helped to increase cardiovascular ultrasound scanning by forty to fifty percent in the US between 1993 and 1999.[68]

Figure 9 Tube (in black) fitted with a miniature ultrasound probe (at the tip). Once swallowed, the probe enabled unobstructed scans of the heart muscle from the throat.

Source: Wells (1993).

Acuson and other companies developed scanners with faster computers and more efficient, sensitive probes. Acuson introduced a device in 1996 that produced images[69] with four times the detail at five times the speed of its older scanners.[70] Subsequent devices used high-powered computers to produce 3-D images that obstetricians used to locate defects in the blood vessels in fetal brains and to dazzle parents with detailed pictures of the faces of their unborn babies. Other specialists used the 3D images to assess bladder functioning and to inspect the intestines, heart, or the major arteries that feed the brain.[71]

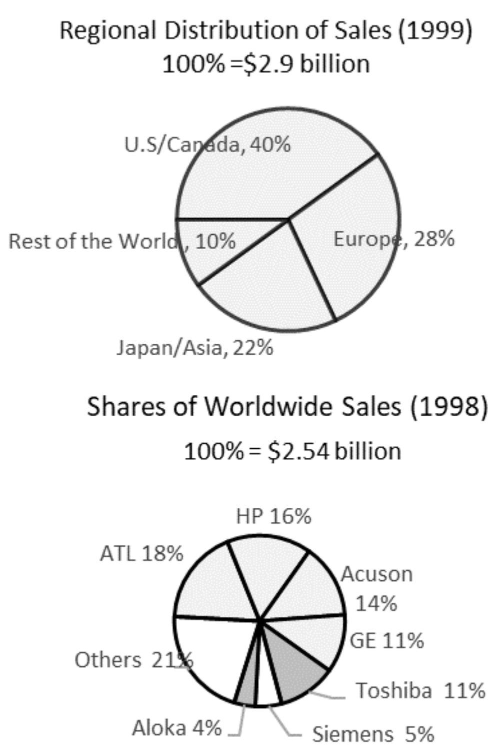
The shrinking size of computers enabled the introduction of smaller devices. The US Defense Advanced Research Projects Agency (DARPA) had given ATL a grant in 1996 to develop laptop-sized units for military use in combat conditions; these devices were introduced in 1999. Other compact units that could be moved on carts proved particularly popular with physicians in emerging markets who worked in small offices. Some companies also introduced low-cost scanners for these markets. Medison, a 1985 South Korean startup, sold inexpensive scanners in South Korea, India, Turkey, and Pakistan, and GE formed joint ventures to produce cheaper scanners in China, India, and Thailand.[72]

The Situation in 2000.

Worldwide sales of ultrasound devices had continued to grow in the 1990s, albeit at a slower pace than before, rising from about $1.8 billion worldwide in 1990 to about $3 billion in 2000.[73] US sales remained highest in 2000, at $1.16 billion, and European sales revenues were next highest, at $812 million. However, sales in Asia (including Japan) and the rest of the world had begun to catch up: revenues in Japan/Asia totaled $638 million, and revenues in the rest of the world totaled $290 million in 2000. (See **Figure 10**)

Ultrasound had attracted about 40 entrants (worldwide) in the 1990s. As in the 1980s, many entrants had introduced innovative products that complemented their other medical devices. For instance, Japan's Olympus, which sold cameras used to inspect the stomach, intestines, uterus, or bladder, introduced a miniaturized ultrasound probe used in minimally invasive abdominal and pelvic surgeries. Similarly, Boston Scientific, a leading American producer of stents to treat heart patients, introduced a miniature probe to diagnose heart problems and problems with blood flow.[74] These newcomers, who sold a relatively narrow range of specialized devices, had not however gained much share of overall ultrasound sales.

Figure 10 Distribution of Ultrasound Sales by region (1999) and by company (1998)



Source: Frost & Sullivan. (2001)

The top four companies that accounted for fifty-nine percent of ultrasound sales worldwide in 1998 – ATL (which was acquired by Philips that year), HP, Acuson, and GE -- had all entered before the 1980s. All offered a wide range of devices and had invested in increasing sales in countries that had not previously been large ultrasound markets.

Based just on this case and its exhibits, do you see opportunities for a recent or new entrant to enjoy profitable growth in the 2000s?

- Yes/No

If "yes," be prepared to explain what opportunities you foresee and for what kind of entrant, and if "no," why not?

Exhibit 1 Pioneering ultrasound researchers and their collaborators, pre-1954.

Physician(s)	University	Collaborators	Pathologies Diagnosed	Device Design	Date
John Wild (surgeon)	Minnesota	Donald Neal, John Reid (engineers)	Breast cancer	Probe mounted on apparatus, unit displayed crude cross-sectional image	1952
Douglass Howry (radiologist) and Joseph Holmes (nephrologist)	Colorado	W.R. Bliss, Gerald Posakony (engineers)	Breast, liver, and kidney cancers	Probe mounted on apparatus, unit displayed crude cross-sectional image	1952
Inge Edler (cardiologist)	Lund	Carl Hellmuth Hertz (physicist)	Faulty heart valves	Hand-held probe, unit recorded measurements but did not display image	1953

Sources: Adrian (2013), Koch (1993), and Edler, Inge, and Kjell Lindström. (2004)

Exhibit 2 Pioneering ultrasound researchers and their collaborators, 1955-1958

Physician(s)	University	Collaborators	Pathologies Diagnosed	Device Design	Date
Lars Leksell (neurologist)	Lund		Bleeding in brain	Two hand-held probes, unit recorded measurements but did not display image	1955
Kenji Tanaka (surgeon), Toshio Wagai (surgeon), and Shuichi Hayashi (surgeon)	Tokyo and Jutendo	Rokuro Uchida (physicist) and Yoshimitsu Kikuchi (engineer)	Brain, breast, and abdominal organ cancers	Hand-held probe, unit recorded measurements but did not display image	1956
T. Yoshida (cardiologist), and Y. Nimura (cardiologist)	Osaka	Shigeo Satomura (physicist)	Heart Disease	Hand-held probe, unit recorded measurements but did not display image	1956
G. Henry Mundt (ophthalmologist) and William F. Hughes (ophthalmologist)	Illinois		Eyeball Injuries	Probe mounted on mechanical arm, unit recorded measurements but did not display image	1956
Ian Donald (obstetrics/gynecologist)	Glasgow	Thomas Brown (engineer)	Cancers of the kidney, liver, spleen, and reproductive organs; problems with pregnancy, reproductive organs.	Two designs: Hand-held probe, unit displayed crude cross-sectional image, and Probe mounted on frame or mechanical arm, unit displayed crude cross-sectional image	1958

Sources: Szabo (2013), Kevles (1998), Blume (2013), Campbell (2013), and and Edler, Inge, and Lindström (2004).

Exhibit 3 Ultrasound Market Entrants, 1960 to 1969

Company	Origin/Domicile	Medical Application	First Introduced
Aloka	Spinoff of Japan Radio Company/Japan	Brain, fetus	1960
NEC Corp.	Communications/Japan	Brain	1960
Sonicaid	Startup/United Kingdom	Fetus, fetal heart	1960
Siemens	Diagnostic devices (X-ray, mammography in development)/Germany	Brain, eyeball, heart	1961
Physionics Engineering	Startup/United States	Soft tissue (General/abdomen)	1963
Kelvin Hughes	Industrial flaw detectors/United Kingdom	Brain, eyeball, heart	1963
Smith Kline	Pharmaceuticals, diagnostic devices/United States	Heart	1963
General Precision and Smith Kline Instruments	Defense, computers, pharmaceuticals, diagnostic devices/United States	Eyeball	1963
Metrix	Ultrasound equipment/United States	Abdomen	1963
Sperry-Rand	Defense, computers, industrial flaw detectors/United States	Heart	1964
Krautkramer	Industrial flaw detectors/Germany	Brain, eyeball, heart	1964
Kretztechnik	Industrial flaw detectors/Austria	Fetus	1964
Smiths Industries	Aviation/United Kingdom	Fetus	1964
Hewlett Packard	Computers/United States (medical based in Denmark)	Fetal heart	1967
Nuclear Enterprises	Medical instruments/United Kingdom	Fetus	1967
Unirad	Startup/United States	General/abdomen	1968
Picker	Diagnostics devices (X-ray machines, mammography in development)/United States	General/abdomen	1968
Grumman Corp.	Defense/United States	Eyeball	1968
Toshiba	Defense, communications, diagnostic devices (X-ray)/Japan	General/abdomen	1968
Magnaflux	Industrial flaw detectors/United States	Brain, heart	1969
Gould	Electronics/United States	*unknown*	*unknown*

Sources: Frost & Sullivan. (1975) Colton (1982), and Mitchell (1988).

Note: As the sources above acknowledge, any listing of ultrasound market participants is likely incomplete because ease of entry encouraged numerous participants.

Exhibit 4 Chronology of Selected Ultrasound Imaging Developments and Enabling Technologies

Decade	Selected Ultrasound Developments	Enabling Technologies
Pre-WWII	Echo-ranging	Vacuum tube amplifiers
1940s	Images	Radar, Sonar Supersonic Reflectoscope Colossus and ENIAC computers and transistors
1950s	Measurements of distance Measurements of distance recorded over time. Doppler ultrasound Cross-sectional images constructed from scans made from many angles	Integrated circuits Phased-array antennas
1960s	Cross-sectional images made with probe that touches the body	Moore's law Microprocessors Large-scale integration of transistors on chips Handheld calculators
1970s	Analog and digital components rendering grayscale images. Grayscale image displays Rapid image production that records motion over time Probes with multiple transducers	Random access memory Erasable and programmable read-only memory Application-specific integrated circuits Scientific calculators Altair (the first personal computer)
1980s	Doppler devices capable of locating problems with blood flow. Color-coded images of blood flow	Gate arrays Digital signal processing Chips Surface mount components Computer-aided design of large-scale integrated circuits
1990s	Digital systems 3D imaging	Low-cost analog-to-digital converters Powerful personal computers 3D image processing software Nanotechnology Signal processing Broadband transducers
2000s	3D imaging that records motion over time Hand-carried and pocket ultrasound units	Miniaturization Advanced signal processing High-speed architectures

Source: Szabo (2013).

Exhibit 5 The National Science Foundation's Ultrasound Innovation Experiment

"In the early 1970s, the National Science Foundation (NSF), in a program proposal, concluded that US manufacturers were not undertaking enough development work for commercializing medical ultrasound.… In 1973, ultrasound was growing more vigorously outside the US, and this growth was spurred by government support. Australia, in fact, had set up a separate research institute for ultrasound experimentation.

"The NSF in 1973, therefore, decided to create an incentives program to spur American industry's involvement in ultrasound … [It developed] performance specifications for an instrument that would presumably meet a real medical need and that was technically feasible. Any company creating an instrument to specifications would have clinical testing sites in the VA system [Veterans Administration hospitals] made available. The program was announced in February 1974 and had a deadline of April 30, 1978. Although 12 companies [listed below] did sign up for the program, not one developed a product to NSF specifications. In a review of the incentives program, Arthur D. Little compared the growth of commercial activity in four sectors of diagnostic medicine. They concluded that the development time for ultrasound was normal, that the NSF's basic hypothesis was incorrect, and that the incentives program really had provided no incentives."

--excerpted from Geisler and Heller (2012)

Participants:

Actron Industries (McDonnell Douglas)

American Optical

Baird Atomic

Beckman Instruments

Diagnostic Electronics Corporation

Grumman Health Systems

Litton Medical Products

Picker Corporation

RCA

Rohe Scientific

Smith Kline Instruments

Unirad Corporation

Sources: Colton (1982) and Geisler and Heller (2012).

Exhibit 6 Ultrasound Market Entrants, 1970 to 1982

Company	Location	Experience
Actron Industries (part of McDonnell Douglas)	United States	Defense
Acuson	United States	Startup
Advanced Diagnostics Research Ultrasound (ADR)	United States	Startup
Advanced Technology Laboratories (ATL)	United States	Startup
Alvar Electronics	France	Communications, electronics
American Optical	United States	Diagnostic devices
Arvin/Echo	United States	Communications, electronics
ATS Laboratories	United States	Startup
Ausonics (div of Nucleus)	Australia	Diagnostic devices
Bach-Simpson	Canada	Electronics, engineering equipment
Baird Atomic	United States	Scientific instruments
Beckman Instruments	United States	Diagnostic devices
Bio-Dynamics (div of Boehringer Mannheim--later Biosound)	Germany	Diagnostic devices
Bionetics	United States	Aviation, electronics
Bioscan	United States	Startup
Bruel & Kjaer	Denmark	Communications, defense, engineering equipment
Carolina Medical Electronics	United States	Diagnostic devices
Colgate-Palmolive	United States	Consumer products
Compagnie Generale de Radiologie (CGR)	France	Diagnostic devices
Cooper Medical-Xenotec	United States	Diagnostic devices
Corometrics	United States	Diagnostic devices
D.E. Hokanson	United States	Startup
Dakota Medical Systems	United States	Startup
Dapco Industries	United States	Defense, electronics
Dennon Instruments	United States	unknown
Diagnostic Sonar	United Kingdom	Startup
Diagnostics Electronics Corp.	United States	Diagnostic devices
Diasonics	United States	Startup
Digisonics	United States	Startup
Dubernard	France	unknown
Dunn Instruments	United States	unknown
DuPont	United States	Pharmaceuticals, diagnostic devices
Eastman Kodak	United States	Photographic, diagnostic equipment and supplies
Echomed	United States	unknown
ECLAT	Germany	Startup
Eigen Video	United States	Startup
Electra-Physics Laboratories	United States	Startup
Elscint	Israel	Diagnostic devices
G. D. Searle	United States	Pharmaceuticals, diagnostic devices

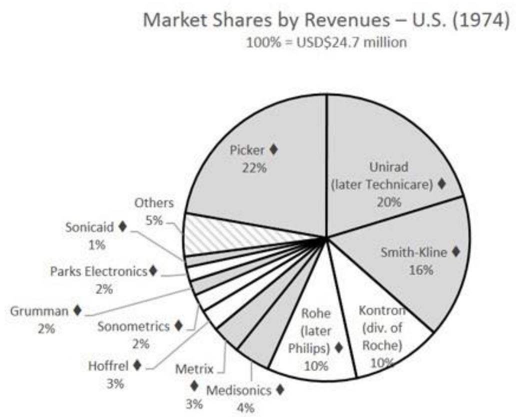
Company	Location	Experience
General Electric (GE)	United States	Diagnostic devices
General Electric Company	United Kingdom	Defense, electronics, communications
GST Laboratories	United States	Startup
High Stoy Technological Corp.	United States	Startup
Hitachi	Japan	Diagnostic devices
Hoffrel Instruments	United States	Diagnostic devices
Holosonics	United States	unknown (likely startup)
Honeywell	United States	Defense
Illinois Imaging and Electronics	United States	Diagnostic devices
Irex Medical Systems	United States	Diagnostic device components
KB-Aerotech	United States	Industrial flaw detectors
Kontron (div of Hoffmann-La Roche)	Switzerland	Pharmaceuticals, diagnostic devices
Kranzbuhler	Germany	Diagnostic devices
Life Instruments	United States	Surgical instruments
Litton Industrial Products	United States	Defense
Matrix Instruments	United States	Diagnostic devices
Matsushita Electric Co.	Japan	Electronics
Medasonics	United States	Startup
MedCorp	United States	unknown
Mediscan	United States	unknown
Medrix Corp.	United States	unknown
Medtronic/Medical Data Systems	United States	Diagnostic devices
Microsonics	United States	unknown
Narco Bio-Systems	United States	Diagnostic devices
National Ultrasound Corp.	United States	unknown
NISE Inc.	United States	unknown
Nuclear Associates	United States	Diagnostic devices
Oldelft Corp. of America	Netherlands/United States	Startup
Omnimedical	United States	unknown
Organon Teknika	Netherlands	Pharmaceuticals, diagnostic devices
OTE Biomedica	Italy	Diagnostic devices
Panametrics	United States	Industrial measurement equipment
Parker Laboratories	United States	Diagnostic devices
Pennsylvania X-ray Corp.	United States	Diagnostic devices
Pharmaceutical Innovations	United States	Startup
Philips	Netherlands	Diagnostic devices
Pie Data Medical	United Kingdom	Startup
Polaroid Corp.	United States	Photographic equipment and supplies, consumer products
Princeton Electronic Products	United States	Diagnostic devices

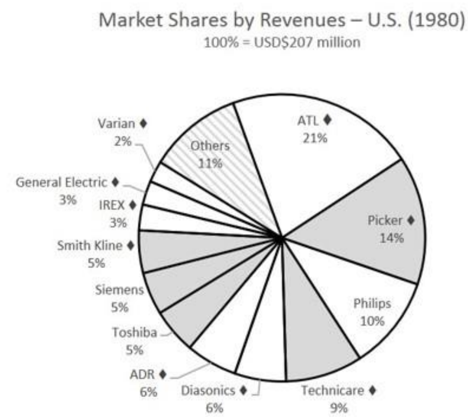
Company	Location	Experience
Pyramid Medical	United States	Startup
Radiation Measurements	United States	Diagnostic devices
Radx Corp.	Australia	Startup
Raytheon Medical Systems	United States	Defense, electronics, communications, diagnostic devices
RCA	United States	Communications
Rogers Instruments	United States	Medical equipment and supplies
Rohe Scientific Corp.	United States	Diagnostic devices
Rorer Corporation	United States	Pharmaceuticals
Schiff Photo Mechanics	United States	Startup
Second Foundation	United States	unknown
Shimadzu	Japan	Diagnostic devices
Sin-Med Benelux	Netherlands	unknown
Sonics Imaging	United States	Startup
Sono-Diagnostics	United States	unknown
Sonometrics	United States	unknown
Sonoscan, Inc.	United States	Startup
Space-Tek	United States	unknown
Squibb Medical Systems	United States	Pharmaceuticals
Technicare	United States	Diagnostic devices
Thorn-EMI	United Kingdom	Diagnostic devices
Toitu	Japan	Diagnostic devices
USA Imaging, Inc.	United States	unknown
Ultra-Cal, Inc.	United States	Startup
Unigon Industries	United States	Diagnostic devices
Varian Ultrasound	United States	Diagnostic devices
VAS Corp.	United States	Diagnostic devices
Xenotec	United States	unknown (likely startup)
Xerox	United States	Diagnostic devices
Xonics	United States	Diagnostic devices
Yokogawa	Japan	Diagnostic devices

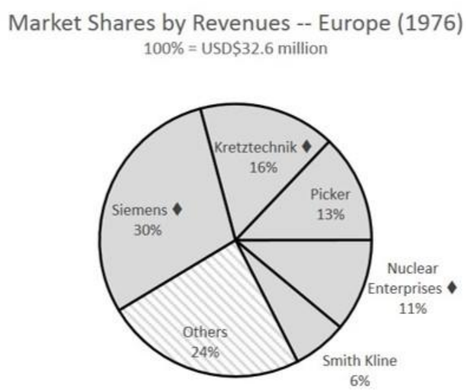
Sources: Frost & Sullivan. (1975, 1982, 1983) , Colton (1982), Mitchell (1988), and the FDA PMA and 510(k) databases.

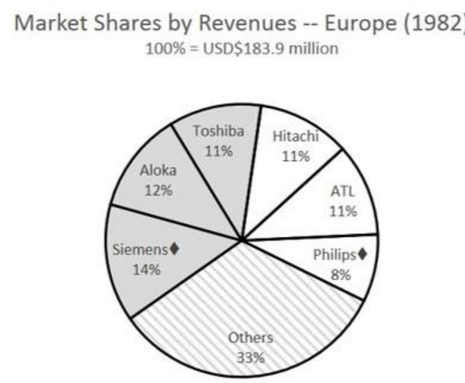
Note: As the sources above acknowledge, listings of ultrasound participants are likely to be incomplete because ease-of-entry encouraged numerous participants.

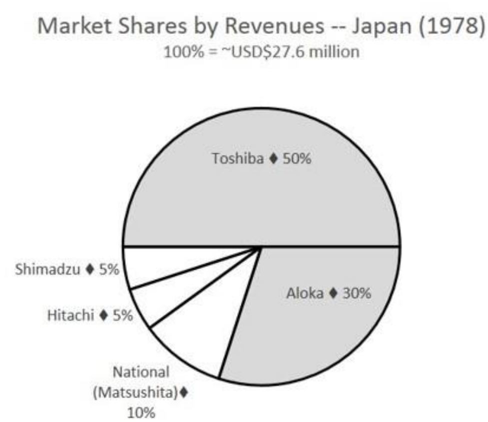
Exhibit 7 1970s and Early 1980s Market Shares in the US, Europe, and Japan











Sources: Bisconte (1980), Frost & Sullivan. (1975, 1976, 1982, 1983)

Note: Companies with 1960s-vintage ultrasound businesses (including those that acquired 1960s-vintage entrants) are grayed. Domestically based companies are marked with a diamond (♦). Philips was granted a US patent for an ultrasound device in 1966 but entered the market in the 1970s with the acquisition of Rohe. European sales revenues for 1976 are a full-year estimate based on partial-year data.

Endnotes

[1] Thomas L. Szabo, *Diagnostic Ultrasound Imaging: Inside Out*, 2nd edition. (Amsterdam: Academic Press, 2013), http://nrs.harvard.edu/urn-3:hul.ebook:MIL_550808; 25.

[2] Adrian Thomas, *The History of Radiology*, Oxford Medical Histories (Oxford: Oxford University Press, 2013), 123; Szabo, *Diagnostic Ultrasound Imaging*; Bettyann Kevles, *Naked to the Bone: Medical Imaging in the Twentieth Century*, The Sloan Technology Series (Reading, Mass: Addison-Wesley, 1998). Cost comparison based on data in: Frost & Sullivan. (27 June 2013) 2013 Global Medical Imaging Equipment Market Outlook. Accessed September 2016. Mitchell, William. "The Diagnostic Imaging Industry, 1896-1988." Unpublished report. University of Michigan Business School, 1988. Chapter 4, page 3. Accessed March 22, 2016. https://faculty.fuqua.duke.edu/~willm/bio/cv/Dissertation/.

[3] EKGs record the electrical activity of hearts through small electrode patches attached to the skin of chests, arms, and legs. The recordings help diagnose poor blood flow to heart muscles ('ischemia'), heart attacks, thickened heart muscles, and other abnormalities, such as high potassium or high or low calcium in electrolytes.

[4] H. Gohr and T.H. Wedekind proposed diagnostic ultrasound in Germany in 1940. Andre Denier proposed diagnostic ultrasound in France in 1946. Denier may have worked on a prototype, but it is not clear if he ever finished it and was able to test it. See Edler, Inge, and Kjell Lindström. "The History of Echocardiography." *Ultrasound in Medicine & Biology* 30, no. 12 (December 2004): 1565–1644. doi:10.1016/S0301-5629(99)00056-3. After World War II, the Austrian neurologist Karl Dussik and his physicist brother Friedrich demonstrated an ultrasound scanner intended to diagnose brain tumors. For a few years, the Dussiks believed their device had worked, because it did produce images that seemed to show the crude outlines of the brain. However, follow up tests conducted by both the Dussiks and other researchers showed the shapes were produced by overlapping echoes from both the brain and the skull. Thomas, *The History of Radiology*, 2013; Edler and Lindstrom, "The History of Echocardiography."; Newman and Rozycki, "The History of Ultrasound"; Siddharth Singh and Abha Goyal, "The Origin of Echocardiography," *Texas Heart Institute Journal* 34, no. 4 (2007): 431–38; Thomas, Banerjee, and Busch, *Classic Papers in Modern Diagnostic Radiology*.

[5] One device created the "slice" by combining images taken from several overlapping angles around the patient, and the other device created the "slice" by combining a series of adjacent measurements taken in a row across the patient into one larger image.

[6] S. Campbell, "A Short History of Sonography in Obstetrics and Gynaecology," *Facts, Views & Vision in ObGyn* 5, no. 3 (2013): 213–229. Although they had separately arrived at similar ends, John Wild (the surgeon) and Douglass Howry (the radiologist) had begun their work for different reasons. Wild had investigated ultrasound with specific clinical applications in mind, first to locate injuries to the intestines, and then later as a method for detecting breast cancer and preparing patients for surgery. Howry had become interested in ultrasound as a theoretical alternative to X-rays while in medical school. First, he built and refined the device to produce anatomically accurate images, and then, after he began working with nephrologist Joseph Holmes, Howry tested its diagnostic capabilities for abdominal diseases and breast cancer. See: Ellen Koch, "In the Image of Science? Negotiating the Development of Diagnostic Ultrasound in the Cultures of Surgery and Radiology," *Technology and Culture* 34, no. 4 (1993): 858, 886. Re: the development of echocardiography, see: Edler and Lindstrom, "The History of Echocardiography."

[7] Fye, Bruce. Caring for the Heart: Mayo Clinic and the Rise of Specialization. New York: Oxford University Press, 2015, 427.

[8] Thomas, *The History of Radiology*, Chapter 8; Nicolson and Fleming, *Imaging and Imagining the Fetus*; Campbell, "A Short History of Sonography in Obstetrics and Gynaecology"; G. H. Mundt and W. F. Hughes, "Ultrasonics in Ocular Diagnosis," *American Journal of Ophthalmology* 41, no. 3 (March 1956): 488–98; Kevles, *Naked to the Bone,* Chapter 10; Joseph H. Holmes, "Diagnostic Ultrasound during the Early Years of A.I.U.M.," *Journal of Clinical Ultrasound* 8, no. 4 (August 1, 1980): 299–308, doi:10.1002/jcu.1870080404; Edler and Lindstrom, "The History of Echocardiography."; Yoshimitsu Kikuchi et al., "Early Cancer Diagnosis through Ultrasonics," *The Journal of the Acoustical Society of America* 28, no. 4 (July 1, 1956): 779–779, doi:10.1121/1.1905117; Masaki Kitajima et al., "The history of endoscopy and endoscopic surgery in Japan," *Nihon rinsho. Japanese journal of clinical medicine* 68, no. 7 (2010): 1215–23. One Japanese researcher may have had some contact with early American researchers in the 1950s, but for the most part, Japanese physicians explored ultrasound on their own and developed advances, like Doppler technology, that were different from the advances developed by American and European researchers. However, by the 1960s and 1970s, researchers from the U.S., Europe, and Japan routinely met and exchanged ideas at conferences and newly established World Congresses on Ultrasound.

[9] Campbell, "A Short History of Sonography in Obstetrics and Gynaecology," 215.

[10] P. N. T. Wells and Marvin C. Ziskin, *New Techniques and Instrumentation in Ultrasonography*, Clinics in Diagnostic Ultrasound; v. 5 (New York: Churchill Livingstone, 1980). D. N. M. D. White and L. F. Hanna, "Automatic Midline Echoencephalography: Examination of 3,333 Consecutive Cases with the Automatic Midline Computer," *Neurology* 24, no. 1 (January 1974): 80–93.

[11] Edler and Lindstrom, "The History of Echocardiography."; Fye, *Caring for the Heart*; Wells and Ziskin, *New Techniques and Instrumentation in Ultrasonography.*

[12] Edler and Lindstrom, "The History of Echocardiography."; Fye and Fye, *Caring for the Heart*. The devices that measured blood flow relied on the "Doppler effect," whereby motion changes the pitch of the sound waves received, and thus came to be known as "Doppler" ultrasound.

[13] Campbell, "A Short History of Sonography in Obstetrics and Gynaecology."

[14] William Gordon Mitchell, "Dynamic Commercialization: An Organizational Economic Analysis of Innovation in the Medical Diagnostic Imaging Industry" (University of California, Berkeley, 1988), http://search.proquest.com.ezp-prod1.hul.harvard.edu/docview/303668403/abstract?; J G Terrill, "Cost-Benefit Estimates for the Major Sources of Radiation Exposure.," *American Journal of Public Health* 62, no. 7 (July 1972): 1008–13. Mitchell, "The Diagnostic Imaging Industry" pages 3-4 and Chapter 4; Frost & Sullivan. (1975) *The Ultrasonic Medical Market.* Thomas, *The History of Radiology*, 129-132; Nicolson and Fleming, *Imaging and Imagining the Fetus,* 132, 135-136, and Chapter 9; Kevles, *Naked to the Bone,* 229-230; Blume, *Insight and Industry,* 105-110.

[15] Later, however, ultrasound producers would sell multi-purpose devices and product lines for a wide range of applications.

[16] Blume, Insight and Industry, Chapter 3; Nicolson and Fleming, Imaging and Imagining the Fetus. Colton, Analysis of Five National Science Foundation Experiments. Mitchell, "The Diagnostic Imaging Industry," Chapter 4.

[17] Toshiba became a market leader in the 1980s and Siemens in the 2000s.

[18] These included: Smith Kline (U.S), Sperry-Rand (U.S.), Kelvin Hughes (UK), and NEC Corp (Japan).

[19] Companies that sold outside their home markets in the 1960s included: Physionics (Picker), Smiths (NE), Siemens, Kretztechnik, Aloka, Smith Kline, and Hewlett Packard.

[20] Unirad would enter the European market in the 1970s. See Frost & Sullivan. (November 1976) European Markets for Medical Ultrasonic Equipment, page 82. Blume, *Insight and Industry,* Chapter 3; Nicolson and Fleming, *Imaging and Imagining the Fetus*. Colton, *Analysis of Five National Science Foundation Experiments.* Mitchell, "The Diagnostic Imaging Industry," Chapter 4; "History of Ultrasound in Obstetrics and Gynecology, Parts 1-3," accessed October 6, 2016, http://www.ob-ultrasound.net/history.html.

[21] For more on the development of different cardiovascular ultrasound applications, see: Fye, Bruce. *Caring for the Heart*, 427. See also the discussion of Stuart Campbell's work on fetal abnormalities in Nicolson and Fleming, as well as Goro Inada and Mineko Ishizaki, "Comparative Studies on X-ray and Ultrasound Diagnoses of Cross Section Images of Human Limbs," *Nagoya Medical Journal,* 15, no. 1 (1969): 19–22.

[22] Some devices required technicians to "rock" the transducers back and forth as they moved them laterally. Devices like the Diasonograph that mounted the transducers on arms eliminated the need for rocking, but the technician still had to move the transducer by hand as it skimmed back and forth across the area to be scanned. See the descriptions in S. Campbell, "A Short History of Sonography in Obstetrics and Gynaecology," *Facts, Views & Vision in ObGyn* 5, no. 3 (2013): 213–229.

[23] Years later, hospitals would have similar problems when they installed early CT and MRI equipment.

[24] Nicolson and Fleming, *Imaging and Imagining the Fetus,* 132, 135-136, and Chapter 9; Thomas, *The History of Radiology*, 129-132; Kevles, *Naked to the Bone,* 229-230; Mitchell, "Dynamic Commercialization," 3-4; Blume, *Insight and Industry,* 105-110; Ian Donald, "On Launching a New Diagnostic Science," *American Journal of Obstetrics and Gynecology* 103, no. 5 (1969): 609–628, doi:10.1016/0002-9378(69)90559-6. Susan Bartlett Foote and Will Mitchell, "Selling American Medical Equipment In Japan," *California Management Review; Berkeley* 31, no. 4 (Summer 1989): 146.

[25]Those who stayed in likely used their other businesses to keep their ultrasound operations going. Blume, *Insight and Industry,* Chapter 3; Nicolson and Fleming, *Imaging and Imagining the Fetus*. Colton, *Analysis of Five National Science Foundation Experiments.* Mitchell, "The Diagnostic Imaging Industry," Chapter 4; "History of Ultrasound in Obstetrics and Gynecology, Parts 1-3," accessed October 6, 2016, http://www.ob-ultrasound.net/history.html.

[26] After attending one of Feigenbaum's lectures, a Mayo Clinic cardiologist persuaded the clinic to purchase its first cardiovascular ultrasound unit and undertake research; within five years, the number of cardiovascular ultrasound procedures performed at the clinic increased ten-fold.

[27] Frost & Sullivan. (June 1982). *Medical Ultrasound Imaging Equipment Markets in the U.S.*, 123; Nicolson and Fleming, *Imaging and Imagining the Fetus,* Chapter 9; Fye, *Caring for the Heart,* 432-436; Campbell, "A Short History of Sonography in Obstetrics and Gynaecology."

[28] Fye, *Caring for the Heart,* 428-429. Nicolson and Fleming, *Imaging and Imagining the Fetus,* 8-9, 203, 205, 207-209, 211, 220, as well as Chapter 9. See also: "Letter from the Editor," *Journal of Clinical Ultrasound* 1, no. 1 (March 1, 1973): 1–1, doi:10.1002/jcu.1870010102; Charles W. Hohler, "Private Practice Use of Real-Time B Scan Ultrasound in Obstetrics and Gynecology," *Journal of Clinical Ultrasound* 6, no. 4 (August 1, 1978): 241–43, doi:10.1002/jcu.1870060410; "Letter from the Editor," *Journal of Clinical Ultrasound* 2, no. 3 (September 1, 1974): 173–76, doi:10.1002/jcu.1870020303. "Mission & Purpose." Accessed October 12, 2016. http://www.sdms.org/about/who-we-are/mission-purpose. "About ASE | American Society of Echocardiography." Accessed October 12, 2016. http://asecho.org/about-ase/. "About BMUS | BMUS." Accessed October 12, 2016. https://www.bmus.org/about-bmus/. "Who Is SVU? - Society for Vascular Ultrasound." Accessed October 12, 2016. http://www.svunet.org/about/whois. "History." Accessed October 12, 2016. http://www.wfumb.org/about/history.aspx. "About SOPE." Accessed October 12, 2016. http://www.sopeonline.org/SOPEONLINE/About/SOPEONLINE/About_SOPE.aspx?hkey=acd4e930-9c30-4ab0-9043-d3a10b42be21. "Mission & Purpose." Accessed October 12, 2016. http://www.sdms.org/about/who-we-are/mission-purpose. "40th Anniversary: Progress through Time." Accessed May 12, 2017. http://www.ardms.org/Pages/Progress-through-time.aspx.

[29] The very earliest development of grayscale scanning was done by George Kossoff at the Ultrasound Institute in Australia at the end of the 1960s, but the commercial devices based on his research and prototypes did not appear until later in the 1970s, after other companies had developed and introduced other grayscale devices. Frost & Sullivan. (June 1982). Medical Ultrasound Imaging Equipment Markets in the U.S.; Fye, Bruce. *Caring for the Heart,* 434-436*: Mayo Clinic and the Rise of Specialization*. New York: Oxford University Press, 2015; Wells and Ziskin, *New Techniques and Instrumentation in Ultrasonography*; Mitchell, "The Diagnostic Imaging Industry," Chapter 4; Campbell, "A Short History of Sonography in Obstetrics and Gynaecology"; Edler and Lindstrom, "The History of Echocardiography"; Bo Eklöf, Kjell Lindström, and Stig Persson, *Ultrasound in Clinical Diagnosis: From Pioneering Developments in Lund to Global Application in Medicine* (OUP Oxford, 2011); Blume, *Insight and Industry,* 106-112; Kai Thomenius, personal communication.

[30] Frost & Sullivan. (June 1982). Medical Ultrasound Imaging Equipment Markets in the U.S.; Fye, Bruce. Caring for the Heart, 434-436; Wells and Ziskin, New Techniques and Instrumentation in Ultrasonography; Mitchell, "The Diagnostic Imaging Industry," Chapter 4.

[31] Frost & Sullivan. (June 1982). Medical Ultrasound Imaging Equipment Markets in the U.S.; Fye, Bruce. Caring for the Heart, 434-436; Wells and Ziskin, New Techniques and Instrumentation in Ultrasonography; Mitchell, "The Diagnostic Imaging Industry," Chapter 4; Campbell, "A Short History of Sonography in Obstetrics and Gynaecology"; Edler and Lindstrom, "The History of Echocardiography"; Bo Eklöf, Kjell Lindström, and Stig Persson, Ultrasound in Clinical Diagnosis: From Pioneering Developments in Lund to Global Application in Medicine (OUP Oxford, 2011); Blume, Insight and Industry, 106-112; Kai Thomenius, personal communication.

[32] Frost & Sullivan. (June 1982). Medical Ultrasound Imaging Equipment Markets in the U.S.; Fye, Bruce. Caring for the Heart, 434-436; Wells and Ziskin, New Techniques and Instrumentation in Ultrasonography; Mitchell, "The Diagnostic Imaging Industry," Chapter 4; Campbell, "A Short History of Sonography in Obstetrics and Gynaecology"; Edler and Lindstrom, "The History of Echocardiography"; Bo Eklöf, Kjell Lindström, and Stig Persson, Ultrasound in Clinical Diagnosis; Blume, Insight and Industry, 106-112; Kai Thomenius, personal communication.

[33] Frost & Sullivan. (June 1982). *Medical Ultrasound Imaging Equipment Markets in the U.S.* Ultrasound was also used to diagnose masses on the spleen and pancreas, and occasionally used to confirm diagnoses of jaundice.

[34] Szabo, Diagnostic Ultrasound Imaging, Table 1.1.

[35]Frost & Sullivan. (June 1982). *Medical Ultrasound Imaging Equipment Markets in the U.S;* Mitchell, "The Diagnostic Imaging Industry," Chapter 4; Campbell, "A Short History of Sonography in Obstetrics and Gynaecology"; Edler and Lindstrom, "The History of Echocardiography"; Fye, Bruce. *Caring for the Heart,* Chapter 18. Organon Teknika offered a movie-producing device for obstetrical applications much later, after it was acquired by Akzo in 1977.

[36] See Colton, Analysis of Five National Science Foundation Experiments.

[37] Mitchell, "The Diagnostic Imaging Industry," Chapter 4, particularly page 13.

[38] Campbell notes that the prices of some of the new obstetrical ultrasound equipment declined in relation to the old devices during the period--see Campbell, "A Short History of Sonography in Obstetrics and Gynaecology," 219; Manuel Trajtenberg, *Economic Analysis of Product Innovation : The Case of CT Scanners*, Harvard Economic Studies ; v. 160 (Cambridge, Mass: Harvard University Press, 1990), 92, 455, and note 14; Mitchell, "The Diagnostic Imaging Industry," 8.

[39] Frost & Sullivan. (June 1982). Medical Ultrasound Imaging Equipment Markets in the U.S., 98-107, 123; Mitchell, "The Diagnostic Imaging Industry," 9, 17. See also: J. L. Johnson and D. L. Abernathy, "Diagnostic Imaging Procedure Volume in the United States," *Radiology* 146, no. 3 (1983); 852-853.

[40] Johnson and Abernathy, "Diagnostic Imaging Procedure Volume in the United States," 852-853.

[41] Frost & Sullivan. (June 1982). *Medical Ultrasound Imaging Equipment Markets in the U.S.,* 98-107, 123; Mitchell, "The Diagnostic Imaging Industry," 9, 17. See also: Johnson and Abernathy, "Diagnostic Imaging Procedure Volume in the United States," 852-853.

[42] These included: Carolina Medical Electronics (U.S.), Pennsylvania X-Ray Corporation (U.S.), Bio-Dynamics (Germany), and Ausonics (Australia).

[43] These included: High Stoy Technological Corporation (U.S.), Medasonics (U.S.), and Radx (Australia).

[44] Frost & Sullivan. (June 1982). *Medical Ultrasound Imaging Equipment Markets in the U.S.* Frost & Sullivan. (April 1983). *Ultrasound Imaging Equipment Markets in the EEC.* Mitchell, "The Diagnostic Imaging Industry," Chapter 4; Colton, editor. *Analysis of Five National Science Foundation Experiments*.

[45] ATL was founded in 1969 to produce marine sonar. In 1974, it licensed technology from the University of Washington and entered the diagnostic ultrasound market. In 1980, it was acquired by Squibb, a U.S.-based pharmaceutical company. Mitchell, "The Diagnostic Imaging Industry," 19-20. Squibb spun ATL off in 1992, after which ATL developed another pioneering product: portable ultrasound. ATL was acquired and absorbed into Philips in 1998.

[46] ATL licensed cutting-edge cardiovascular ultrasound technology from University of Washington researchers and marketed it to both cardiology and radiology departments. The company entered in 1974 and topped the U.S. market in 1980 with twenty-one percent share. However, as we shall see, ATL lost significant ground in the early 1980s. Mitchell, "The Diagnostic Imaging Industry," 19-20.

[47] According to Frost & Sullivan, European radiologists adopted ultrasound first, followed by obstetricians and cardiologists. This seems to contradict the account given in Nicolson and Fleming, which notes that Ian Donald had a harder time convincing radiology departments to try his device in the late 1960s and early 1970s than he did ob/gyn departments. Frost & Sullivan does state that the largest areas of growth for ultrasound in Europe in the 1970s were obstetrics and cardiology. Frost & Sullivan. (April 1983). *Ultrasound Imaging Equipment Markets in the EEC.* Page I-xii. Mitchell, "The Diagnostic Imaging Industry," Chapter 4; Blume, *Insight and Industry,* 112. Japanese price and adoption estimates according to J.-C. Bisconte, "Les Technologies Biomedicales au Japon" (March 1980). See section on ultrasound, as well as Aloka and Toshiba company profiles. Japanese sales in 1980 were $61 million. Japan was the second largest market by individual country that year, after the U.S.

[48] Frost & Sullivan. (June 1982). Medical Ultrasound Imaging Equipment Markets in the U.S. Frost & Sullivan. (April 1983). Ultrasound Imaging Equipment Markets in the EEC. Frost & Sullivan. (April 1986) The Ultrasonography market in Europe, 5. Mitchell, "The Diagnostic Imaging Industry," Chapter 4.

[49] "Ultrasound Is Probing New Markets." *BusinessWeek*, no. 2788 (May 2, 1983): 35–37. Blume, page 112. Janus, Cynthia L., and Samuel S. Janus. "Ultrasound: State of the Art." *Journal of Clinical Ultrasound* 9, no. 5 (June 1, 1981): 217–18. doi:10.1002/jcu.1870090503. See also Mitchell, "The Diagnostic Imaging Industry," Chapter 4 for an estimate of the pace of exit and entry, as well as the FDA's 510(k) and PMA online searchable databases. In all fewer than fifty companies appear to have entered in the 1980s, and more than forty exited.

[50] Coste, Pierre. "An Historical Examination of the Strategic Issues Which Influenced Technologically Entrepreneurial Firms Serving the Medical Diagnostic Ultrasound Market" (ProQuest Dissertations Publishing, 1989). See also: "Ultrasound Is Probing New Markets." *BusinessWeek*, no. 2788 (May 2, 1983): 35–37. Mitchell, "The Diagnostic Imaging Industry," Chapter 4. Frost & Sullivan. (June 1982). *Medical Imaging Equipment Markets in the U.S.* Mitchell, "Dynamic Commercialization."

[51] Wells and Ziskin, New Techniques and Instrumentation in Ultrasonography, Chapter 9.

[52] Eklöf, Bo, Kjell Lindström, and Stig Persson. *Ultrasound in Clinical Diagnosis,* 182-186; Acuson's founders also funded their first years with second mortgages on their homes. Within five years of the launch of their first scanner, the company had added on-site customer training to its support services and began marketing to cardiologists. See Smithsonian Video History Program (1997). *The History of Acuson Ultrasound Machines.* Video transcript. 72-81, 172; as well as Willon, Beth. *The Business Journal.* 5.51 (Apr. 11, 1988): 9. Initially, founder Samuel Maslak had thought the new computers would bring the cost of his ultrasound devices down. Smithsonian Video History Program (1997). *The History of Acuson Ultrasound Machines.* Video transcript. 67-78; Mitchell, "The Diagnostic Imaging Industry," 24-25; Frost & Sullivan. (April 1986). *The Ultrasonography Market in Europe,* 63-65.

[53] Eklöf, Bo, Kjell Lindström, and Stig Persson. *Ultrasound in Clinical Diagnosis,* 182-186; see also Frost & Sullivan. (April 1986). *The Ultrasonography Market in Europe,* 63-65.

[54] Acuson had been unable to patent its computer hardware and software – only the company's probe had patent protection.

[55] A few university-based groups were also developing computed sonography in the late 1970s and early 1980s.

[56] As previously mentioned, ATL had pioneered development of devices that both monitored blood flow and produced grayscale movies, which allowed it to capture significant share and lead the U.S. market at the end of the 1970s. By 1980, ATL had shed its original business of marine sonar and had been acquired by the U.S. pharmaceutical company Squibb. Squibb would subsequently spin the company off in 1992, after which ATL developed another pioneering product: portable ultrasound. ATL was acquired and absorbed into Philips in 1998.

[57] Acuson did copyright the phrase "computed sonography," and when ATL tried to use it in their advertising, Acuson sued. See: Mitchell, "The Diagnostic Imaging Industry," 24-25.

[58] Color cardiovascular ultrasound was made possible by adding Doppler capabilities to the cardiovascular scanners that produced grayscale moving images. The devices superimposed color images of blood flow (with different colors to indicate the speed and direction) on the grayscale moving images of the beating heart, highlighting problems like blood churning through leaky valves. Edler and Lindstrom, "The History of Echocardiography."; Liv Hatle, "Noninvasive Measurements of Intracardiac Blood Flow Velocities with Doppler Ultrasound," *Acta Medica Scandinavica* 221, no. 2 (January 12, 1987): 133–36, doi:10.1111/j.0954-6820.1987.tb01256.x.; Souhrada, "Imaging Devices' Shifting Uses Affect Market"; Anderson, "Trends in Equipment Acquisition"; P. N. T. Wells, *Advances in Ultrasound Techniques and Instrumentation*, Clinics in Diagnostic Ultrasound ; v. 28 (New York: Churchill Livingstone, 1993); Fye, *Caring for the Heart,* 436-438; Frost & Sullivan. (April 1986) *The Ultrasonography Market in Europe.* 48-56; Mitchell, "The Diagnostic Imaging Industry," 25. Aloka's first color Doppler ultrasound was easier to read but more difficult to operate. However, several companies rapidly offered improved devices that required less skill to operate. See also: D. Holthaus, "Moving Color Images Reveal More about Blood Flow," *Hospitals* 61, no. 14 (July 20, 1987): 80. Despite being first to introduce the innovation, Aloka did not grow its shares in the U.S. market or the European markets. Frost & Sullivan. (April 1986) *The Ultrasonography Market in Europe.* 62-65, 162-169, 214. The devices were enthusiastically adopted in Sweden, however. See: Eklöf, Bo, Kjell Lindström, and Stig Persson. *Ultrasound in Clinical Diagnosis,* 182-186.

[59] Frost & Sullivan. (April 1986) *The Ultrasonography Market in Europe.* 48-56; estimated increases in use are based on study of top five most common diseases in Medicare patients – See: Gehlbach, Stephen H., Adamache, Killard W., and Cromwell, Jerry. "Changes in the Use of Diagnostic Technologies Among Medicare Patients, 1985 and 1990." *Inquiry.* 33:363-372 (Winter 1996/97); page 368, 370, and Table 3. Souhrada, "Imaging Devices' Shifting Uses Affect Market." Anderson, "Survey Identifies Trends in Equipment Acquisitions." F. Sabatino, "As Cardiology Market Matures, Technology's Impact Is Clearer," *Hospitals* 64, no. 20 (October 20, 1990):

62, 64, 66–68. See also Wagner, Mary. "Ultrasound evolution; New advances, applications making the technology a tool of choice for initial screenings and a target of turf battles," *Modern Healthcare* April 6, 1992; and Gonzales, 1992.

[60] The guidelines (put into place in 1984 and finalized in 1985) which were developed in consultation with industry were intended to help companies determine if new devices operated in the same way that early devices had. If the new devices met the guidelines, they were not required to conduct clinical trials before marketing. Companies were required to conduct clinical trials for some of the devices developed in the 1990s, such as an ultrasound catheter for use in heart surgeries. Barbara Bolsen, "Question of Risk Still Hovers over Routine Prenatal Use of Ultrasound," *JAMA* 247, no. 16 (1982): 2195–2197, https://doi.org/10.1001/jama.1982.03320410003001; "The National Institutes of Health (NIH) Consensus Development Program: Diagnostic Ultrasound Imaging in Pregnancy," accessed November 14, 2017, https://consensus.nih.gov/1984/1984UltrasoundPregnancy041html.htm. G. H. Myers, "FDA Regulation of Diagnostic Ultrasound," in *IEEE 1985 Ultrasonics Symposium*, 1985, 652–55, doi:10.1109/ULTSYM.1985.198591; Mel. E. Stratmeyer, "FDA Model for Regulatory Purposes," *Ultrasound in Medicine & Biology*, Second World Federation of Ultrasound in Medicine and Biology Symposium on Safety and Standardization in Medical Ultrasound, 15 (January 1, 1989): 35–36, doi:10.1016/0301-5629(89)90212-3; Dana Nickell, "Endosonics Receives FDA Approval to Begin Human Trials for Heart Use of Combined Ultrasound-Balloon Angioplasty Catheter," *Business Wire*, 1990, 1.

[61] John Friar, "Technology Strategy: The Case of the Diagnostic Ultrasound Industry" (ProQuest Dissertations Publishing, 1987), 108-116.

[62] Frost & Sullivan. (June 1982). *Medical Ultrasound Imaging Equipment Markets in the U.S.* Frost & Sullivan. (April 1983) *Ultrasound Imaging Equipment Markets in the EEC*. Mitchell, "The Diagnostic Imaging Industry," Chapter 4. See also the FDA's 510(k) and PMA databases online at https://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/Databases/default.htm

[63] Acuson tried to replicate its U.S. strategy of hiring a direct sales force in England, France, Germany, and Sweden but failed to gain much share. The company used a distributor in Japan. Frost & Sullivan. (April 1986) *The Ultrasonography market in Europe,* 6-8. Eklöf, Bo, Kjell Lindström, and Stig Persson. *Ultrasound in Clinical Diagnosis: From Pioneering Developments in Lund to Global Application in Medicine*. OUP Oxford, 2011; pages 182-186; Acuson's devices sold better in Sweden than elsewhere in Europe.

[64] Japanese entrants estimated based on reports in the FDA's 510(k) database, Smithsonian Video History Program (1997). *The History of Acuson Ultrasound Machines.* Video transcript, and Frost & Sullivan. (April 1986) The Ultrasonography market in Europe. According to some observers, Japanese rules that required retesting to gain approval for imported devices from the Ministry of Health and Welfare discouraged entry into the Japanese market in the 1980s. These rules were a frequent subject of trade talks and were eventually altered in the 1990s. See, for example: Mary H. Piscatelli, *American-Japanese Trade Impasse: The Regulation of Medical Device Imports into Japan,* Syracuse J. Int'l L. & Com. 156 (1985) 12. However, ultrasound devices did not require retesting under Japanese rules, therefore entry was likely discouraged by other factors, such as Japan's history of being at the forefront of ultrasound research and development since the 1950s and the ongoing dominance of its 1960s-vintage entrants.

[65] Japanese market leaders are assumed to be Toshiba, Aloka, and Hitachi, based on their standing as world market leaders in 1988. See: Eklöf, Bo, Kjell Lindström, and Stig Persson. *Ultrasound in Clinical Diagnosis: From Pioneering Developments in Lund to Global Application in Medicine*. OUP Oxford, 2011; page 184, 188.

[66] 1977 U.S.-based startup Diasonics held the third largest share of the French and German markets. Frost & Sullivan. (April 1986) *The Ultrasonography market in Europe,* 6-8. Eklöf, Bo, Kjell Lindström, and Stig Persson. *Ultrasound in Clinical Diagnosis,* 182-186; Acuson's devices sold better in Sweden than elsewhere in Europe.

[67] Producers reportedly continued to sell ultrasound in order to be seen as "a total imaging company." Frost & Sullivan. (April 1986) The Ultrasonography market in Europe, 5-6

[68] For a list of new accessories, including tiny probes used inside the esophagus and veins, developed by companies during this time see the FDA's 510(k) database. "The History of Acuson Ultrasound Machines," 89-93. Eklöf, Lindström, and Persson. *Ultrasound in Clinical Diagnosis.* Fye, *Caring for the Heart,* 438-442. "The Best Choice for Cardiovascular Ultrasound." Accessed October 5, 2016. http://aloka-europe.de/entity19.aspx. "MBI's Albunex Ends Long FDA Review with first U.S. Ultrasound Contrast Approval | Diagnostic Imaging," August 31, 1994. http://www.diagnosticimaging.com/articles/mbis-albunex-ends-long-fda-review-first-us-ultrasound-contrast-approval. Paefgen, Vera, Dennis Doleschel, and Fabian Kiessling. "Evolution of Contrast Agents for Ultrasound Imaging and Ultrasound-Mediated Drug Delivery." *Frontiers in Pharmacology* 6 (September 15, 2015). doi:10.3389/fphar.2015.00197. Levin, David C, Vijay M Rao, Andrea J Maitino, Laurence Parker, and Jonathan H Sunshine. "Comparative Increases in Utilization Rates of Ultrasound Examinations among Radiologists, Cardiologists, and Other Physicians from 1993 to 2001." *Journal of the American College of Radiology* 1, no. 8 (August 2004): 549–52. doi:10.1016/j.jacr.2004.01.022. Porter, Thomas R. "The Utilization of Ultrasound and Microbubbles for Therapy in Acute Coronary Syndromes." *Cardiovascular Research* 83, no. 4 (2009): 636–642. doi:10.1093/cvr/cvp206. Ito, Koichi, Kazumasa Noro, Yukari Yanagisawa, Maya Sakamoto, Shiro Mori, Kiyoto Shiga, Tetsuya Kodama, and Takafumi Aoki. "High-Accuracy Ultrasound Contrast Agent Detection Method for Diagnostic Ultrasound Imaging Systems." *Ultrasound in Medicine & Biology* 41, no. 12 (December 2015): 3120–30. doi:10.1016/j.ultrasmedbio.2015.07.032. Note: another series of studies done between 1984 and 2012 at a single teaching hospital (Brigham & Women's, Boston) showed an overall decline for ultrasound use in the radiology department beginning around 1990. See: Khorasani, R, P K Goel, N M Ma'luf, L A Fox, S E Seltzer, and D W Bates. "Trends in the Use of Radiology with Inpatients: What Has Changed in a Decade?" *American Journal of Roentgenology* 170, no. 4 (April 1, 1998): 859–61. doi:10.2214/ajr.170.4.9530023. Matin, Amin, David W. Bates, Andrew Sussman, Pablo Ros, Richard Hanson, and Ramin Khorasani. "Inpatient Radiology Utilization: Trends over the Past Decade." *American Journal of Roentgenology* 186, no. 1 (January 1, 2006): 7–11. doi:10.2214/AJR.04.0633. Shinagare, Atul B., Ivan K. Ip, Sarah K. Abbett, Richard Hanson, Steven E. Seltzer, and Ramin Khorasani. "Inpatient Imaging Utilization: Trends of the Past Decade." *American Journal of Roentgenology* 202, no. 3 (February 20, 2014): W277–83. doi:10.2214/AJR.13.10986. Meanwhile, ultrasound use in their emergency department has been slowly growing since 1993. See: Raja, Ali S., Ivan K. Ip, Aaron D. Sodickson, Ron M. Walls, Steven E. Seltzer, Joshua M. Kosowsky, and Ramin Khorasani. "Radiology Utilization in the Emergency Department: Trends of the Past 2 Decades." *American Journal of Roentgenology* 203, no. 2 (July 23, 2014): 355–60. doi:10.2214/AJR.13.11892. Heller, Michael, Scott Melanson, John Patterson, and James Raftis Do. "Impact of Emergency Medicine Resident Training in Ultrasonography on Ultrasound Utilization." *The American Journal of Emergency Medicine* 17, no. 1 (January 1, 1999): 21–22. doi:10.1016/S0735-6757(99)90007-4.

[69] Acuson also incorporated the capacity to make color-coded images of blood flow into their devices.

[70] Smithsonian Video History Program (1997). *The History of Acuson Ultrasound Machines.* Video transcript. 96, 102, 153.

[71] Frost & Sullivan notes that 3D ultrasound was available but in its "infancy," making the transition from research to clinical use in the 1990s. Frost & Sullivan. (1999) World Ultrasound Equipment. Chapter 5. Frost & Sullivan. (2001) *World Medical Diagnostic Ultrasound Imaging Equipment Markets.* Accessed December 2016; 3-5, 5-5, 6-1. A. Rossi et al., "Evaluation of Fetal Cerebral Blood Flow Perfusion Using Power Doppler Ultrasound Angiography (3D-PDA) in Growth-Restricted Fetuses," *Facts, Views & Vision in ObGyn* 3, no. 3 (2011): 175–80. Bjorn Volkmer et al., "Transrectal 3D-Ultrasound with Contrast Media in the Diagnosis of Vesico-Intestinal Fistula Formation," *The Journal of Urology*, 1999, 393, https://doi.org/10.1097/00005392-199904020-00574; V. I. Krasnopolskji et al., "3D-Ultrasound Diagnostics in the Determination of Normal Bladder Anatomy and at the Incontinence," *International Journal of Gynecology and Obstetrics* 70 (2000): B75–B75, https://doi.org/10.1016/S0020-7292(00)85149-8; Andreas Delcker and Hans-Christoph Diener, "3D-Ultrasound of the Carotid Arteries," *European Journal of Ultrasound* 1, no. 4 (1994): 337–344, https://doi.org/10.1016/0929-8266(94)90063-9; Andreas Delcker, "Influence of Data Acquisition on Accuracy in Carotid Plaque Volume Measurements with 3D-Ultrasound," *European Journal of Ultrasound* 4, no. 3 (1996): 161–168, https://doi.org/10.1016/S0929-8266(96)00194-2.

[72] Dong-Jae Kim, "Falls from Grace and Lessons from Failure: Daewoo and Medison," *Long Range Planning*, The Corporate Transformation of Korean Firms, 40, no. 4–5 (August 2007): 446–64, doi:10.1016/j.lrp.2007.06.003; Tim Smart and Pete Engardio, "GE's Brave New World. (Cover Story)," *BusinessWeek*, no. 3345 (November 8, 1993): 64–70; "GE Joint Venture Will Build Scanners in China | Diagnostic Imaging," May 22, 1991, http://www.diagnosticimaging.com/articles/ge-joint-venture-will-build-scanners-china; Gita Piramal, Sumantra Ghoshal, and Sudeep Budhiraja, *World Class in India: A Casebook of Companies in Transformation* (New Delhi, India: Penguin, 2001), Case 13. See also: Frost & Sullivan. (20 July 1999) *World Diagnostic Imaging Equipment Markets.* Accessed March 2016.

[73] Eklöf, Lindström, and Persson. *Ultrasound in Clinical Diagnosis,* 188.

[74] In another instance, Dymax, a small Pennsylvania ultrasound specialist entered the U.S. market in 1990 with ultrasound devices designed to assist in the rapid location of major arteries during invasive procedures. They sold only twenty devices until they entered the Japanese market in 1992, where they expected to sell between 150-200 devices in a year. Like Olympus, Dymax specialized through the 1990s and 2000s, rather than branching out to produce other types of ultrasound devices. Boston Scientific continues to specialize in cardiovascular probes but has branched out somewhat to challenge Olympus by offering gastrointestinal and gynecological probes. See: Marano, Ray. "Medical device manufacturer finds a market in Japan." *Pittsburgh Business Times* 20 Jan.1992: 5. *Business Insights: Essentials*. Web. 19 Feb. 2018.