Computed tomography and MRI

By Sven Weum

Computed tomography

Conventional radiography is a valuable tool that is still responsible for the largest number of examinations in most radiology departments. However, traditional X-ray examinations have several drawbacks that limit their ability to visualize low-contrast tissues and three-dimensional (3D) information. Due to the large X-ray beam used in conventional radiographic examinations, scattered photons represent at least 50 % of the radiation absorbed by the film or digital detector [1]. Scatter creates background intensity in the image that does not relate to the visualized anatomy. These drawbacks were overcome with the introduction of computed tomography, or plainly CT.

The British engineer Godfrey Hounsfield at EMI Laboratories was interested in optimizing systems to utilize all available information. In his legendary article in *British Journal of Radiology* published 1973, he wrote: "In the conventional film technique a large proportion of the available information is lost in attempting to portray all the information from a three-dimensional body on a two-dimensional photographic plate, the image superimposing all objects from front to rear." [2] He then described the world's first CT system. The X-ray tube, detectors and collimators were fixed on a common frame with the tube and detectors placed on each side of the patient's head. The frame was systematically rotated around the head, taking 160 readings between every rotation of one degree. A total of 28.800 readings were stored in a disc file for processing by a computer. By calculating 28.800 equations with 6.400 variables, the computer was able to produce a matrix of 80 x 80 numerical values representing the degree of X-ray absorption by a similar matrix of anatomic locations within a slice through the patient's head. The values were printed as numbers on a line printer and viewed on a cathode ray-tube as pixels with gray tones reflecting the numerical values. Six axial images were made during a period of 35 minutes per patient.

Even though the images produced by Hounsfield's CT system were extremely coarse compared to those made with modern scanners, this was a huge improvement in comparison to conventional radiography. According to Hounsfield, the values of the absorption coefficients of various tissues were calculated to an accuracy of 0.5 %. Within the brain, the tissue absorption values found in different tissues including cerebrospinal fluid cover a 4 % range. By adjusting image contrast and brightness so that this 4 % range, also called *window*, covered the whole gray scale from black to white, different tissues of the brain could be visualized on the screen. Hounsfield constructed a scale with absorption values where air was given the value -500, water 0 and bone approximately +500. Later the values were doubled to cover -1000 to +1000, water still having an absorption value of zero. Nowadays this scale is used by radiologists all over the world, and the values are named *Hounsfield units* after their inventor.

In 1979 Allan Cormack and Godfrey Hounsfield were given the Nobel Prize in Medicine or Physiology for inventing the CT scanner. "Cormack had been working on the concept of scanning slices of the body from various angles and rotations. But it was Hounsfield's work on pattern recognition and the use of computers to analyse readings that made the CT scanner possible", *The Lancet* wrote in their obituary article when Hounsfield died in 2004. In the same article, professor emeritus and RSNA president Brian Lentle was cited saying: "I think when people saw the very first CT images – and they were, by modern standards, not great images – whenever any of us saw those images we realised that radiology was never going to be the same again." [3]

The history of radiology would go on for 76 years from the discovery of X-rays to the first clinical CT images were made in 1972 [4], and radiology has never been the same since. During the following 40 years, there have been many revolutionary technological improvements to CT that have benefited clinical practice and provided new possibilities for scientific research.

The first CT scanner was only able to scan the head. The patient had to lie still for 35 minutes in the scanner, and a rubber cap surrounded with water was covering the patient's head. In 1974 the first body scanner was introduced that enabled imaging of the whole body without the need for water surrounding the scanned part of the body. New hardware and more efficient computer algorithms for image reconstruction vastly reduced scanning time and increased image quality. Subsequent generations of scanners used several different scanning techniques and numbers of detectors. A breakthrough for scanner speed came with the introduction of the low voltage slip ring in 1987 [1]. Until that time, cables connecting the rotating parts of the scanner required that the rotation stopped after each rotation and reversed its direction. Scanning, braking and reversing took 8-10 seconds while only 1-2 seconds were used for data acquisition.

With the introduction of the slip ring, electrical power and signals could be transferred without fixed connections, making continuous rotation of the X-ray tube and detectors possible. In spiral CT, or helical CT, the examination table is smoothly moved through the gantry during the examination. In this way, data is collected in a spiral shaped path allowing much shorter scanning times. Spiral CT has been available since 1989 [5]. The shortened scan time allowed larger parts of the body to be examined in a single breath hold and entire areas to be scanned within the vascular enhancement phase after intravenous contrast injection [6]. With this new technology, CT angiography (CTA) became an alternative to conventional angiography. With CTA both large and small vessels may be visualized in spite of the fact that contrast medium is injected in a peripheral vein and not via selective catheterization.

Even though configurations of several X-ray detectors had been used in CT scanners for many years, it was not until 1998 that the so-called multi-slice, or multi-detector CT (MDCT) scanner, was introduced [5]. In earlier CT scanners, all detectors were used for image acquisition within one single slice of the body. In MDCT scanners several detectors are used in the longitudinal direction allowing the continuous acquisition of several parallel slices. Modern scanners may have

up to 320 parallel detectors at 0.5 mm covering an area of 16 cm that may be scanned in 0.35 seconds [7]. In this way a larger anatomical region as for instance the whole heart may be visualized in one single rotation without even moving the examination table.

The short scanning time and high spatial resolution of MDCT provided many new possibilities for CT scanning. Even 16-slice MDCT, which has now been available for a decade, provides an isometric spatial resolution of less than one millimeter, which makes detailed 3D reconstructions of organs and even small contrast-filled vessels possible. With the newest MDCT scanners an isometric resolution down to 0.3-0.4 mm is achievable.

Figure 1 Modern MDCT and DECT scanners provide new and exciting diagnostic possibilities. With no table movement the patient's heart may be scanned in a fraction of a second. The first DECT scanner in Northern Norway was a donation from Trond Mohn.

In recent years dual-energy CT (DECT) has also become available. Modern DECT scanners are dual-source CT (DSCT) scanners with two X-ray tubes and two sets of detectors mounted on a CT gantry with 90 degrees offset. One great advantage with these scanners is that the combination of two sets of tubes and detectors

makes it possible to obtain a complete volume acquisition in one quarter of a gantry rotation. This means that with a 0.33 second rotation time, a volume may be captured in only 83 milliseconds. Such temporal resolution is ideal for cardiac imaging because motion artifacts due to cardiac movement can be omitted. In addition, so-called dual energy information may be obtained if the two X-ray tubes are operated with different voltage [8].

In his article published in 1973 Hounsfield also described the principle of DECT scanning: "It is possible to use the machine for determining approximately the atomic number of the material within the slice. Two pictures were taken of the same slice, one at 100 kV and the other at 140 kV. If the scale of one picture is adjusted so that the values of normal tissue are the same on both pictures, then the picture containing the material with high atomic number will have higher values at the corresponding place on the 100 kV picture. One picture can then be subtracted by the other by the computer, so that areas containing high atomic numbers can be enhanced." [2]

Modern DSCT scanners do this process with two separate X-ray tubes at the same time, and the software can then remove for instance calcium or contrast medium after acquisition. Pre-contrast images may be artificially constructed from images taken with intravenous contrast by subtracting the attenuation created by the contrast medium. This is one way of reducing radiation dose to the patient, as pre-contrast scanning in some cases may be omitted. In the same way, bone may be artificially removed from the pictures for better visualization of soft tissues and vessels. The same technique may also be used to differentiate between kidney stones and gallstones of different chemical constituents [8].

The high isometric spatial resolution of CTA provides many possibilities for the visualization of small vessels used in reconstructive surgery. With 3D and multi-planar reconstructions (MPR) CTA may provide detailed visualization of vascular anatomy and 3D models of large vessels as well as tiny perforators. Modern post-processing software is easy to use and provides almost endless possibilities for MPR and 3D reconstructions. While such software packages used to be expensive

and provided by the industry, many open source alternatives are now available. In the study reported in paper III, the open source DICOM viewer OsiriX was used in the reading and reconstruction of CTA images. For research purposes this free version of OsiriX may be used on any Mac computer running OS-X. A commercially available version, called OsiriX MD, is approved by the FDA diagnostic imaging in medicine. It is our experience that OsiriX is very user-friendly and that it provides excellent reconstructions that are as good as, or in some cases even better than, those provided by commercially available software, an experience shared by other researchers [9-11].

Magnetic resonance imaging

The basis for magnetic resonance imaging (MRI) is the physical phenomenon called *nuclear magnetic resonance* (NMR) which was discovered before and developed just after World War II [12]. In 1971 Raymond Damadian reported in *Nature* that NMR could be used to detect malignant tissue [13], and a number of medical physicists started working to build a scanning device using NMR [14]. In 1973 Paul Lauterbur published a small article in *Nature*, initially rejected for publication, where he described what he called *NMR zeugmatography*, which actually was an early prototype of MRI [15].

In the 1970s practical use of MRI in medicine was still a distant dream. As late as December 1981 General Electric Company, which is now one of the leading manufacturers of MRI equipment, did not consider MRI technically feasible [16]. In 2003 Lauterbur and Mansfield were given the Nobel Prize in Physiology or Medicine for their work that made MRI possible. Damadian claimed that Lauterbur had stolen his idea about MRI, as he had filed a patent in 1972 where he considered the possibility of making T_1 measurements in vivo in the human body [16]. However, in his Nobel lecture, Lauterbur credited Damadian for discovering that some malignant tissue had longer NMR relaxation times than many normal tissues [17].

For the acquisition of MRI the body is placed in a strong magnetic field that is more than 10.000 times as strong as the magnetic field of the Earth. Short electromagnetic radio frequency (RF) pulses are sent into the body, where the energy is absorbed by hydrogen nuclei in the different tissues. These hydrogen nuclei, or protons, in turn transmit radio signals as echoes that can be picked up by a receiver coil. The strength of these echoes reflects the number of protons in different parts of the body.

To create images of specific organs of the body, the MRI scanner must acquire a signal from each part of these organs and effectively separate signals from different parts of the body. During a dinner in September 1971, Paul Lauterbur got the idea to use "a large set of simple linear gradients, oriented in many directions in turn in three dimensions" [17]. The theory of MRI was conceived. To accomplish this task, an MRI scanner uses separate gradient coils to vary the magnetic field with successive gradients in three dimensions. The signal picked up by the receiver coil is a sum of signals from every possible position in the body. By changing the magnetic gradients and adapting the right RF pulses, the scanner can make a huge data set and calculate the signal strength from all parts the chosen body region.

Signals from protons decay with unequal speeds depending on their various environments. Protons in different molecules have different magnetic properties, which influence the so-called relaxation time. Therefore the magnitude of the radio signal picked up by the receiver coil is monitored some time after the end of the transmitted RF pulse that started the process. Different tissues show different signal strengths, and hydrogen in different molecules may have different relaxation times. Hydrogen in pathological lesions and tumors often have other relaxation times than surrounding tissues which makes them detectable on MRI [12].

In 1984 Norwegian central authorities felt that the time had come to evaluate the introduction of MRI in Norway. The original intention of the authorities was to start with one unit at one of the university hospitals and gain some experience.

However, the first diagnostic MRI unit in Norway was not purchased by the government but after private fund raising. This first MRI unit was installed at Stavanger County Hospital in 1986 [18]. In 1987 a government-appointed committee with the mandate of assigning healthcare priorities decided that MRI should have "zero priority" in the Norwegian health care system. MRI was defined as "health care services which are demanded, but unnecessary and without documented health effect". The committee also claimed that MRI has "rather limited diagnostic value" and that its superiority in comparison to other modalities is restricted mainly to the diagnosis of rare conditions in the central nervous system [19]. Only university hospitals and the large regional hospitals were allowed to buy MRI equipment. These restrictions given by the government were not withdrawn until 1993 [20]. The Norwegian Professor of Radiology and MRI pioneer Hans Jørgen Smith stated in 2001, "the introduction of MRI in Norway is a good example of the inadequacy of central political control of detailed health political issues". He did, however, see signs of change for the better in this country that he conclusively called "the last Soviet state" [18].

Today more than 10 years later things have changed. MRI has become standard equipment in almost all hospitals and all radiologists are supposed to learn basic MRI skills as an inevitable part of their radiological education. While the first prototypes needed several hours to produce an image, modern scanners produce images in seconds and even in real time during acquisition. New pulse sequences for different imaging tasks are continuously being developed for imaging of anatomy, pathology and dynamic processes like flow and drug metabolism. With functional MRI subtle changes in cerebral blood flow can be registered and linked to specific mental or physical activities. With MR spectroscopy we can get detailed information on the distribution of chemical substances in a defined region of interest within the body.

Unlike traditional X-ray examinations and CT, MRI does not use ionizing radiation. Except for the possibility of heating tissues by the RF pulses sent into the body, no potentially harmful side effects have been registered. Too much heating is avoided by limiting the amount of RF energy used by the different

sequences. Normally a local tissue temperature increase up to 1 degree Celsius is accepted, and most imaging sequences cause much less heating [12]. The temperature effect is therefore no threat in the daily use of MRI. However, wire loops like ECG and other cables can act as RF antennas and cause overheating and even burns. Also jewelry and even some tattoos may act as antennas and cause local burns [12]. Unless the patient has a traditional pacemaker or other internal devices that are not MRI safe, such side effects can easily be omitted.

For many years it was a common conception that even contrast media used in relation to MRI examinations were totally safe. However, *nephrogenic systemic fibrosis* (NSF) is a seldom occurring but very serious complication of gadolinium based contrast media. The first cases of NSF were identified in 1997, but it took three years before it was reported in peer-reviewed literature, and its correlation with gadolinium based contrast media was not reported until 2006 [21]. Almost all documented cases of NSF have occurred in patients with moderate or severe renal dysfunction [22]. Today it is common practice to give gadolinium based contrast media only to patients without renal failure.

The good tissue contrast, high spatial resolution and to a large degree lack of harmful side effects have made MRI a very attractive alternative in a wide range of indications for medical imaging including plastic surgery. Most conditions that cause anatomical changes or tissue edema may be visualized with MRI.

REFERENCES

1. Goldman, L.W., *Principles of CT and CT technology.* J Nucl Med Technol, 2007. **35**(3): p. 115-28; quiz 129-30.
2. Hounsfield, G.N., *Computerized transverse axial scanning (tomography). 1. Description of system.* Br J Radiol, 1973. **46**(552): p. 1016-22.
3. Oransky, I., *Sir Godfrey N. Hounsfield.* Lancet, 2004. **364**(9439): p. 1032.
4. Hounsfield, G.N. *Computed Medical Imaging*. Nobel lecture 1979; Available from: http://www.nobelprize.org/nobel_prizes/medicine/laureates/1979/hounsfield-lecture.pdf.
5. Fuchs, T., M. Kachelriess, and W.A. Kalender, *Technical advances in multi-slice spiral CT.* Eur J Radiol, 2000. **36**(2): p. 69-73.

6.   Kalender, W.A., et al., *Spiral volumetric CT with single-breath-hold technique, continuous transport, and continuous scanner rotation.* Radiology, 1990. **176**(1): p. 181-3.

7.   Sorantin, E., et al., *Experience with volumetric (320 rows) pediatric CT.* Eur J Radiol, 2012.

8.   Petersilka, M., et al., *Technical principles of dual source CT.* Eur J Radiol, 2008. **68**(3): p. 362-8.

9.   Rozen, W.M., et al., *Achieving high quality 3D computed tomographic angiography (CTA) images for preoperative perforator imaging: now easily accessible using freely available software.* J Plast Reconstr Aesthet Surg, 2011. **64**(3): p. e84-6.

10.   Fortin, M. and M.C. Battie, *Quantitative Paraspinal Muscle Measurements: Inter-Software Reliability and Agreement Using OsiriX and ImageJ.* Phys Ther, 2012.

11.   Kim, G., et al., *Accuracy and Reliability of Length Measurements on Three-Dimensional Computed Tomography Using Open-Source OsiriX Software.* J Digit Imaging, 2012.

12.   Forshult, S., *Magnetic Resonance Imaging - MRI - An Overview*. Vol. 2007:22. 2007, Karlstad, Sweden: Karlstad University Studies.

13.   Damadian, R., *Tumor detection by nuclear magnetic resonance.* Science, 1971. **171**(3976): p. 1151-3.

14.   Smith, F.W., *Magnetic resonance imaging: another Scottish first.* Surgeon, 2006. **4**(3): p. 167-73.

15.   Lauterbur, P.C., *Image Formation by Induced Local Interactions - Examples Employing Nuclear Magnetic-Resonance.* Nature, 1973. **242**(5394): p. 190-191.

16.   Prasad, A., *The (Amorphous) anatomy of an invention: The case of magnetic resonance Imaging (MRI).* Social Studies of Science, 2007. **37**(4): p. 533-560.

17.   Lauterbur, P.C. *All science is interdisciplinary - from magnetic moments to molecules to men*. Nobel lecture 2003.

18.   Smith, H.J., *The introduction of MR in the Nordic countries with special reference to Norway: Central control versus local initiatives.* Journal of Magnetic Resonance Imaging, 2001. **13**(4): p. 639-644.

19.   NOU, *Retningslinjer for prioriteringer innen norsk helsevesen (Guidelines for priorities in the Norwegian health care system)*. Norges offentlige utredninger. Vol. 23. 1987, Oslo: Universitetsforlaget.

20.   Smith, H.J., *Fra prioritet null til nobelpris (From zero priority to Nobel Prize).* Tidsskr Nor Laegeforen, 2003. **123**(23): p. 3352.

21.   Thomsen, H.S., *Nephrogenic systemic fibrosis: history and epidemiology.* Radiol Clin North Am, 2009. **47**(5): p. 827-31, vi.

22.   Martin, D.R., *Nephrogenic system fibrosis: a radiologist's practical perspective.* Eur J Radiol, 2008. **66**(2): p. 220-4.