A Novel Approach for Implementation of Dual Energy Mapping Technique in CT-Based Attenuation Correction Using Single kV_P Imaging: A Feasibility Study

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Abstract— **In the CT-based attenuation correction methods, dual-energy technique (DECT) is the most accurate approach, which has been limited due to the increasing patient dose. In this feasibility study, we have introduced a new method that can implement dual-energy technique with only a single energy CT scan. In this method, with having the CT image in one energy, we generate the CT image at the second energy (from now we call it virtual dual-energy technique). The attenuation map at 511 keV was generated using bilinear (the most commonly used method in commercially available PET/CT scanners), dual-energy and virtual dual-energy technique in phantom and patients data. In the phantom study, the created attenuation map using mentioned methods are compared to the theoretical values calculated using XCOM cross section library. In the patient study, the generated attenuation map using dual-energy method is considered as gold standard. The results in the phantom data show 10.1 %, 4.2 % and 4.3 % errors for bilinear, dual-energy and virtual dual-energy techniques respectively. Also, the results in the patient data show the virtual dual-energy has better agreement with the dual-energy method rather than the bilinear method especially in the bone tissue (1.5 % and 8.9 % respectively).**

Keywords— **PET/CT, DECT, attenuation correction, attenuation map, energy-mapping.**

I. Introduction

Hybrid positron emission tomography/computed tomography (PET/CT) units have been designed and been commercially available since 2000 [1]. The additional morphological information provided by PET/CT scanners in contrast to stand alone PET scanners can be of additional diagnostic value for the physicians. Another benefit of PET/CT systems is the faster examination time, since the attenuation map for PET data correction is obtained from the CT scan and not from the much longer transmission scan [2].

Although fast and precise CT-based attenuation correction (CTAC) method yields a noise free attenuation map in comparison with transmission scan, but CT images provide linear attenuation coefficients (LAC) of the tissues at effective CT energies (~ 60-80 keV) rather than 511 keV which is the energy of PET imaging, so it is necessary to convert the LAC at CT energies to those corresponding to 511 keV [3]. Several energy mapping strategies including scaling [4], segmentation [4], hybrid (Segmentation and scaling) [4], bilinear [5] and dual-energy (DECT) [6] have been proposed that convert the LACs of CT images to the LACs of 511 keV. It should be noted that most commercially available PET/CT scanners use the bilinear method.

The best of these mentioned methods is dual energy technique [7]. Some of the drawbacks of this method that render it impractical for commercial PET/CT scanners are the additional dose to the patient, resulting from two CT scans at two different kV_Ps, increasing the scanning time as well as cost. In this feasibility study we have introduced a new method that can implement dual-energy technique with only a single energy (kV_P) CT imaging. In this method, with having the CT image in one energy, we generate the CT image at the second energy.

II. Materials and Methods

A. kV_P Conversion Curves

The Alderson RANDO (Radiology Support Devices Company, USA) phantom [8] was scanned by a LightSpeed VCT scanner (GE Healthcare Milwaukee, USA) with four different tube voltages (80, 100, 120, and 140 kV_P) and tube current of 300 mA. The analysis on the acquired images was done by AMIDE [9] image viewer. More than 400 different ROIs were selected in each image and the mean CT numbers for each ROI at one kV_P was plotted versus the same values at another kV_P. Finally the best curve was fitted for each plot to obtain kV_P Conversion Curves (which scale CT numbers at different tube voltages to each other), in three regions including lung tissue (HU<-100), soft tissue (-100<HU<200) and bone tissue (HU>200). This classification improves the precision of the resulted kV_P conversion curves.

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The kV_P Conversion curves have been reported for the combination of 80 kV_P/140 kV_P. It should be noted that in dual energy method, the accuracy of estimating attenuation map at 511 keV is directly related to the difference of the pair energies used in each combination [8]. The calculated kV_P Conversion Curves can be used for virtual generation of a CT image in other kV_Ps. Having the CT image of a patient in one energy and generating the second image in another energy, we are now able to implement the dual energy technique which is called the virtual dual-energy method.

B. Phantom Study

For this study, a polyethylene cylindrical phantom (250±0.5 mm diameter) was constructed. This phantom is consisted of 16 cylindrical holes (20±0.5 mm diameter) with four holes in the middle (5±0.5 mm diameter) which were filled with air. One of the 16 holes was filled with water and the others were filled with different concentrations of K_2HPO_4 in water (for modeling of soft tissue and bones with different densities). The concentration of these K_2HPO_4 solutions was varied from 60 mg/cc to 1800 mg/cc to simulate bones with different densities.

This phantom was scanned by the LightSpeed VCT scanner at energy levels of 80 and 140 kV_Ps and tube current of 400 mA. By using the kV_P Conversion Curves, phantom image at 80 kV_P was derived from 140 kV_P. As the noise of the CT image is lower in higher kV_Ps, CT image at 80 kV_P was derived from 140 kV_Ps.

C. Patient Study

In sixteen patients, CT scan was done at the energy levels of 80 and 140 kV_Ps in just one slice (ethic license number 1432, Tehran University of Medical Sciences). The data was acquired from the LightSpeed VCT scanner. By using the kV_P Conversion Curves, patient image at 80 kV_P was derived from 140 kV_P, similar to the phantom study.

D. Generation of μmap and Comparison Strategy

The reconstructed CT images (512×512 matrix size) were at first down-sampled to 128×128 and then smoothed using a 5-mm Gaussian kernel to match the resolution of the PET images. Then bilinear, dual-energy and virtual dual-energy methods were used to convert CT pixel values in Hounsfield units (HU) to an attenuation map (μmap) at 511 keV. The virtual dual-energy method was implemented using the CT image at 140 kV_P and the generated CT image at 80 kV_P which is derived from 140 kV_P.

In the phantom study, the generated μmaps using each method were compared to the true value extracted from XCOM cross section library, as gold standard, for different concentrations of K_2HPO_4, while in the patient study μmap derived from the dual-energy method was considered as the gold standard. An ROI analysis was used for calculation of the percentage relative differences between the values calculated from the attenuation maps generated using different methods and the gold standard. On the 16 CT images, 120 ROI were selected. These ROIs were divided into soft, bone and lung groups. At last the average relative difference for each group to gold standard values for every method was calculated.

E. kV_P Conversion Curves

Figure 1 shows the kV_P Conversion Curves obtained from by CT scans of RANDO phantom at tube voltages of 80 and 140 kV_Ps. The conversion equations for this combination are shown in Table 1.

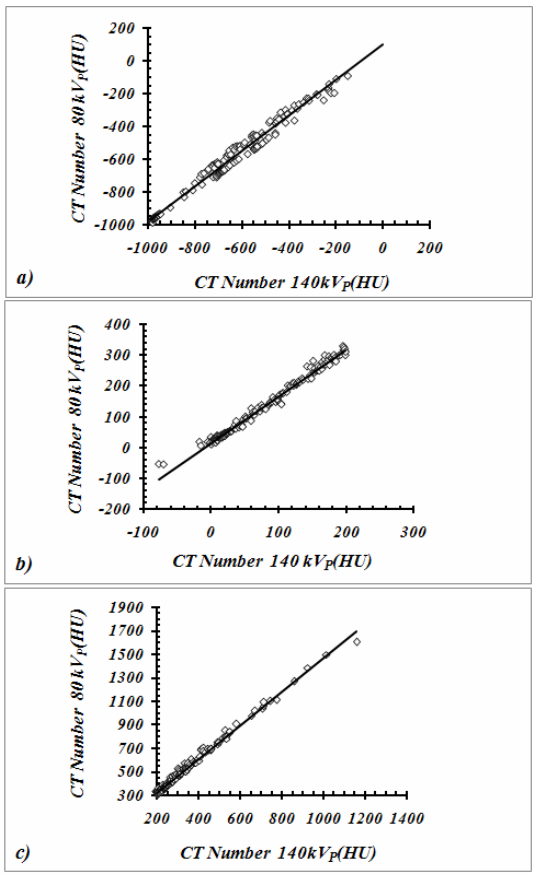

Fig. 1 The kV_P Conversion Curves obtained from by CT scans of RANDO phantom for the combination of 80 kV_P/140 kV_P at (a) Lung tissue, (b) Soft tissue and (c) Bone tissue

Table 1 The conversion equations for 80 kV_P /140 kV_P at different tissues

Tissue Type	Conversion Equation from 140 kV_P to 80 kV_P
Lung Tissue (HU<-100)	$HU_{80kVp} = (1.083 \times HU_{140kVp}) + 94.60$
Soft Tissue (-100<HU<200)	$HU_{80kVp} = (1.529 \times HU_{140kVp}) + 9.911$
Bone Tissue (HU>200)	$HU_{80kVp} = (1.431 \times HU_{140kVp}) + 33.45$

F. *Phantom Study*

Figure (2) shows the original CT image of the polyethylene phantom at 140 kV_P and the generated attenuation maps using bilinear, dual-energy and virtual dual-energy methods.

Table (2) summarizes the percentage relative difference between the calculated linear attenuation coefficients at 511 keV for different regions of phantom and the true values extracted from the XCOM cross section library.

The average relative difference in all regions calculated using bilinear, dual-energy and virtual dual-energy methods are 10.1%, 4.2%, 4.3% respectively.

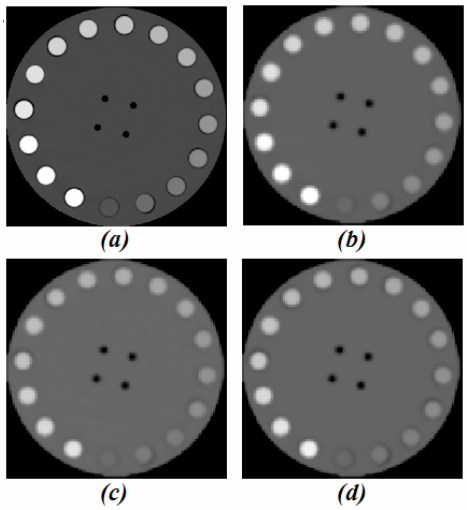

Fig. 2 Original CT image (a) and generated attenuation maps using bilinear (b), dual energy (80 and 140 kVps) (c) and virtual dual-energy (d)

Table 2 Percentage relative difference between the calculated LACs for different concentrations of K_2HPO_4 and the reference values extracted from the XCOM cross section library

C †(mgr/cc)	Bilinear	DECT	Virtual DECT
Water	**0.0**	**1.0**	**0.0**
120	**4.9**	**2.9**	**2.0**
180	**6.6**	**0.9**	**1.9**
240	**11.0**	**3.7**	**5.5**
300	**12.5**	**4.5**	**4.5**
360	**12.9**	**4.3**	**4.3**
480	**13.8**	**4.1**	**4.9**
540	**14.3**	**3.2**	**4.0**
600	**14.2**	**3.1**	**3.9**
660	**15.0**	**2.3**	**4.5**
720	**15.4**	**2.2**	**3.7**
840	**14.0**	**0.0**	**2.8**
900	**12.9**	**1.4**	**0.7**
1200	**9.8**	**6.1**	**3.7**
1500	**3.9**	**12.1**	**8.3**
1800	**0.5**	**15.6**	**12.6**
Average	**10.1**	**4.2**	**4.3**

†Concentration of K_2HPO_4 in solution.

G. *Patients Study*

Figure (3) shows one chest slice of original patient CT image at 140 kV_P and the generated attenuation maps using bilinear, dual-energy and virtual dual-energy methods in the same slice.

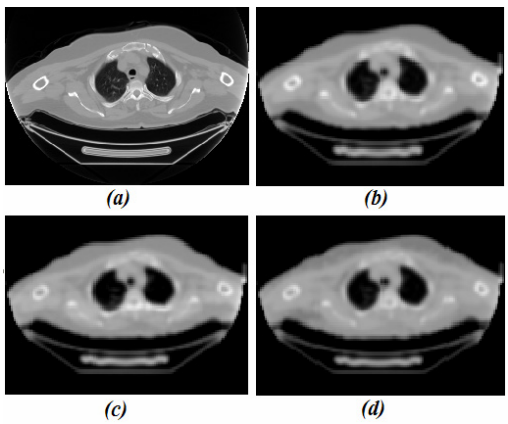

Fig. 3 Original patient CT image (a) and generated attenuation maps using bilinear (b), dual energy (80 and 140 kV_Ps) (c) and virtual dual-energy (d)

Figure (4) shows the correlation plots for each energy mapping method and DECT.

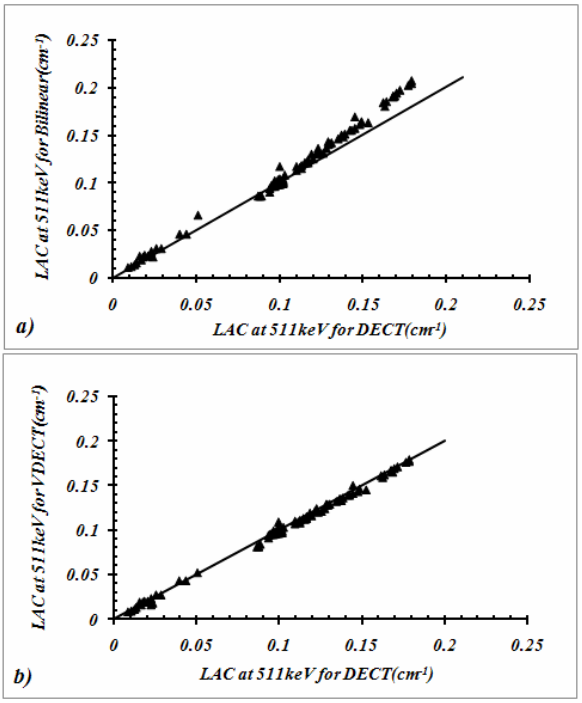

Fig. 4 The correlation plots between a) bilinear and DECT, b) virtual DECT and DECT

Table (3) summarizes the percentage relative difference between the calculated LAC at 511 keV for bilinear and virtual dual-energy and dual-energy (as the gold standard) in different tissues including lung, soft and bone.

Table 3 Percentage relative difference between the calculated LAC at 511 keV for bilinear and virtual dual-energy with dual-energy (as the gold standard) in different regions of patients

Tissue Type	Bilinear	Virtual DECT
Lung Tissue	16.4	8.0
Soft Tissue	1.6	2.2
Bone Tissue	8.9	1.5

III. Conclusion

Among different CTAC methods of PET data, the bilinear method is the common used method in most commercial PET/CT scanners. This method has an acceptable accuracy in lung and soft tissue, but overestimates in bone tissue. Also, the dual-energy method has a good estimation of attenuation coefficients at 511 keV for all tissues, but the use is limited because of its high dose. In this feasibility study we have introduced a new method that can implement dual-energy technique with only a single energy (kV_P) CT imaging.

As shown in table (2), that dual-energy and virtual dual-energy have the lowest errors in obtaining LACs at 511 keV (4.2 % and 4.3 % respectively).

In the patient study results, figure (4) and table (3), the virtual dual-energy has better agreement with the dual-energy method rather than the bilinear method especially in the bone tissue (1.5 % and 8.9 % respectively).

In this feasibility study, we present results showing the virtual dual-energy approach has the same performance as dual-energy in all tissues, while the proposed method has additional potential advantages of a lower patient dose. It should be noted, all presented results were obtained in the absence of contrast agents and metal implants.

Further evaluation using a clinical PET/CT database is underway to evaluate the potential of the technique in a clinical setting.

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