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Development of computed tomography – past and present scanner generations

Computed tomography (CT) was introduced in the early 1970s and has revolutionized the practice not only of diagnostic radiology but also of the whole field of medicine. CT was the first technology to marry a computer to a medical imaging machine, the first to display x-ray images as cross sections. Improvements in image quality, acquisition speed have resulted from recent technical developments in helical and, more recently, multiple-row detector technologies (3, 5).

The purpose of this article is to present the development of CT and the differences between the scanner generations.

COMPUTED TOMOGRAPHY

CT is a method for acquiring and reconstructing an image of a thin cross section of an object. CT forms a cross-sectional image, without superimposition of structures that occurs in plane film imaging and the sensitivity of CT to subtle differences in x-ray attenuation is at least a factor of 10 higher than normally achieved by screen-film (5). A CT scanner makes many measurements of attenuation through the plane of a given thickness cross section of the body. These data are used to reconstruct a digital image of the cross section, with each pixel in the image representing a measurement of the mean attenuation of a boxlike element (a voxel) that extends through the thickness of the section. An attenuation measurement quantifies the fraction of radiation removed in passing through a given amount of a specific material of thickness (5).

The image reconstruction process derives the average attenuation coefficient values for each voxel in the cross section by using many rays from many different rotational angles around the cross section. Mathematically, the attenuation value for each voxel could be determined algebraically with a very large number of simultaneous equations by using all ray sums that intersect the voxel. There are a number of advanced reconstruction techniques that are currently used in the CT image reconstruction process (5).

As a final step, the individual voxel attenuation values are scaled to more convenient integers and normalized to voxel values containing water. Voxels containing materials that attenuate more than water (e.g., muscle tissue, liver, and bone) have positive CT numbers, whereas materials with less attenuation than water (e.g., lung or adipose tissues) have negative CT numbers. With the exception of water and air, the CT numbers for a given material will vary with changes in the x-ray tube potential and from manufacturer to manufacturer (5).

In 1917 Radon revealed the mathematical principles of image reconstruction. And in 1979, Sir Godfrey N. Housfield and Alan M. Cormack were awarded the Nobel prize in medicine for the "development of computer assisted tomography." A variety of CT geometries have been developed to acquire the x-ray transmission data for image reconstruction. These geometries, commonly called *generations*, remain useful in differentiating scanner designs (5).

FIRST-GENERATION CT SCANNERS

The first commercial scanner invented by Housfield – the EMI Mark I scanner – was introduced in 1973. This scanner acquired data with an x-ray beam collimated to a narrow beam directed to a single detector on the other side of the patient; the detector and the beam were aligned in a scanning frame. A single projection was acquired by moving the tube and detector in a straight-line motion (translation) on the opposite sides of the patient. To acquire the next projection, the frame rotated 1°, then translated in the other direction. This process of translation and rotation was repeated until 180 projections were obtained (Fig. 1A). The earliest versions required about 4.5 minutes for a single scan and thus were restricted to regions where patient motion could be controlled (the head). Since procedures consisted of a series of scans, procedure time was reduced somewhat by using two detectors so that two parallel sections were acquired in one scan. Although the contrast resolution of internal structures was unprecedented, images had poor spatial resolution (on the order of 3 mm for a field of view of 25 cm and 80 x 80 matrix) and very poor z-axis resolution (~13-mm section thickness) (5).

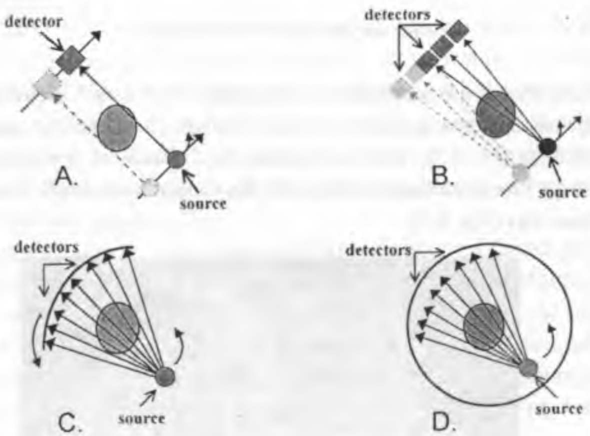

Fig. 1. The diagrams of the different CT scanners generations: A – the first-generation, B – the second-generation, C – the third-generation, D – the fourth-generation

SECOND-GENERATION CT SCANNERS

The main impetus for improvement was in reducing scan time ultimately to the point that regions in the trunk could be imaged. By adding detectors angularly displaced, several projections could be obtained in a single translation. One early design used three detectors each displaced by 1°. Since each detector viewed the x-ray tube at a different angle, a single translation produced three projections (Fig. 1B). Hence, the system could rotate 3° to the next projection rather than 1° and had to make only 60 translations instead of 180 to acquire a complete section. Scan times were reduced by a factor of three. Designs of this type had up to 53 detectors, were fast enough to permit acquisition during a single breath hold, and permit scans of the trunk of the body. Because rotating anode tubes could not withstand the wear and tear of rotate-translate motion, this early design required a relatively low output stationary anode x-ray tube (5).

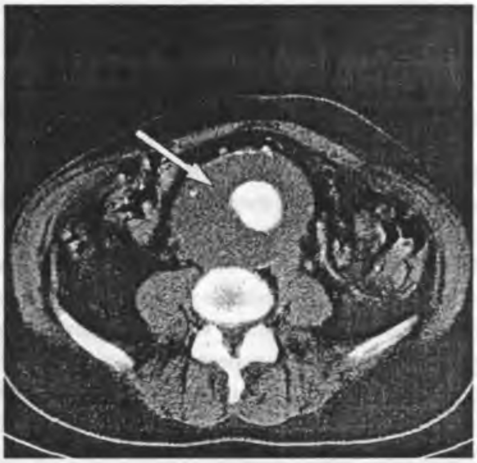

Fig. 2. Transverse CT image of the abdominal aorta aneurysm (arrow) from the early sequential scanner. The poor image quality and very low resolution are evident

THIRD-GENERATION CT SCANNERS

Designers realized that if a pure rotational scanning motion could be used, then it would be possible to use higher-power, rotating anode x-ray tubes and thus improve scan speeds in thicker body parts. One of the first designs to do so was the so-called third generation or rotate-rotate geometry. In these scanners, the x-ray tube is collimated to a wide, fan-shaped x-ray beam and directed toward an arc-shaped row of detectors (Fig. 1C).

Fig. 3. 3D image of abdominal arteries from the single slice helical scanner. Bone structures and larger vessels are visible, but renal arteries are difficult to assess, and only proximal segment of visceral arteries are visible

During scanning, the tube and detector array rotate around the patient, and different projections are obtained during rotation by pulsing the x-ray source or by sampling the detectors at a very high rate. The number of detectors varied from 300 in early versions to over 700 in modern scanners. Nearly all current helical scanners are based on modifications of rotate-rotate designs. Typical scan times are on the order of a few seconds or less, and recent versions are capable of subsecond scan times (1, 5).

FOURTH-GENERATION CT SCANNERS

This design evolved nearly simultaneously with third-generation scanners and also eliminated translate-rotate motion. In this case, only the source rotates within a stationary ring of detectors. The x-ray tube is positioned to rotate about the patient within the space between the patient and the detector ring. One clever version, which is no longer produced, moved the x-ray tube out of the detector ring and tilted the ring out of the x-ray beam in a wobbling motion as the tube rotated. This design permitted a smaller detector ring with fewer detectors for a similar level of performance (Fig. 1D). Early fourth-generation scanners had some 600 detectors and later versions had up to 4,800. Within the same period, scan times of fourth-generation designs were comparable with those of third-generation scanners. One limitation of fourth-generation designs is less efficient use of detectors, since less than one-fourth are used at any point during scanning. These scanners are also more susceptible to scatter artifacts than third-generation types, since they cannot use antiscatter collimators. CT scanners of this design are no longer commercially available except for special-purpose applications (5).

Until around 1990, CT technology had evolved to deliver scan plane resolutions of 1–2 lp/mm (Fig. 2), but z-axis resolution remained poor and interscan delay was problematic due to the stopstart action necessary for table translation and for cable unwinding, which resulted in longer examination times. It was soon realized that if multiple sections could be acquired in a single breath hold, a considerable improvement in the ability to image structures in regions susceptible to physiologic motion could result. However, this required some technological advances, which led to the development of helical CT scanners (5).

The introduction of spiral CT in the early 1990s constituted a fundamental evolutionary step in the development and ongoing refinement of CT imaging techniques, that finally allowed true 3D image acquisition within a single breath hold. The technique involves the continuous acquisition of projection data through a 3D volume of tissue by continuous rotation of the x-ray tube and detectors and simultaneous translation of the patient through the gantry opening. Three technological developments were required: slipring gantry designs, very high power x-ray tubes, and interpolation algorithms to handle the noncoplanar projection data (1–6).

In helical acquisition sections could be overlapping along the scan axis, thus greatly improving data sampling and making 3D reconstructions practical. Images can be acquired in a single breath hold, the 3D reconstructions are free of the misregistration artifacts caused by involuntary motion that limit conventional CT (1, 5, 6). True 3D volumes could be acquired that can be viewed in any perspective, making the promise of true 3D radiography a practical reality. A final benefit was that since overlapping sections were generated by mathematical methods rather than overlapping x-ray beams, the improved z-axis sampling was achieved without a radiation dose penalty to the patient. During helical scans, the table motion causes displacement of the fan beam projections along the z- axis; the relative displacement is a function of the table speed and the beam width. The ratio of table displacement per 360° rotation to section thickness is termed *pitch*, an important dimensionless quantity with implications for patient dose and image quality (1, 2, 5).

With the helical CT complete organs could be scanned in about 30–40 seconds; artifacts due to patient motion and tissue misregistration due to involuntary motion were virtually eliminated. It became possible to generate sections in any arbitrary plane through the scanned volume. Significant improvements in z-axis resolution were achieved. Near-isotropic (isotropic viewing refers to the situation in which MPR images can be created in any plane with the same spatial resolution as the original sections) resolution could be obtained with the thinnest (~1 mm) section widths at a pitch of 1, but this could be done only over relatively short lengths due to tube and breath-hold limitations. Volume data became the basis for applications such as CT angiography, which has revolutionized the noninvasive assessment of vascular disease (Fig. 3). The section sensitivity profiles of helical CT images are different compared with those of conventional CT images, which are influenced by the type of interpolation algorithm and the selected pitch (3–6). When single-row detector helical scanners had reached their limits, next improvement would be to make more efficient use of the x-rays that are produced by the tube while improving z-axis spatial resolution; this led to the development of multiple-row detector arrays. The basic idea actually dates to the very first EMI Mark I scanner, which had two parallel detectors and acquired two sections simultaneously. By late 1998, all major CT manufacturers launched multiple-row detector CT scanners capable of acquiring at least four sections per rotation. The arrangement of detectors along the z-axis and the widths of the available sections vary between the systems. By increasing the number of CT scanner detector rows, data acquisition capability dramatically increases while greatly improving the efficiency of x-ray tubes. Further developments in scanner rotational speeds and tube outputs have made isotropic resolution a practical possibility with even better improvements on the horizon. Current multiple-row detector scanners can scan large 40-cm volume lengths in less than 30 seconds with near-isotropic resolution and image quality that could not be envisioned at the time of Housfield's invention (3, 5).

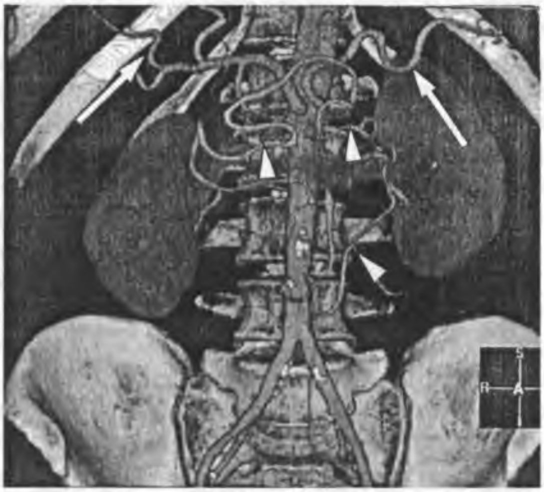

Fig. 4. 3D image of abdominal arteries from multi-row helical scanner. The image quality and resolution is very impressive; large arteries (arrows) are seen as well as very small visceral vessels are easily seen (arrowheads)

The benefits of multi-section CT relative to single-section helical CT are significant. The examination can be performed with thinner sections, leading to higher spatial resolution along the longitudinal axis of the patient. Scanning can be performed much faster, resulting in improved temporal resolution and reduced motion artifacts. Intravenously administered iodinated contrast material can be delivered at a faster rate, increasing contrast enhancement in the images. These factors combine to improve the spatial, temporal, and contrast resolution of the images, significantly increasing the diagnostic accuracy of the examination (3–6).

One of the most important promises of multiple-row detector technology is that of true isotropic spatial resolution, that is, cubic voxels, so that the image is equally sharp in any plane traversing the scanned volume. CT angiography, which was possible with the single-row detector helical scanners, became practical with multiple-row detector scanners (Fig. 4). This technology also opens up new possibilities for applications in trauma, geriatric, and pediatric examinations. Improved accuracy in 3D volume coverage has led to the development of CT fluoroscopy and CT virtual endoscopy (3–6).

CONCLUSIONS

Early CT scanners revolutionized the radiology, cross-section images were the mile stone in the medical diagnosis. But possibilities of modern multiple-row detector helical CT scanner are far beyond what Housfield inventing his first CT scanner could even imagine. Isotropic spatial reconstruction open resulting in improved accuracy in 3D volume coverage has led to the development of CT fluoroscopy and CT virtual endoscopy. The examination time and radiation dose have been significantly reduced.

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SUMMARY

Computed tomography (CT) was introduced in the early 1970s and has revolutionized the practice not only of diagnostic radiology but also of the whole field of medicine. CT was the first technology to marry a computer to a medical imaging machine, the first to display x-ray images as cross sections. Improvements in image quality, acquisition speed have resulted from recent technical developments in helical and, more recently, multiple-row detector technologies. The purpose of this article is to present the development of CT and the differences between the scanner generations. There are four main generations of CT scanner, first with single detector, second generation using several detectors, the third generation with pure rotational scanning motion, and the fourth generation with a ring of detectors. The next step in CT development has been invention of helical systems, and multiple-row scanners. The development in the scanner technique was accompanied by the development in software and clinical applications, making 3D imaging a reality, and such applications as CT angiography, virtual angiography, virtual endocopy, or perfusion CT widely used in everyday practice. Early CT scanners revolutionized the radiology, cross-section images were the mile stone in the medical diagnosis. But possibilities of modern multiple-row detector helical CT scanner are far beyond what Housfield inventing his first CT scanner could even imagine. Isotropic spatial open reconstruction resulting in improved accuracy in 3D volume coverage has led to the development of CT fluoroscopy and CT virtual endoscopy. The examination time, and radiation dose have been significantly reduced.

Rozwój tomografii komputerowej – generacje tomografów komputerowych

Tomografia komputerowa została wprowadzona we wczesnych latach siedemdziesiątych i zrewolucjonizowała zarówno diagnostykę obrazową jak i medycynę jako taką. Była to pierwsza metoda obrazująca ciało człowieka w przekrojach poprzecznych. Celem artykułu jest przedstawienie rozwoju tomografii komputerowej oraz różnic między tomografami komputerowymi różnych generacji. Wyróżnić można cztery główne generacje tomografów komputerowych: pierwszą generację z pojedynczym detektorem, drugą generację z kilkoma detektorami, trzecią generację z pełnym ruchem obrotowym i czwartą generację z pierścieniem detektorów. Dalszy rozwój to opracowanie techniki spiralnej i jej rozwinięcie, czyli tomografy wielorzędowe. Rozwój techniki i oprogramowania umożliwił uzyskanie izotropowych rekonstrukcji wtórnych, umożliwiających trójwymiarowe obrazowanie struktur, jak angiografia TK, wirtualna angiografia, wirtualna endoskopia oraz zaawansowane techniki, jak perfusion TK. Tomografia komputerowa zrewolucjonizowała diagnostykę obrazową i była krokiem milowym w diagnostyce. Ale możliwości współczesnych wielorzędowych tomografów komputerowych daleko wykroczyły poza to, co pionier tomografii, Housfield, mógł sobie wyobrazić, umożliwiając rzeczywiste obrazowanie trójwymiarowe i obrazowanie w niemal dowolnej płaszczyźnie bez utraty jakości obrazów. Ponadto zredukowano znacząco dawkę promieniowania i czas badania.