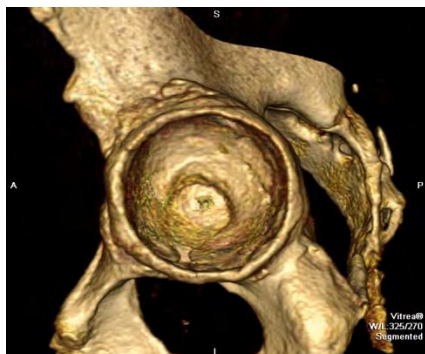
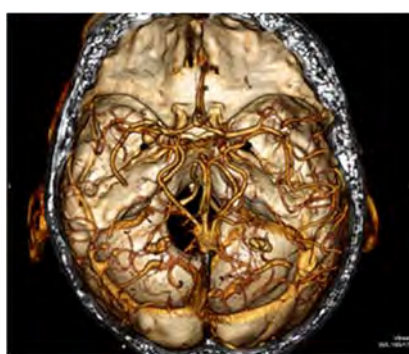


1. CT for Technologists

System Components

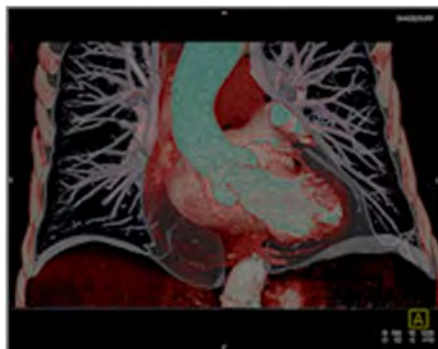


Sagittal view of the acetabulum free from superimposition of the femoral head



Circle of Willis. 3D volume-rendering technique displaying the cerebral vasculature

CT for Technologists is a training program designed to meet the needs of radiologic technologists entering or working in the field of computed tomography (CT). This series is designed to augment classroom instruction and on-site training for radiologic technology students and professionals planning to take the review board examinations, as well as to provide a review for those looking to refresh their knowledge base in CT imaging.



Coronal view of volume-rendering technique displaying the aortic root and ascending aorta

Release Date: September 2011
Expiration Date: October 1, 2018

This material will be reviewed for continued accuracy and relevancy. Please go to www.icpme.us for up-to-date information regarding current expiration dates.

OVERVIEW

CT for Technologists: 1 • System Components introduces the learner to the components of the CT unit, including parts of the computer and scanner. The function of each of the components is addressed, and the variation in configurations of scanners is discussed.

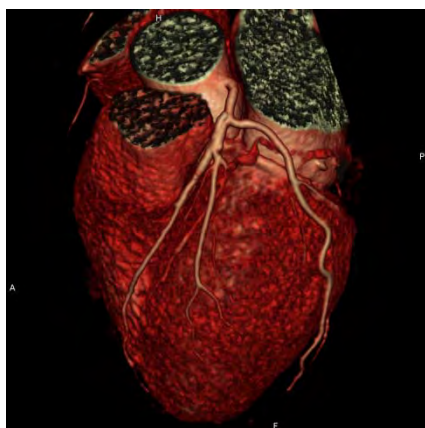
EDUCATIONAL OBJECTIVES

After completing this material, the reader will be able to:

- Identify the components of the CT computer and describe each of their functions
- Explain the mechanical interactions of the gantry scanner components
- Compare the characteristics of the various generations and types of scanners

EDUCATIONAL CREDIT

This program has been approved by the American Society of Radiologic Technologists (ASRT) for 1.0 hours of ARRT Category A continuing education credit.



CT Coronary Artery Angiography. 3D volume-rendering technique displaying coronary arteries

Images courtesy of NYU Langone Medical Center Department of Radiology

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Linda McLean, MS, has no conflicts to report.

Victoria Phoenix, BS, has no conflicts to report.

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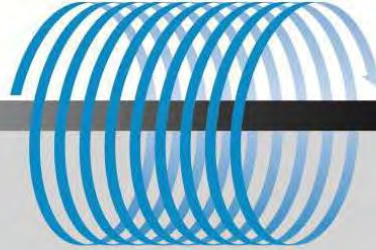


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1. CT for Technologists

System Components



After completing this material, the reader will be able to:

- Identify the components of the CT computer and describe each of their functions
- Explain the mechanical interactions of the gantry scanner components
- Compare the characteristics of the various generations and types of scanners

INTRODUCTION

The advent of CT scanning in the 1970s made possible a wide range of dimensional diagnostic images. For the first time, images provided clear differentiation of anatomic structures and offered numerous perspectives on the same area of interest for different types of studies. Since its inception, CT scanning has grown more sophisticated, more sensitive, and more complex. It is important for anyone working with this remarkable modality to have a full understanding of the many factors involved in achieving diagnostic CT images.

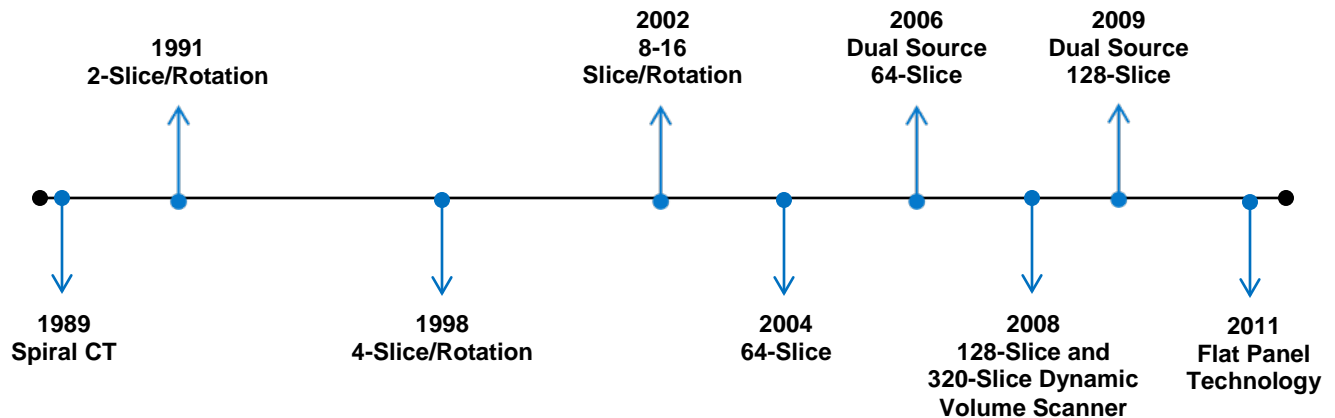
Introduction
System Operation: Overview
Basic CT Components
Scan Controller
Host Computer
Components of the CT System
X-ray Production
Scanner Generations
Summary

The following material reviews the components of the CT unit, including the parts of the computer and the scanner. The many components of an individual CT system will vary from site to site, so a good understanding of the operational capacities of each component and the interplay between them is required for execution of accurate and useful images. The functions of each are addressed and the scanner configurations discussed.

SYSTEM OPERATION: OVERVIEW

Significant advances in technology throughout the 1960s and early 1970s resulted in the development of a type of medical imaging that could display anatomic structures without superimposition and with a significantly broader range of tissue **contrast** than by traditional x-ray methods. In 1973, the first description of what was later to be called “computed tomography” (CT) was published by G. Hounsfield and associates in *The British Journal of Radiology*.

CT scanners obtain individual, cross-sectional “slices” by utilizing thinly collimated x-ray beams taken at different angles around the circumference of the same region and reconstructing images through the use of computer technology. The first CT units were limited to displaying images in the axial plane; hence the early term “computerized axial tomography” or “CAT scan” became popularized. The current preferred term, CT, reflects the more complex procedure used today. Over the past two decades, the basic CT system has undergone many design changes and enhancements resulting in improvements in the overall quality of the images and speed of the system. As a result, CT imaging has reduced the need for invasive diagnostic procedures, eg, exploratory laparotomy.



The CT scanning operation is a multi-level process involving many steps of data acquisition, image reconstruction, display, and storage. A rotating x-ray tube sweeps around the patient, and the transmitted **photons** resulting from the x-ray interaction with the patient’s tissues are captured by a circle of fixed (third generation) or moving (fourth generation) ring of **detectors** or two tubes and two detectors (**dual source**). The detectors measure the energy from the photons as light (**scintillation**), converting this light output into electrical (**analog**) signals that are then converted to digital data. Finally, the computer receives the digital data and initiates the image reconstruction process for display, manipulation, and storage.

KEY TERMS

system console

central array processing unit (CPU)

image reconstruction system (IRS)

liquid crystal display (LCD)

cathode ray tube (CRT)

read-only memory (ROM)

random-access memory (RAM)

laser camera

BASIC COMPONENTS OF THE CT SCANNING SYSTEM

While individual configurations may vary somewhat from location to location, the basic components necessary to perform the CT operation are always the same. A CT suite requires the use of two rooms: the control room (free from radiation exposure) and the imaging or scanner room (where the patient undergoes the CT procedure). The computer equipment located in the control room, where the technologist or operator is

stationed, includes the computer, console with the **liquid crystal display** (LCD) or **cathode ray tube** (CRT), and archival storage. The equipment used to perform the actual scans of the patient is located in the imaging room and includes the x-ray tube, detectors, table, and **gantry** (**Figure 1**).

Computer

The computer performs a variety of tasks in the CT process. It offers advantages both in terms of the significantly enhanced volume of images it can store and retrieve and the highly accelerated speed and increased accuracy in data communication. The single function performed by the computer that distinguishes the CT image is the reconstruction process.



Figure 1. CT scanner.

Courtesy of Siemens Healthcare

The computer unit includes several hardware (mechanical) components that execute the specific software programs used to reconstruct and manipulate the imaging data (**Figure 2**).

These units are all kept in the control room, where temperature and humidity are controlled to protect the integrity of the mechanisms. The five hardware elements include:

- System console (or input device)
- Central processing unit ([CPU]/image reconstruction system [IRS])
- Internal memory (or hard drive)
- Output device
- External memory (or storage unit)

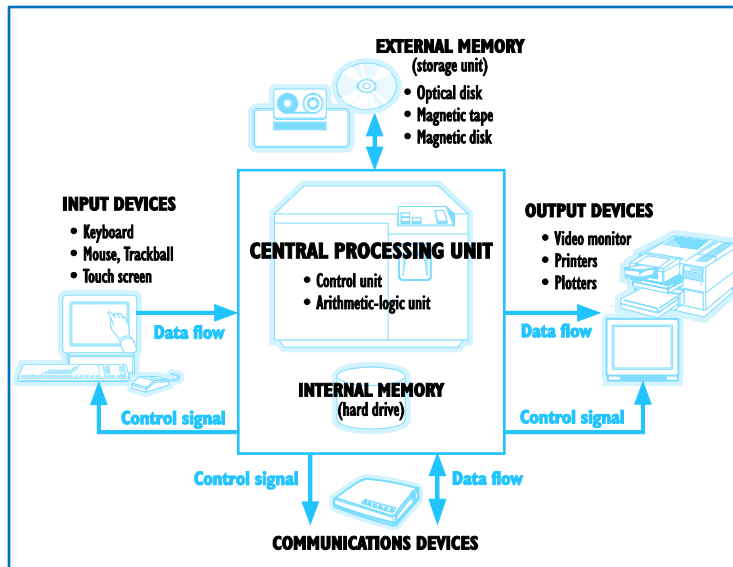


Figure 2. Diagram of the computer components in a CT system.

The system console is the main control center from which the technologist gives instructions to the entire CT system. Most modern consoles have a look and feel similar to a PC (keyboard with mouse). Older units utilize plasma screen technology. Using these devices, the technologist is able to input scan parameters, patient information, and instructions for postprocessing, filming, archiving, and networking. The appearance of this screen is called the “user interface”.

Many systems utilize graphic images to initiate tasks, eg, folders or icons. The combination of these icons and the workflow is referred to as the **graphical user interface (GUI)**.

The **central array processing unit** or CPU (also referred to as the image reconstruction system [IRS]), is where the raw data are received and reconstructed into the final CT image. The appearance of the final image is influenced by reconstruction **algorithms**. Modern CPU/IRS are asked to perform a huge number of image reconstruction calculations at blinding speeds. Postprocessing can be done at the scanner or at separate work stations depending on the type of license and type of equipment.

Once processed, images are sent to an output device such as a laser printer, Picture Archival and Communication System (PACS), DVD, CD-ROM, external universal serial bus (USB) drive or offline workstation. Simultaneously, the images are sent for archival storage.

Software

CT tasks can be subdivided into three basic categories, each of which utilizes unique software:

1. Operating system of the computer. This is the permanent software program through which all applications must run.
2. Applications programs. These are developed to execute specific tasks and are at the level at which instructions are input into the system to initiate all mechanical processes, as well as receive information and submit it to output and storage. The technologist needs to be thoroughly familiar with the use of the applications software in order to run the system.

3. System tools. These tools are the computer languages the system requires to execute the applications. They are also used by service technicians for system maintenance, upgrades, and problem solving.

Cathode Ray Tube and the Liquid Crystal Display

A cathode ray tube (CRT) is the monitor on which the technologist views all the activities of the computer system. The screen is coated with phosphorescent particles that display a picture constructed from tiny image spots called **pixels**. These pixels form a grid (matrix) and the greater the number of pixels, the greater the resolution. The “brightness” or “darkness” of each pixel is determined by the CT number or **Hounsfield unit** (HU) assigned to each pixel. This number results from the **attenuation**—the reduction in intensity of an x-ray beam—of photons passing through the patient. The HU is an arbitrary scale that assigns water a value of zero (0). Any tissue denser than water will appear brighter, and any tissue less dense than water will appear darker. Four thousand levels of gray (2,000 above and 2,000 below 0) can be recognized within a pixel; however, only 256 shades can be displayed at any given time. The processes of “window” and “level” adjust the scale to optimally visualize the body area of interest and suspected disease process; these processes will be discussed in detail in later material.

In recent years there has been a shift from CRT to liquid crystal display (LCD) monitors because of their low cost, compact size, low power consumption, good color representation, excellent image resolution, and luminance (brightness). Resolution of the monitors can vary from 1200x1600 pixels to 1536x2048 pixels depending on the type of LCD. The luminance of the LCD monitor must be calibrated to the CT equipment to highlight anatomical imaging anywhere from 1–300 candelas (a unit of luminous intensity) per meter squared (cd/m²) and according to Digital Imaging and Communications in Medicine (DICOM) standards.

Memory

Two types of internal memory are used in every CT computer system, each serving a different function. **Read-only memory** (ROM) is reserved for long-term storage of internal data, such as the operating system. **Random-access memory** (RAM) is available for the temporary storage of information, such as the data received from an individual CT scan.

Internal memory on a computer is located on the hard drive and retained on hard disks sealed within the hard drive. This type of memory is accessible to the user through the input devices.

Archival Data Storage

Older systems utilized a compact form of data storage called magnetic optical discs (MOD) that held several gigabytes of data, allowing greater amounts of data to be archived in a small space. A busy CT practice could store a year's worth of cases on one or two bookshelves. Optical disks use a laser beam to write (burn) data as binary code into the surface of a metallic disk. Two types of disks are used: the write-once-read-many (WORM) disk with a storage capacity from 122 megabytes (MB) to 6.4 gigabytes (GB) and a rewritable/erasable disk with a capacity of 2.5 GB, which is used to accommodate the need for frequent updates of the data on a file. In recent years, the DVD has become a very good storage medium, holding up to 4.7 GB of data and physically much more compact than MODs. External hard drive devices are commonly used to archive data and are capable of holding mass amounts of data from gigabytes to terabytes. But by far the largest and most efficient form of data storage and display that involves networking data to large storage mainframes is a Picture Archiving Communication System (PACS) with storage capacities of multiple terabytes (one billion bytes or 1000 gigabytes).

Laser Cameras

A laser camera can be employed to record CT images for interpretation. All systems now utilize a 14"x17" size film with image formatting varying between 12:1, 15:1, and 20:1.

SCAN CONTROLLER

The scan controller, or system console, is the central core of the CT scanning system and is responsible for image acquisition. The operator enters patient information and initiates the appropriate imaging protocols at the scan console using the keyboard, mouse, or touch-screen monitor. As the scan sequence is initiated, the technologist is able to view the scans on the monitor and make adjustments to improve image quality and correct the display of anatomy while remaining at the system console. This central arrangement of all the input devices allows the technologist to optimize scan protocols, ensure that a complete high-quality examination is produced based on the protocols developed by the site, and display and postprocess the image data utilizing multiplanar (MIP) reformations and three-dimensional (3D) applications.

HOST COMPUTER

While a CT system can include a number of networked computer stations, only one computer—the host computer—has the ability to initiate the scan by turning on the x-ray tube. The host computer contains software instructions that control data acquisition, processing, and display. Other monitors may also display information, and linked computers may store additional data.

The host computer ultimately controls the functions of all of the CT components, including the rotation speed of the x-ray tube in the gantry, radiation dose, scan range, reconstruction and **display field of view**, and reconstruction type (algorithm). Following image acquisition, the host computer directs the images along the network either to the laser camera for filming, a PACS for online archiving and display, a 3D workstation for postprocessing, or an off-line archival media such as MOD, DVD, or USB.

COMPONENTS OF THE CT SYSTEM

The CT technologist inputs a wide variety of instructions at the console, including imaging parameters and storage instructions (**Figure 3**). These instructions are recognized by the operating system of the host computer, encoded in binary format recognizable by the scan controller. The scan controller converts these **digital signals** to continuous waveform (analog) signals by passing through a **digital-to-analog**

KEY TERMS

scan controller

data acquisition system (DAS)

digital-to-analog converter (DAC)

transformer or high-voltage generator (HVG)

amplifier

sample/hold (S/H)

analog-to-digital converter (ADC)

array processor

(DAC) converter so the signals can “instruct” all facets of the scanning procedure: the gantry is told how fast to turn, the table is told how quickly and how far to move; the x-ray tube current is set to regulate dose, etc. A **high-voltage generator** (HVG) or **transformer**, which may be inside or outside the gantry, converts the low-level line voltage to the kilovolt levels used to produce x-rays. As the tube rotates, the x-rays pass through the patient and the attenuated x-rays are received by the detectors. At the detectors, these signals are converted into electrical signals. The signals are greatly amplified to increase their power. The signals are sampled and then converted via the **analog-to-digital converter** (ADC) into data that the **array processor** reads and reconfigures into a temporary image. Finally, the host computer takes the image data and processes it for final storage.

Scan Controller

The host computer issues instructions to the scan controller, which in turn regulates the operation and timing of the patient table, the gantry, and the high-voltage generator.

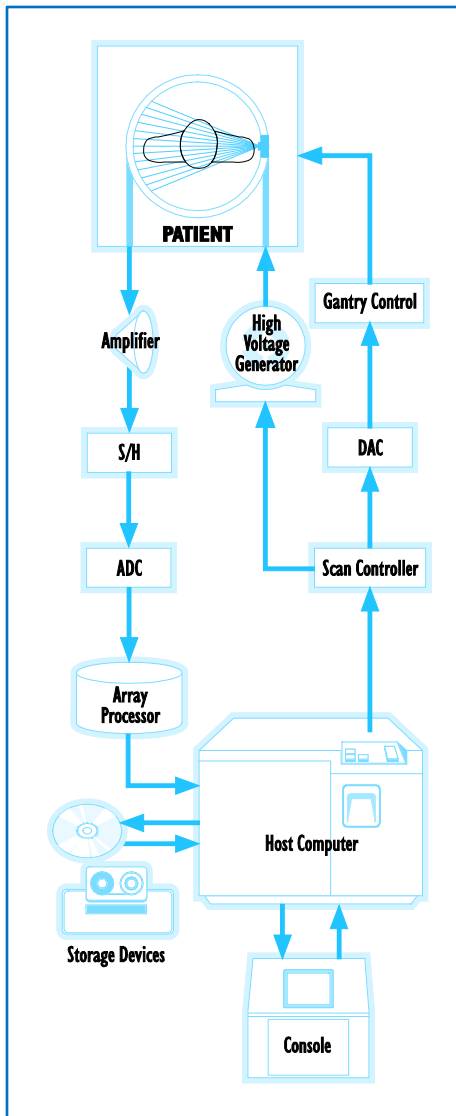


Figure 3. Block diagram of a typical CT system.

Data Acquisition System (DAS)

A set of electronics located between the detector array and the host computer controls the operations of the system that influence the intake of data. The DAS performs a series of three tasks: amplifying the signal emanating from the detector, converting the signal to digital, and then sending it on to the computer. On a modern CT system, these functions must be completed for over 700 detectors each time the tube sweeps around the patient (usually in less than a second). The components of the DAS that perform these tasks include the digital-to-analog converter, high-voltage generator, amplifier, **sample/hold**, and the analog-to-digital converter.

Digital-to-Analog Converter (DAC)

Before the instructions from the scan controller (in the form of signals) can be interpreted, the signals must be converted into a continuous analog waveform signal. This conversion is performed by the DAC located between the scan controller and the gantry.

High-Voltage Generator (HVG)

The high-voltage generator is the unit that generates the voltage necessary to produce x-rays. Depending on the generation of the scanner, the HVG may be located either inside or outside the gantry.

Transformer

The transformer, another form of HVG, provides the CT units the necessary power to operate. The supplied voltage from the power company is usually less than what the CT scanner needs to operate, so the transformer will usually be a step-up type (versus a step-down transformer, which reduces the voltage) that amplifies the voltage, giving the tube the necessary power it needs to generate x-rays. In other words, a transformer changes one voltage to another.

However, a transformer does not change power levels. If 100 watts is supplied to a transformer, 100 watts will come out the other end. Actually, there are minor losses in the transformer, but these are insignificant.

A transformer is made from two coils of wire close to each other and sometimes wrapped around an iron or ferrite core. Power is fed into one coil, the primary, which creates a magnetic field. The magnetic field causes current to flow in the other coil, the secondary. Note that this does not work for **direct current** (DC). The number of times the wires are wrapped around the core or number of turns determines how the transformer changes the voltage.¹

The transformer is usually located outside of the CT suite.

Amplifier

The amplifier is where signals go immediately after leaving the gantry. These **analog signals** are amplified without conversion and sent on to the sample/hold unit.

Sample/Hold (S/H)

The sample/hold is located between the amplifier and the analog-to-digital converter (ADC). This is where the area of interest is sampled to differentiate among structures with various densities and then assigned various shades of gray to the pixels to represent those structures. The S/H determines the relative attenuation of the beam by the tissues that were scanned.

Analog-to-Digital Converter (ADC)

The ADC is the unit that takes the analog signal output by the scanning equipment and converts it into a digital signal that can be understood and analyzed by the computer. The unit has three major components to perform three separate operations: sampling, **quantization**, and coding. In sampling, the system takes portions, or samples, of the continuous analog signal. The quantizing component processes the sample data into discrete-time, discrete-value signals. Next, the digital signal is coded with a specific binary bit sequence correlating to each sample of output from the quantizer.

Array Processor

The array processor is a specialized high-speed computer that takes hundreds of detector measurements from hundreds of different projections and pieces them back together at a very high rate of speed. The array processor is also responsible for **retrospective reconstruction** and postprocessing of image data. The number of array processors affects the image reconstruction time, which is the time it takes to reconstruct the images in the dataset.

Storage Devices

Internal storage is housed on the hard drive (or system disk) of the computer. Because the internal hard drive has limited space for data, it is used mainly for temporary storage. In addition to PACS, permanent archiving of scanned images is reserved for external storage devices, such as CD-ROM, MOD, DVD, and USB drives.

KEY TERMS

gantry

patient table or couch

aperture

cathode

anode

focal spot

SCANNER ROOM

Gantry

All of the components for generating x-rays, moving the tube around the patient, collimating to the appropriate protocol-driven slice thickness, and the detectors are housed in a unit called the gantry (**Figure 4**). All continuous motion (helical or spiral) CT scanners—whether single or multislice configurations—utilize **slip ring** technology. The slip ring also transmits high-voltage across the system, eliminating the need for cumbersome cables that restrict tube rotation to a single pass per slice. All gantries are designed with a round **aperture** of about 50–85 cm (usually 70 cm, depending upon the model and manufacturer) to allow room for insertion of both the patient and the table. The x-ray tube and detectors are located at the interior aspect of the gantry assembly, which is the portion of the mechanism that rotates around the patient. Any patient who exceeds the weight limits of the table should not be scanned because table functions will be compromised, as could patient safety.

Depending on the area of interest, the gantry may need to be tilted to protect, for example, the patient's eyes on a head scan. Some models of gantries may be designed to tilt to up to a $\pm 30^\circ$ angle to adjust positioning. Gantry tilt is severely limited with some types of multislice CT systems. Depending on the geometry and the algorithm processes of the multislice detector, gantry tilt may or may not be available. Today there are systems that utilize an adjustable head holder, tilting various degrees to compensate for gantry angulation.



Figure 4. Patient on the table, preparing to enter the gantry.

Courtesy of Siemens Healthcare

It is important that the patient be positioned so that the area of interest is centered within the scan field and well away from the outer edges of the scanning field where the image quality is poor. Positioning lights mounted to the gantry are arranged in sets of three to help the technologist align the patient properly.

PLANE SPECIFICATIONS

The x and y axes are positional coordinates that involve centering the patient within the gantry correctly. The x-axis is the lateral or horizontal plane, and the y-axis is the vertical or AP/PA plane (anterior/posterior or posterior/anterior). Ideally, the anatomy of interest should be centered correctly for imaging and technique purposes. In terms of *imaging*, the anatomy should appear in the middle of the **display field of view** (DFOV); in terms of *technique*, the dose modulation will be correctly calculated when the area of interest is in the center of the **scan field of view** (SFOV).

Patient Table or Couch

The patient table serves as the support and transport device for the patient throughout the scanning procedure. The surface of the table is generally curved; flat tables are used for radiation therapy planning. After the patient lies on the table, the technologist gives instructions from the console for the table to slide into the gantry for the exam. Most couches allow for scanning from the head to the mid-thigh with movement in 1mm increments. Each table has a maximum weight recommendation of 400–485 lbs; bariatric tables can hold up to 660 lbs, depending on the size of the gantry aperture.

X-RAY PRODUCTION

In the first CT scanning experiments, Hounsfield identified x-rays as being superior to monochromatic gamma rays in the capture of high-contrast CT images. The original 60-hertz (Hz) generators were housed in large units across the room from the scanner and were connected to the gantry and x-ray tube by long high-tension cables. Obviously this configuration was awkward. Current systems contain the high-voltage generator/transformer either in the gantry itself, where it rotates with the unit or in a stationary setting on the outside of the unit. In both cases, the bulky cables have been eliminated. The x-ray unit of a CT system today includes the generator or transformer (see page 8), x-ray tube, **collimators** and filters, and detectors.

KEY TERMS

- x-rays
- photons
- bremsstrahlung*
- braking radiation
- characteristic radiation
- electron beam
- anode
- cathode
- envelope
- tube current
- tube voltage

X-rays are produced from electrons, which are particles bearing a negative electric charge. When fast-moving electrons pass through an atom, a large amount of their energy is lost and expelled in the form of x-ray photons. X-ray photons produced in this manner are called **bremsstrahlung** or “braking radiation,” the type of radiation that accounts for 80–90% of the radiation used in CT imaging. Another type of radiation, characteristic radiation, is produced when the same fast-moving electrons collide with the electrons inside of a target atom, expelling the native electron and taking its place. The energy released by this process also creates x-ray photons and accounts for the remainder of CT x-rays.

To create an image, the x-ray tube produces a beam of fast-moving electrons directed at target material in the tube to produce x-ray photons. The tube contains two types of electronic disks called the **cathode** and the **anode**. The cathode is a compact unit of tungsten filaments, the temperature of which determines the current of electrons flowing into the anode. The anode assembly consists of a rotor, hub, and bearing unit. It also contains a large disk that is generally made of brazed graphite or chemical vapor deposition (CVD) or an all-metal disk composed primarily of titanium.

All-metal anode disks are too heavy to be used in **spiral/helical scanning**. Tungsten is a particularly dense material with an atomic number of 74, but while most metals melt between 300° and 1500° C, the melting point of tungsten is over 3400° C. This high heat tolerance makes tungsten particularly adapted to use in spiral/helical scanning where high heat-storage capacities and fast cooling are needed.

As the anode disk rotates in its assembly, the electron beam strikes the target material to generate the majority of energy produced in the x-ray tube. The cathode and anode assemblies are insulated from each other by a metal envelope. Some models still use a glass envelope, which insulates well against heat and electricity but has the disadvantage of forming tungsten deposits as a result of vaporization. Metal envelopes are larger and can sustain higher tube currents.

A specific tube current (milliamperere [mA]) and tube voltage (kilovoltage [kV]) applied through the tube drives the electron beam from the cathode to the target material located in the anode. The technologist controls current and voltage to produce optimal images by selecting the proper mA to alter the cathode filament temperature and produce a specific number of electrons, and by adjusting the kV to control the energy level. Changes to the energy level impact the penetration of the x-rays through the patient’s body, affecting the ultimate quality of the images produced.

X-ray Tube

The x-ray tube in CT scanning generates x-rays when high energy photons (from the cathode) are drawn against a target (anode) as a result of applied voltage. The constant use of the CT tube over the period of scanning results in severe heating. The modern CT tube requires high anode heat storage capacity of 2–5 million heat units with rapid dissipation (400,000 heat units/m) needed for volumetric scanning techniques.

This high rate of heat dissipation is generally achieved with an oil-, liquid-, or fan-cooled system, allowing for rapid scanning techniques at high power levels. Tungsten is

used as the target material due to its unusually high heat tolerance. Because tube heating and cooling limit tube life and speed of scanning, manufacturers have conducted extensive research in efforts to increase effectiveness and tube life. Modern tubes will last for 150,000–200,000 slices. This will serve a busy practice for slightly less than one year.

The tube itself is mounted on a rotating frame inside the gantry apparatus. The rotating anodes are usually made of rhenium, tungsten, gadolinium, and a molybdenum alloy, utilizing a small target angle (focal spot) of about 11–12° and a rotation speed of 3,600 to 10,000 rotations per minute (rpm). The target angle is fixed. Current systems utilize a “moving” focal spot, allowing the accumulation of twice the information obtained in a single rotation (**Figure 5**).

Collimators and Filters

Collimation is used in traditional x-ray technology to limit the amount of radiation exposure to the specific area of interest. Collimation is already part of the technology of fan beam radiation used in CT scanning and serves the dual function of reducing scatter radiation and improving image contrast. The main purpose of collimation is to ensure that a consistent beam width is received by the detectors.

Filters help reduce image noise by lowering the amount of low-energy photons hitting the detectors. Filtering creates more uniform energy, which adds information to the process, as opposed to projecting non-uniform energy, which may diverge and act as scatter and therefore degrade image quality by adding noise.

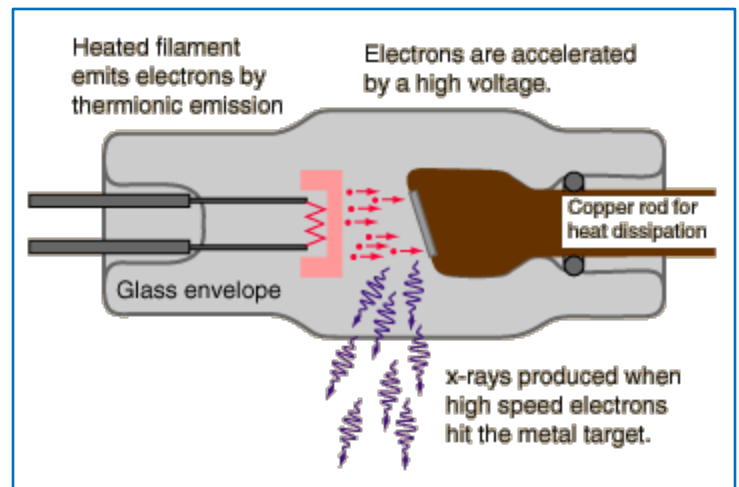


Figure 5. X-ray tube mechanism.

Courtesy of "HyperPhysics" by Rod Nave, Georgia State University²

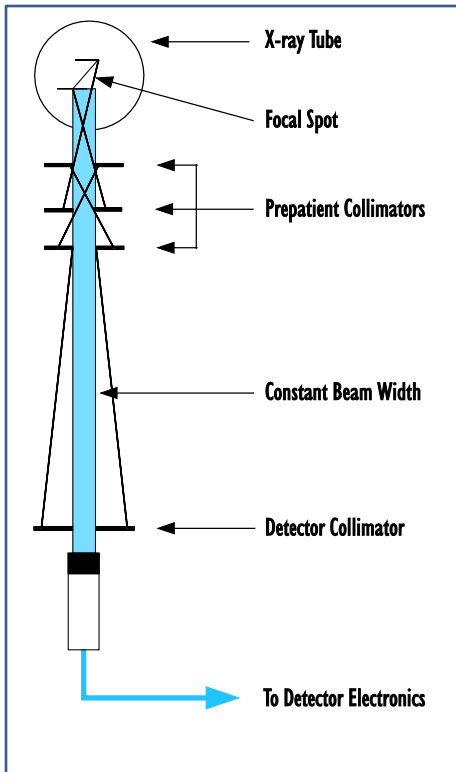


Figure 6. Collimation scheme typical of CT scanning.

Collimators are set at both the prepatient and postpatient levels. Prepatient collimators are located adjacent to the x-ray beam as it exits the tube to control its shape. Postpatient (or detector) collimators reduce the amount of scatter radiation occurring after the beam has passed through the patient. Axial resolution of the image is improved by controlling scatter radiation, but the prepatient and postpatient collimators must be in perfect alignment to achieve optimal imaging quality (**Figure 6**).

Both the size of the collimators and the geometry between them define the width of the slice of the scan (**Figure 7**). There are always fixed collimators set in front of the detectors, but the addition of movable collimators can alter the geometry between them all to achieve very thin slices. These kinds of changes will, in turn, impact the actual radiation dose received by the patient.

Detectors

X-rays produce analog signals that must be converted to digital signals so the computer can analyze them and reconstruct an image. In a CT scanning system, the detectors recognize and measure the ionizing output from incidental x-rays that pass through the patient and transform them into digital electrical signals. The detectors, located in the gantry, are highly sensitive and can measure very small attenuation differences in tissue. An air-reference detector, also located in the gantry, measures the intensity of the x-ray beam from the tube. The measurement value of the intensity is then used as a reference point for reconstruction of the image.

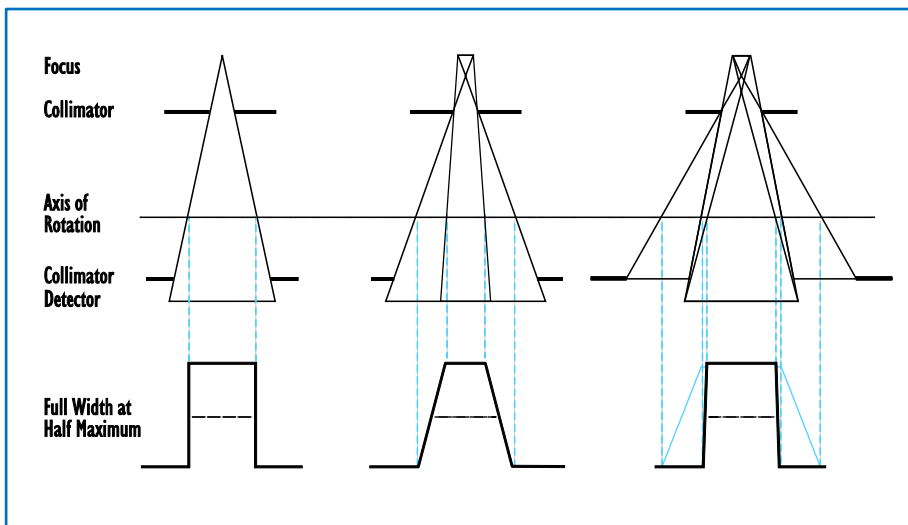


Figure 7. Geometry of collimators/detectors used to determine scan slice width. The presence of a detector collimator will positively influence the slice profile, shown in solid lines. The dose profile, shown in dotted lines, will remain wide, however, and exceed the slice profile.

The relationship between the arrangement of the tube, the beam shape, and the detectors is referred to as the **detector geometry**. This relationship has undergone many design changes and characterizes the generation of the scanner. First- and second-generation scanners used a translate-rotate scanning motion, which required 20 seconds to 4.5 minutes to complete. These scanners are now obsolete. Improvements in the relationship between the tube and detectors led to the third- and fourth-generation scanners that are in use today.

Current CT systems generally employ hundreds of detectors set inside the gantry. The specific number and location of detectors varies by manufacturer and model (**Figure 8**). In third-generation scanners, the x-ray tube and detectors are set in fixed alignment and rotate together 360° around the patient using fan beam geometry. The third-generation scanner may utilize a start/stop scan or a continuous rotating tube design in which the detector modules are located in a 30–40° curved arc detector array. The detectors can then measure attenuated radiation as it passes through the patient from different views.

Fourth-generation scanners also use fan beam technology, most often with a continuous rotating design employed by slip ring technology in which the detectors are located in a stationary ring outside of the rotating x-ray tube.

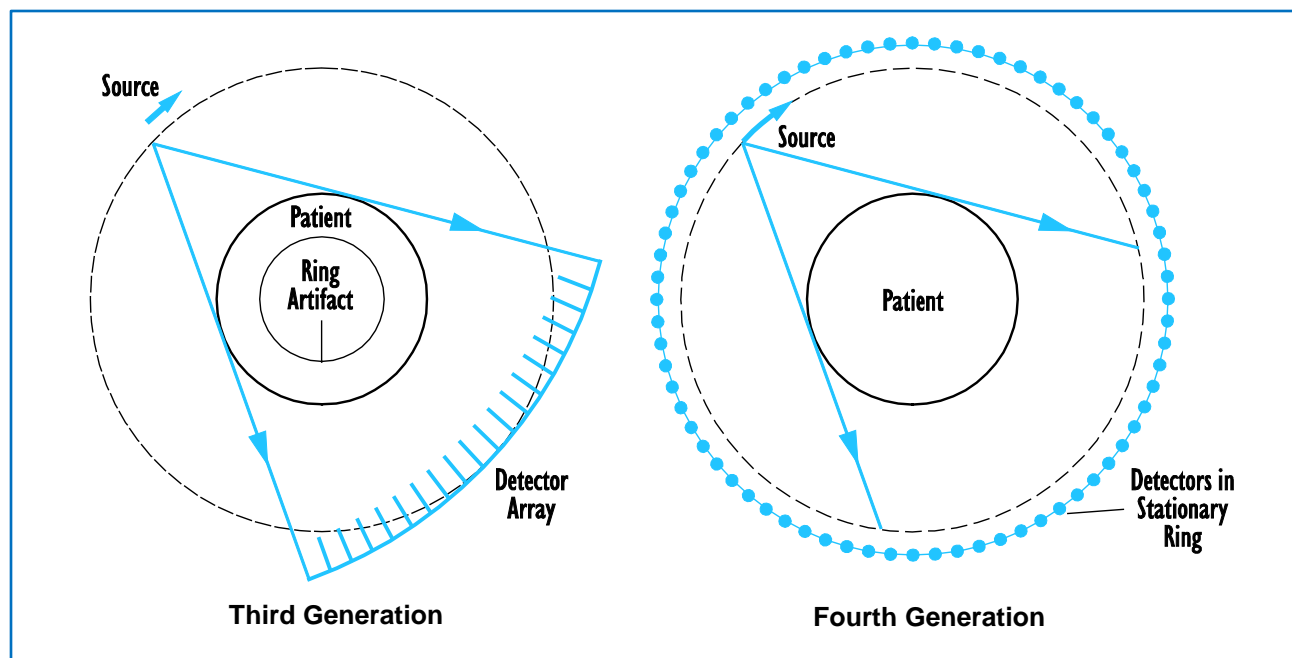


Figure 8. Examples of third-generation and fourth-generation scanners.

By necessity, detectors must be very small and uniform for placement within the gantry—no more than 44” from the image—as tight alignment is very important for the prevention of **artifacts**. In addition, the technologist must frequently calibrate the CT scanner to maintain consistency and stability in capturing x-rays. Capture efficiency is determined by the size and the distance between the detectors. Depending upon the manufacturer, there are variations in the recovery time between capture and discard of x-rays by specific detectors. All of these factors combine to influence the efficiency and image quality produced by an individual CT system. The efficiency of a detector array is measured in terms of several parameters, including capture efficiency, absorption efficiency, stability, response time, dynamic range, and reproducibility (**Table 1**). In addition, there are different types of detector configurations such as fixed and adaptive array designs. In fixed array, there are gaps that separate the detectors; in adaptive array, there are fewer gaps between the detectors.

Table 1. Measures of Detector Efficiency

Capture efficiency	the efficiency with which the detectors gather the photons exiting from the patient
Absorption efficiency	the number of photons absorbed by the detectors
Stability	the consistency of detector’s response
Response time	the speed at which the detector records an event and recovers for the next event
Dynamic range	the accuracy in the response to both low and high levels of transmitted radiation
Reproducibility	the consistency of responses to similar levels of transmitted radiation

Two main types of detector systems are currently in use. Scintillation detectors first convert x-rays into light and then convert the light signals into electricity. Gas ionization detectors make direct conversions from x-rays into electrical energy.

SCINTILLATION OR SOLID STATE DETECTORS

Scintillation detectors, also called solid state detectors, utilize a solid state scintillation crystal mounted beside a photomultiplier tube (**Figure 9**). X-ray photons are absorbed by the crystal, which then emits flashes of light proportional to the energy of the photons and location of the contact. The light is amplified by the photomultiplier tube and continues through the x-ray tube to the cathode to be converted into electrons. The electrons are then amplified by a series of **dynode** semiconductors as they travel through the tube toward the anode. Upon striking the anode, the electrons are converted into a digital signal for computer processing (**Figure 10**).



Figure 9. Scintillation crystal and various detector assemblies.
Courtesy of Saint-Gobain Crystals

A significant benefit of scintillation or solid state detectors is their increased **sensitivity**. Sensitivity refers to the number of light photons created by the rare earth material after the detector is struck by an x-ray. A sensitive detector will produce more photons (light output) than a less sensitive detector when the same dose of x-ray interacts with it, meaning a more efficient detector allows scanning to occur with fewer x-rays and therefore a lower dose. Scintillation detectors need less frequent calibration than do gas-filled detectors, and therefore daily patient scanning demands are easier to meet. The cost for solid state detectors is higher than for gas, but there are advantages: increased efficiency reduces the need for tube loading and is associated with lower patient dose, reduced **noise** on the

image, and a longer tube life. Despite the increased cost, most CT machines manufactured today are outfitted with scintillation detectors.

Scintillation detectors do have disadvantages. Although sodium iodide scintillation crystals are nearly perfect in their x-ray efficiency, they produce a **lag** or afterglow, a type of artifact that limits their use in doing ultrafast CT. Chemical engineers have fashioned detectors from such elements as bismuth germanate, cesium iodine, or cadmium tungstate because these significantly reduce afterglow. A crystal lattice of the rare earth compound gadolinium oxysulfide (GOS) has been produced that has a large x-ray absorption coefficient. Because of its fast decay, GOS reacts very rapidly to changes in x-ray intensity. These properties make GOS the ideal scintillator not only for time-critical medical imaging like angiographic or perfusion cases but dynamic applications like multiphase imaging.

The efficiency of the system's detectors is also dependent on the manufacturer's spacing of the detectors along the circumference of the gantry. The tighter the spacing of the plates in the detector array, the more efficient they are. Unfortunately, the irregular shape of the crystals prevents extremely tight spacing and thus detector efficiency may be reduced by as much as 50% of their theoretic intrinsic efficiency. Nevertheless, scintillation detectors are a great improvement over gas-filled detectors.

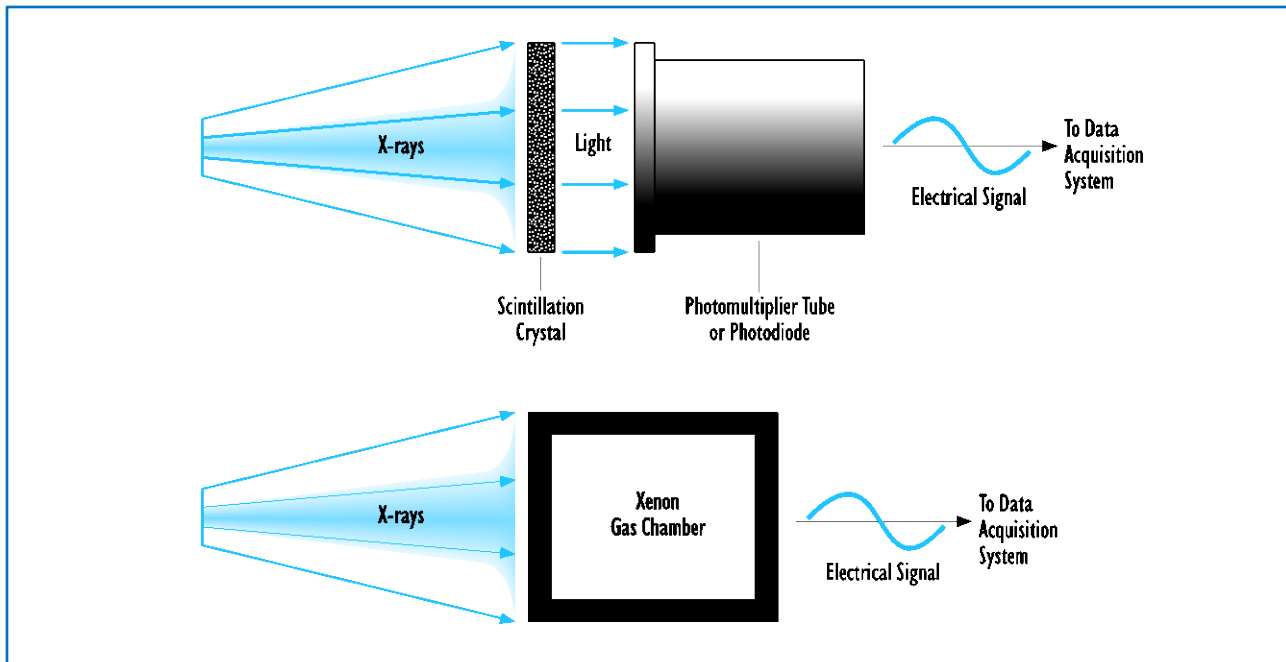


Figure 10. Diagram showing two methods of x-ray photon conversion. **TOP.** The scintillation crystal detector first converts x-rays into light that, when sent through a photomultiplier tube, is amplified and converted into an electrical signal. **BOTTOM.** The xenon gas chamber converts x-rays directly into electrical signals.

XENON GAS IONIZATION CHAMBER

First introduced with third-generation scanners, xenon gas detectors measure ionization in the air by collecting electrons into individual chambers separated by tungsten plates. As x-rays fall into the individual gas-filled chambers, they release ions that are either positively or negatively charged that are then attracted to the oppositely charged plates. A small but measurable current is produced by the migration of ions. This current is translated into a digital signal sent back to the computer (**Figure 10**).

Xenon gas is most frequently used because it is the heaviest of inert gases, which improves the efficiency of gas ionization chambers. The constancy of the pressure of xenon gas in the chambers contributes to the improved sensitivity of the detector. Xenon has a fast rate of decay, reducing the potential for afterglow and thereby reducing the chance for artifacts. Its major disadvantage is that it is less efficient than solid state or scintillation detectors. Xenon gas atoms are widely spread and therefore must be contained in a highly pressurized, long, narrow air-tight chamber for x-rays to collide with the gas atoms. It is the length of the chambers that limit use in more modern multislice scanners.

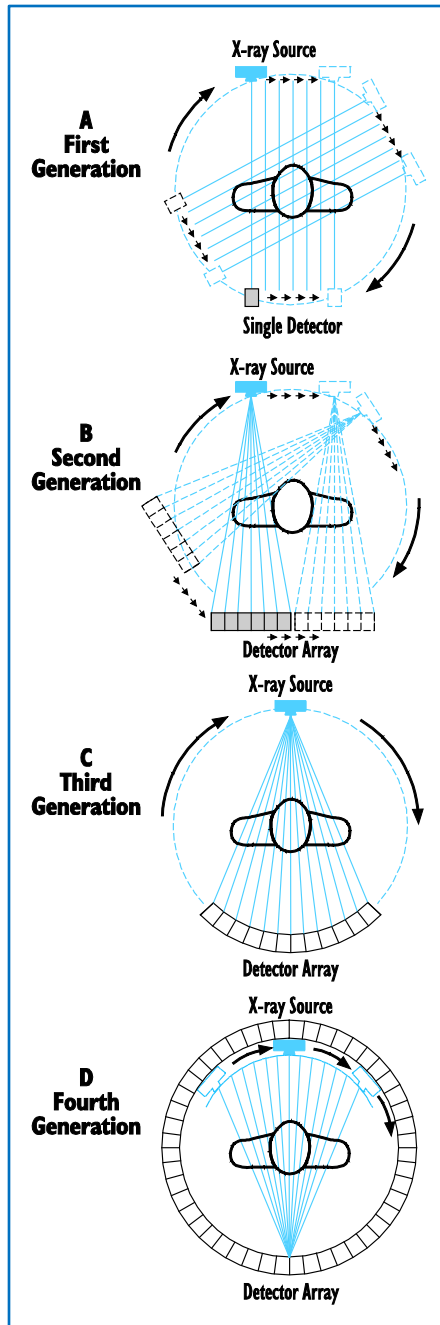


Figure 11. Depiction of four generations of scanners.

Xenon gas detectors only work with third-generation scanners in which the end of the chamber is perfectly aligned with the CT tube at all times and the entering x-rays are at consistent angles for detection. Even in this case, intrinsic detection efficiency is less than 50%, although this efficiency is preserved by tight detector spacing, as the ion chambers are each only about 1 mm in width with almost no interspace.

SCANNER GENERATIONS

Scanning technology has seen a great deal of rapid advancement since the introduction of the first CT scanner in the early 1970s, but the changes to the scanners themselves were so dramatic that they are described in terms of generations. The fourth generation of scanners appeared in 1978, only about six years after the first generation (**Figure 11**).

First Generation

The original scanners, now considered “first generation,” were only intended for scanning of the head, with no capability for total

body imaging. The head was immobilized and surrounded with a water bag to eliminate air pockets on the image. A

finely collimated x-ray beam or “pencil beam” was used in a single tube with a single detector or sometimes with a pair of detectors affixed to a C-shaped arm. First-generation scanners used a translate-rotation motion to scan the head from side to side, indexing the field 1° at a time until 180° had been indexed.

KEY POINTS

- Pencil-beam technology
- Single or paired detectors
- X-ray tube and detector is translated across a stationary patient
- Translation-rotation by 1° to a total of 180° for a single slice
- Shortest scan time was 4.5–5 minutes

The x-ray tube was turned on during the scanning phase and off during the indexing phase of the scan. In units that utilized two detectors, the total time for the examination was reduced by half but still required 4.5 minutes for the scan and 5 minutes for image reconstruction. CT examinations frequently called for scanning of 10–12 sections, which took 25–35 minutes or longer to complete.

Second Generation

Second-generation scanners were up to 10 times faster than were first generation scanners. These scanners utilized a linear array of up to 30 detectors and a fan-shaped beam to cover a greater area by translation across the patient with fewer rotations. The major advantage to fan beam scanners was the significant reduction in scan time to 10–90 seconds per slice. CT

of the body—which required the patient to hold his or her breath and had not been possible with 5-minute scan times—could be accomplished in a minute or less. The major disadvantage was the increase in scatter radiation because detector collimators were not used. The detectors were instead covered with lead masks to reduce the amount of scatter radiation reaching the detectors.

KEY POINTS

- Fan beam technology
- Up to 30 detectors in straight line array
- Ten times faster than first-generation scanners (average 20 seconds per slice)
- Translation-rotation in 5° increments

Third Generation

With the introduction of third-generation scanners that used a widened fan beam, it became possible to scan the entire body with one pass. The tube and detector array rotated continuously within the gantry up to 360°—spiral or helical scanning—around the patient instead of translating across the patient. These new scanners held a curved array of 250–750 detectors that produced as many as 700,000 measurements per slice, using a

scan path of a full circle rather than a semi-circle. These scanners also reduced scan time to 1–12 seconds per scan, which made it possible for dynamic scanning at a rate of about four images per minute and decreased production of artifacts associated with respiration. Third-generation scanners are still very much in use, and some can make a pass in less than 1 second. It is with third-generation scanners that slip ring technology became available.

KEY POINTS

- Currently in use
- Widened fan beam technology
- First scanner capable of spiral/helical scanning
- Tube and detector array rotate within the gantry—they do not translate
- Hundreds of detectors arranged in a curved arch improve image quality
- Scan times of 1–12 seconds or less
- Introduced slip ring technology

Fourth Generation

The main difference between third- and fourth-generation scanners is the setting of even more detectors—up to 2000—in a 360° ring. By fixing the detectors, they remain stationary in a ring that revolves, reducing the need for recalibration. Fan beam technology is still used, with arcs wider than 360° possible and scan times of less than a second.

KEY POINTS

- Currently in use but infrequently
- Fan beam technology
- Detectors are set in a ring configuration and do not travel with the tube
- Uses both circular-detector array and nutating ring designs
- Slip ring technology is used in some systems

However, these changes do not necessarily represent

improvements, and fourth-generation scanners have not replaced third-generation devices.

Two configurations of rotating fan beam technology are currently in use. The first includes a wide-geometry rotating fan beam that revolves in a full circle to strike the stationary detectors. A second technology includes “nutating” rings that tilt or wobble to receive a perpendicular beam emanating from a tube that also rotates full circle. In this configuration, the beam rotates outside of the nutating ring and the detectors tilt, improving the geometric angles at which the beams are received.

Both dynamic scanning and overscanning are made even more feasible by the new technology.

Dynamic scanning is performed by scanning clockwise and then counterclockwise, which reduces the interscan time without the need to index the gantry. Fourth-generation scanners can execute up to 15 scans per minute, which may improve as computer processing time decreases. For overscanning, the technologist uses an arc greater than 360°, instructing the computer to display the data from multiple scans as a single image.

SLIP RING TECHNOLOGY

The introduction of the slip ring to both third- and fourth-generation scanners was an important development in CT technology as it made spiral/helical scanning possible. Slip rings conduct electrical energy across a rotating cylindrical surface to system components such as the generator and x-ray tube.

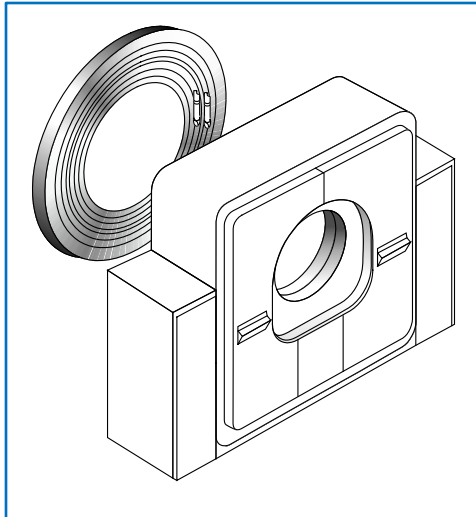
KEY POINTS

- Allows spiral/helical scanning
- Conducts electrical energy across a rotating cylindrical surface
- Gantry rotates continuously, accelerating data collection
- Dynamic CT of moving organs

Although various designs exist, they all utilize brushes made of a conductive material such as silver graphite alloy that slide along grooves in the ring to maintain conduction (**Figure 12**). This design allows for continuous rotation of the gantry, substantially accelerating data collection so that dynamic CT of moving organs can be achieved. Continuous rotation in a single direction also allows for the scan sequence to be initiated at any time.

HIGH-VOLTAGE SLIP RINGS

High-voltage slip rings (HVSRs) are configured so that AC power is delivered first to the high-voltage generator located outside of the x-ray tube. Power is relayed through the slip ring to the x-ray tube, causing it to rotate and perform the scan.



LOW-VOLTAGE SLIP RINGS

Low-voltage slip rings (LVSRs) are also available from some manufacturers. In this design, the x-ray tube and HVG are both mounted to the scan frame so that they rotate together. Low-voltage brushes deliver electrical impulses through contact with the grooves on a stationary cylinder. Power is then transmitted from the slip ring to a high-voltage generator and then to the x-ray tube.

Figure 12. A slip ring design, shown outside of the gantry unit.

Fifth Generation

Fifth-generation scanners are highly specialized and are referred to as high-speed scanners. They acquire scan data in milliseconds (ms) using a beam sweep arrangement of multiple targets instead of a tube. The primary disadvantages are poor image quality due to noise and patient exposure to higher doses of radiation. For these reasons, fifth-generation scanners are primarily used in cardiac imaging, where the need to minimize motion artifacts may justify higher patient dose.

KEY POINTS

- Highly specialized
- Very fast scanning
- Beam sweep of multiple targets
- Designed for cardiac imaging

The third- and fourth-generation scanners are widely used today and can utilize either sequential (conventional) or volume data acquisition. Sequential, or scan/stop, data acquisition is obtained as the tube rotates around the patient: data are collected in one position, the scan is stopped, the patient couch is moved to the next position, and the scanning continues. This process is repeated until the entire area of interest has been scanned.

In contrast, volume data acquisition, also called spiral/helical scanning, procures information on large areas rather than one slice at a time. The x-ray tube rotates continuously around the patient in a spiral or helical path to scan an entire area during a single breath hold. The patient couch or table moves slowly through the gantry for a single exposure.

ELECTRON BEAM CT (EBCT)

Electron beam CT is a fifth-generation technology that was developed specifically for the purpose of high-speed scanning of the heart in motion. In this modality, the source is a microwave-accelerated electron beam rather than an x-ray. The tightly focused beam is driven along a tungsten target ring to direct the rays, with no moving parts in the mechanism. EBCT can produce up to eight slices simultaneously, with scan times as short as 50 milliseconds.

KEY POINTS

- Highly specialized
- Square 2D array of detectors
- Provides a volume of data

Cone Beam CT (CBCT)

Cone Beam Computed Tomography (CBCT) scanners have been available for craniofacial imaging since 1999 in Europe and 2001 in the United States. Rather than a

conventional linear fan beam, the scanner uses a cone-shaped x-ray beam to produce images of the bony structures of the skull. Conventional medical scanners use a single row or a series (4, 8, 12, 32, 64, 128, 256, and 320) of solid state detectors paired with a fan-shaped beam to capture the attenuated x-ray. CBCT scanners use a square two-dimensional array of detectors to capture the cone-shaped beam. As a result, the CT unit provides a set of consecutive slices of the patient, while the CBCT scanner provides a volume of data. Subsequently, reconstruction software is applied on the cone beam volumetric data to produce a stack of 2D gray-scale level images of the anatomy.³ Cone beam scanning is used in dental and breast imaging, as well as for oncology studies (**Figure 13**).

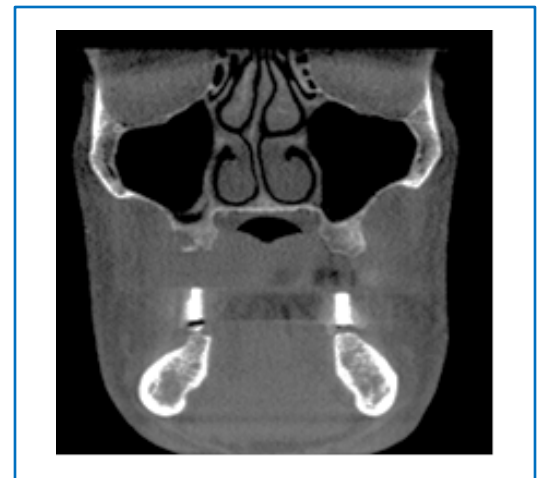


Figure 13. Dental image acquired using cone beam technology.
Courtesy of 3D Maxillofacial Imaging Centers

Dual Source CT

Dual source CT is a generation of scanner that has revolutionized CT scanning by utilizing two tubes and two detectors to achieve ultrafast, motion-free imaging of structures while applying low dose parameters and maintaining diagnostic imaging quality (**Figure 14**).

KEY POINTS

- Dual energy and lower temporal resolution
- Achieves ultrafast, motion-free images
- Low dose parameters while maintaining diagnostic image quality

Although dual source CT uses less radiation than conventional CT, power can be increased when needed, making dual source CT a good alternative for scanning obese patients, for example. Because the two tubes act in concert, dual source is also ideal for imaging pediatric patients as scan times can be reduced to sub-seconds. Finally, dual source is an excellent option in cardiac imaging, where increased temporal resolution is essential.



Figure 14. Example of a dual source CT unit.
Courtesy of Siemens Healthcare

Flat Panel CT

Flat panel technology is making its way into clinical practice and is used for intraoperative, dental, and inner ear imaging. The development of this new technology provides more robust images of soft tissue and vascular structures by merging fluoroscopic images fused with CT-like images, thus adding value to both modalities.

SUMMARY

Computed tomography remains a powerful radiologic tool in the arsenal of imaging modalities. CT scanners are being continually refined and upgraded, allowing for faster acquisition and processing of multiple scans, reduced scan times, lower radiation dose, reduced motion, thinner slices, and whole organ and whole body visualization. CT will continue to be relied upon not only for first-line imaging but for definitive diagnosis and treatment planning.

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GLOSSARY

algorithm

a mathematical process applied to raw data for the purposes of reconstruction, filtering, or enhancement of an image

analog signal

a type of electrical signal that is directly measurable as voltage, light, x-rays, or number of rotations

analog-to-digital converter (ADC)

a device that converts analog signals into digital binary code that can be read and interpreted by the computer; its three major components are sampling, quantization, and coding

anode

the electrode at the end of an x-ray tube that, when struck by an electron beam, produces x-ray photons

aperture

the donut-shaped opening in the gantry through which the patient and patient table will pass during the scan

array processor

a device that reconstructs images from raw data at a very high rate of speed

artifact

an appearance on a radiographic image that is unrelated to the anatomical subject. Includes aliasing, beam hardening, edge-gradient effects, and metal and motion artifacts

attenuation

the reduction in the intensity of an x-ray beam as it passes through a patient

back-projection

a reconstruction process by which raw data are put into the image format (generally with filtering); also known as the summation or linear supposition method

bremsstrahlung

the term used for braking radiation, which comprises 80-90% of the x-rays used in CT scanning

cathode

the electrode in an x-ray tube from which an electron beam is initiated

cathode ray tube (CRT)

the monitor on which the image is displayed

central processing unit (CPU)

the "brain" of the computer that directs and controls all of the other components

collimator

small electrical conductor that is used to shape the electron beam in the x-ray tube and reduce scatter radiation around the detectors

contrast

amount of differentiation between pixel shades of gray in a CT image

data acquisition system (DAS)

the electronics positioned between the detectors and the computer responsible for collecting image data

detector

one of hundreds or thousands of identical receptor units that measure attenuated x-rays after they have passed through the patient

detector geometry

the relationship between the arrangement of the tube, the beam shape, and the detectors

digital signal

a type of electrical signal that is in the form of binary code that can be read by a computer - often called "raw data"

digital-to-analog converter (DAC)

a device that converts digital signals from the scan controller into a continuous analog waveform signal so that the instructions from the scan controller can be interpreted; located between the scan controller and the gantry

direct current (DC)

unidirectional flow of electric charge as opposed to alternating current (AC) when the movement of electric charge periodically reverses direction

display field of view (DFOV)

a reconstruction factor that refers to the area of interest after an image is reconstructed on the display; also called *reconstruction field of view*

dual source

CT unit utilizing two tubes and two detectors that rotate in the same plane and are at 90-degree angles from each other

dynode

a nonspecific type of electrode, including an anode or cathode

filtering

the process of applying a reconstruction algorithm to an image

gantry

the unit that houses the imaging components for x-ray production and data acquisition

graphical user interface (GUI)

the combination of graphic images, eg, folders or icons, and the workflow

hertz (Hz)

the standard (SI) unit of frequency; equal to the old unit cycles per second; named for German physicist Heinrich Hertz (1857-1894)

high-voltage generator

the unit that generates the voltage necessary to produce x-ray photons

Hounsfield units (HU)

the information contained in a single pixel assigned a value correlating to a shade of gray; also called CT units

image matrix

the electronic plane of pixels that combine to form the image displayed on a monitor

kVp

the maximum tube voltage from the cathode to the anode

lag (afterglow)

a type of artifact; can be produced when sodium iodide scintillation crystals are used

linear attenuation coefficient

the rate at which x-rays are diminished after passing through a patient

linearity

accuracy of a CT scanner, calibrated against the CT value of water

liquid crystal display (LCD)

device used to view CT images. It is of compact size, low power consumption, good color representation, excellent image resolution, and luminance (brightness). Resolution of the monitors can vary from 1200x1600 pixels to 1536x2048 pixels depending on the type of LCD.

localizer scan

a method of scanning that shows tissues superimposed without clear differentiation; also called a scout, topogram, or reference image

modulation transfer function (MTF)

the frequency dependent ratio of object contrast to image contrast. MTF permits qualitative determination of the spatial resolution of an imaging system.

noise

spots or blotches appearing on low-contrast images

oblique angle

an angle that is not a multiple of 90 degrees

phantom

an artificial object, with a known CT value, that is weighted and configured for scanner testing of various parameters

photon

a particle of energy

pixel

a two-dimensional picture element that represents the smallest discrete block in a digital image display field; from "picture element"

random-access memory (RAM)

temporary storage of information in the CPU of a computer

quantizer

part of the analog-to-digital converter that converts large samples of data into smaller data samples

read-only memory

primary long-term data storage on the CPU of a computer

retrospective reconstruction

reconstruction of an image after raw data have been saved; includes multiplanar reconstruction and 3-D surface rendering

sample/hold (S/H)

the object being scanned is sampled to differentiate structures within the object and to assign various shades of gray to the pixels representing the structures

scan field of view (SFOV)

a reconstruction factor that refers to the area of interest the scan field size is set to cover

scintillation

the property of luminescence when excited by ionizing radiation; a scintillation crystal is used in the CT unit to help convert electrons into a digital signal for computer processing

scout

another term for a localizer scan; also called a topogram or reference image

sensitivity

the number of light photons created by a rare earth material after the detector is struck by an x-ray

slip ring

a large metal ring inside the gantry that rotates the scanning components and relays signals to and from the computer to perform the scan

spiral/helical scanning

a scanning method in which certain x-ray tubes rotate continuously around a patient until the entire area of interest has been scanned; also called volume data acquisition

terabyte

one trillion bytes or 1,000 gigabytes

transformer

amplifies the voltage to give the tube the necessary power it needs to generate x-rays

voxel

a three-dimensional volume of tissue that corresponds to an individual pixel on a CT image; from "volume element"

windowing

a term describing computer manipulation of an image using the gray scale; includes both window level and window width

ABBREVIATIONS OF TERMS

AC	alternating current	kV	kilovolts
ADC	analog-to-digital converter	LCD	liquid crystal display
AP	anterior/posterior	LVSR	low-voltage slip rings
CBCT	cone beam CT	mA	milliampere
CPU	central processing unit	MB	megabyte
CRT	cathode ray tube	MIP	multiplanar
CT	computed tomography	MOD	magnetic optical disk
CVD	chemical vapor deposition	MPR	multiplanar reconstruction
DAC	digital-to-analog converter	MTF	modulation transfer function
DAS	data acquisition system	PA	posterior/anterior
DC	direct current	PACS	picture archiving and communication system
DFOV	display field of view	PC	personal computer
EBCT	electron beam computed tomography	PM	preventive maintenance
FOV	field of view	RAM	random-access memory
GB	gigabyte	ROM	read-only memory
GOS	gadolinium oxysulfide	RPM	rotations per minute
GUI	graphical user interface	SFOV	scan field of view
HU	Hounsfield unit(s)	S/H	sample/hold
HVG	high-voltage generator	USB	universal serial bus drives
HVSR	high-voltage slip rings	WORM	write-once-read-many
Hz	hertz	WL	window level
IRS	image reconstruction system	WW	window width
Kb	kilobytes		