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Impact of X-ray tube settings and metallic leads on neurological PET imaging when using CT-based attenuation correction

Mohammad Reza Ay[a,b,*], Habib Zaidi[a]

[a]Division of Nuclear Medicine, Geneva University Hospital, Geneva, Switzerland
[b]Department of Medical Physics, Tehran University of Medical Sciences, Tehran, Iran

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Abstract

The use of X-ray CT images for CT-based attenuation correction (CTAC) of PET data results in the decrease of overall scanning time and creates a noise-free attenuation map (μmap). Given that different tube voltages and currents are used in clinical PET/CT scanning protocols depending on patient size and the body region under study, this work was designed to evaluate the effect of tube settings and the presence of deep brain stimulation (DBS) metallic leads on the accuracy of CTAC. A commercial anthropomorphic head phantom and an in-house made polyethylene phantom were used in order to quantitatively measure the effect of the nominated parameters, using quantitative analysis of created μmaps, generated attenuation correction factors and reconstructed neurological PET emission data. A maximum absolute relative difference of 0.9% was observed between average CT numbers of images acquired at 300 mA and those acquired with tube currents from 20 to 280 mA in steps of 20 mA. Slopes equal to 5.79×10^{-5}, 5.34×10^{-5} and 3.92×10^{-5} for calibration curves corresponding to CT numbers greater than 0 HU were obtained at tube voltages of 140, 120 and 80 kVp, respectively. A relative difference of 36% and 27% for CT numbers of cortical bone measured at 80 kVp were observed in comparison with images acquired at 140 and 120 kVp, respectively. It was concluded that the attenuation map derivation is independent of tube current used for the settings explored in this work. Likewise, the visual qualitative interpretation and quantitative analysis of neurological PET emission images is independent of X-ray tube voltage. The DBS metallic leads do not create any visible or quantifiable artifacts in the reconstructed neurological PET images owing to their small size.

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Keywords: Attenuation correction; PET/CT; Tube voltage; Tube current; Quantification; Metallic lead

1. Introduction

The advent of dual-modality PET/CT imaging had great impact on improving the value of diagnostic PET in localizing, evaluating and monitoring treatment response for head and neck cancer and is equally valuable for other localizations that are difficult to pinpoint [1]. In addition, the use of CT images for CT-based attenuation correction (CTAC) of PET data decreases overall scanning time and creates a noise-free attenuation map (μmap). With the introduction of hybrid PET/CT systems in clinical setting, precise conversion from CT numbers derived from low-energy polyenergetic X-ray spectra to linear attenuation coefficients (LACs) at 511 keV became essential in order to perform accurate CTAC. The most common CTAC procedure requires a bi-linear calibration curve, which is generally calculated at a preset tube voltage (120–140 kfVp) [2]. However, since the CT images may be acquired at different kVp, depending on the patient size and region under study, and considering the fact that the CT number of a particular tissue is tube voltage dependent; it was hypothesized that using a calibration curve calculated at a particular tube voltage for images that may be acquired in different tube voltages might propagate a significant error during the CTAC procedure [3].

*Corresponding author. Department of Medical Physics, Tehran University of Medical Sciences, Tehran, Iran. Tel.: +98 21 66466383; fax: +98 21 66950821.
E-mail address: mohammadreza_ay@tums.ac.ir (M. Reza Ay).

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It is well known that a high tube current improves CT image quality at the expense of increasing patient dose. With the introduction of PET/CT systems, several questions had to be answered, one of them is "to which limit can the CT tube current be reduced while still yielding adequate μmaps for attenuation correction of PET data?". Kamel et al. [4] investigated the effect of varying tube current and showed that a low tube current CT is sufficient for CTAC using comparative quantitative analysis of reconstructed clinical PET images. Likewise, a new preprocessing algorithm was proposed recently to use a single ultra-low dose CT scan for both μmap construction and lesion localization [5].

During the last few years, deep brain stimulation (DBS) techniques have been established as a therapy method for Parkinson's disease. Some studies reported potential appearance of metallic artifacts. However, the impact of the presence of DBS metallic leads on the accuracy of CTAC has not been investigated before.

The aim of this work was twofold: firstly, study the impact of using different X-ray tube settings on the accuracy of CTAC through quantitative analysis of created μmaps, generated attenuation correction factors (ACFs) and reconstructed neurological PET emission data using experimental anthropomorphic phantom studies and secondly, investigate the effect of artefacts resulting from the presence of metallic leads used in DBS techniques for the treatment of Parkinson's disease on CTAC in neurological PET studies.

2. Material and methods

To investigate the effect of X-ray tube voltage and presence of DBS metallic leads on the accuracy of CTAC, experimental measurements of the anthropomorphic striatal phantom (Radiology Support Devices Inc., Long Beach, CA) were performed. This phantom consists of four small cavities that can be filled independently representing the left and right caudate and left and right putamen. In addition, there is a larger main chamber surrounding the four small cavities representing the rest of the brain. This study relied on the use of PET and CT data acquired on separate PET and CT scanners as a combined PET/CT scanner was not available to us during the study design. The main motivations behind the choice of cerebral imaging is that automated multimodality coregistration techniques work relatively well and can be applied most successfully to neurological studies. An activity concentration (^{18}F) ratio of 1:8 between the main chamber and small cavities were used for the PET emission study which lasted 25 min followed by a 10 min post-injection transmission scan performed using single-photon emitting point sources of Cs-137 on the ECAT ART PET scanner (CTI/Siemens, Knoxville, TN). Thereafter, CT data from the same region were acquired using the Aquilion CT scanner (Toshiba Medical Systems Corporation, Tokyo, Japan) at 240 mA and different tube voltages (80, 120 and 140 kVp) in order to apply the CTAC procedure to the emission data. Calibration curves calculated at 120 kVp were used to create sets of μmaps from acquired CT images. The apparent recovery coefficient (ARC) and activity concentration were calculated for the five compartments of the phantom as figures of merit for the quantitative analysis of reconstructed PET images. Partial volume correction was applied to the striatal phantom images using the popular geometric transfer matrix (GTM)-based method as described in our previous study [3].

A polyethylene cylindrical phantom ($\varnothing 250 \pm 0.5$ mm) containing 16 cylindrical holes ($\varnothing 20 \pm 0.5$ mm) was made in order to investigate the effect of tube current on the accuracy of CTAC. Fourteen syringes were filled with K_2HPO_4 solution and water with concentration varying between 50 and 900 mg/cm^3 to simulate cortical bone with different densities. The prepared syringes together with two additional syringes containing water and air were inserted into the polyethylene phantom's holes. Subsequently, the phantom was scanned on the Aquilion CT scanner in tube currents varying between 20 and 300 mA with a step of 20 mA at 120 kVp tube voltage. Bi-linear calibration curves were calculated at 120 kVp tube voltage according to the method proposed by Bai et al. [2] in order to apply CTAC to PET emission data sets.

The corresponding attenuation correction factors were calculated by down-sampling of the CT image matrix to 128×128 followed by smoothing using a 6-mm Gaussian filter to match the resolution of actual PET scanner used in this study. Thereafter the CT number values in Hounsfield units were transformed to linear attenuation coefficients at 511 keV using the calculated bi-linear curve. The created μmaps ($128 \times 128 \times 47$) were forward-projected generating 47 ACF sinograms. The attenuation corrected data were reconstructed with 3DRP reprojection algorithm using ECAT 7.2.1 software. It should be emphasized that, whereas the CT and PET images were acquired on different scanners, to avoid any artifacts arising from misalignment of images during CTAC the CT and PET images were aligned accurately using multi-modality software (off-line fusion) in HERMES workstation (Nuclear Diagnostics AB, Stockholm, Sweden).

To characterize the magnitude of potential artifacts arising from the presence of DBS metallic leads on generating CTAC, the Platinum/Iridium metallic leads having a diameter of 1.27 mm were inserted in CT images of the striatal phantom. The CT numbers of related pixels were substituted with 4000 HU owing to the fact that CT numbers above 4000 HU are truncated by software implemented on commercial CT scanners. The created attenuation maps were used for attenuation correction of the PET emission data.

3. Results

The RSD striatal phantom's μmap when CT images are acquired at 80, 120 and 140 kVp and scaled using a calibration curve derived at 120 kVp were calculated. Thereafter, the created μmaps were used for attenuation correction of PET emission data. The ARC values for each compartment were calculated after partial volume correction. There is no visually significant difference between the images corrected for attenuation using different methods. After partial volume correction of the emission images corrected for attenuation using CT images acquired at 80 and 140 kVp, an average relative difference of −2.9% and 0.7% with the images acquired at 120 kVp was observed between absolute activity concentrations in five regions of the anthropomorphic striatal phantom when CT images are converted to μmaps using a single calibration curve derived at 120 kVp, respectively. A detailed analysis of the impact of tube voltage on the accuracy of CTAC has been addressed elsewhere [3].

Fig. 1 shows the percentage relative difference of CT numbers in four different regions of the cylindrical phantom between the image acquired at 300 mA and images acquired with various tube currents. A maximum absolute relative difference of 0.9% was observed between average CT numbers of images acquired at 300 mA and those acquired with tube currents from 20 to 280 mA in steps of 20 mA. Fig. 1 shows that the CT numbers are tube current (mA) independent, owing to the fact that increasing tube current increases S/N ratio and decreases statistical fluctuations in the images, thus improving image quality. The statistical fluctuations of CT numbers in low current CT images are substantially reduced during the down-sampling and smoothing processes intrinsic to the CTAC procedure.

The acquired phantom images with different tube currents were used for calculation of μmaps and ACFs. Fig. 2 shows one slice of the original CT image, calculated μmap and ACF sinograms using CTAC method for images acquired at minimum (20 mA) and maximum (300 mA) tube current.

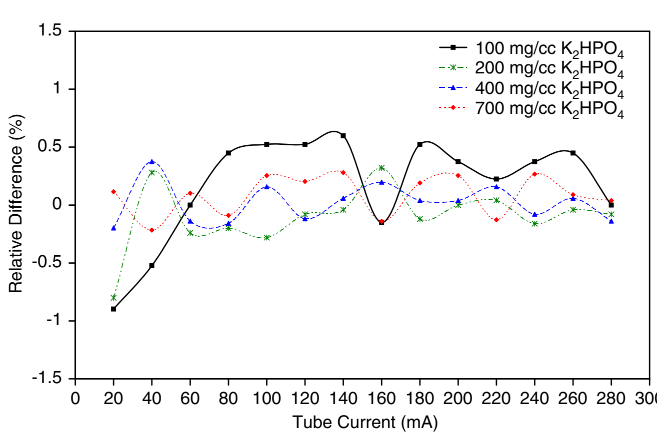

Fig. 1. Percentage relative difference between CT numbers (HU) of four regions in the designed polyethylene phantom between the image acquired at 300 mA and those acquired with tube currents from 20 to 280 mA in steps of 20 mA.

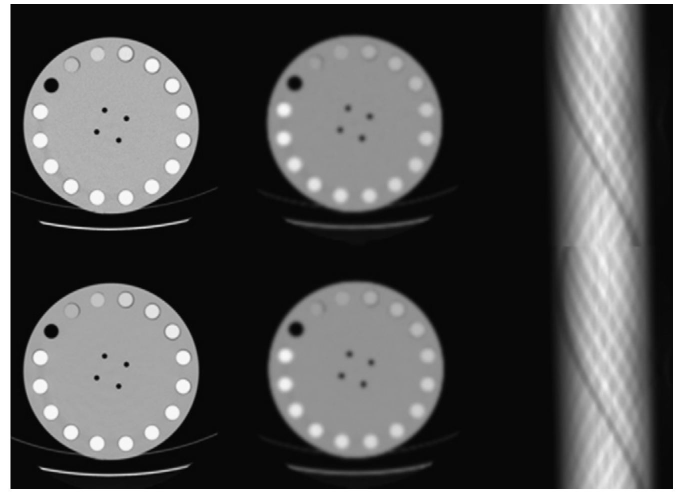

Fig. 2. From left to right the original CT image of the phantom acquired in 120 kVp, the calculated μmap at 511 keV using CTAC and ACF sinogram (view 23/47) at 20 mA (top) and 300 mA (bottom).

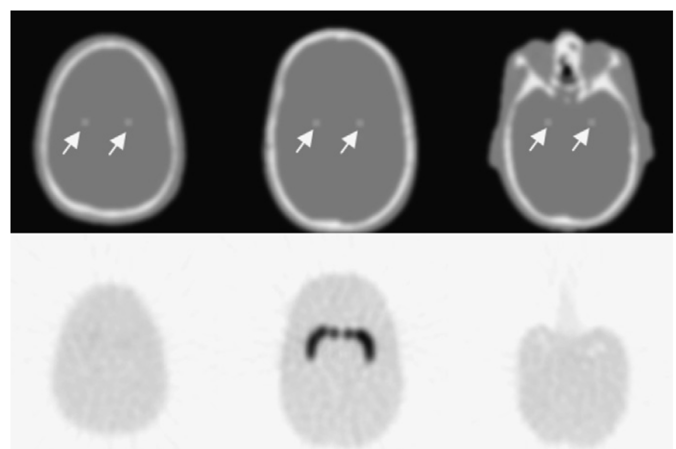

Fig. 3. Calculated μmap after manual insertion of metallic DBS leads into the CT images of RSD phantom (top). Reconstructed emission images after CTAC using created μmaps (bottom).

The impact of metallic DBS leads used for treatment of Parkinson's disease on CTAC was investigated in this study by inserting metallic leads in an appropriate region of the RSD striatal phantom's CT images (Fig. 3). The new set of CT images was used for attenuation correction of emission data using CTAC. The reconstructed PET emission images shown in Fig. 3 show that the DBS metallic leads do not create any visible or quantifiable artifacts in CT-based attenuation correction.

4. Conclusion

In this study the impact of tube voltage (kVp), tube current (mA) and presence of DBS metallic leads on the accuracy of CT-based attenuation correction method was investigated in detail using experimental phantom measurements. It was concluded that the attenuation map derivation is independent of tube current used for the settings explored in this work. The visual qualitative interpretation and quantitative analysis of neurological PET emission images is independent of X-ray tube voltage. The DBS metallic leads do not create any visible or quantifiable artifacts in the reconstructed neurological PET images owing to their small size.

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