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Using Voxel Count Measurements Based On X-Ray Attenuation Coefficient Principle to Estimate Organ Volume during CT Scan

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ABSTRACT

The study provided a simple method of using voxel count method to estimate organ volume together with x-ray attenuation coefficient principle**.** The aim is to discuss the role of x-ray attenuation coefficient in CT organ volume measurements using voxel count method. The method involve using the principle of linear attenuation coefficient which describes the fraction of a beam of x-rays or gamma rays that is absorbed or scattered per unit thickness of the absorber to enable tissue differentiation and hence the used of volume elements method, where the body is literally divided into 3-dimensional rectangular boxes with known size and thickness. This value basically accounts for the number of atoms within a specified distance of a material and the probability of a photon being scattered or absorbed from the nucleus or an electron of one of these atoms. A graph of linear attenuation coefficients versus radiation energy are used to separate between various body tissues. At a specific energy the difference in attenuation between two tissues is greatest at a specific radiographic contrast in an image. Hence, this variation enable a separation and subsequent measurements of varied tissues. Therefore, it is extremely useful to determine various linear attenuation coefficients of tissues to enable various variations to be determine for clinical application.

Keywords : X-Ray Attenuation, Voxel Count Method, Linear Attenuation Coefficient, Gamma Rays

I. INTRODUCTION

Basically, computed tomography (CT) imaging are explain by the basic principle of physics. These are based on the theories and principle of radiation physics of absorption and attenuation to produced tomographic slice images [16]. These CT images are produced based on the attenuation coefficient which is essentially describe as Transmitted Intensity and Linear X-ray Attenuation Coefficient. The process involve a change both in narrow beam of mono-energetic photons and x-ray beam intensity at some distance in a material expressed in the form of an equation as:

$$dl(x) = -I(x) * n * \sigma * dx \quad (1)$$

Where
dl = the change in intensity
I = the initial intensity
n = the number of atoms/cm^3
σ = a proportionality constant that reflects the total probability of a photon being Scattered or Absorbed

dx = the incremental thickness of material traversed
When this equation is integrated to represent the total photon being scattered or absorbed, it becomes:

$$\boldsymbol{I = I_0 e^{-n\sigma x}} \tag{2}$$

The product of the number of atoms/cm^3 (n) and the proportionality constant (σ), that is (nσ) is known as the linear attenuation coefficient (μ). Therefore the equation can be written as:

$$\boldsymbol{I = I_0 e^{-\mu x}} \tag{1}$$

Where: I = the intensity of photons transmitted across some distance x

I_0 = the initial intensity of photons

e = a proportionality constant that reflect the total probability of photon being absorbed or scattered

μ = the linear attenuation coefficient

x = distance travel

The linear attenuation coefficient (μ) describes the fraction of a beam of x-rays or gamma rays that is absorbed or scattered per unit thickness of the absorber. This value basically accounts for the number of atoms in a cubic volume of material and the probability of a photon being scattered or absorbed from the nucleus or an electron of one of these atoms.

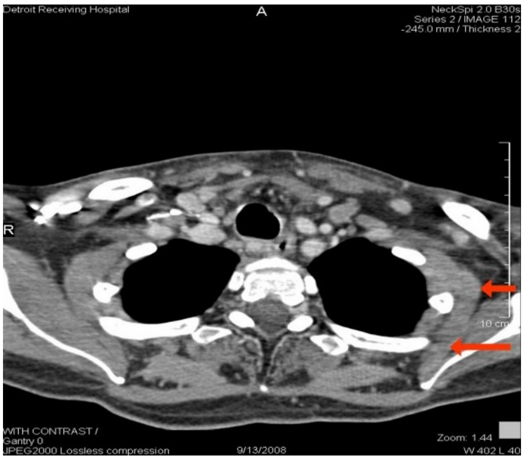
Using the transmitted intensity equation above, linear attenuation coefficients can be used to make a number of calculations. These include:

- The intensity of the energy transmitted through a material, in this case the patient body when the incident x-ray intensity, the material or the tissue and the material thickness or tissue type are known. This account for the absorbed dose to patients undergoing CT scan.
- The intensity of the incident x-ray energy when the transmitted x-ray intensity, tissue, and tissue type are known. This help to set the tolerance level to various organs and tissues.
- The type of tissue when the incident and transmitted intensity, and the tissue are known.
- The material can be determined from the value of μ when the incident and transmitted intensity, and the material thickness are known.

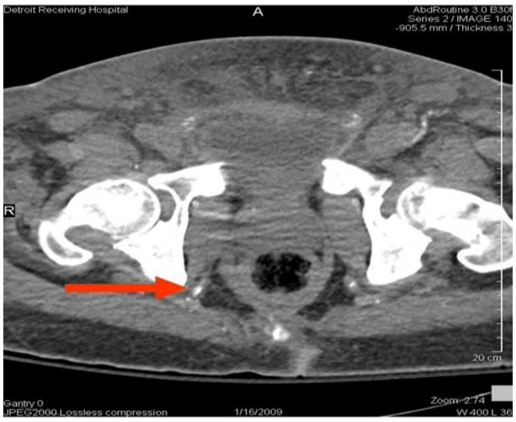
Generally, CT imaging anatomy involve the following regional body examinations. The brain, head and neck, thorax, abdomen and pelvis, and the upper and lower extremities.

Brain

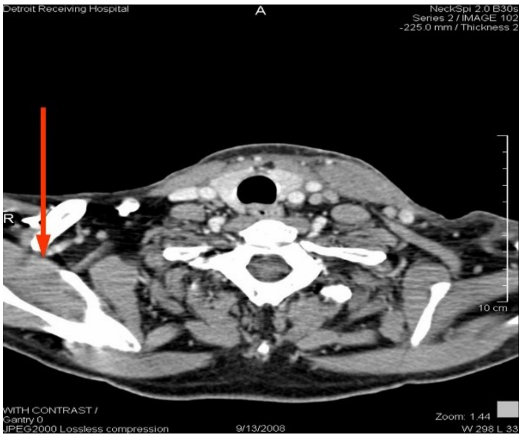
Head and Neck



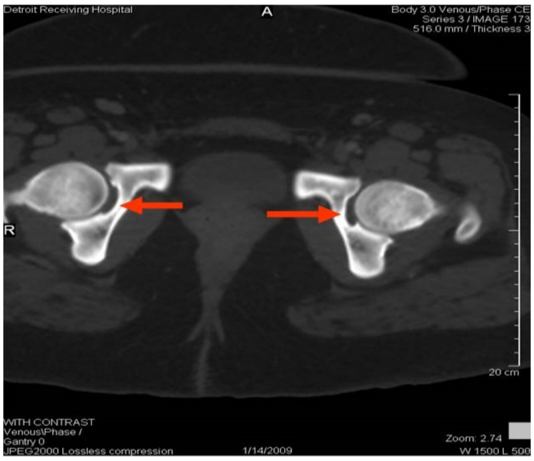
Thorax



Abdomen and Pelvis



Upper Extremity



Lower Extremity

The most common among these scans is the abdominal CT scan, because the scan can be performed on the abdomen for a large number of studies including;

- The abdomen and pelvis CT scan contain the digestive organs as well as the urinary (Kidney and bladder), endocrine, and reproductive systems.
- A CT scan of the abdomen or pelvis may be done to look for abscesses, tumors, kidney stones, infections or for the cause of unexplained abdominal pain.
- Abdominal scans can be used to help pinpoint a tumor and assist a health professional before a biopsy is performed.
- A CT scan of the abdomen/pelvis can also be used to monitor the progress of tumor treatment by measuring the growth or atrophy of the tumor.

OBJECTIVES

This study discussed the importance of x-ray attenuation coefficient in CT organ volume measurements using voxel count method.

II. LITERATURE REVIEW

BASIC PRINCIPLE OF VOXEL COUNT MEASUREMENTS

CT scan form cross sectional pictures elements (pixels) of the scan area. These cross sectional images are divided into a number of slices which together form the organ. After the discovery of the CT number Sir Godfrey Hounsfield conceived that a slice can be divided into a matrix of 3-dimensional rectangular boxes or volume element (voxel) of tissues as shown in fig 1. Then, if X and Y directions are within the plane of a slice, whereas the Z direction is along the axis of the slice thickness direction. That is, the Z dimension of the voxels corresponds to the slice thickness. The X and Y voxel dimensions ("W" in fig 1) depend on the size of the area over which the x-ray measurements are obtained (the scan circle) as well as on the size of the matrix (the number of rows and columns) into which the slice is imagined to be divided. For example, suppose that each translation covers 250 mm. After collection of all of the views, the measurements cover a scan circle with a diameter of 250 mm. If this scan circle is divided into a matrix of 250 rows × 250 columns, each voxel is 1 × 1 mm. If a 512 × 512 matrix is used (as is common today), each voxel is approximately 0.5

× 0.5 mm. This measured matrix is referred to as the reconstruction matrix.

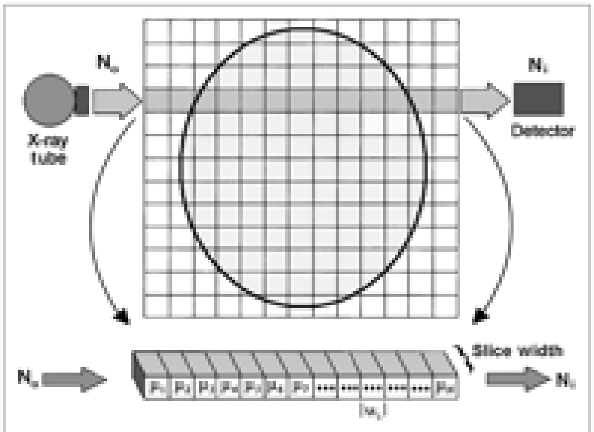


Figure 1: Voxel representation of human tissue

BASIC PRINCIPLE OF X-RAY

ATTENUATION COEFFICIENT

Attenuation decreases the intensity of electromagnetic radiation due to absorption or scattering of photons. Attenuation does not include the decrease in intensity due to inverse-square law geometric spreading. Therefore, calculation of the total change in intensity involves both the inverse-square law and an estimation of attenuation over the path. The primary causes of attenuation in matter are the photoelectric effect, Compton scattering, and, for photon energies of above 1.022 MeV, pair production.

Attenuation coefficient can be linear, when it described the attenuation of a beam through a specified distance or hemispheric when it described the attenuation of radiant energy through a given volume of a material. In both cases it described and characterizes how easily it can be penetrated by a beam of light, sound, particles, or other energy or matter. During these penetration by particles or photons in medical imaging the photons are either absorbed or scattered, which is commonly described us attenuation and the value of attenuation is refer to us the coefficient. A large attenuation coefficient means that the beam is quickly "attenuated" (weakened) as it passes through the tissue e.g. bone tissues, and a small attenuation coefficient means that the tissue is relatively transparent to the beam e.g. lungs tissues. In other words the small attenuation coefficient indicates that tissue in question is relatively transparent, while a larger value indicates greater degrees of opacity.

Furthermore, attenuation coefficient describes the extent to which the radiant flux of a beam is reduced as it passes through a specific material. It is used in the context of

- X-rays or Gamma rays, where it is denoted $\boldsymbol{\mu}$ and measured in cm^{-1};
- neutrons and nuclear reactors, where it is called macroscopic cross section (although actually it is not a section dimensionally speaking), denoted $\boldsymbol{\sigma}$ and measured in m^{-1};
- ultrasound attenuation, where it is denoted α and measured in $dB\cdot cm^{-1}\cdot MHz^{-1}$;
- Acoustics for characterizing particle size distribution, where it is denoted $\boldsymbol{\alpha}$ and measured in m^{-1}.

III. METHODOLOGY

LINEAR X-RAY ATTENUATION COEFFICIENT

The linear attenuation coefficient (μ) describes the fraction of a beam of x-rays or gamma rays that is absorbed or scattered per unit thickness of the absorber. This value basically accounts for the number of atoms within a specified distance of a material and the probability of a photon being scattered or absorbed from the nucleus or an electron of one of these atoms.

Sir Godfrey Hounsfield developed a method to calculate linear attenuation coefficient values (μ) for each individual tissue voxel of various human organs using CT number. This was done by expressing the x-ray transmission measurements (N_i) as sum of attenuation values occurring in voxels along path of ray for N_i. To understand how each measurement can be reduced to a sum of the attenuation values in the voxels along the path of a ray, consider the row of voxels in fig 1, where N_o is x-ray intensity entering the row of voxels, N_i is the detector-measured intensity, w_i is the path length of the ray travelled through the voxel, and μ_i is the attenuation coefficient of the material contained within that voxel.

$$\boldsymbol{N_i = N_0 e^{-w_i \mu_i}} \tag{4}$$

Now, consider the intensity N_1 exiting the first voxel (attenuation μ_1). Using the expression for exponential attenuation in equation **4** as;

$$\boldsymbol{N_1 = N_0 e^{-w_1 \mu_1}} \tag{5}$$

Similarly, given that the intensity N_1 enters the second voxel, the intensity exiting the second voxel is given by equation **5** as:

$$\boldsymbol{N_2 = N_1 e^{-w_2 \mu_2} = N_0 e^{-w_1 \mu_1} e^{-w_2 \mu_2}} \tag{6}$$

Given that intensity N_2 enters the third voxel, the intensity exiting the third voxel is calculated as equation **6** follows:

$$\boldsymbol{N_3 = N_2 e^{-w_3 \mu_3} = N_0 e^{-w_1 \mu_1}\, e^{-w_2 \mu_2} e^{-w_3 \mu_3}}$$
(7)

Proceeding in this fashion through the N_i intensity entering the last voxel yields equation **7** as:

$$\boldsymbol{N_i = N_0 e^{-(w_1 \mu_1)} e^{-(w_2 \mu_2)} e^{-(w_3 \mu_3)} .. e^{-(w_n \mu_n)}} \tag{8}$$

It is important to note that the product of exponential functions is equal to the sum of their exponents, as in equation **8**, and dividing both sides by N_o, taking a negative natural logarithm of each side, yields equation **9**:

$$\boldsymbol{-In\left(\frac{N_i}{N_0}\right) = w_1 \mu_1 + w_2 \mu_2 \ + w_3 \mu_3 \ldots \ldots \ldots + w_n \mu_n} \tag{9}$$

N_i is the measurement obtained by the detector for this ray, and N_o is known from in-air reference detector measurements or from prior calibration scans.

The left side of Equation **9** can be describe as the processed data point N_i'. Each term $w_i\mu_i$ represents the attenuation occurring within voxel i, which is designated U_i, yielding equation **10**:

$$\boldsymbol{N_i{}' = U_1 + U_2 + U_3 + U_4 + \cdots + U_n} \quad 10)$$

Hence, $N_i{}' = w_i \mu_i$ for i number of voxels
With known value of the intensity $N_i{}'$ and the width w_i in measuring the attenuation through a specific organ volume say the renal volume, the linear x-ray attenuation coefficient can be calculated.

Also, the contribution of each linear x-ray attenuation coefficient values for each voxel to the total linear x-ray attenuation coefficient by the whole renal volume can be determine as.

$$\mu = \frac{N}{w} \tag{11}$$

Where N is the photon intensity through single voxel and w is the width of the renal voxel through which the photon pass.

However, the total linear x-ray attenuation coefficient by the entire renal volume is define as;

$$\mu_i = \frac{N_i{}'}{w_i} \tag{12}$$

Where $N_i{}'$ is the photon intensity through the entire organ and w_i is the volume width of the organ through which the photon pass.

HEMISPHERICAL X-RAY ATTENUATION COEFFICIENT

Hemispherical attenuation coefficient is the radiant flux absorbed or scattered by a volume per unit distance, divided by that received by the volume. It described the attenuation of radiant energy through a specific volume in the direction of propagation. In the case of CT scan with the patients laying in the supine position, denoted μ, with reciprocal metre (m^{-1}) as the SI units and it's defined mathematically as;

$$\mu = -\frac{1}{\Phi_e}\frac{d\Phi_e}{dz} \quad (14)$$

Where

- Φ_e is the radiant flux or power;
- Z is the path traveled by the beam in the volume.

Rearranging equation 14 give;

$$-\mu\int dz = \frac{1}{\Phi_e}\int d\Phi_e \quad (15)$$

By integration

$$-\mu z + k = In\Phi_e \quad (16)$$

Hence,

1) $\boldsymbol{In\Phi_e = k - \mu z}$ (17)
   where k is the constant of integration.

2) A graph of $\boldsymbol{ln\Phi_e}$ against **z** give μ as a slope with the intercept defining the integral constant.

IV. DISCUSSIONS

For the ray shown in the fig 1 above, w_i is the voxel width W and is equal for all voxels in each slice for the same patient, but varied from individual to individual depending upon the setup parameter for each patient. The w_i value are determined by dividing the reconstruction diameter by the number of row or column and describe as the voxel spacing. For instance if the reconstruction diameter for a scan is 332.8 and the column by row is 512x512 then the voxel spacing will be 0.650/0.650. the volume of each volume element (voxel) can be determine by finding the product of the voxel spacing (length and width) and a single slice thickness and the total voxels of the entire organ calculated by adding all the volume of the individual slice together.

However, in the more general case for other angles, a ray may pass through a voxel at an angle or only partially through a voxel, in this case the w_i may differs for some voxels. In any case, because voxel size as well as the path width of each ray is known, w_i can be calculated and the attenuation coefficient μ_i of voxel can be determined with known intensity. The use of linear attenuation coefficients is for selecting a radiation energy that will produce the most contrast between particular tissues in a radiograph. Say, for example, during scanning the abdomen the energy deposited to the tissues in the abdomen is in the range of 80 to 120 keV that it is necessary to detect the various tissues and separate them for identification. A graph of linear attenuation coefficients versus radiation energy can be used to separate between various body tissues. At a specific energy the difference in attenuation between two tissues is greatest at a specific radiographic contrast in an image. Hence, it is extremely useful to determine various linear attenuation coefficients of various tissues for clinical application.

Since a linear attenuation coefficient is dependent on the density of a material, the mass attenuation coefficient is often reported for convenience. However, this can be normalize by multiplying the mass attenuation by the density of the tissue to obtain a linear attenuation coefficient, which is constant for a particular tissue. That is to convert a mass attenuation coefficient ($\frac{\mu}{\rho}$) to a linear attenuation coefficient (μ), simply multiply it by the density (ρ) of the material.
Mathematically,

$$\mu = \left(\frac{\mu}{\rho}\right)\boldsymbol{\rho} \quad (18)$$

It is also envisaged that the scanned slice as being composed of matrix of small boxes of tissue called voxels, each with attenuation coefficient μ. The total number of voxel is the sum of the voxels in each slice. CT scan image matrix consist of voxels within a specific region of interest which may be drawn to represent an organ and the total volume of the organ may be calculated with a known pixel size in 2D and a slice thickness forming the 3D element of the mage. The summation of all these voxel in each slice form the volume of the organ. In other words the volume of a single voxel is calculated as the product of the slice thickness x row x column and the entire organ volume as slice thickness x row x column x total voxel in the organ. That is, assuming an organ has a total voxel of 47449, a slice thickness of 5mm and a pixel size of 0.740 x 0.740 mm, then the organ volume will be 129.915. The organ volume is calculated as 5 x 0.740 x 0.740 x 47449 = 129.915 cm^3

V. CONCLUSION

The attenuation coefficient is dependent upon the type of material and the energy of the radiation or initial photon intensity. Generally, for electromagnetic radiation, the higher the energy of the incident photons and the less dense the material in question, the lower the corresponding attenuation coefficient will be. With known initial photon energy in medical imaging, the attenuation coefficient depend largely on the patient size and type of tissue. With known total number of voxels and size, number of slice and slice thickness the volume of a scan area can be estimated. The SI unit of attenuation coefficient is the reciprocal metre (m^{-1}).

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