Different Energy Mapping Methods in CT-Based Attenuation Correction in PET/CT Systems

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ABSTRACT

This paper presents the result of assessing different attenuation correction methods for PET data according to CT data (CTAC). These methods are intended for use with a combined PET/CT scanner. We discuss five possible methods of energy mapping from the CT energies to the required 511keV. CT images are obtained using a computerized whole body phantom, 4DXCAT, which is simulation of physically and anatomically of human body. Materials and methods: The aim of this study is to compare different energy-mapping techniques: scaling, segmentation, hybrid, bilinear calibration curve and dual energy approach through attenuation map generated from CT data through XCAT phantom. The CT images acquired from XCAT phantom is applied to generate µ-maps in 511keV. Then these generated µ-maps are compared to the image acquired from XCAT phantom in 511keV as the gold standard image. For comparing methods we use three ways: Assessing different ROIs, correlation coefficients and difference images for comparing pixel by pixel. Results and Discussion: Nearly all energy-mapping methods shown similar results in soft tissues. A noticeable relative difference is seen in lung tissues in Segmentation method which refers to the variability in densities. Also a bias in bone in the same method, which is due to the extended borders of the segments. In Scaling results for different tissues are acceptable beside bone as it has a high photoelectric ratio. Hybrid and Bilinear are somehow good. Dual Energy reports the best results.

INTRODUCTION

Today, diagnostic imaging is consisting of various branches. The information of imaging is divided into anatomical and function groups. In some systems as CT, MRI imaging based on anatomical techniques, the tumor is detected when the tissue is physiologically changed but in some systems including PET, SPECT imaging based on physiological techniques, metabolic changes are detected in the early stage. It is obvious that there are many instances in which it would be desirable to integrate the information obtained from two modalities of the same patient. The combination of PET-CT was introduced in the early 1990s by Townsend. The first prototype of PET-CT scanner was made in 1998 [1-9].

In PET/CT systems, based on the data, CT is applied for attenuation correction of PET data. In CTAC, at first the patient undergoes CT scan and then at the same position, PET scan is taken of the patient [10, 11].

In converting CT attenuation to be used as data in PET image, there are two problems. The first problem is the high difference between the energy of CT, PET photons. As attenuation coefficient depends on energy and the main issue in attenuation correction by CT is conversion of the coefficients of CT energy, the energy at 120 kVp to PET energy, energy at 511keV and the second problem is the difference between single energy spectrum in PET and extensive energy spectrum in CT.

In PET imaging, annihilation photons at 511kev are applied while CT diffuses the photons with extensive energy spectrum 40 to 140 kev. This photoelectric overcome in CT energies range and Compton overcome at 511 kev create error in conversion of the images of CT energies to PET energy.

There are various methods for energy mapping to convert attenuation coefficients in CT energy to PET energy. These methods are including scaling, segmentation, hybrid (scaling+ segmentation) [12], bilinear [9, 13] and dual energy approach [14, 15].
Although there are some studies performed regarding the comparison of energy mapping methods by various groups [160-29], no comprehensive study is performed in this regard as all the methods are done with the phantom physiologically and anatomically close to body anatomy. The performed studies are done based on 2 or 3 methods or physical phantoms are used in them with inevitable errors. The current study aimed to study all the existing methods of energy mapping to obtain the attenuation map at 511keV of CT images in combinational PET/CT systems by XCAT human computer phantom [30,31] and the advantages and disadvantages of these methods are reviewed.

1- Materials and methods:

This study was conducted in three stages including CT image simulation as basic image, PET image simulation as reference image and the final stage applying energy mapping methods on CT image.

1-2 Simulation of CT image as basic image

To test the various methods of energy mapping on CT images, at first by XCAT-4D phantom, CT images are built. To obtain CT images in XCAT phantom, at first the required energy as 74keV and effective energy at 120kVp in this paper were entered in the files and after creating phantom, the image is observed by Amide software. It can be said that the obtained image of XCAT phantom is based on attenuation coefficient. Thus, to use it in CT-based studies, at first the coefficients should be converted to CT numbers in accordance with equation (1) and it is done in MATLAB software.

\[
CT\text{number} = \frac{\mu - \mu_{H2O}}{\mu_{H2O}} \times 1000
\]  

(1)

After the conversion of attenuation coefficients to CT numbers, the image is read by Amide software. CT image of whole body XCAT phantom at 74keV equal to 120kVp is shown in Figure 1. CT image is acquired of phantom 128x128, resolution 0.3215 and its output is as linear attenuation coefficients (cm\(^{-1}\)) in Raw data format.

![CT image of whole body XCAT phantom from sagittal and coronal view](image.png)

**Fig. 1:** CT image of whole body XCAT phantom from sagittal and coronal view

2-2 Simulation of PET image as reference image:

The reference image is obtained by putting the value 511keV for energy in the required section. This image is applied to compare the attenuation maps of various methods of mapping.

2-3 Applying mapping methods on CT image

After various energy mapping methods on CT image, the simulation is applied. By entering the image based on CT numbers in MATLAB software, the changes of each method are applied on the image and then the image is observed in Amide software.

2-3-1 Scaling methods

The scaling approach applies conversion coefficient equal to the ratio of attenuation coefficients of water at CT energy to water attenuation coefficient at PET energy.

Conversion coefficient in scaling was 1.94:

\[
\text{Scaling factor} = \frac{\mu_{\text{water}}(\text{CT})}{\mu_{\text{water}}(\text{PET})}
\]  

(2)
Scaling factor = 1.94

The conversion coefficient was applied by MATLAB software on CT image and attenuation map is generated from PET energy. The image of applying scaling methods on CT image is shown in Figure 2.

![Attenuation map generated from PET energy after applying scaling method on CT image.](image)

**Fig. 2:** The attenuation map generated from PET energy after applying scaling method on CT image.

In this scaling method, an effective energy is selected to display CT spectrum ranging 50 to 80 keV.

2-3-2 Segmentation method:

This method is consisting of two stages. In the first stage, the reconstructed CT image is segmented into different tissue types. In the second stage, the linear attenuation coefficient value for each tissue type is then replaced with appropriate attenuation coefficients at 511 keV.

Typical choices for tissue types are soft tissue, bone, and lung. This segmentation can be done based on CT numbers as for $800 < \text{HU} < 0$ - lung tissue, for $0 \leq \text{HU} < 300$ for soft tissue and $300 \leq \text{HU}$ bone and for $\text{HU} \leq 800$ for air are considered.

![Attenuation map generated from PET energy after applying segmentation method on CT image.](image)

**Fig. 3:** The attenuation map generated from PET energy after applying segmentation method on CT image.

2-3-3 Hybrid (segmentation-scaling) method:

The hybrid method is the combination of segmentation and scaling method. In this method for most materials except bone, the ratio of the attenuation coefficient for all tissues in two energies is essentially constant. Thus, at first a threshold is determined to remove the bones from CT image.

In this study, the number $300_{\text{CT}}$ is considered as a threshold because CT of bone tissues is above 300, then due to the differences of physical attributes of bone and soft tissues for each part, a different conversion coefficient is applied. For non-bone tissues, soft tissues, the conversion coefficient is the ratio of linear attenuation coefficient of water at CT, PET energies, the same coefficient used in scaling and for the bones, the conversion coefficient is the ratio of linear attenuation coefficient of cortical bone at PET, CT energies. The linear attenuation coefficient of the bone at both energies is achieved in accordance with XCOM section [32]:
3) \( \mu_{\text{bone(CT)}} = 0.4934 \, \text{cm}^{-1} \)
4) \( \mu_{\text{bone(PET)}} = 0.1715 \, \text{cm}^{-1} \)

Thus, conversion coefficient for bone tissues is equal to:

5) \( \text{Bone scaling factor} = \frac{\mu_{\text{bone}(\text{CT})}}{\mu_{\text{bone}(\text{PET})}} \)
   
   Bone scaling factor = 2.87

Now by having conversion coefficients for soft and bone tissues, in CT image of each of the tissues are multiplied by the coefficient to obtain the linear conversion coefficient of each tissue at PET energy [26].

**Fig. 4**: Mapping image of hybrid method

2-3-4 bilinear method:

if the unknown matter \( X \) as the combination of water and \( A \) matter is imaged in CT imaging, \( , \) by equation (6), and CT values of \( X, A \) matter, we can calculate linear attenuation coefficient of \( X \) at \( E \) energy.

\[
\mu_X(E) = px \times \mu_X(E)
\]

In the above equation \( P_x, \mu_X(E) \) are density and mass attenuation coefficient of \( X \), respectively. To convert CT values to linear attenuation coefficients by equation (6), two linear equations are obtained.

As the body tissues are divided into two groups, in the first group the tissues their CT number is less than or equal to zero (\( H_U \leq 0 \)), they are the combinational of water and air (\( A = \text{Air} \)) and in the second group, the tissues their CT is more than zero (\( H_U > 0 \)) and they can be assumed as the combination of water and bone. (\( A = \text{Cortical bone} \)).

To calculate the required parameters in equation (6), the practical measurements are required. Table (1) shows the equations of bilinear curves generated in 4 voltages of CT scanner.

| Table 1: The equations of bilinear curves generated in 4 voltages of CT scanner |
|---|---|
| If \( H_U \leq 0 \): \( \text{LAC}_511 = 96 \times 10.6 \, \text{HU} + 0.096 \) | 80 kVp |
| If \( H_U > 0 \): \( \text{LAC}_511 = 54 \times 10.6 \, \text{HU} + 0.096 \) | 100 kVp |
| If \( H_U \leq 0 \): \( \text{LAC}_511 = 63.54 \times 10.6 \, \text{HU} + 0.096 \) | 120 kVp |
| If \( H_U > 0 \): \( \text{LAC}_511 = 73.87 \times 10.6 \, \text{HU} + 0.096 \) | 140 kVp |
| If \( H_U \leq 0 \): \( \text{LAC}_511 = 96 \times 10.6 \, \text{HU} + 0.096 \) | |
| If \( H_U > 0 \): \( \text{LAC}_511 = 81.44 \times 10.6 \, \text{HU} + 0.096 \) | |

Based on calibration curve in various energies of figure (5), we can obtain for each CT image, linear attenuation coefficient of one by one of its pixels.
In this study, calibration curves at 120kVp were applied by MATLAB software to CT image to acquire linear attenuation coefficient of each pixel at 511 keV. Figure (6) illustrates bilinear map attenuation method.

![Fig. 5: The calibration curve at different energies](image)

2-3-5 Imaging method with dual energy:

In this method the CT image at two different energies is acquired. Attenuation coefficient is as the weight sum of extracting photoelectric and Compton contributions. The different contributions (photoelectric and Compton) can then be scaled separately in energy, then are converted separated in each energy and then are added to acquire total attenuation.

Dual energy is an accurate method because both photoelectric and Compton components are converted separately. Compton is decreased linearly with energy but photoelectric is combined as E\(^{-3}\) and finally with each other and total \(\mu\) is obtained at the required energy.

The attenuation map generated by dual energy method is shown in Figure 7.

![Fig. 6: bilinear map attenuation method](image)

![Fig. 7: The attenuation map generated by dual energy method](image)
2-4 The strategy of evaluation of various methods of energy mapping:

In this study, the comparison of the attenuation maps of various energy mapping methods and simulated reference image is made by ROI plotting, designing correlation curves and differential image method to acquire the error of each method to the reference.

2-4-1 The comparison via the regions of interest:

In ROI analysis comparison, at first some ROIs are defined on reference image and images generated of various methods of energy mapping. Then, the linear attenuation coefficient (LAC) is determined for the tissue and LAC values are compared in the interest regions in reference image and the images of 5 energy mapping methods.

In order to locate the ROI (Regions of Interest) exactly in the similar coordinate, in the reference image of Amide, ROIs are selected, then attenuation maps are opened in the same page. Thus, ROI coordinate selected in reference image and the images of 5 methods are along with each other. An example of ROI in generated attenuation maps is shown in Figure 8.

![Figure 8](image)

Fig. 8: The attenuation map generated from CT image of phantom with some of the regions of interest in coronal and sagittal views

2-4-2 The comparison of correlation curve methods:

By the descriptive statistical methods, we can express the features of a set of data. Correlation coefficient is a mathematical index being applied about the two or multi-variate distributions. Dispersion diagram is applied to represent the correlation between two variables. To review the error of each energy mapping by the data generated of the attenuation coefficients in various tissues, correlation curve is plotted. The diversion value of y=x line acquires the correlation and error range.

2-4-3 The comparison of differential image method:

In this method, the existing feature of amide software is applied and the reference images generated of XCAT phantom of the image of each method are subtracted.

3-Results:

3-1 The results of the comparison via the regions of interest:

The linear attenuation coefficients generated of various energy mapping methods are compared with the reference image.

The percent of relative difference between LAC in ROI of attenuation maps with LAC value in ROI of reference image as a criterion to compare attenuation maps were calculated. The less the value of error, it means that the required method is suitable for that tissue. Table 3 illustrates the error percent of each of energy mapping methods.

<table>
<thead>
<tr>
<th>Dual energy</th>
<th>Scaling</th>
<th>bilinear</th>
<th>Hybrid</th>
<th>Segmentation</th>
<th>Standard</th>
<th>ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.027</td>
<td>0.027</td>
<td>0.025</td>
<td>0.025</td>
<td>0.028</td>
<td>0.026</td>
<td>Lung</td>
</tr>
<tr>
<td>0.087</td>
<td>0.097</td>
<td>0.087</td>
<td>0.087</td>
<td>0.087</td>
<td>0.092</td>
<td>Soft tissue</td>
</tr>
<tr>
<td>0.090</td>
<td>0.100</td>
<td>0.090</td>
<td>0.090</td>
<td>0.091</td>
<td>0.096</td>
<td>Brain</td>
</tr>
<tr>
<td>0.091</td>
<td>0.097</td>
<td>0.087</td>
<td>0.087</td>
<td>0.091</td>
<td>0.097</td>
<td>Muscle</td>
</tr>
<tr>
<td>0.091</td>
<td>0.101</td>
<td>0.090</td>
<td>0.091</td>
<td>0.091</td>
<td>0.096</td>
<td>Kidney</td>
</tr>
</tbody>
</table>
As is shown in error percent table:
In lung bilinear and hybrid methods had low error, thus for energy mapping, the images of this region can be suitable. The segmentation method reported considerable error. This is because in some tissues from one region to another one, the density is changed continually. This value in lung tissue reaches 30%. Thus, any error in tissues segmentation leads into the error in attenuation coefficient value. Thus, the segmentation method for lung tissue can not be a good method for lung tissue.
In soft tissue, bilinear, hybrid, segmentation methods had equal error percent, thus the three methods are applied for energy mapping.
In the kidney, the hybrid and segmentation methods were suitable.
In the heart, hybrid and bilinear methods had low error percent.
In the liver, bilinear had low error.
For the bones, bilinear method had considerable low error. In bone region, the maximum error was dedicated to scaling because bone has high calcium content and its photoelectric deficit is high.

3-2 The results of the comparison by correlation curves methods:
Figure (9) shows the correlation curves of attenuation coefficients in different tissues, the equation of this curve and correlation coefficient for scaling, segmentation, hybrid and bilinear and dual energy methods.
Fig. 9: Correlation curves of attenuation coefficients in different tissues, the equation of this curve and correlation coefficient a) scaling, b) segmentation, c) hybrid, d) bilinear, E) dual energy.

3-3 The results of the comparison of differential image method:
In figure 10, the reference image of XCAT phantom, the image of each mapping method and differential image were shown and by the results we can find about the existing error of each method.

Fig. (1-10): (a) The reference image of energy 511, b. The image of scaling, C. The differential image of scaling and reference image
Fig. (2-10): (a) The reference image of energy 511, b. The image of mapping, C. The differential image of hybrid and reference image.

Fig. (3-10): (a) reference (b) bilinear method mapping (c) the differential image.

Fig. (4-10): (a) Reference image, (b) mapping image of dual energy (c) Differential image.
4- **Discussion and conclusion:**

In this study, it was attempted to do the comparison of various energy mapping methods accurately in which the errors of the patient and physical phantoms don’t exist. To do so, at first by 4DXCAT software phantom, the reference image (the image at 511 keV) was made and then various energy mapping were applied on CT image to be compared with reference image. Based on the results of 3 methods being used to evaluate the image mapping methods, after the comparison of the attenuation maps generated from reference image, it was defined that in bone region, bilinear and dual energy mapping methods and in muscle tissue, scaling had the best results.

In other regions as soft tissue, lung and heart, the errors were similar.

The following points about each of mapping methods are considerable.

**4-1 scaling mapping method:**

The reported results showed that scaling method was suitable for the regions in which Compton has the dominant effect and in bone tissue, the error percent of scaling method is considerable and this is because the bone due to calcium content has high photoelectric deficit.

**4-2 Segmentation mapping method:**

In segmentation method whole-body is segmented into water, air and bone and as in each tissue, the attenuation tissue is not constant and in most of the tissues the density changes are high in various parts.

In this method, the error for soft tissue, brain and kidney was 5.45%, 5.2%, 5.2%, respectively less than other tissues.

The error in spines bone, heart and kidney was 8.1%, 8.9%, 8.9%, respectively showing that considerable changes of tissue density are from one region to another.

Thus, in these tissues, considering a value for LAC for a tissue causes error. The more whole body is segmented to more tissues; the attenuation map is more exact.

This method presents a good attenuation coefficient for the regions with dominant Compton and for the regions with the dominance of photoelectric, there is no good approximation and the error is high for the tissues with high atomic number.

**4-3 Hybrid mapping method:**

At low energies, the ratio of LAC in CT and PET is equal for water, muscle and air, but it is different significantly for the bone. This shows that attenuation coefficient of air, water and muscle is associated with electron density due to Compton interaction. But the attenuation coefficient of bone in CT energy (low energies) is associated with photoelectric due to the existence of calcium. After the measurement of error by this method, it was defined that for lung, bone and heat tissues, the error is 3.8%, 4.5%, 5.1%. The error is because of bone at CT energy is associated with photoelectric but of water, air and muscle is associated with Compton.

The error of this method is because of the ratio of bone in different dual energy both in low energies range.

**4-4 Bilinear method:**

The minimum error in this method is dedicated to bone tissue. Then, lung with 3.8%, heart and liver and soft tissue 5.1%, 5.1%, 5.4%, respectively show the error percent. The maximum error observed in this method was dedicated to muscle tissue with 10.3 % difference.

In the previous studies, to apply this method, to reduce the noise, high currents were used to increase the dose of the patient. However, in this paper as in XCAT, the noise was ignored and ideal case was considered in its design, there is no need to high current and the same result can be achieved in imaging at low current.

**4-5 Dual energy method:**

In this method, to obtain $\mu$ at 511 keV, the Compton and photoelectric effects are obtained separately and then are combined with each other. Thus, the physical details of the tissues are considered and the acceptable results are achieved.

The drawbacks of this method are delivery of extra dose to the patient. On the other hand, as two images are subtracted, the noise is increased. The image mostly depends upon the effective energy. Thus, the error in generating the effective CT energy creates error in the results. Dual energy method is theoretically accurate but its SNR is lower compared to other mapping methods.

In this method, the lowest error is dedicated to lung and brain tissue. In bone tissue, there was a considerable difference compared to other methods as the error of bone tissue in this method was 4.6%, 6.3% and it is considerable compared to the error of other methods (15.4% segmentation and 15.3% hybrid).

4.6 The comparison of the study on XCAT phantom and physical and software phantom
By the comparison of the results of applying the research method on XCAT phantom and the comparison with other results of software and physical phantoms as K2HPO4, we can say that regarding the studies performed on K2HPO4 phantom, the bone was equal to soft tissue and as in soft tissue, the dominant effect is Compton, the bone attenuation coefficient was E-1 and it meant that μ of bone was higher than the real value. On the other hand, in the study performed on K2HPO4 phantom, there was a problem that all kinds of bones such as a bone tissue (cortical bone) are considered. It means that bone density for different bone tissues is considered equal but XCAT phantom is designed as in terms of the tissues properties as atomic number and density are close to the real values. Thus, XCAT phantom showed photoelectric and Compton effects as with direct association with the atomic number of the tissue with accurate results.

6- Future recommendation:

The current study aimed to acquire attenuation maps at 511 keV by various energy mapping methods and the comparison of these methods with each other. As XCAT phantom is designed as error factors as noise are eliminated, the study can be performed with the conditions in which there is noise to be close to the real conditions. In addition, in the images from the phantom, activity effects are ignored. In the rest of this study, we can apply attenuation map obtained for reconstruction of PET images. The comparative evaluation in this study is in the stage of the comparison of attenuation maps and the review of the effect of attenuation map on PET data, after the attenuation correction process can be done in the following of this study.

Also, applying the hidden anatomical data in CT images can help the performance of dispersion correction methods.

REFERENCES


