Automatic Cardiac Gating of Small-animal PET from List-mode Data

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***Abstract*— This work presents a method to obtain automatically the cardiac gating signal in a PET study of rats, by employing the variation with time of the counts in the cardiac region, that can be extracted from list-mode data. In an initial step, the cardiac region is identified in the image space by backward-projecting a small fraction of the acquired data and studying the variation with time of the counts in each voxel inside said region, with frequencies within 2 and 8 Hz. The region obtained corresponds accurately to the left-ventricle of the heart of the rat. In a second step, the lines-of-response (LORs) connected with this region are found by forward-projecting this region. The time variation of the number of counts in these LORs contains the cardiac motion information that we want to extract. This variation of counts with time is band-pass filtered to reduce noise, and the time signal so obtained is used to create the gating signal. The result was compared with a cardiac gating signal obtained from an ECG acquired simultaneously to the PET study. Reconstructed gated images obtained from both gating information are similar. The method proposed demonstrates that valid cardiac gating signals can be obtained for rats from PET list-mode data.**

***Index Terms*— Image reconstruction, Positron emission tomography, Cardiac Gating, self-gating, automatic gating, list mode data**

I. Introduction

CARDIAC motion blurs PET imaging of the heart, which causes a degradation of spatial resolution. This leads to incorrect SUV values and inaccurate quantitative measurements. It is especially important when a ROI in the left ventricle is used to obtain the blood input function [1].

Cardiac and respiratory gating has been used for years in humans [2] and small animal PET scanners [1,3]. In these studies, cardiac motion was estimated by hardware-based mechanisms, recording for instance ECG signals and volume changes. However, this additional equipment may not be available or may not work properly, and thus, it would be highly desirable to reconstruct an adequate cardiac gating signal without any additional equipment.

Automatic gated motion detection has been proposed to correct for cardiac and respiratory motion in humans [4-7]. In these works, in order to estimate respiratory and cardiac motions, the variation of the number of counts with time was studied in the whole acquisition [4], as a function of the counts in a few axial slices [5], as a function of counts in some voxels of the reconstructed images [6], or as a function of counts in large sinogram bins [7].

However, to the best of our knowledge, these kind of automatic cardiac gating methods have not been applied yet to small animal PET acquisitions. Cardiac frequency of rats, of the order of 4 Hz, is significantly higher than human one. This implies that the number of counts detected in each cycle is small, and thus the determination of the cardiac motion is more challenging than for human PET acquisitions.

In this work, we present the results of a cardiac-gated study of a rat obtained without any external signal, performed with the ARGUS scanner [8], a small animal PET scanner that achieves a resolution of 1 mm with iterative reconstruction [9]. This demonstrates the ability of performing cardiac gating in rats based only on list-mode PET data.

Due to the low number of coincidences acquired in each cardiac cycle, it was necessary a precise selection of the region with the most significant variations in the expected heartbeat frequencies (left ventricle). In these small-animal acquisitions, we were unable to employ methods based on the variation of counts in the whole acquisition or on each slice, because they do not provide enough signal-to-noise ratio (SNR) to determine the cardiac motion.

The proposed procedure for obtaining the cardiac gating signal is general and may be applied to other PET scanners, as long as their sensitivity is high enough to collect enough number of counts in each heartbeat.

II. Materials and Methods

A. Data Acquisition

The data was acquired with the high-resolution small-animal PET scanner ARGUS [8]. This scanner acquires data in list-mode files that are by default stored as LOR-histogram files [10]. Nevertheless, it may also acquire and store data for dynamic and gated acquisitions in list-mode files. These files store the LOR number, which defines crystal detector pair, for

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each measured coincidence in an event-by-event basis, plus time information. External information from respiratory and cardiac measurements can be included in the list files in steps of the order of one ms. The transaxial FOV of the scanner was 68 mm and the axial one 48 mm. Two acquisitions of 10 and 30 minutes of a 220 g Wistar rat injected with 35 MBq of FDG were used for this study.

The procedure followed to locate the cardiac region and the cardiac motion is schematically displayed in Fig. 1.

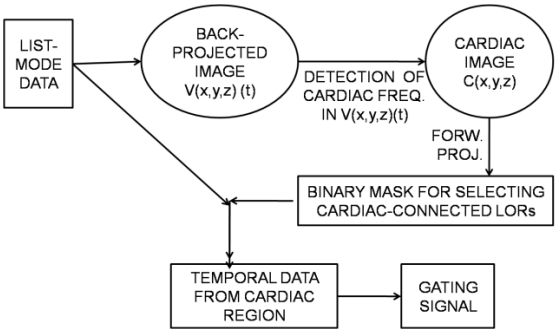

Fig. 1. Flowchart of data processing.

B. Automatic Location of the Cardiac Region

In this section we describe the main steps followed to find automatically the position of the left-ventricle. To this end we used the variation of counts with time at typical heartbeat frequencies of rats. Only those voxels located at the cardiac region have a significant count variation at those frequencies.

For this analysis, it is not necessary to use all the acquired data. A small fraction of the measured coincidences of about 30 seconds is enough to find the cardiac region accurately. Thus, the total time required to obtain and verify that a useable cardiac signal is available is very modest. This would allow for on-line implementation of this procedure during data acquisition.

In a first step, list-mode data are fully-3D back-projected, without any filtering, into a low resolution image of 55 × 55 × 21 voxels. These images are stored in steps of 33 ms. The size of the voxels and the temporal bin size ensure well enough spatial and time resolution, while also accumulating enough number of counts in each voxel. Several thousands of these images are obtained, corresponding to about 1 minute acquisition. Image samples obtained with this procedure are shown in Fig. 4. This requires less than one minute in a single CPU. In case necessary, this could be speed-up using modern and powerful GPUs [11]. A sinogram with all the counts accumulated in the time bins is also stored for further analysis.

The variation of counts in each individual voxel of the back-projected images along time frames is then analyzed in the frequency domain with a FFT algorithm. The resulting spectrum is smoothed using an average window to obtain the maximum amplitude of the signal (Max) inside the spectral range explored of 2 Hz - 8 Hz. On the other hand, the background (bg) level of the spectral amplitude spectrum is also obtained. The cardiac motion signal-to-noise ratio (CM-SNR) obtained in the frequency domain is then defined as:

$$\mathrm{CM-SNR} = \left(\frac{\mathrm{Max} - \mathrm{bg}}{\mathrm{bg}} \right)^2 \qquad (1)$$

An image of 55×55×21 voxels containing the values of the heartbeat SNR is stored. A threshold of 1/3 of the maximum CM-SNR value is used in order to separate the cardiac region from the rest of the image. The region obtained for the left-ventricle can be compared with an FBP image computed from the accumulated sinogram. Despite the poor image quality of this image, it allows for a quick verification of the correct region identification (see Fig. 3).

C. Automatic Cardiac Gating

Once the cardiac region has been identified, LORs connected to it are determined by fully-3D forward-projection of the cardiac region identified in the image with the method previously described. Again, this requires less than 1 minute in a single CPU. A binary (connected / not connected) mask is obtained for all the LORs. Only those data in the list-mode acquisition that appear in a LOR connected to the cardiac region are used to study cardiac motion. This is a very important step in order to increase the SNR for the cardiac signal. Thus, all events in the list-more data are read and weighted by the binary mask. The resulting total number of coincidences organized in 33 ms time bins are stored.

The 1-dimensional data obtained from the selected LORs are analyzed in the Fourier domain. A significant peak at 4 Hz can be found, as shown in Fig. 2. In order to reduce the effect of variations of the heartbeat of the rat during the PET acquisition or any cardiac arrhythmia, the Fourier analysis may be performed using a sliding time window of a few minutes. This will be further investigated in a future work.

The time data is then band-pass filtered at the central frequency of the peak. A second-order Butterworth filter was used for this task. The filtered data represent the variation of counts in the left ventricle caused by the heartbeat. In order to obtain a gating signal from them, it is required to choose the phase of the cardiac cycle that will represent the time mark. Zero-crossing of the signal with the time axis, estimated from linear interpolation to increase time resolution, was employed.

In the last step, using the gating signal as a reference, list-mode data are then divided into several (seven, in the example presented here) independent gated frames. Data are stored in LOR-histogram files for each gate, which is the usual format used for this scanner.

The gated frames are finally reconstructed separately with the fully-3D iterative reconstruction code FIRST [9] with 1 iteration and 40 subsets. The number of voxels in these gated reconstructed images was set to 175 × 175 × 61. FIRST (fast iterative reconstruction software for (PET) tomography) implements a fully 3D iterative reconstruction of PET data based on a realistic model of radiation emission and detection.

D. Validation of the Results

The dependence of the quality of the automatic location of the cardiac region on the length of data used was studied via the detectability of the cardiac region defined based on the Rose model of statistical detection as [12]:

$$Detectability = \frac{C - B}{3\sigma_B} \quad (2)$$

where C is the average value in the cardiac region, B is the mean background evaluated 10 mm away from the cardiac region and σ_B is the background standard deviation.

In order to validate the method, the resulting gated signal was compared to the one obtained with an external cardiac signal, which can be considered as gold standard. The external signal was acquired by equipment specifically developed to record and analyze the ECG signal from small animal and to yield the binary gate signal indicating the beginning of every cardiac cycle. This external gate is also available in the data acquired in this work.

Thus, gated-data based on this external signal or with the self gate obtained with the method proposed in this work, were reconstructed. The resulting images are shown in Fig. 5.

III. RESULTS

The frequency spectrum for the counts of a voxel located in the left ventricle is shown in Fig. 2. It can be seen that, due to cardiac motion, there is a clear peak at around 4 Hz. This peak is not present in voxels far from the cardiac region other. The position and width of this peak corresponds to the ones seen in the spectrum of the external ECG gating signal.

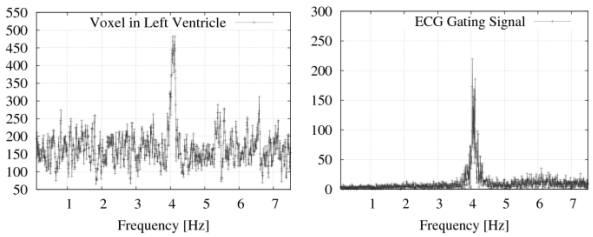

Fig. 2. Frequency spectrum of the counts in a voxel in the left-ventricle (left), obtained with the procedure described in this work, and from the external ECG gating signal (right).

The results from the method outlined in this work to locate the cardiac region can be seen in Fig. 3. On the left, the image obtained from the CM-SNR in each voxel is shown. In the center, a reconstructed low-resolution FBP image obtained with the same data used to locate the heart is displayed. On the right, the FBP image is shown combined with the SNR image after being segmented with a threshold. It can be seen that the region with highest CM-SNR correspond to the left ventricle.

The impact on the ability of identifying the cardiac region of the number of data used, is shown in Fig. 4, where the detectability of the cardiac region, as defined in (2), increases with the number of data. In the first case (A), 500 time bins of 33 ms were used. The detectability is then 1.1, which indicates that the cardiac region could only be detected with difficulty. In the second case (B), the number of time bins is 1000 and in this case, the resulting detectability is 6.4, high enough to identify the heart adequately. In the last case (C), with 4000 time bins (132 seconds of acquisition), the detectability jumps to 24.3.

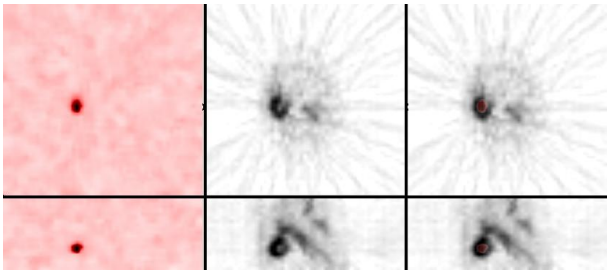

Fig. 3. Low-resolution image with the CM-SNR values, which gives the location of the cardiac region (left), low-resolution FBP image obtained from a small fraction of the data (center), and both images combined with the threshold applied to segment the cardiac region (right). In the three cases, transverse (above) and coronal (below) views of the images are shown.

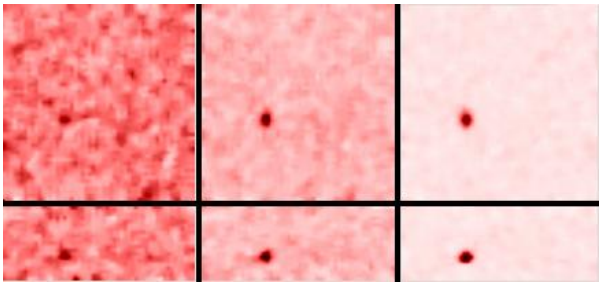

Fig. 4. Detectability of the cardiac region as a function of the number of time bins of 33 ms taken for the analysis.. 500 bins (A), 1000 bins (B), and 4000 bins (C).In the three cases, the transverse (above) and coronal (below) view of the images are shown.

Finally, the images reconstructed with the 3D-OSEM iterative reconstruction software FIRST, gated with the external signal and with the method proposed in this work are compared in Fig. 5.

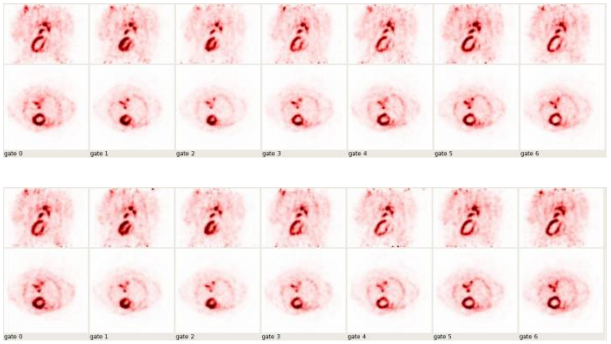

Fig. 5. Image reconstructed from five seven frames gated from the external ECG signal (top) and from the self-estimated signal (bottom). In both cases, transverse (above) and sagittal (below) view of the images are shown.

Transverse and sagittal views of each reconstructed gated image is shown in Fig. 5. It can be seen that in both cases the motion of the heart is adequately frozen.

IV. Conclusions

In this work, an automatic cardiac gating procedure for small-animal PET acquisitions is proposed. The results shown here, demonstrate that it is possible to obtain the gating signal in a list mode PET acquisition of a rat, simply by studying the variation with time of the counts in the cardiac region. Furthermore, we propose a procedure to automatically identify the heart in the image space by means of fast back-projecting a small fraction of the acquired data. This localization procedure can be also used for other purposes, such as cardiac segmentation.

These results have been compared with the ones obtained with a gating signal from external ECG recording and analyzing equipment. The agreement between both sets of gated images is very good, with a high correlation between them. The method is currently being applied to more acquisitions and it is being extended to mice. Automatic respiratory motion detection in rats will also be explored in a future work.

This code has been tested with acquisitions from the small-animal PET scanner ARGUS. This procedure is quite general and may be applied to other PET scanners. It only requires list-mode data and that the count rate in these studies is high enough to have good SNR.

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