Ministry of Higher Education and Scientific Research

Al-Ma'moun University College

كليــة المــأمون الجامعــة

للعام الدراسي (2023–2024)

Physics of Computed Tomography

Lecture (2)

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Physics of Computed Tomography

Ray projection

The CT x-ray tube (typically with energy levels between 20 and 150 keV), emits N photons (monochromatic) per unit of time. The emitted x-rays form a beam that passes through the layer of biological material of thickness Δx. A detector placed at the exit of the sample, measures $N + \Delta N$ photons, ΔN smaller than 0. Attenuation values of the x-ray beam are recorded and the data is used to build a 3D representation of the scanned object/tissue.

There are two processes of absorption: the photoelectric effect and the Compton effect. This phenomenon is represented by a single coefficient. In the particular case of CT, the emitter of x-rays rotates around the patient and the detector, placed on diametrically opposite sides, picks up the image of a body section (beam and detector move in synchrony).

Unlike x-ray radiography, the detectors of the CT scanner do not produce an image. They measure the transmission of a thin beam (1-10 mm) of x-rays through a full CT of the body. The image of that section is taken from different angles, and this allows to retrieve the information on the depth (in the third dimension).

The CT deals with the attenuation of the x-rays during the passage through the body segment. However, several features distinguish it from conventional radiology:

- The image is reconstructed from a large number of measurements of attenuation coefficients. It gathers together all the data coming from the elementary volumes of material through the detectors.
- To obtain tomographic images of the patient from the "preprocessed" CT dataset, the computer uses complex mathematical algorithms for image reconstruction. Using the computer, it presents the elementary surfaces of the reconstructed image from a projection of the data matrix reconstruction, the tone depending on the attenuation coefficients.
- Back projection is the most direct way of recontructing an image. However, each image point is surrounded by a halo-shaped star that degrades the contrast and blurs the boundary of the object. To avoid this, the method of filtered back projection is used.

- Before the data are presented on the screen, the conventional rescaling was made into CT numbers, expressed in dimensionless Hounsfield Units (HU). Hounsfield chose a scale that reflects the four basic x-ray densities in the human body, with the following values:

- air = -1000 HU (Hounsfield units)
- fat = -60 to -120 HU
- water = 0 HU
- compact bone = +1000 HU

The final image contains CT numbers in each voxel.

CT Image

The Computed tomography number (CT number) is a selectable scan factor based on the Hounsfield scale. Each elemental region of the CT image (pixel) is expressed in terms **of** Hounsfield units (HU) corresponding to the x-ray attenuation (or tissue density). CT numbers are displayed as gray-scale pixels on the viewing monitor. White represents pixels with higher CT numbers (bone). Varying shades of gray are assigned to intermediate CT numbers e.g., soft tissues, fluid and fat. Black represents regions with lower CT numbers like lungs and air-filled organs.

For radiologists, the most important output from a CT scanner is the image itself. The variable signal intensity in CT results from tissue discrimination based on the variations in attenuation between "voxels," which depends on differences in voxel density and atomic number of elements present and is influenced by the detected mean photon energy. Image that produces CT which will show later is composed of pixels (picture elements) and each pixel on it represents the average x-ray attenuation in a small volume (voxel) that extends through the tissue section. In addition, all tissues within single pixel in a real CT image will be the same shade of gray.

As a final step, the individual voxel attenuation values are scaled to more convenient integers and normalized to voxel values containing water. The CT image does not show μ values directly, but the intensity scale (called the CT number) used in the reconstructed CT image is defined by:

$$CT_{number} = \frac{\mu - \mu_{water}}{\mu_{water}} \times 1000$$

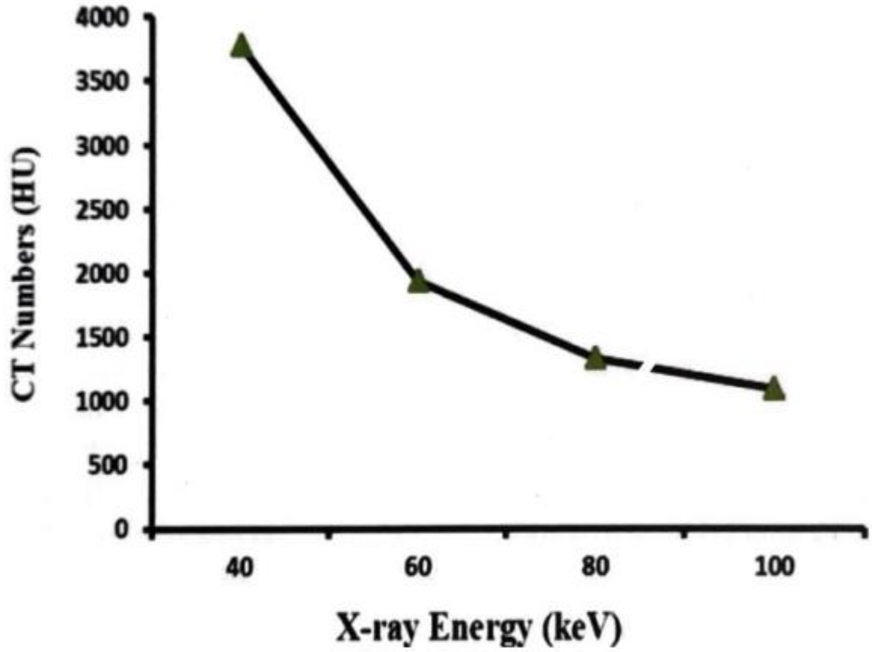
where μ is the measured attenuation of the material in the voxel and is the linear attenuation coefficient of water. This unit is often called the Hounsfield unit (HU), honoring the inventor of CT. Voxels containing materials that attenuates more than water (e.g. muscle tissue, liver, and bone) have 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.

By definition, water has a CT number of zero. The CT number for air is –1000 HU, since . Soft tissues (including fat, muscle, and other body tissues) have CT numbers ranging from –100 HU to 60 HU. Cortical bones are more attenuating and have CT numbers from 250 HU to over 1000 HU. The linear attenuation coefficient is magnified by a factor over 1000. Medical scanners typically work in a range of –1024 HU to +3071 HU.

The contrast and metal objects have values from several hundred to several thousand HU. Because of the large dynamic range of the CT number, it is impossible to adequately visualize it without modification on a standard grayscale monitor or film. Typical display devices use eight-bit grayscales, representing 256 different shades of gray. If a CT image is displayed without transformation, the original dynamic range of well over 2000 HU must be compressed by a factor of at least 8.

Variation in CT Numbers with X-ray Energy

When an X-ray beam of varying energy over a range of energies is passed through the body of a patient, low-energy X-ray photons are absorbed and removed from the beam within a short length. As a result the average energy of the remaining beam gets higher. This process is called hardening of the beam. The hardening of the beam continues as the beam further penetrates in the body. Since the average energy of the hardened beam is higher than the original beam allowed to fall on the body, therefore, its penetration ability also increases. Since the CT numbers depend upon the absorption ability of X rays, therefore, variation in X-ray energy causes a change in CT numbers of the same tissue as illustrated in Fig. 1.



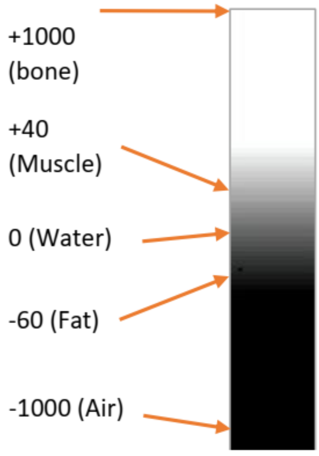
Variation in CT number with X-ray beam energy

The above figure, shows variation in the CT numbers of cartilage bone with the energy of X-ray beam. The figure shows that the CT number of a tissue decreases with increasing beam energy. This variation in CT number also brings changes on the gray scale, causing complications in the imaging process. Therefore, a better option is to use a monochromatic beam of X-ray photons. The energy of X-ray beam is controlled by and proportional to the X-ray tube voltage. The higher the tube voltage, the more energetic X-ray beams are obtained. Thus, controlling the tube voltage can solve the problem of variation in energy and can produce a monochromatic beam to avoid variation in CT numbers. Proper X-ray generator calibration is important for accurate and reproducible CT numbers.

Example: Calculate the CT number for the muscle with the following data:

μ	80 Kev	100 Kev	150 Kev
μ_{water}	0.1835	0.1707	0.1504
μ_{muscle}	0.1892	0.1760	0.1550

Tissue	Range of CT Numbers (HU)
Bone	500 to 3000
Liver	40 to 60
Grey Matter (Brain)	35 to 45
White Matter (Brain)	20 to 30
Blood	30 to 45
Muscle	10 to 40
Water	0
Fat	-60 to -150
Lung	-500
Air	-1000



Gray Scale

Table 1 Tissues' CT numbers and gray scale.

Table 1 gives CT numbers of various tissues in HUS.

$$HU = \left\{\frac{\mu_{tissue} - \mu_{water}}{\mu_{water}}\right\} \times 1000$$

At 80 keV

$$HU = \{(0.1892 - 0.1835)/(0.1835)\} \times 1000 = 31$$

At 100 keV

$$HU = \{(0.1760 - 0.1707)/(0.1707)\} \times 1000 = 31$$

At 150 keV

$$HU = \{(0.1550 - 0.1504)/(0.1504)\} \times 1000 = 31$$