Al-Mustaqbal University

College of Engineering

Biomedical Engineering Department

Subject Name: Biom. Instrumentation Design II 2

5^{th} Class, Second Semester

Subject Code: MU0115202

Academic Year: 2025-2026

Lecturer: Mr. Mahir Rahman

Email: mahir.rahman@uomus.edu.iq

Lecture No.: 1

Lecture Title: Introduction to Computed Tomography

https://eng.uomus.edu.iq/DefaultDep.aspx?depid=13

Lecture One

Computed Tomography

BACKGROUND

Conventional radiographs depict a three-dimensional object as a two-dimensional image. This results in overlying tissues being superimposed on the image, a major limitation of conventional radiography. Computed tomography (CT) overcomes this problem by scanning thin sections of the body with a narrow x-ray beam that rotates around the body, producing images of each cross section. Another limitation of the conventional radiograph is its inability to distinguish between two tissues with similar densities. The unique physics of CT allow for the differentiation between tissues of similar densities.

The main advantages of CT over conventional radiography are in the elimination of superimposed structures, the ability to differentiate small differences in density of anatomic structures and abnormalities, and the superior quality of the images.

TERMINOLOGY

The word tomography has as its root *tomo*, meaning to cut, section, or layer from the Greek *tomos* (a cutting). In the case of CT, a sophisticated computerized method is used to obtain data and transform them into “cuts,” or cross-sectional slices of the human body. The first scanners were limited in the ways in which these cuts could be performed. All early scanners produced axial cuts; that is, slices looked like the rings of a tree visualized in the cut edge of a log. Therefore, it was common to refer to older scanning systems as computerized axial tomography, hence the common acronym, CAT scan.

Newer model scanners offer options in more than just the transverse plane. Therefore, the word “axial” has been dropped from the name of current CT systems. If the old acronym CAT is used, it now represents the phrase computer-assisted tomography.

Although all CT manufacturers began with the same basic form, they added features and functionality to the existing technology. As each feature was developed, each manufacturer gave the feature a name. For this reason, the same feature may have a variety of different names, depending on the manufacturer. For example, the preliminary image each scanner produces may be referred to as a “topogram” (Siemens), “scout” (GE Healthcare), or “scanogram” (Toshiba). Another well known example is a method of scanning that, generically, is referred to as continuous acquisition scanning; this method can also be called “spiral” (Siemens), “helical” (GE Healthcare), or “isotropic” (Toshiba) scanning.

CT image quality is typically evaluated using a number of criteria:

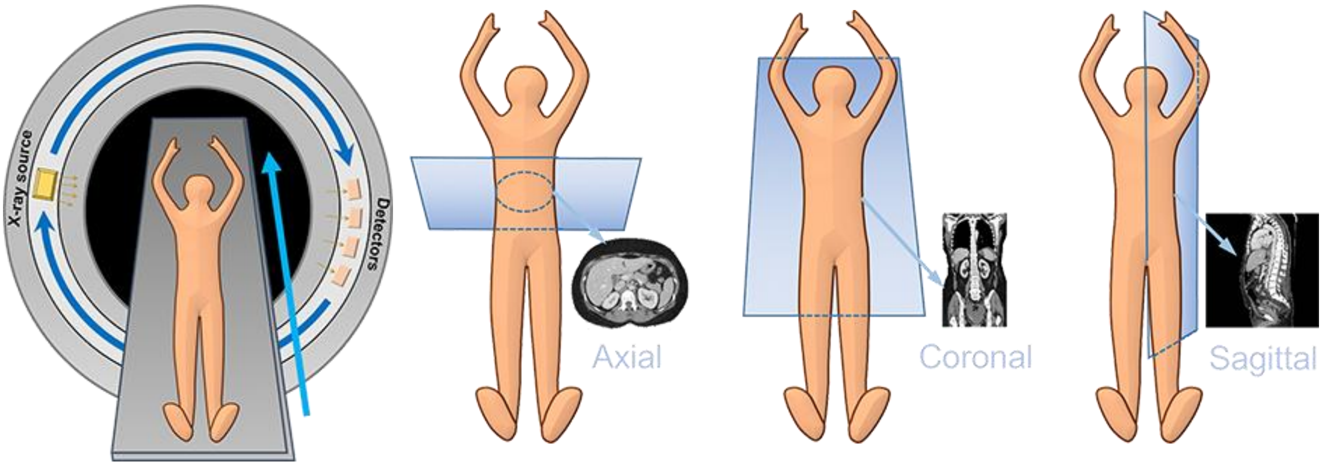
- Spatial resolution describes the ability of a system to define small objects distinctly.
- Low-contrast resolution refers to the ability of a system to differentiate, on the image, objects with similar densities.
- Temporal resolution refers to the speed that the data can be acquired. This speed is particularly important to reduce or eliminate artifacts that result from object motion, such as those commonly seen when imaging the heart.

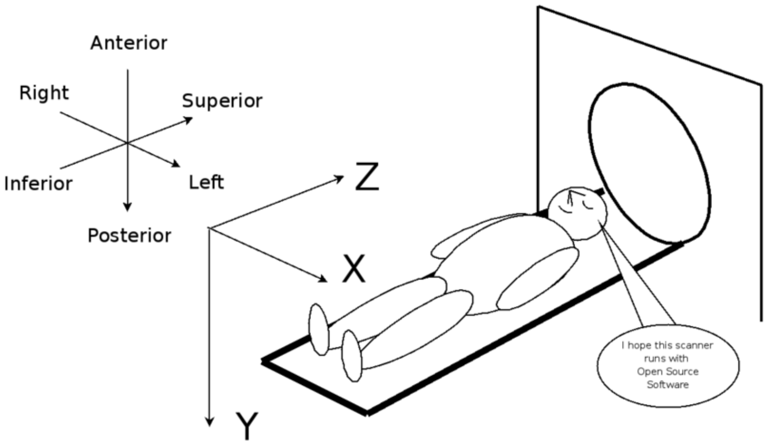
COMPUTED TOMOGRAPHY DEFINED

Computed tomography uses a computer to process information collected from the passage of x-ray beams through an area of anatomy. The images created are cross-sectional. To visualize CT, the often-used loaf of bread analogy is useful. If the patient’s body is imagined to be a loaf of bread, each CT slice correlates to a slice of the bread.

The individual CT slice shows only the parts of the anatomy imaged at a particular level. For example, a scan taken at the level of the sternum would show portions of lung, mediastinum, and ribs, but would not show portions of the kidneys and bladder.

Each CT slice represents a specific plane in the patient’s body. The thickness of the plane is referred to as the *Z* axis. The *Z* axis determines the thickness of the slices (Fig. 1-1). The operator selects the thickness of the slice from the choices available on the specific scanner. Selecting a slice thickness limits the x-ray beam so that it passes only through this volume; hence, scatter radiation and superimposition of other structures are greatly diminished. Limiting the x-ray beam in this manner is accomplished by mechanical hardware that resembles small shutters, called collimators, which adjust the opening based on the operator’s selection.





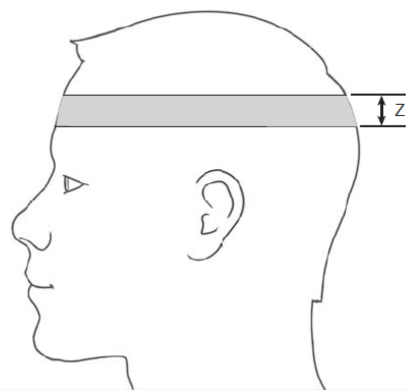


FIGURE 1-1 The thickness of the cross-sectional slice is referred to as its *Z* axis.

The data that form the CT slice are further sectioned into elements: width is indicated by *X*, while height is indicated by *Y* (Fig. 1-2). Each one of these two-dimensional squares is a pixel (picture element). A composite of thousands of pixels creates the CT image that displays on the CT monitor. If the *Z* axis is taken into account, the result is a cube, rather than a square. This cube is referred to as a voxel (volume element).

A matrix is the grid formed from the rows and columns of pixels. In CT, the most common matrix size is 512. This size translates to 512 rows of pixels down and 512 columns of pixels across. The total number of pixels in a matrix is 262,144. Because the outside perimeter of the square is held constant, a larger matrix size (i.e., 1,024 as opposed to 512) will contain smaller individual pixels. Each pixel contains information that the system obtains from scanning.

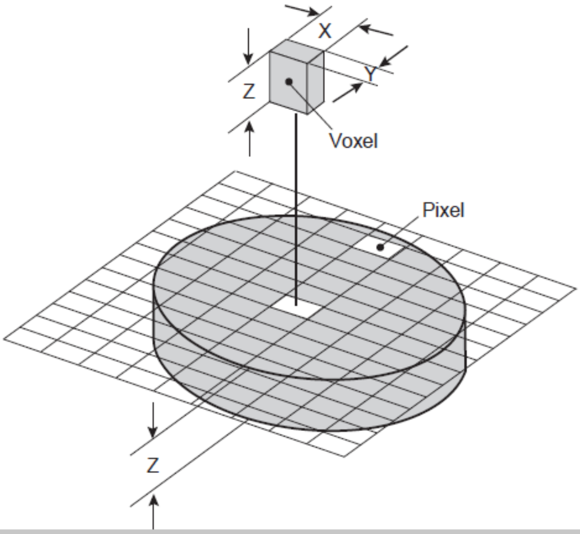


FIGURE 1-2 The data that form the CT slice are sectioned into elements.

BEAM ATTENUATION

The structures in a CT image are represented by varying shades of gray. The creation of these shades of gray is based on basic radiation principles. An x-ray beam consists of bundles of energy known as photons. These photons may pass through or be redirected (i.e., scattered) by a structure. A third option is that the photons may be absorbed by a given structure in varying amounts, depending on the strength (average photon energy) of the x-ray beam and the characteristics of the structure in its path. The degree to which a beam is reduced is a phenomenon referred to as attenuation.

In CT, the x-ray beam passes through the patient's body and is recorded by the detectors. The computer then processes this information to create the CT image. The quantities of x-ray photons that pass through the body determine the shades of gray on the image.

By convention, x-ray photons that pass-through objects unimpeded are represented by a black area on the image. These areas on the image are commonly referred to as having low attenuation. Conversely, an x-ray beam that is completely absorbed by an object cannot be detected; the place on the image is white. An object that has the ability to absorb much of the x-ray beam is often referred to as having high attenuation. Areas of intermediate attenuations are represented by various shades of gray.

The number of the photons that interact depends on the thickness, density, and atomic number of the object. Density can be defined as the mass of a substance per unit volume. Dense elements, those with a high atomic number, have many circulating electrons and heavy nuclei and, therefore, provide more opportunities for photon interaction than elements of less density.

To better understand how these physical properties of an object affect the degree of beam attenuation, envision a single x-ray photon passing through an object. The more atoms in its path (the greater the object's thickness and density), the more likely that an atom in the object will interact with the photon. Similarly, the more electrons, neutrons, and protons in each atom, the higher the likelihood of photon interaction. Therefore, the number of photons that interact increases with the density, thickness, and atomic number of the object (Fig. 1-3).

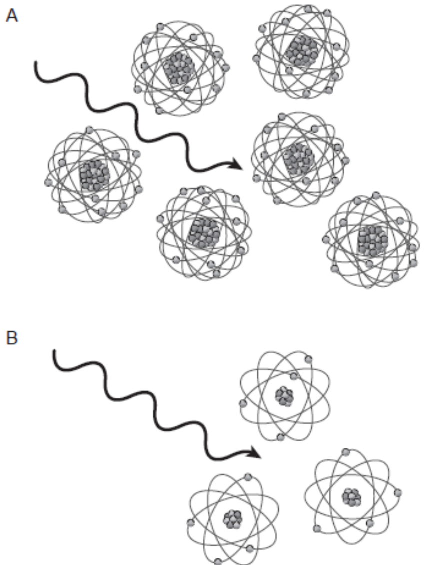


FIGURE 1-3 The relative number of photons that interact increases with the increased density, thickness, and atomic number of the object. In (A), the object in the path of the photon is thicker, denser, and composed of heavier atoms than that of the object depicted in (B); hence, the photon is much more likely to be attenuated in (A).

The amount of the x-ray beam that is scattered or absorbed per unit thickness of the absorber is expressed by the linear attenuation coefficient, represented by the Greek letter μ. For example, if a 125-kVp x-ray beam is used, the linear attenuation coefficient for water is approximately 0.18 cm^{-1}. This means that about 18% of the photons are either absorbed or scattered when the x-ray beam passes through 1 cm of water (Table 1-1).

TABLE 1-1 Linear Attenuation Coefficients (cm^{-1}) at 125 kVp for Various Tissues

Tissue	Linear Attenuation Coefficient (cm^{-1})
Air	0.0003
Fat	0.162
Water	0.180
Cerebrospinal fluid	0.181
White matter	0.187
Gray matter	0.184
Blood	0.182
Dense bone	0.46

Reprinted with permission from Bushong S. Radiologic Science for Technologists: Physics, Biology, and Protection. St. Louis: Mosby, 1993:420.

In general, the attenuation coefficient decreases with increasing photon energy and increases with increasing atomic number and density. It follows that if the kVp is kept constant, the linear attenuation coefficient will be higher for bone than it would be for lung tissue. That is, bone attenuates more of the x-ray beam than does lung, allowing fewer photons to reach the CT detectors. Ultimately, this results in an image in which bone is represented by a lighter shade of gray than that representing lung. The CT image is a direct reflection of the distribution of linear attenuation coefficients. For soft tissues, the linear attenuation coefficient is roughly proportional to physical density. For this reason, the values in a CT image are sometimes referred to as density.

Metals are generally quite dense and have the greatest capacity for beam attenuation. Consequently, surgical clips and other metallic objects are represented on the CT image as white areas. Air (gas) has very low density, so it has little attenuation capacity. Air-filled structures (such as lungs) are represented on the CT image as black areas.

To differentiate an object on a CT image from adjacent objects, an oral or intravenous administration of a contrast agent is often used to create a temporary artificial density difference between objects. Contrast agents fill a structure with a material that has a different density than that of the structure. In the cases of agents that contain barium sulfate and iodine, the material is of a higher density than the structure. These are typically referred to as positive agents. Low-density contrast agents, or negative agents, such as water, can also be used. Figure 1-4 A shows an image taken at the level of the kidneys without contrast enhancement. Figure 1-4B shows the same slice after the intravenous injection of an iodinated contrast agent. The kidneys and blood vessels are highlighted because of the high-density contrast they contain.

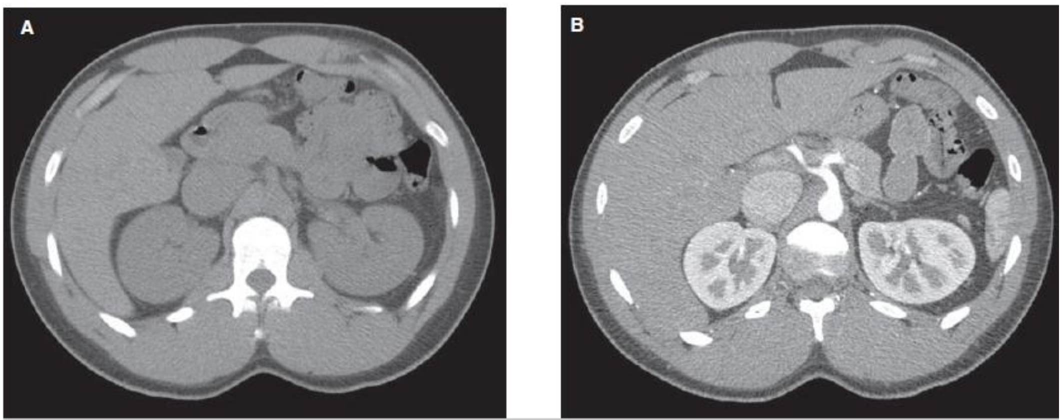


FIGURE 1-4 In (A), the slice has been taken at the level of the kidneys without contrast enhancement. Note the difficulty in differentiating blood vessels from surrounding structures. In (B), the slice has been taken after the administration of intravenous contrast media.

HOUNSFIELD UNITS

In CT, the beam attenuation capability of a given object can be quantified. Measurements are expressed in Hounsfield units (HU), named after Godfrey Hounsfield, one of the pioneers in the development of CT. These units are also referred to as CT numbers, or density values.

Hounsfield arbitrarily assigned distilled water the number 0 (Fig. 1-5). He assigned the number 1000 to dense bone and −1000 to air. Objects with a beam attenuation less than that of water have an associated negative number.

Conversely, substances with an attenuation greater than that of water have a proportionally positive Hounsfield value.

The Hounsfield unit of naturally occurring anatomic structures fall within this range of 1000 to −1000. The Hounsfield unit value is directly related to the linear attenuation coefficient: 1 HU equals a 0.1% difference between the linear attenuation coefficient of the tissue as compared with the linear attenuation coefficient of water.

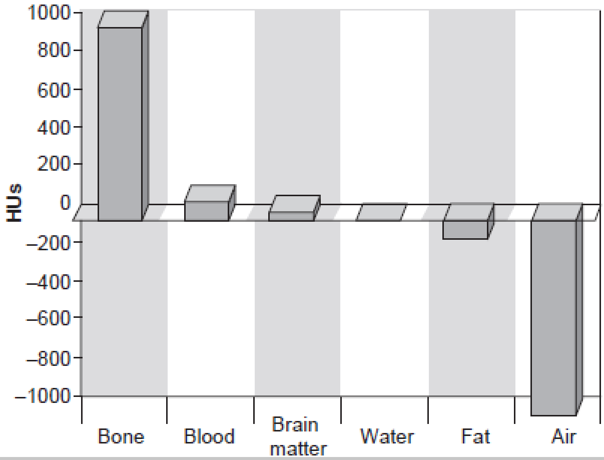


FIGURE 1-5 Approximate Hounsfield units.

Using the system of Hounsfield units, a measurement of an unknown structure that appears on an image is taken and compared with measurements of known structures. It is then possible to approximate the composition of the unknown structure. Factors that contribute to an inaccurate Hounsfield measurement include poor equipment calibration, image artifacts, and volume averaging.