

# Extraction of Information from CT Images for PET and Radiotherapy Planning

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## Abstract

*In this work we study the relationship between Hounsfield Units obtained from a CT image and PET attenuation coefficients and Line Energy Transfers (LET) for electrons with energies up to 1 MeV. For this purpose, simulations with PENELOPE of the attenuation of x-rays emitted from a CT scanner have been performed, as well as for the calculation of the attenuation of 511 KeV photons and LET for electrons. To measure the relationship between these magnitudes we compare the results obtained with our simulations with the ones obtained following the Hybrid method proposed by Kinahan. The assessment of tissue properties according to their Hounsfield Units obtained within this Hybrid method is good (discrepancies with the actual values given by the PENELOPE simulations are below 10 %) for the majority of tissues studied, with the noticeable exception of adipose tissue and compact bone*

## 1. Introduction

CT images are routinely used in radiotherapy treatment planning to determine both clinical and physical information of human tissues. The main physical information obtained with CT comprises size, shape and location of the outlines, inhomogeneities and, via the Hounsfield Units (HU), relative electron density and LET of electrons in the tissues can be estimated [1]. HU are defined as [1]:

$$HU \equiv 1000 \left( \frac{\mu - \mu_w}{\mu_w} \right) \quad (1)$$

Where  $\mu$  is the attenuation coefficient of x-rays in the tissue under consideration and  $\mu_w$  is the attenuation coefficient in water. These values depend on the electron density, effective atomic number ( $Z_{\text{ef}}$ ) and on the quality and energy of the beam used in the CT scanner.

The relationship between relative electron density and Hounsfield Units has been measured by several authors [2] – [4]. For materials with an average atomic number similar to that of water, HU lies on or near a straight line that passes through  $HU = -1000$  for air and  $HU = 0$  for water. However, for materials with an atomic number different to that of water, the HU values lie above this line, with different results for different scanners. These differences lead to the standard recommendation that the

relationship between electronic density and HU should be determined through measurements for each scanner used in treatment planning.

Furthermore, the CT image can be used to improve the image quality of PET images, both for CT-based attenuation correction [5] and for material dependent positron range correction [6], [7].

As it has been discussed in Kinahan's work [5], there are three different methods to obtain the attenuation correction factors in PET images from a CT scan: scaling, segmentation and hybrid methods.

1 – Scaling: This approach estimates the attenuation map in PET by multiplying the CT image by the ratio of attenuation coefficients of water at CT and PET photon energies. This method exhibits a large error for materials with atomic number quite different to the one of water.

2 – Segmentation: This method estimates the attenuation map in PET by segmenting the reconstructed CT image into different tissue types. Typical choices for tissue types are soft tissue (water), bone and lung. This method has a significant important problem that very inhomogeneous tissues may not be accurately represented by a discrete set of segmented values.

3 – Hybrid methods: They are based on a combination of scaling and segmentation methods. The attenuation map in PET is estimated first using a threshold value in HU to separate out the bone component of the CT image, and then using separate scaling factors for the bone and non-bone component. This method has also been applied for CT-based attenuation correction of SPECT data in SPECT-CT scanners [8].

In this work we assess the relationship between the Hounsfield Units and PET attenuation coefficients and LET for electrons with energies up to 1 MeV, by means of Monte Carlo simulations with PENELOPE [9] code. To study the relationship between these magnitudes estimated with the usual methods, we compare the results of our simulations with the ones obtained following the Hybrid method proposed by Kinahan.

## 2. Materials and methods

### 2.1. PET/CT scanners studied in this work

The CT subsystems studied in this work have been:

- ARGUS small animal PET/CT scanner [10]. This is a small animal scanner, with low emission x-ray energies. The characteristics of the CT subsystem are presented in Table 1. As most small animal scanners, it uses relatively soft x-rays to enhance contrast of soft tissue.

- Siemens Biograph TruePoint clinical PET/CT scanner [11]. This is a clinical scanner, with higher emission x-ray energies. The characteristics of the CT subsystem for this scanner are presented in Table 2.

FOV	6.8 x 6.8 cm <sup>2</sup>
Active Area	12 x 12 cm <sup>2</sup>
Pixel size	50, 100, 200 $\mu$ m
Detectors	Scintillators: CsI
Beam width	35 $\mu$ m
Energy (max)	0 – 50 kV (variable)
Current (max)	1 mA

**Table 1.** Main characteristics of CT subsystem of the ARGUS scanner [10].

FOV	50 x 70 cm <sup>2</sup>
Detectors	Ultrafast ceramics
Number of detectors	17664
Beam width	0.8 mm scan and 0.5 mm axial
Energy (max)	80 / 110 / 130 kV
Current (max)	345 mA

**Table 2.** Main characteristics of CT subsystem of the Siemens Biograph scanner [11].

### 2.2. Simulation of x-rays spectra emitted by the CT scanner

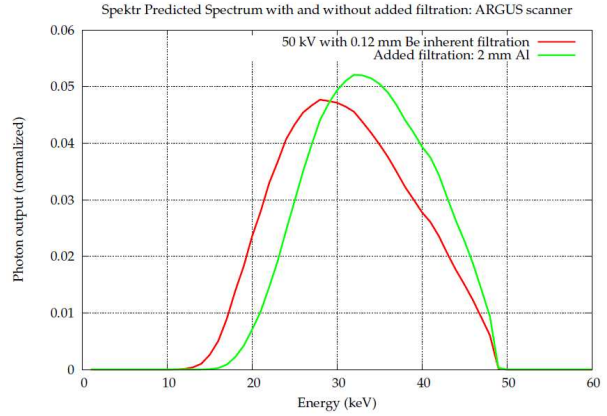
The analysis of x-rays spectra and associated beam-quality characteristics was performed with the Spektr [12] tool.

Spektr was designed to provide a flexible and extensible tool for calculation of x-ray spectra, application of x-ray filters and analysis of several spectral characteristics. The primary components of the tool are a library of Matlab<sup>TM</sup> functions and a database of x-ray attenuation coefficients for elements and compounds. This database includes mass and mass-energy attenuation coefficients for elements with  $Z = 1 - 92$  and for selected compounds gathered from the National Institute of Standards and Technology (NIST) tables [13]. The tool operates in the energy range 1 – 150 keV with 1 keV energy bins.

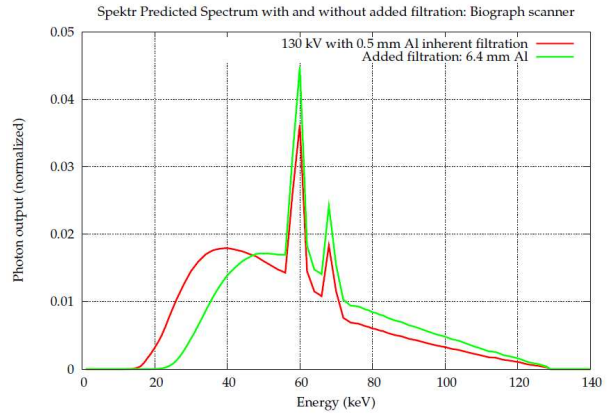
Figure 1 shows the x-ray spectra emitted by ARGUS small animal PET/CT scanner, with and without 2 mm Al external filtration, obtained with the Spektr tool.

Figure 2 shows the x-ray spectra emitted by Siemens Biograph PET/CT scanner, with and without 6.4 mm Al external filtration, also obtained with the Spektr tool.

The mean energy of the emitted spectra is 34.0 keV for the ARGUS PET/CT scanner (with 2 mm Al external filtration) and 63.7 keV for the Siemens Biograph PET/CT scanner (with 6.4 mm Al external filtration and  $E_{\max} = 130$  keV).



**Figure 1.** X-ray spectra for ARGUS scanner obtained with spektr tool. With only inherent filtration (red) and with external Al filtration (green).



**Figure 2.** X-ray spectra for Biograph scanner obtained with spektr tool. With only inherent filtration (red) and with external Al filtration (red).

### 2.3. PENELOPE simulation

We performed a Monte Carlo simulation of the radiation-matter interaction with PENELOPE code [9]. This way, the attenuation of x-rays emitted by the ARGUS and Biograph scanners in different biological tissues was calculated. The different compositions of the tissues simulated in this work were obtained from ICRP [14]. PENELOPE simulations were also performed for the calculation of the attenuation of 511 keV photons and the LET for electrons with different energies. To assess the accuracy of the determination of the relationship between CT data and electronic density of biological tissues, the attenuation of 511 keV photons and the LET for electrons, we compare our simulations with the results obtained following the Hybrid method proposed by

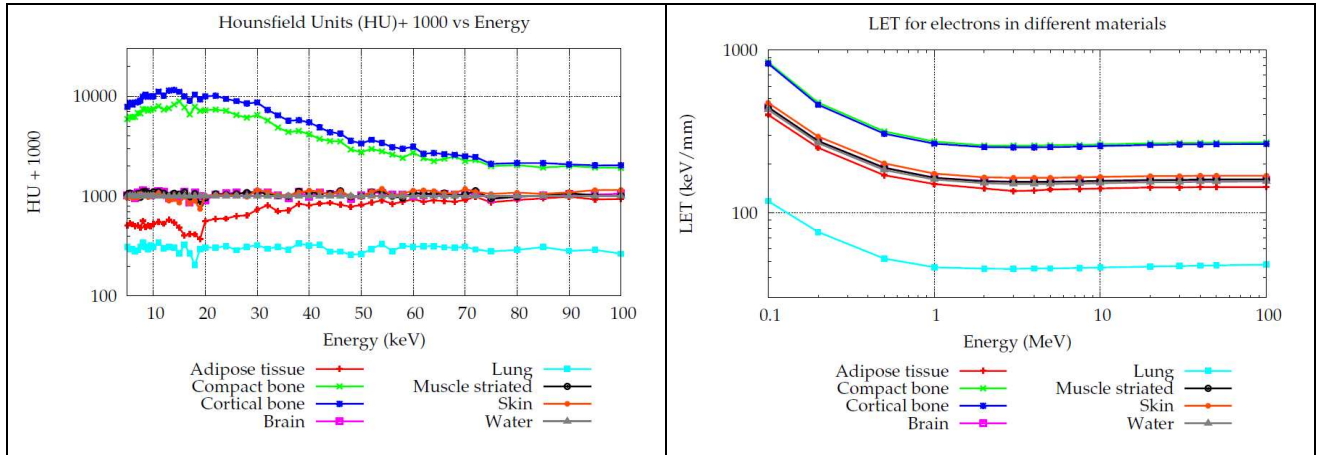
Kinahan [5]. Thus, the results of the simulation are employed as a benchmark of the Hybrid method.

### 3. Results

Figure 3 shows the energy dependence of the Hounsfield Units and the LET for electrons obtained with PENELOPE simulations in different biological tissues. Note that the LET for electrons with energies higher than 1 MeV is almost constant, and before that energy the curves for different tissues are parallel. Thus, the results

obtained for 1 MeV electrons are to a large extent valid to all other energies.

Table 3 shows the relationship between the HU and the LET of 1 MeV electrons obtained with PENELOPE simulations and with the hybrid method proposed by Kinahan for the ARGUS PET/CT and Siemens Biograph PET/CT scanner. Table 4 shows the relationship between the HU and the PET attenuation obtained with PENELOPE simulations and with the hybrid method proposed by Kinahan, also for ARGUS and Biograph scanners.



**Figure 3.** Energy dependence of the HU (left) and LET for electrons (right) obtained from PENELOPE simulations in the following biological tissues: Adipose tissue, compact bone, cortical bone, brain, lung, muscle striated, skin and water.

Biological tissue	Electronic density	Hounsfield - PENELOPE		LET – Kinahan (hybrid method)		LET - PENELOPE	Error (%)	
		ARGUS	Biograph	ARGUS	Biograph		ARGUS	Biograph
Adipose tissue	0.902	-303	-125	0.697	0.874	0.917	24	4.7
Air	0.001	-999	-999	0.001	0.001	0.001	0.0	0.0
Compact bone	1.696	4297	1867	1.502	1.564	1.746	14	11
Cortical bone	1.638	6035	2333	1.704	1.704	1.704	0.0	0.0
Brain	1.023	39	43	1.005	1.013	1.031	2.6	1.7
Lung	0.294	-696	-700	0.304	0.299	0.288	5.3	3.8
Muscle striated	1.019	26	42	1.003	1.013	1.031	2.7	1.7
Skin	1.069	54	72	1.006	1.022	1.091	7.8	6.3
Water	1.000	0	0	1.000	1.000	1.000	0.0	0.0

**Table 3.** Relationship between HU and LET for electrons (1 MeV, relative to water) obtained from PENELOPE and with the hybrid method proposed by Kinahan. Electronic density and LET values are given relative to water.

Biological tissue	Electronic density	Hounsfield – PENELOPE		Atten. PET - Kinahan (hybrid method)		Atten. PET - PENELOPE	Error (%)	
		ARGUS	Biograph	ARGUS	Biograph		ARGUS	Biograph
Adipose tissue	0.902	-303	-125	0.697	0.874	0.929	25	6.0
Air	0.001	-999	-999	0.001	0.001	0.001	0.0	0.0
Compact bone	1.696	4297	1867	1.524	1.589	1.766	14	10
Cortical bone	1.638	6035	2333	1.736	1.736	1.736	0.0	0.0
Brain	1.023	39	43	1.005	1.014	1.029	2.3	1.5
Lung	0.294	-696	-700	0.304	0.299	0.296	2.5	1.0
Muscle striated	1.019	26	42	1.003	1.013	1.035	3.1	2.1
Skin	1.069	54	72	1.007	1.023	1.092	7.8	6.4
Water	1.000	0	0	1.000	1.000	1.000	0.0	0.0

**Table 4.** Relationship between HU and PET attenuation coefficients obtained from PENELOPE and with the Hybrid method proposed by Kinahan. Electronic densities and PET attenuation values are given relative to water.

## 4. Conclusions

The identification of the properties of tissues with the Hybrid method proposed by Kinahan is fair (discrepancies about 5% with the benchmark PENELOPE simulations) for the majority of tissues of biological interest studied, with the noticeable exception of adipose tissue and compact bone, where the discrepancies can be as high as 25% and 15% for relatively soft x-ray energies, like the ones found in preclinical scanners. The discrepancies are reduced to less than 5% for x-ray emission energies typical of clinical scanners (e.g. Siemens Biograph PET/CT scanner).

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