Continuous bed motion acquisition for an LSO PET/CT scanner

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Abstract**-- Standard whole-body PET/CT protocols collect PET emission data for a sequence of discrete, overlapping bed positions. An alternative acquisition mode in which the patient bed moves continuously through the scanner has some significant advantages, including uniform axial signal-to-noise, elimination of resolution artifacts by sampling continuously in the axial direction, and a reduction in both noise from detector normalization and artifacts from small patient movements. To validate this approach, continuous bed motion acquisition has been implemented on a high resolution, 16-slice LSO PET/CT scanner (CPS Innovations, Knoxville, TN). The emission data are acquired in list mode with the bed moving at a constant velocity in the range 0.3-0.7 mm/s for a total scan time in patients of around 20 minutes covering an axial extent of 36-84 cm. The absolute position of the bed is read and inserted directly into the list mode data stream. Following acquisition, the emission data are rebinned into a fully 3D data set and reconstructed using a 3D OSEM algorithm. Continuous movement of the patient bed yields uniform signal-to-noise throughout the axial imaging field. For short imaging times, the bed movement in the standard acquisition becomes a significant fraction of the total scan time and continuous bed motion acquisition offers a more efficient alternative. Results are presented for some representative patient studies with both step-and-shoot and continuous bed motion acquisition.**

I. INTRODUCTION

THE advantages of acquiring PET emission data with a continuous movement of the patient bed has been recognized for over a decade since the introduction of whole-body scanning [1, 2]. The approach is comparable to that of spiral CT where the bed moves continuously during data acquisition and for one particular rotating PET scanner design, the continuous bed motion approach has been termed spiral PET [3]. Currently, however, whole-body images are acquired in step-and-shoot mode at a small number of discrete bed positions. For 2D whole-body PET imaging, the sensitivity profile, and hence the signal-to-noise ratio (SNR), is uniform throughout the axial field-of-view. In 3D, the sensitivity profile is peaked at the center and in order to achieve a more uniform SNR, contiguous bed positions are typically overlapped by up to 25% of the axial field-of-view of the scanner [4]. Increasingly the overlap improves the uniformity of the SNR at the expense of increasing both the number of bed positions and the time spent in stopping and starting the bed motion. Acquisition at multiple small steps (i.e., less than one axial plane width) also improves sampling [5, 6], eliminating resolution artifacts due to axial under sampling. Continuous bed motion is thus the logical extension of multiple small discrete increments [1, 2] and recently this approach has been implemented for both PET scanners [7, 8] and PET/CT [9] scanners. In addition to improved axial sampling and uniform SNR, advantages also include a reduction in noise from detector normalization and a reduced sensitivity to small patient movements.

We present results of continuous bed motion acquisition for an LSO PET/CT scanner, a *biograph* Sensation 16 (Siemens Medical Solutions). Continuous bed motion acquisition is compared with the standard step-and-shoot methodology for a series of patients.

II. MATERIALS AND METHODS

A. The PET/CT scanner design

The *biograph* Sensation 16, manufactured by CPS Innovations (Knoxville, TN) and distributed by Siemens Medical Solutions (Hoffman Estates, IL) comprises a high resolution LSO-based PET scanner combined with a 16-slice Sensation 16 CT scanner (Siemens Medical Solutions, Forschheim, Germany), as shown in Figure 1. The PET scanner incorporates new high resolution LSO detectors; the blocks are 13 x 13 pixels, with each pixel 4 mm x 4 mm in size. The scanner used in these studies has also been upgraded to incorporate the new, fast PICO-3D electronics [10]. The spiral CT has a 16-row, UFC™ detector with a 0.5 s rotation time. The gantry design has a 70 cm patient port and an optional flat bed to facilitate applications in radiation oncology. To eliminate variations in vertical bed deflection due to the weight of the patient, the pallet is fixed to one end of a support pedestal and the entire assembly moves

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continuously on floor-mounted rails, as shown schematically in Figure 2a. The scan range for combined PET and CT imaging is up to 190 cm. The bed speed is selectable from 0.3 – 150 mm/s and for continuous movement of the bed, a direct connection between the ACS and the bed controller has been installed that bypasses the standard CT control system.

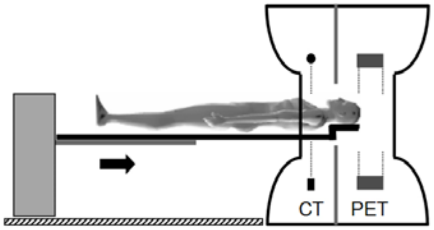
Fig. 1. The *biograph* Sensation 16 high resolution PET/CT scanner installed in the Cancer Center at the University of Tennessee, Knoxville.

B. Step-and-shoot acquisition protocol

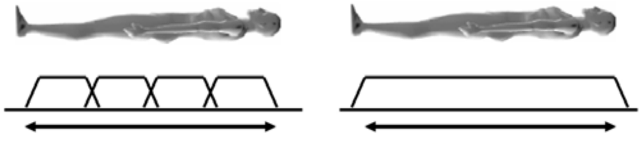
Following an injection of 10 mCi (370 MBq) of ^{18}F-fluoro deoxyglucose (FDG) and a 90 min uptake period, the patient is positioned in the scanner. A topogram (scout scan) is acquired first and the appropriate axial range for the spiral CT scan defined on the topogram. The number and location of discrete bed positions for the PET acquisition are selected to match the axial range of the spiral CT, taking into account the chosen overlap between bed positions. The fast scanning capability of the 16-slice MDCT allows the acquisition to be completed in around 13 s with a protocol of breath hold at partial inspiration. The CT scan has no breathing artifacts and is a good anatomical match to PET images acquired with shallow breathing. Following completion of the CT scan, the bed is advanced into the PET imaging field and a sequence of overlapping bed positions acquired for a time of 3-5 min per position, depending on the patient size and clinical indication. In each position, PET data are acquired for an active axial length of 16.2 cm and the bed moves 11.6 cm between positions resulting in an overlap of 4.6 cm (23 planes, each 2 mm thick) to obtain a more uniform axial sensitivity profile (Figure 2b). The patient is scanned moving out of the scanner in the caudo-cranial direction starting at the bladder to minimize the signal due to FDG excretion.

C. Continuous bed motion acquisition protocol

Prior to installation in the scanner, the patient gives informed consent to remain in position during the acquisition of the continuous bed motion part of the study. The full research protocol has been approved by the Institutional Review Board of the University of Tennessee, Knoxville. The scan range of the continuous bed movement is calculated to ensure comparable imaging times for each of the axial planes for which data has been acquired during the step-and-shoot acquisition. This necessitates acquiring an additional axial length of the scanner both before and after the extent covered by the step-and-shoot acquisition (Figure 2c). The continuous bed motion data were acquired in the cranio-caudal direction with the patient moving back into the scanner. For all patients, the axial extent acquired with continuous bed motion that had comparable counts/plane to the step-and-shoot acquisition was less than the range covered by the step-and-shoot.



(a) PET/CT schematic



(b) step-and-shoot

(c) continuous movement

Fig. 2. (a) Schematic of a combined PET/CT scanner; (b) the sensitivity profiles for the step-and-shoot acquisition, and (c) the sensitivity profile for the continuous bed motion acquisition. Note the non-uniform sensitivity profile for the step-and-shoot and the additional axial scan range that must be acquired with continuous movement to ensure comparable count statistics over the same range (arrow) as the step-and-shoot.

The PET emission data are acquired in list mode where each event is specified as a sinogram offset and the list mode stream includes time marks (in ms), singles rates and the absolute bed position (in hundredths of mm). Previous work did not record the bed position directly in the list mode data. Instead, either a time stamp was registered so that the bed position could be calculated assuming a constant velocity [7], or a separate file containing the bed position and total count rate data was recorded in addition to the list mode data file [9]. In this work, the bed velocity is typically in the range 0.3-0.7 mm/s, and is chosen to ensure equivalent acquisition statistics per plane as for the step-and-shoot acquisition. At speeds in the range 0.25-4.0 mm/s, it has been shown with an ECAT HR+ (4.5 mm x 4.5 mm detectors) that the axial spatial resolution is relatively insensitive to bed speed [7]. The typical size of a list mode file is 0.5 Gbytes. Attenuation correction factors are generated from the CT images scaled to 511 keV [11] and the same factors are used for both acquisition modalities, thus avoiding any additional radiation exposure for the patient.

D. Data processing

After 3D normalization, the step-and-shoot sinogram data are reconstructed in the standard way using CT-based attenuation correction, Fourier rebinning and attenuation-weighted 2D-OSEM (2 iterations; 8 subsets). Reconstruction is with a ring difference of 27 and a span of 11. Each PET bed position is reconstructed immediately following completion of acquisition and during data collection of the next position. Once acquisition and reconstruction of the final bed position is complete, the individual data sets are assembled into a 3D volume and smoothed with an isotropic 5 mm 3D Gaussian filter. The width of the filter is adjusted according to the patient size and acquisition statistics. For comparison with the continuous acquisition, the data are also reconstructed with a fully 3D implementation of the OSEM algorithm.

The list mode data acquired with continuous bed motion are rebinned into a complete 3D sinogram set based on the bed position inserted into the list mode stream. Such sinogram sets contain over 2000 sinograms for up to 430 axial planes (segment 0). Again, for comparison purposes, the same axial sampling is implemented as for step-and-shoot, even though improved axial sampling can, in principle, be achieved with continuous bed motion. For these data, 2D normalization is applied to correct the geometrical variation; however, the improved sensitivity uniformity of the new LSO crystals in this PET/CT design obviates the need for a separate detector sensitivity correction factor. With BGO, the sensitivity factors for continuous bed motion were averaged over all axial planes in order to generate the 2D sensitivity normalization sinogram. This correction is not required with LSO. After normalization and attenuation correction, the rebinned list mode data are reconstructed with the same 3D OSEM implementation as used for the step-and-shoot acquisition, with the same parameter settings. The two different acquisition modes can then be compared directly.

III. RESULTS: PATIENT STUDIES

Eleven patients were acquired after an uptake period of 90 min (range: 80-150 min) following an injection of 11 mCi of FDG (range: 8.9-13.4 mCi) using the standard step-and-shoot mode of acquisition. After completion of the standard PET/CT acquisition, an additional PET acquisition with continuous bed motion was performed for each patient. The patients were instructed to remain still between the two PET acquisition protocols to facilitate comparison and to be able to use the same CT scan for attenuation correction of both studies, thus avoiding additional radiation exposure to the patient. Owing to the decay of the ^{18}F, the activity level at the start of the continuous bed motion is typically reduced by 25% compared to the level at the start of the step-and-shoot. There may also be some additional target-to-background changes between the two acquisitions due to clearance of FDG.

Three representative patient cases are presented to illustrate these preliminary studies. The first (Figure 3) is a 78 year old female patient referred for evaluation of a right apical pulmonary nodule seen on CT. The patient was injected with 13.4 mCi of FDG and scanned with arms raised after an uptake period of 125 min. The step-and-shoot was acquired as 6 bed positions for a time of 3 min per position. The total axial extent scanned was 73.2 cm and the activity at the start of the scan was 6.1 mCi. Continuous bed motion data were acquired for a scan duration of 15 min with the bed moving at 0.38 mm/s for a travel of 34.2 cm. The activity at the start of the scan was 5.4 mCi. The total extent scanned was 50.4 cm (34.2+16.2 cm), less than for the step-and-shoot. The appropriate images from the CT were extracted to correct for attenuation. For this patient, both data sets are reconstructed using a 2D-OSEM algorithm. Sagittal and coronal images are shown for the step-and-shoot (Figure 3, top) and continuous bed motion (Figure 3, bottom).

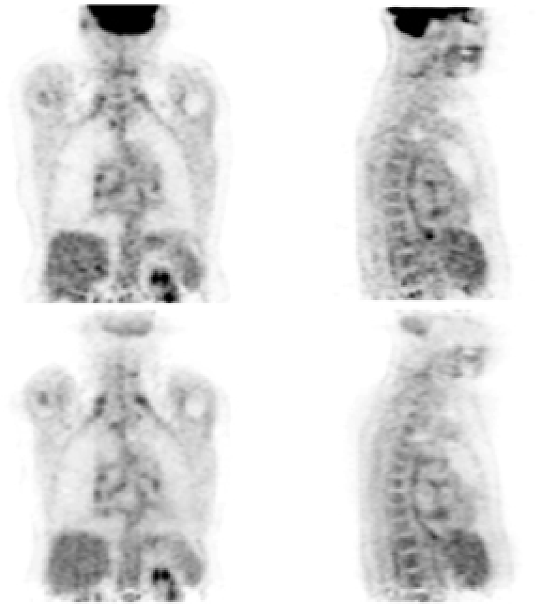


Fig. 3. Coronal and sagittal images for a patient being re-staged for lung cancer. The images were acquired with step-and-shoot (top) and continuous bed motion (bottom). The data were reconstructed with Fourier rebinning and 2D-OSEM.

A second patient study is shown in Figure 4. The patient is a 69 year old male who was being assessed following the discovery of a solitary pulmonary nodule on his CT scan. An injection of 13 mCi of FDG was followed by an uptake time of 138 min. The patient was scanned with arms raised. The step-and-shoot scan comprised 7 bed positions with a scan time of 4 min per position. The activity at start of scan was 6.1 mCi. The total axial extent scanned was 84.6 cm. The activity at the start of the continuous bed motion was 5.4 mCi; a 15 min scan was acquired at a bed velocity of 0.38 mm/s corresponding to a bed travel of 34.2 cm covering an axial extent of 50.4 cm. For this study, a total of 400k–500k true counts per plane were acquired for step-and-shoot and 550k–600k for continuous bed motion. Transaxial and coronal images for this patient reconstructed with 3D-OSEM are shown in Figure 4 for step-and-shoot (top) and continuous bed motion (bottom).

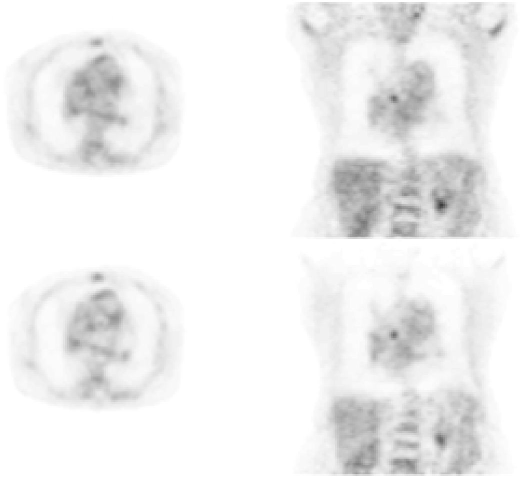


Fig. 4. Transaxial and coronal images for a patient being assessed for a solitary pulmonary nodule. The images were acquired with step-and-shoot (top) and continuous bed motion (bottom). The data were reconstructed with 3D-OSEM.

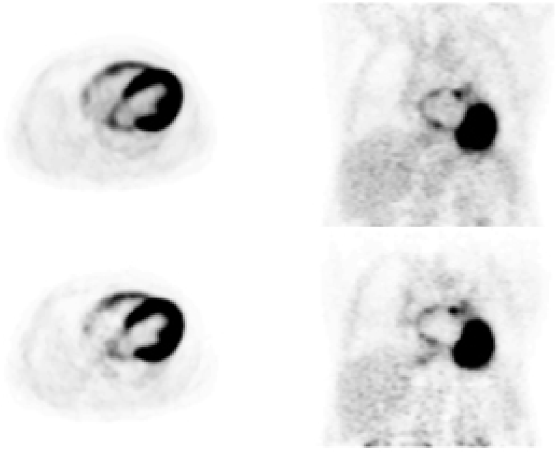


Fig.5. Transaxial and coronal images for a 60 year-old patient being re-staged for breast cancer following surgery and chemotherapy. The images were acquired with step-and-shoot (top) and continuous bed motion (bottom). The data were reconstructed with 3D-OSEM.

A third and final patient study is shown in Figure 5. A 60 year-old female with a history of breast cancer since 1988 was referred for re-staging post mastectomy and chemotherapy. The patient was injected with 10.1 mCi of FDG followed by an uptake period of 101 min. The patient was scanned with arms raised. The step-and-shoot scan comprised 7 bed positions with a scan time of 4 min per position, thus also covering an axial range of 84.6 cm. The activity at start of scan was 5.4 mCi. The activity at the start of the continuous bed motion acquisition was 4.4 mCi; a 20 min scan was acquired at a bed velocity of 0.38 mm/s corresponding to a bed travel of 45.6 cm covering 61.8 cm axially. Transaxial and coronal images at the level of the heart for this patient reconstructed with 3D-OSEM are shown in Figure 5 for step-and-shoot (top) and continuous bed motion (bottom).

IV. DISCUSSION

Brasse et al. [9] were the first to explore continuous bed motion acquisition with a first generation commercial PET/CT scanner. They compared the results for both phantoms and patients with the standard step-and-shoot methodology. For a torso phantom with spherical inserts they demonstrated a 45% improvement in contrast for the smallest, 10 mm diameter sphere when imaged with continuous bed motion. The spheres were placed in the overlap region between two bed positions to enhance the benefit due to continuous bed motion. They observed an overall improvement in contrast using continuous bed motion ranging from 16% to 45% for spheres of diameter 22 mm to 10 mm with a contrast ratio of 3:1. Qualitatively, they also observed an overall improvement in patient image quality with continuous bed motion acquisition.

The contrast improvement observed by Brasse et al. [9] is most likely due to the increased axial sampling that can be achieved with continuous bed motion: axial sampling is not limited by the detector dimensions. However, with the 4 mm detectors in the HI-REZ *biograph* Sensation 16, it is unlikely that for routine clinical whole-body scans, axial subsampling of more than a factor of 2 will be necessary [7]. In addition, the acquired statistics will obviously impose a lower limit on the subsampling interval. For comparison purposes with the clinical step-and-shoot scan, this work did not investigate the role of axial subsampling.

To ensure a meaningful comparison every effort was made to reconstruct the data from both step-and-shoot and continuous bed movement acquisitions in exactly the same manner. The step-and-shoot data were reconstructed at each bed position using either a fully 3D-OSEM algorithm or the Fourier rebinning and 2D-OSEM algorithm that is currently standard on the PET/CT scanner. The continuous bed motion data is acquired and rebinned as one complete 3D sinogram set covering the entire axial extent scanned. The large size of the data set currently precludes reconstruction as a single 3D volume and therefore it was divided into sub-volumes. Each sub-volume can then be reconstructed with the identical algorithm and smoothing parameters as the step-and-shoot to ensure a meaningful comparison. For the reasons stated earlier, the normalization files are computed differently whereas the attenuation correction factors are the same.

The differences between the two acquisition methodologies are expected to be subtle except potentially in the overlap region between two bed positions where a more significant improvement in signal-to-noise should occur, as observed by Brasse et al. [9]. For the patient shown in Figure 3, there is improved definition of FDG uptake in the spine and mediastinum with continuous bed motion, and more uniform activity in the liver (lower noise). The apparent lower activity in the brain is due to the different axial scan ranges (73.2 cm for step-and-shoot and 50.4 cm for continuous bed motion). For the patient shown in Figure 4, low levels of activity in the ribs are more clearly seen on the transaxial section acquired with continuous bed motion. Again, the activity in the spine shows improved definition. Similar improvements can be observed for the patient shown in Figure 5. Comparable subtle differences were also reported in previous studies [7, 9] acquired in 3D. Obviously such improvements in noise structure and image quality do not apply to PET images acquired in 2D where the SNR is already uniform.

The primary aim of continuous bed motion acquisition is to achieve a uniform signal-to-noise throughout the axial extent scanned. This can only be achieved with step-and-shoot by increasing the overlap between bed positions which is a less efficient approach. Since the axial sampling can be chosen based on the bed speed and the available statistics, artifacts that have been identified [5, 6] due to axial undersampling can be reduced or eliminated. The need for full 3D volume normalization is eliminated because every line-of-response is viewed by multiple pairs of detectors. Thus, the detector normalization can be simplified by integrating the correction factors in the axial direction, and the noise introduced by normalization can be reduced. Therefore, by reducing noise and increasing axial sampling, there is a potential to improve the detectability of lesions, especially those in the overlap region between two bed positions. Finally, by eliminating the sudden, periodic movement of the bed, patients are able to rest quietly reducing the possibility of sudden small movement as the bed starts and stops.

To date, much of the effort to evaluate continuous bed motion acquisition has been quantified on phantoms, with only a subjective visual assessment of a small number of patient studies. This work is no exception, and it is important to collect a sufficiently large sample of patients scanned with both methodologies to be able to make an objective assessment of the benefits of continuous bed motion. Now that the tools are available to acquire and reconstruct continuous bed motion data routinely, the future focus of this work will be to collect a significant number of patient studies. Such studies should provide a definitive assessment of the advantages or otherwise of continuous bed motion acquisition. The indications are, however, from this and earlier work, that there are definite advantages to performing 3D whole-body PET scans with continuous movement of the patient bed.

V. CONCLUSION

This work has explored the feasibility of performing PET acquisitions on a state-of-the-art combined PET/CT scanner with a continuous movement of the patient bed. The results suggest that improved signal-to-noise and image quality can be obtained with slow, continuous bed movement although further work is required to quantify these benefits in patient studies.

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