Low Dose Interpolated Average CT for PET/CT Attenuation Correction Using an Active Breathing Controller (ABC)

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Abstract- **While the complexity of implementation hampers the use of 4D PET/CT in the clinics, previously we developed and evaluated an interpolated average CT (IACT) method for attenuation correction (AC) in PET/CT. This study aims to evaluate the clinical implementation of IACT using an active breathing controller (ABC). This system consists of a spirometer for monitoring respiratory cycle and an airway-sealing unit. Real time detection of the change of flow volume and air flow direction by a flow sensor was used to determine the end-inspiration and end-expiration phases, while the valve of the ABC was closed for ~6 s to suspend the patients breathing and the helical CT (HCT) scans were manually turned on. To demonstrate the clinical feasibility of this system, two subjects were recruited for the PET/CT scans. Thoracic PET scans were acquired 1 hr after 328 MBq and 406 MBq ^{18}F-FDG injections for each subject respectively, using 3 mins per bed position for 2 bed positions. The PET sinograms were reconstructed with AC using: (i) standard HCT (120 kV, smart mA (30-150 mA), 0.984:1 pitch); (ii) IACT obtained from 2 end-inspiration and end-expiration breath-hold HCTs (120 kV, 10 mA) using ABC to assure that the captured phases represented the free-breathing state as in PET acquisition. For IACT, multi-resolution B-spline registration algorithm and nonlinear interpolation were used to generate the interpolated phases between the two extreme phases. The final IACT was obtained by averaging the original and interpolated phases. The PET reconstructed image quality was assessed by visual observation and image profiles. Results showed that PET images using HCT for AC had severe artifacts near the diaphragm comparing to IACT, as confirmed by the image profiles. The IACT reduced ~87% radiation dose as compared to HCT. We conclude that IACT provides improved PET reconstructed image quality as compared to HCT with reduced radiation dose. IACT for PET AC is feasible and robust in clinical practice with the aid of ABC.**

I. INTRODUCTION

In PET/CT scan, the temporal difference of PET and CT leads to mis-registration and respiratory motion artifacts in the PET reconstructed images. Cine average CT (CACT) was developed for attenuation correction (AC) [1] in PET images and showed significantly less misalignment and artifacts as compared to conventional helical CT (HCT) based AC. Its main problem is relatively high radiation dose. Previously we developed an interpolated average CT (IACT) method, generated from helical CTs of the end-expiration and end-inspiration phases and interpolated phases between these two phases using deformable image registration [2]. We performed a simulation study to evaluate the accuracy and robustness for IACT for different respiratory motion amplitudes and misplacement of the two extreme phases [3]. In this study, we further investigate the clinical feasibility of IACT and its potential radiation dose reduction using an active breathing controller (ABC).

II. METHODS

A. ABC design:

Voluntary breath-hold of end-expiration and end-inspiration phases performed by the patients themselves probably could not represent the normal breathing state as in the PET acquisition. Using these phases to generate IACT may introduce even more artifacts as compared to conventional HCT. Thus, to capture two breath-hold CT scans at normal end-inspiration and end-expiration phases, an ABC system (Fig. 1 a & b) was developed in this study. This non-invasive device integrated a spirometer, an air mask and a tube-valve system that were controlled by a personal computer (PC). The flow sensor detected real-time breathing flow rate of the patients and sampled the signal to the microcontroller. The microcontroller preprocessed the signal and sent it to the PC through a USB connector. A program based on C++ was developed to process the input signal and control the switching of the valve. It can detect the change of the air flow direction to locate the end-inspiration and end-expiration phases. The flow can be integrated to determine the change of lung volume during the respiratory cycle. The operator manually started the CT scan once the patient was controlled to hold their breaths by the ABC during the end-expiration and end-inspiration phases. Before examination, a system calibration was performed to compensate the signal drift. Subjects were coached before actual CT scans to adapt to the ABC. Sampled changes of lung volume during the breathing cycles under the ABC control are shown in Fig. 2.


(a)

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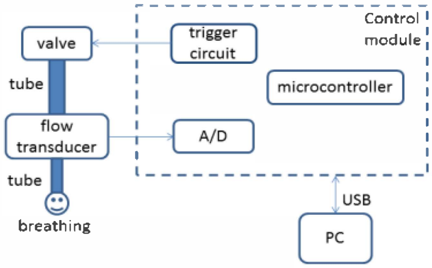


(b)

Fig. 1. (a) Overview and (b) block diagram of the ABC system for PET/CT.

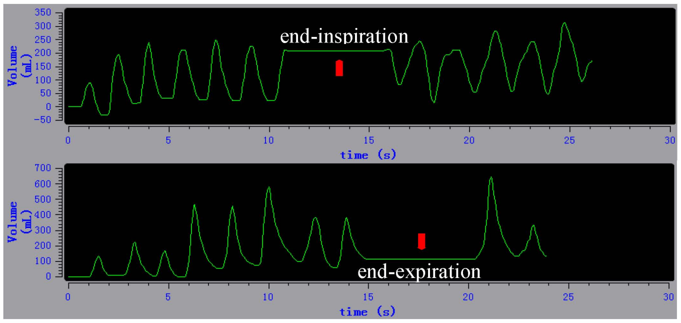


Fig. 2. Change of lung volumes during the externally mediated end-inspiration and end-expiration breath-hold controlled by ABC. Red arrows indicate the closing period of the valve.

B. Clinical setup:

Two normal volunteers were recruited in this study. This study was approved by the local ethics board. Images were acquired using a PET/CT scanner (Discovery VCT, GE Medical Systems, Milwaukee, WI, USA). They were injected with 328 MBq and 406 MBq of ^{18}F-FDG respectively and scanned 1 hr post injection. Thoracic PET data were acquired for 2 bed positions with 3 mins per bed position. One standard helical CT (HCT), two extra end-inspiration and end-expiration breath-hold helical CTs obtained using ABC for IACT were performed for each subject (Fig. 3). The standard HCT acquisition settings were: 120 kV, smart mA (range 30–150 mA) helical mode, 0.984:1 pitch, 0.5 s gantry rotation and total 4.4 s scan time. For IACT, two breath hold CTs were acquired at 120 kV, 10 mA helical modes, 0.984:1 pitch, 0.5 s gantry rotation time and a total of 4.4 s acquisition time for each scan.

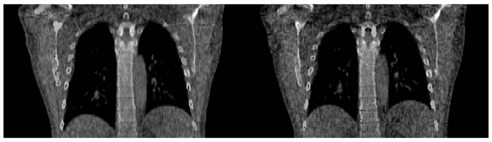


Fig. 3. Left: normal end-inspiration breath-hold CT with ABC. Right: normal end-expiration breath-hold CT with ABC.

C. IACT generation:

B-spline, a deformable image registration algorithm, was applied to calculate the deformation vectors which includes lateral, anterior-posterior and inferior-superior displacement for each voxel on two CT volumes, i.e., end-inspiration and end-expiration phases obtained from ABC, based on the Insight Segmentation and Registration Toolkit (ITK) [4]. One CT image was chosen as the fixed image while the other was used as the moving image. A single rigid registration was conducted in the first step. Three stages of B-spline registration were performed later using multi-resolution method in the second step. The grid resolution of the control points improved and their grid-spacing decreased along different stages in this step. The deformation field was determined when the mean square error of the two CT images was smaller than some positive value ϵ in each resolution level.

The forward deformation vector ϕ_{ie} was calculated from end-inspiration phase #1 to end-expiration phase #7 and backward deformation vector ϕ_{ei} was calculated from phase #7 to phase #1.

For interpolation, an upper liver movement function in one respiratory cycle was used [5]:

$$z(t) = z_0 - b\cos^{2n}\left(\frac{\pi t}{\tau}\right) \tag{1}$$

where $z(t)$ = position of organ at time t, z_0 = position at end-expiration, b = amplitude of motion, τ = period of motion, and n = degree of asymmetry (n = 1 here).

To generate intermediate images, ϕ_{ie} was divided based on $z(t)$ to obtain interpolated deformation fields. Thus, we can generate interpolated phases #2, #3, #4, #5, #6 by warping original phase #1 based on ϕ_{ie} (Fig. 4). Similarly, phases #8, #9, #10, #11 and #12 were warped from phase #7 based on ϕ_{ei}. The final IACT was generated by averaging the interpolated and the 2 original phases.

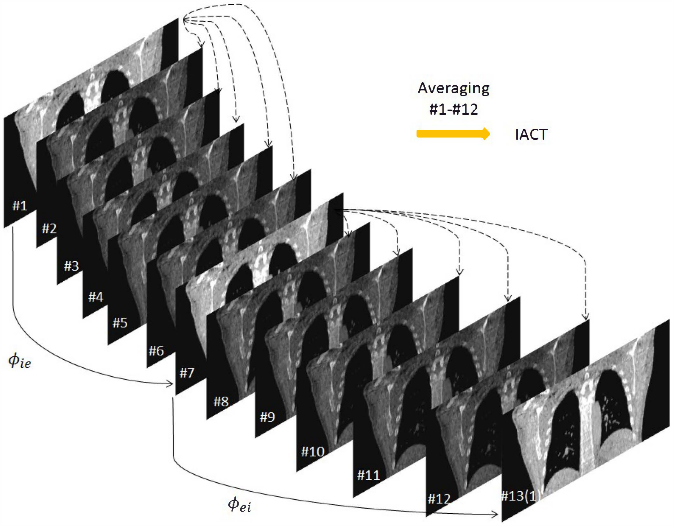


Fig. 4. The deformation fields (ϕ_{ie} & ϕ_{ei}) obtained from B-spline method combined with the empirical sinusoidal function were used to generate the interpolated images for IACT.

D. Data analysis:

The PET sinograms were reconstructed using OS-EM algorithm available on the GE VCT workstation. Attenuation corrections were conducted using HCT and IACT respectively. Their reconstructed PET images quality and associated radiation dose were compared and analyzed:

(i) Image profile

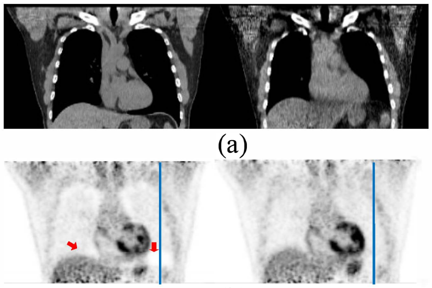
Besides visual assessment, an image profile was drawn vertically across the lung and the diaphragm to demonstrate the misalignment artifacts in the reconstructed images using different CT protocols.

(ii) Radiation dose

Estimated effective doses in mSv were calcuated for different CT protocols and subjects.

III. RESULTS

From visual assessment, breathing artifacts were observed on the PET images with HCT-based AC but they were significantly reduced for those with IACT-based AC (Fig. 5). The quantitative profiles confirmed the potential difference between the 2 sets of PET reconstructed images (Fig. 6). The dose report suggested the IACT had an estimated dose of 0.38 mSv, reducing the dose up to 87% as compared with standard HCT (Table I).


(a)

(b)

Fig. 5. (a) Sample images of HCT (left) and IACT (right) for subject #1. (b) Their associate PET AC images. Red arrows: misalignment artifacts.

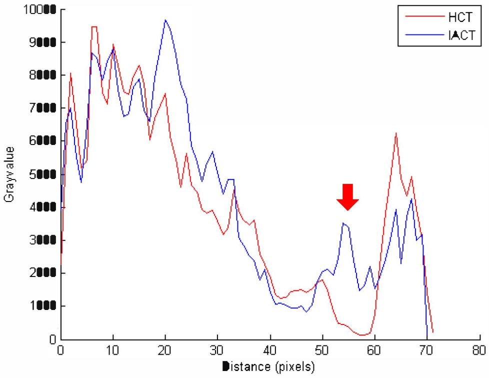


Fig. 6. Image profiles for HCT- and IACT-based AC images. Red arrow indicates the substantial difference between two AC images as shown in Fig. 5b.

Table I. Radiation dose for different CT protocols.

	HCT (mSv)	IACT (mSv)
Subject #1	2.83	0.38
Subject #2	2.04	0.38

IV. DISCUSSION AND CONCLUSION

To the best of our knowledge, this is the first study to utilize ABC in PET/CT study, and it is the critical device to assure the implementation of IACT. Our preliminary results reassured our findings in the previous simulation and clinical study. We conclude that IACT provides improved image quality as compared to HCT with reduced radiation dose. IACT is feasible and robust in clinical practice with the aid of ABC. Further optimization of IACT protocol with consideration of specific patient's breathing condition is warranted.

V. REFERENCE

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