

X-ray and ultrasound in imaging

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X-ray and conventional angiography

The history of radiology started with the epoch-making work of Wilhelm Konrad Röntgen. He was studying the phenomena accompanying the passage of electric current through a vacuum tube, and on the evening of November the 8th 1895 he discovered the rays that would later be named after him. He observed that a vacuum tube connected to high voltage would cause fluorescence of a piece of barium platinocyanide paper. The vacuum tube was encased within a close-fitting shield of black paper to exclude visible light, proving that this was another kind of radiation than light. In his legendary article *On a New Kind of Rays*, Röntgen reported a huge amount of experiments describing the physical properties of the radiation he called X-rays [1]. Fluorescence was visible at a distance of two meters, and he observed that all bodies were transparent to X-ray in varying degrees. "If the hand be held before the fluorescent screen" Röntgen wrote, "the shadow shows the bones darkly, with only faint outlines of the surrounding tissues". He also described the fact that photographic plates are sensitive to X-rays. In 1901 Röntgen received the Nobel Prize in Physics for his discoveries [2].

Almost immediately physicians and physicists all over the world began to work on the development of X-ray equipment for medical use. This new possibility of visualizing anatomy and pathology in vivo was revolutionary to diagnostics as well as medical research. During the next 50 years X-ray technology went through dramatic improvements including the development of better X-ray tubes, high voltage generators, photo-timers for exposure control and films combined with fluorescent screens that vastly increased the sensitivity and quality of examinations. During the same period new techniques such as *stereo-roentgenography* for 3D X-ray acquisition, *planography* for body section

radiography, *kymography* for the visualization of physiological movements and *photofluorography* for image acquisition on small format film were developed [3].

Radiographic examinations have been used in surgery since the very beginning. As early as in 1896, the American surgeon James Burry reported on the successful use of a roentgenogram to locate and remove a small piece of buckshot from the hand of a painter. Professor of Surgery Carl Beck wrote an important textbook on fractures and the clinical use of X-ray, and in 1904 he published his textbook *Roentgen Ray Diagnosis and Therapy* [4].

In the early days bone and foreign bodies provided tissue contrast. With the use of oral contrast agents like bismuth nitrate (and later barium sulphate) the alimentary tract could be studied. The first account of an angiogram involved the injection of *Teichmann's mixture*, a solution of lime, cinnabar and petroleum into the hand of a cadaver [4]. In the early 1920s, Egas Moniz injected sodium iodide directly into the internal carotid artery to produce an X-ray image of the cerebral circulation. Unfortunately, the patient died from status epilepticus [5], but the quest for safer contrast media continued. In 1927 the first commercially available intravenous contrast medium was developed and marketed by Schering for urinary tract radiography [6]. The introduction of intravenous contrast media opened the era of angiography, making the visualization of arteries and veins possible. For plastic surgery, angiography was an important tool that could provide new understanding on vascular malformations, skin circulation and optimal flap design.

The Swedish radiologist and angiography pioneer Sven Ivar Seldinger revolutionized interventional radiology by introducing a new method for the introduction of catheters into vessels [7]. In his article from 1953 Seldinger wrote: "The main principle consists in the catheter being introduced on a flexible leader through the puncture hole after withdrawal of the puncture needle" [8]. Today this technique is used by radiologists all over the world, enabling access to

almost any vessel in the body through arterial or venous access far away from the vessel of interest.

In plastic surgery, as in almost all medical specialties, X-ray technology is widely used in both clinical work and research. One example of research is the work done by Robert Hamas for radiographic visualization of the shape of breast implants in vivo [9]. However, the most significant contribution by radiographic techniques to plastic surgery is in the research area of vascular anatomy and the development of new operative techniques.

In 1889 Manchot, at the age of 23, a few years before the discovery of X-rays, published his pioneering work *Die Hautarterien des menschlichen Körpers*. Almost a century later in 1983 his work was published in English as *The Cutaneous Arteries of the Human Body*. Manchot described the cutaneous perforators and their source vessels, and based on his dissections he even described different cutaneous vascular territories. The development of radiography provided new possibilities for vascular research. In the 1930s Michel Salmon injected entire cadavers with a mixture containing lead oxide and examined the bodies with X-ray. He mapped the entire cutaneous circulation as well as the blood supply of every muscle in the body. He published his work in French in 1936 but it was not available in the English language until 1988 [10]. Based on the research by Manchot and Salmon, Taylor and Palmer published in 1987 a large study on vascular territories in cadavers [11]. They used ink injections with dissections and radiographic analysis of fresh cadavers. Their *angiosome concept* describes a continuous three-dimensional network of vessels in the skin and deeper tissue layers. Their research showed how arteries closely follow the connective tissue framework of the body. The skin is primarily supplied by cutaneous arteries, which vary in caliber, length and density in different regions. The angiosome concept has provided a major contribution to the understanding of tissue circulation and the development of flap surgery.

In 1945 Morgan and Lewis wrote: "Until the present time roentgenology has constituted one of the most dynamic of the medical sciences. There is little

reason to believe that it will ever be other than progressive and fruitful of significant achievements.” [3] They were right in their belief as radiology has gone through even larger progress with the development of new modalities and advanced imaging techniques. And still conventional X-ray technology plays an important role in the daily clinical practice and scientific research of plastic surgery.

Ultrasound and Doppler

In 1773 the Italian scientist Lazzaro Spallanzani observed that blind bats could fly and avoid obstacles as well as bats that could see. Five years later Charles Jurine found that when the ears of bats were plugged with wax, the otherwise superb navigators became helpless and collided with obstacles [12]. More than 150 years passed until Galambos and Griffin used an ultrasonic detector to show that bats navigated by emitting ultrasound and receiving the echoes [13].



Figure 1 Bats effectively use echolocation with ultrasound pulses for navigation and hunting (Photo: Colourbox.com).

In much the same way as bats and dolphins use ultrasound in navigation, ultrasound pulses are used in medical imaging to visualize anatomy and pathology in the human body. The first ultrasound diagnostic systems were developed for industrial use. Prior to the development of ultrasound technology, X-rays were used to control the integrity of ships' metal hulls. The American researchers Sproule and Firestone pioneered the necessary technology for using ultrasound in the megahertz range with ultrasound pulses having durations as short as microseconds. Their technology was developed in 1941 but could not be published until after the war in 1946 [14]. With their equipment tiny defects in steel constructions could be revealed by ultrasonic examination.

During World War II, the English surgeon John Julian Wild cared for many patients with paralytic ileus caused by blast injuries from German bombing. Wild found it difficult to distinguish between paralytic ileus and obstruction and came up with the idea of using ultrasound in the diagnostics. After the war, he moved to America and was employed at Owen H. Wangensteen's laboratory in Minnesota [14]. Wild used a 15 MHz military transducer and was able to measure the thickness of the bowel wall. He was even able to visualize three distinct layers of the intestine in a large water tank [14]. He used so-called A-mode, or *amplitude mode*, which is the simplest form of ultrasound imaging. After transmitting a short ultrasound pulse into the body, the transducer was listening for echoes that were visualized as peaks with varying amplitude on an oscilloscope's cathode ray screen.

Using ultrasound equipment originally made by the U.S. Navy during World War II for the simulation of radar, Wild did several pilot studies on the echo-producing properties of biologic tissue [15]. He observed a striking difference in echo-patterns in carcinomatous ulcers, brain tumors and breast cancer when compared to normal tissue. While other equipment used for ultrasound operated on lower frequencies with relatively low power, this military equipment was able to produce pulses at a frequency of 15 MHz with a peak power of 644 watts per square centimeter. However, the duration of the pulse was only one-half millionth of a second, giving an average intensity that was not more than 1.3

watts per square centimeter. Wild and his coworkers did not observe any unpleasant side effects of ultrasound examination or pathological changes in tissues that had been examined with the machine he named *the echograph* [15]. With the development of B-mode ultrasound, the spikes on the oscilloscope were exchanged with a two-dimensional array of bright and dark spots on a cathode ray screen. Instead of visualizing the amplitude of echoes as peaks on a line, several lines were put together with the brightness of each image component reflecting the amplitude of a single echo. For the generation of B-mode images, Wild used a hand-held instrument with a propagating crystal that scanned to and fro over a range of 6.5 cm within an elliptical water-chamber [16]. Wild developed scanning devices not only for breast cancer screening, but also trans-rectal and trans-vaginal transducers [14].

In 1952 Wild wrote about A-mode and B-mode: “The echographic structures of tissues can be obtained in one dimension, in a manner analogous to a needle biopsy, or in two dimensions, in one plane. Accordingly, the concepts of uni-dimensional and two-dimensional echography can be introduced” [15]. He even wrote that “further developments could produce three-dimensional echography”, a technology that recently has become available in commercially available ultrasound machines. Far ahead of his time, Wild also wrote that “it should be possible to detect tumors of the accessible portions of the gastrointestinal tract both by density changes and also in all probability, by failure of the tumor tissue to contract and relax” [14]. Nowadays, these principles are used in modern ultrasound diagnostics with elastography.

While Wild concentrated on the clinical use of ultrasound, Douglass Howry was working on the development of new equipment. In contrast to Wild who was a surgeon, Howry had a background in radiology. Howry’s ultimate goal was to make images “in a manner comparable to the actual gross sectioning of structures in the pathology laboratory” [17]. Between 1948 and 1952 Howry and Wild, in spite of being unaware of each other’s work, both developed methods for producing cross-sectional images with the help of ultrasound. Howry and his collaborator Bliss who was an engineer, constructed their first B-mode

ultrasound scanner from surplus naval sonar equipment [18]. The patient's body and the transducer had to be submerged under water during the examination. In 1954 Howry and Holmes constructed a B-mode scanner they called *the Somascope*. In this construction they used a surplus rotating ring gear from a Boeing B-29 gun turret to rotate the transducer 360 degrees around the patient [14]. The Somascope produced images with reasonable quality, but as the patient had to stay motionless with the body submerged in a water tank, the machine was impractical for use in clinical settings.

During the first years of the 1950s many researchers around the world worked on the development of ultrasound diagnostics. In Sweden the cardiologist Inge Edler and the nuclear physics graduate student Carl Hellmuth Hertz at Lund University measured heart activity using ultrasound equipment borrowed from a ship construction company in Malmö. Edler later made echoencephalograms of the brain and developed the technique of echocardiography of the heart [4]. In 1957 Effert and colleagues used ultrasound to visualize the movement of the left atrial walls simultaneous with electrocardiography and phonocardiography in the relative assessment of mitral stenosis and incompetence [16].

In Scotland the obstetricians Ian Donald and John MacVicar worked with the physicist Tom Brown to modify industrial ultrasound equipment for use in medical diagnostics. Donald was a veteran of World War II and humbly said about himself that he had "rudimentary knowledge of radar" from his days in the Royal Air Force and "a continuing childish interest in machines, electronics or otherwise – or what my wife would refer to as my "toys"" [19]. He knew the work of Howry who according to Donald "ran into difficulties because of the need to immerse the naked body of his subject in a large tank of water". Donald was given the opportunity of borrowing an ultrasonic metal flaw detector to see if he could discern any differences in ultrasound echoes from varying types of pelvic tumors. "I shall always remember that lovely sunny afternoon of the 21 July 1955 when we took down the factory in Renfrew two cars with their boots loaded with recently excised fibroids, small, large and calcified, and a huge ovarian cyst" Donald wrote [19]. "The people in the factory had also supplied an

enormous lump of steak by way of a control material. There then followed a series of fascinating experiments behind closed doors in their research department”.

John MacVicar joined Donald’s staff in 1956 and helped greatly with the development of new ultrasound probes with barium titanate that could be applied directly to the patient’s abdominal wall through a film of olive oil. Using A-mode they examined hundreds of patients, “but we earned great mockery from our colleagues who naturally suggested that digital palpation was surely good enough” Donald wrote [19]. Their breakthrough came when they were asked to examine a supposedly dying woman with massive ascites due to portal obstruction from a radiologically demonstrated carcinoma of the stomach. The metal flaw detector demonstrated echoes that had to come from a large cyst, and the radiological findings were declared to be an artifact. A massive mucinous cyst was removed from her abdomen, and the patient’s life was saved [19]. One year later they started using ultrasound to study pregnancy and measure the fetal head size. In 1957 they also developed a new B-mode scanner. In their legendary Lancet article published in 1958, Donald et al. described the principles of ultrasound diagnostics with A- and B-mode, illustrated with cases covering various conditions of pregnancy, ovarian cysts, fibroids, ascites and a complicated ovarian tumor [16].

Today the word Doppler is familiar to all who are involved in the practice of medicine. We cannot even imagine using an ultrasound machine without different options for Doppler imaging, which relies on a fundamental physical principle discovered by Christian Johann Doppler in 1842. He discovered the effect that has been named after him by observing ships on the sea and said that “nothing seems easier to understand than the distance and time interval between two successive waves must become shorter for an observer, who is hurrying towards the source of the waves, and longer if he is moving away from it” [20]. In 1845 Christoph Hendrik Diederik Buys Ballot conducted an elegant experiment that proved the truth of Doppler’s theory. A group of trumpet players were positioned on a train wagon blowing a constant tone as the train passed a

group of observers. The observers could verify that the pitch of the trumpets was higher when the train approached them and lower as the train drove away. Doppler was primarily focused on astronomy and the movement of stars and could not have imagined the impact his theory would have on future science and technology. Today the Doppler effect is used not only in astronomical studies, but also in microscopic spectroscopy, radar equipment in satellites and airplanes, direction finding systems and police equipment for speed control in addition to diagnostic ultrasound [21].

The first application of the Doppler effect in medicine involved measurement of different transit times of ultrasound travelling through flowing blood in different directions. Using this principle, Hebray P. Kalmus made an electronic flowmeter in 1954. The Japanese physicist Shigeo Satomura published an article in 1956 reporting that cardiac valvular motions could be registered with the use of Doppler signals, but his work was only published in Japanese and was therefore unknown in the West [14].

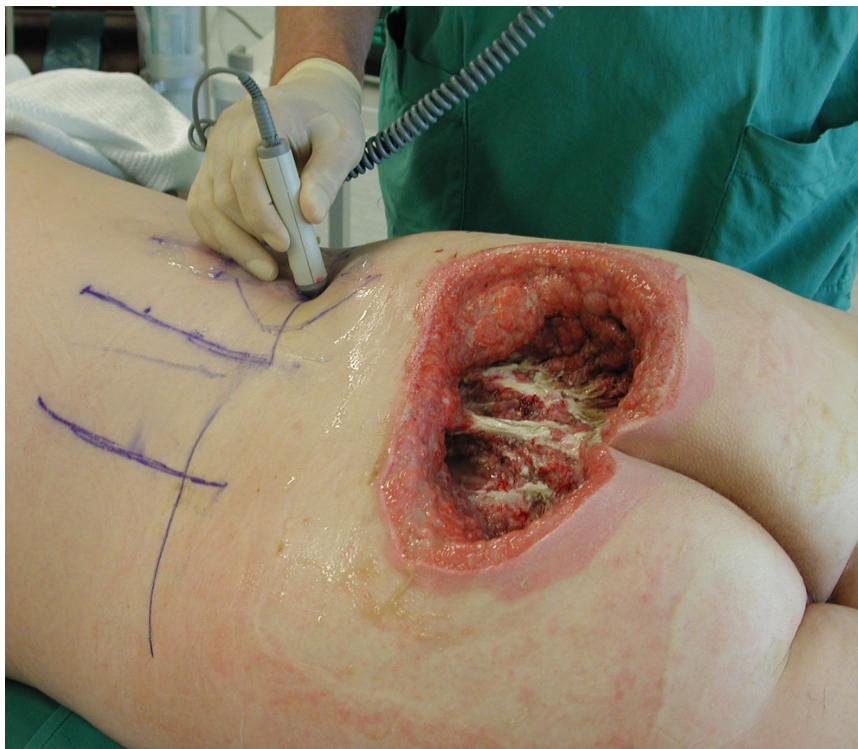


Figure 2 Hand-held Doppler is widely used in the evaluation of arterial perforators. This patient had a large pressure sore that was operated with *The Butterfly Design* using two flaps based on lumbar artery perforators [22].

In 1961 Franklin, Schlegel and Rushmer published a short article in *Science* with the title *Blood flow measured by Doppler frequency shift of back-scattered ultrasound* [23]. In this article they described the simple principle of using the Doppler shift of a continuous ultrasound source to measure blood flow within vessels. Their instrument had two piezoelectric crystals in a plastic cylinder. One of the crystals emits continuous ultrasound at a constant frequency of 5 MHz while the other crystal is used as a receiver. Ultrasound transmitted into a blood vessel is reflected by the blood cells and registered by the receiver crystal. Due to movement of the blood cells, the reflected signal has a slightly different frequency than the transmitted signal according to the Doppler effect. The received signal is amplified and mixed with the transmitted signal to develop a beat signal corresponding in frequency to the Doppler shift. In a *hand-held Doppler* device, this beat signal is sent to a loudspeaker, making arterial and venous flow audible to the ear.

Strandness et al. described the use of a commercially available hand-held Doppler in 1967 [24]. The instrument had a portable main unit connected to a small hand-held transducer, which could be used externally on the skin to assess qualitative information on the velocity of arterial and venous flow. Because of its portability and convenience in operation, the instrument could be easily transported from the laboratory to the bedside, operating room or clinic. In their article, Strandness et al. report the successful use of hand-held Doppler in 84 cases of arterial disease like occlusion, arteriosclerosis and fistulae as well as 17 cases of venous disease like thrombophlebitis, evaluation of extremity edema and monitoring of venous flow after thrombectomy or inferior vena cava ligation.

A prerequisite for spectral Doppler and color Doppler is the use of pulsed-wave Doppler signals. Baker et al. started their work on pulsed-wave Doppler in 1966 and were among the first to produce such an instrument in 1970 [14]. This team also constructed a mechanical transducer that combined real-time imaging with Doppler functions. In 1976 Baker and his coworkers described techniques for

spectral analysis using Fourier transformation performed in real time by a computer to determine if blood was flowing toward or away from the transducer [25]. Graphic curves showing the flow velocity and direction were used to reveal the presence of plaques, intrusions and complete occlusions. In the last paragraph of the article Baker et al. wrote: "When the two methods are combined with a superimposed sound beam vector on the flow image display it may be possible to compute the intervening angle" thereby making quantitative flow measurements possible. Today such functions are integrated in almost all ultrasound machines. Spectral Doppler is instantly available at the push of a button. In color Doppler imaging blood flowing towards and away from the transducer is visualized as respectively red and blue color superimposed on the B-mode picture.

In 1972 Goldberg and Pollack published an article in *Radiology* about their "ultrasonic aspiration transducer" [26]. By drilling a hole in a 2.25 MHz transducer they used A-mode and M-mode for visualizing the tip of a needle as it was introduced via the hole in the transducer and penetrated the skin and deeper tissues. The tip of the needle was visible as a peak on the oscilloscope in A-mode or as a bright dot in M-mode. They used this technique for aspiration of fluid from the thoracic cavity, abdominal cavity, pericardium and renal cysts. In the same article they wrote: "Previously, most aspiration techniques were performed in a hit-or-miss fashion. With this new ultrasonic technique, however, the needle may be accurately guided into the area of interest, and changes of the fluid space during aspiration are known at all times." Later developments, including the use of real-time B-mode have led to a wide repertoire of diagnostic and interventional procedures like ultrasound guided biopsies, installation of contrast media, different kinds of catheterizations, nephrostomy, cholecystostomy, gastrostomy, abscess drainage, introduction of central venous catheters, selective alcohol injections, radioactive therapy, laser, microwave therapy and cryosurgery [27].

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