Impact of respiratory motion correction on SPECT myocardial perfusion imaging using a mechanically moving phantom assembly with variable cardiac defects

Irene Polycarpou, PhD, a,b Isabelle Chrysanthou-Baustert, PhD, c Ourania Demetriadou, MD, d Yiannis Parpottas, PhD, c,e Christoforos Panagidis, MD, f Paul K. Marsden, PhD, a and Lefteris Livieratos, PhD a,g

a Division of Imaging Sciences and Biomedical Engineering, King’s College London, London, United Kingdom
b Department of Health Sciences, European University Cyprus, Nicosia, Cyprus
c Frederick Research Center, Nicosia, Cyprus
d Department of Nuclear Medicine, Limassol General Hospital, Limassol, Cyprus
e General Department (Physics-Mathematics), Frederick University, Nicosia, Cyprus
f Department of Nuclear Medicine, Nicosia General Hospital, Nicosia, Cyprus
g Guy’s and St Thomas’ Hospitals NHS Foundation Trust, London, United Kingdom

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Background. The aim of this study was to determine the impact of respiratory motion correction on SPECT MPI and on defect detection using a phantom assembly.

Methods. SPECT/CT data were acquired using an anthropomorphic phantom with inflatable lungs and with an ECG beating and moving cardiac compartment. The heart motion followed the respiratory pattern in the cranio-caudal direction to simulate normal or deep breathing. Small or large transmural defects were inserted into the myocardial wall of the left ventricle. SPECT/CT images were acquired for each of the four respiratory phases, from exhale to inhale. A respiratory motion correction was applied using an image-based method with transformation parameters derived from the SPECT data by a non-rigid registration algorithm. A report on defect detection from two physicians and a quantitative analysis on MPI data were performed before and after applying motion correction.

Results. Respiratory motion correction eliminated artifacts present in the images, resulting in a uniform uptake and reduction of motion blurring, especially in the inferior and anterior regions of the LV myocardial walls. The physicians’ report after motion correction showed that images were corrected for motion.

Conclusions. A combination of motion correction with attenuation correction reduces artifacts in SPECT MPI. AC-SPECT images with and without motion correction should be simultaneously inspected to report on small defects. (J Nucl Cardiol 2015)

Key Words: SPECT/CT • myocardial perfusion defects • motion correction • cranio-caudal cardiac motion
INTRODUCTION

In clinical SPECT studies, respiratory motion limits the performance of MPI studies. Heart motion induced by respiration affects SPECT acquisition in two ways.\(^1\) First, spatial misalignment between sequentially acquired SPECT and CT may affect attenuation correction of the emission data since SPECT images are acquired for substantially longer time than the CT images. Various studies have shown that such a misalignment may cause image artifacts and under- or over-estimation of tracer activity.\(^2\) Furthermore, respiration may lead to image blurring along the direction of motion, primarily in the cranio-caudal direction, due to the fact that SPECT data are averaged over many respiratory cycles. This can result in misleading displacement of uptake affecting the perceived regional localization in the myocardial walls.\(^3,4\) Motion-induced artifacts can be a source of false-positive findings and may be interpreted as ischemia affecting the diagnosis of coronary artery disease.\(^5\)

A non-uniform blurring of MPI due to motion induced by respiration\(^6\) may affect the ability to detect defects.\(^6\) The respiratory motion of the heart has been previously investigated using computational\(^4\) and physical phantoms.\(^3,4\) It was simulated on physical phantoms with a static cardiac compartment\(^8\) being on an oscillating plate or with static cardiac compartments\(^3,9,10\) inserted within torso phantoms and then being on oscillating plates. The effects of respiratory motion on MPI non-uniformity and on the resulting false-positive rates have also been reported.\(^3,4\) A common method to compensate for motion effects is data gating which divides the motion cycle into a number of gates based on either time or amplitude.\(^7,11\) Further, the respiratory motion of the heart on physical phantoms\(^8,10\) was corrected using motion correction algorithms. However, limited studies, only with computational phantoms\(^6\) using the channelized Hotelling observer algorithm, reported on the effects of respiratory motion on myocardial defect detection.

In this study, the impact of respiratory motion correction on MPI and on defect detection was investigated for heart motion amplitudes of normal and deep breathing. An anthropomorphic phantom, with inflatable lungs, and an ECG beating and moving cardiac compartment, was used to simulate the heart respiration motion. Motion correction was applied using an image-based method with transformation parameters derived from the SPECT data by a non-rigid registration algorithm. SPECT/CT images were acquired for each of the four respiratory gates, from exhale to inhale, in normal and deep breathing modes of the phantom assembly. Defects could be inserted within the myocardial wall of the LV. Two physicians reported on defect present or absent before and after correcting for motion of the AC-SPECT images. A comparison of the quantitative analysis and physicians’ reports before and after motion correction is presented.

MATERIALS AND METHODS

Phantom Assembly

A cardiac phantom of an ECG beating and moving left ventricle with variable defects, and a respiratory phantom of inflatable lungs, constructed at Frederick Research Center, were inserted into an anthropomorphic thorax phantom\(^12\) and used to simulate the heart motion during respiration using routine imaging conditions.

The cardiac phantom consisted of an inner–outer membrane system where the inner membrane represented an LV and the closed cavity within the inner and outer membranes represented the myocardial wall of the LV. Each 2-mm thick ellipsoidal membrane was made of transparent silicone with a density of 1.06 g/cm\(^2\). The end systolic volume was 42 mL and the LV myocardial wall volume was 90 mL. Diastole and systole could be achieved by pumping water into and out of the inner membrane using a stepper motor controlled by the PLC and a piston. Since the myocardial wall cavity was filled with water which is non-compressible, the pressure was transferred from the inner to the outer membrane (Figure 1A). The beating rate (60 beats/minute) and the ejection fraction (45%) followed the Wigger diagram. A 5% deviation was found using the Xeleris Myovation (GE Healthcare) compared to the set ejection fraction. Radionuclide could be injected within the myocardial wall cavity. Defects could be glued on the outer part of the inner membrane (Figure 2A). The ECG signal from a simulator was simultaneously propagated to the PLC to initiate diastole–systole and to the gating signal circuit which fed into the gamma-camera system to trigger gating of data acquisition.

The respiratory phantom consisted of human-sized silicone lungs (Figure 2B). The left lung air volume was 510 mL and the right lung air volume was 565 mL. Each lung was covered with a 1-mm-thick thermoplastic structures forming the lung shape at the inhalation phase allowing inflation in an anatomically correct manner. The breathing cycle and tidal
volume followed a sinusoidal exponential pattern. Two electro-proportional valves, controlled by the respiratory pattern equation in the PLC, regulated the air pressure with respect to time, entering in the lungs for inhalation and escaping from the lungs for exhalation, respectively (Figure 1B). This was achieved using two small pumps with suction and blowing ports that could be used as vacuum pumps and small compressors. The tidal volume was 450 and 550 mL for the normal and deep breathing, respectively. In both cases, the breathing cycle duration was 6 seconds. A 2% deviation was found using OsiriX compared to the set lung volumes.

The cardiac compartment could follow the respiratory pattern in the cranio-caudal direction at the level of the diaphragm. The mechanical system for this motion, a controlled motor by the PLC and a screwed rod, was attached to the outer base of the anthropomorphic phantom (Figures 1C, 3). The beating cardiac compartment was set to perform a maximum displacement of 1.5 and 2.7 cm for the normal and deep breathing conditions, respectively. All three motions could be independently or simultaneously controlled using a PLC.

The respiratory pattern was divided into four isochronous phases (from exhale to inhale). Thus, the breathing lungs and the moving heart could be mechanically stopped at any respiratory phase, as shown in Table 1, while the heart was continuously beating.

The Alderson tissue-equivalent anthropomorphic phantom for nuclear medicine (Radiology Support Devices, Inc.)
was used to simulate an average male and a large male by adding a thorax overlay, and a large female by adding breasts on the thorax overlay (Figure 3). The cardiac and lung compartments were anatomically hold within the thorax using a shaped thin solid-water slab. The thorax was hermetically closed and the rest of the cavity was filled with water to simulate the soft tissue.

**Data Acquisition**

Acquisitions were performed for three body types with no cardiac defects, with two small (0.5 cm thickness, 1 × 1 cm in extent) and with two large (1 cm thickness, 1 × 1 cm in extent) transmural defects. The defects were positioned at the anterior and inferior regions of the LV myocardial wall (Table 2). An activity of 15.5 MBq of Tc 99m was injected into the myocardium wall of the LV based on an estimate of 1.2% uptake of a clinically relevant administered activity.16

SPECT data were acquired in a GE Millennium VG gamma-camera with a single-slice Hawkeye CT at Nicosia General Hospital. Acquisitions were performed using a routine clinical protocol with Low-Energy High-Resolution collimators in 90° (L-mode) orientation. SPECT data were acquired in 60 projections over 180° of rotation on 64 × 64 matrix following the default clinical protocol at 20 seconds per projection. Data were acquired at the required respiratory phase while the heart was continuously beating. A 20% energy window was centered over the 140 keV photopeak of Tc 99m. CT images were acquired in the heart region with 10 mm slice thickness and a matrix size of 128 × 128. SPECT and CT images were acquired in each of the four respiratory phases for the normal and deep breathing, respectively (Table 2).

SPECT data were reconstructed using the ordered-subset expectation-maximization algorithm with three iterations and 16 subsets, as commonly used in clinical practice. The image matrix size was 64 × 64 × 19 with a voxel size of 6.9 × 6.9 × 6.9 mm. The Butterworth filter (cutoff: 0.52 cycles/cm, power: 5) was applied to the reconstructed images. Attenuation correction was applied based on CT-derived attenuation maps. SPECT data were generated with and without motion correction. All data were re-oriented to form short-axis images along the long axis of the LV processed by the same operator in the same way for all reconstructions with and without motion correction.

### Table 1. Lung volumes and cardiac displacement at each of the four respiratory phases, from exhale (phase-1) to inhale (phase-4), for the normal and deep breathing modes

<table>
<thead>
<tr>
<th>Phase</th>
<th>Normal breath</th>
<th></th>
<th>Deep breath</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume (mL)</td>
<td>Displacement (mm)</td>
<td>Volume (mL)</td>
<td>Displacement (mm)</td>
</tr>
<tr>
<td>1</td>
<td>1075</td>
<td>0</td>
<td>1075</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1201</td>
<td>5</td>
<td>1201</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>1373</td>
<td>10</td>
<td>1433</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>1538</td>
<td>15</td>
<td>1635</td>
<td>27</td>
</tr>
</tbody>
</table>

### Table 2. SPECT/CT acquisitions for the three body types, defect types, and breathing modes

<table>
<thead>
<tr>
<th>Body type</th>
<th>Defects</th>
<th>Breathing mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average male</td>
<td>None</td>
<td>Static, normal, deep</td>
</tr>
<tr>
<td></td>
<td>Two small</td>
<td>Static, normal, deep</td>
</tr>
<tr>
<td></td>
<td>Two large</td>
<td>Static, normal, deep</td>
</tr>
<tr>
<td>Large male</td>
<td>None</td>
<td>Static, normal</td>
</tr>
<tr>
<td></td>
<td>Two small</td>
<td>Static, normal, deep</td>
</tr>
<tr>
<td></td>
<td>Two large</td>
<td>Static, normal, deep</td>
</tr>
<tr>
<td>Large female</td>
<td>None</td>
<td>Static, normal, deep</td>
</tr>
<tr>
<td></td>
<td>Two large</td>
<td>Static, normal, deep</td>
</tr>
</tbody>
</table>

Figure 3. Photos of (A) average male, (B) large male, and (C) large female body types of the anthropomorphic phantom.
Motion Correction

Motion correction was applied using an image-based procedure. A non-linear registration algorithm\(^\text{17}\) was applied to register each of the reconstructed SPECT respiratory phases (gates) to the reference gate (lungs at the exhale phase and no heart motion) allowing for possible non-rigid motion patterns in the clinical setting in line with previous studies.\(^\text{18}\) In this way, transformation fields (i.e., displacement vectors between the reference gate and each of the other gates) describing the motion were obtained. The registration algorithm is fully automated voxelwise which estimates non-rigid motion by a combination of multiple local affine components based on an adaptive hierarchical structure.\(^\text{17}\) After deriving the motion fields, each gate was transformed to the reference gate and these were averaged to create the motion-corrected image.

A motion-corrected image was generated from the four SPECT/CT acquisitions obtained when the phantom assembly was mechanically stopped in each of the four respiratory phases, for each breathing mode, defect type, and body type (Table 2). In total, fifteen motion-corrected AC-SPECT images (8 for the normal and 7 for the deep breathing modes) were generated. These images were compared with the corresponding AC-SPECT images (SPECT with breathing lungs and moving heart, and AC with CT at the reference gate). Figure 4 shows an example of co-registration of SPECT with CT.

Image Assessment

The motion-corrected AC-SPECT images were qualitatively and quantitatively compared to the AC-SPECT images to assess the effectiveness of motion correction in reducing motion artifacts. For the quantitative comparison, the percentage increase of the myocardial perfusion uptake values after applying motion correction was calculated for each of the 17 segments of the polar maps.

Two experienced nuclear medicine physicians reported on images without defects and with one or two defects. The physicians did not know about the phantom parameters or image correction (AC, MC). The physicians reported on the defect absence or presence. The physicians’ report was correct if the defect position was correctly identified. The results from the report on each defect were evaluated as True Positive (TP), True Negative (TN), False Positive (FP), and False Negative (FN).

Figure 4. Example of transverse, coronal, and sagittal planes of the registered SPECT and CT for the average male with no defects.

RESULTS AND DISCUSSION

Figure 5 shows SPECT images of the four respiratory phases obtained for the large female with no defects performing normal breathing. Figures 6 and 7 show AC-SPECT images without motion and performing normal and deep breathing before and after MC, obtained for the average male with no defects and the large female with large defects, respectively. Motion-induced artifacts cause seemingly reduced anterior and inferior wall uptake introducing false-positive findings. The corresponding polar maps of Figure 7 are shown in Figure 8 together with the percentage increase of the myocardial perfusion uptake for each LV segment after applying motion correction. A visual inspection of the AC-SPECT images shows that motion due to respiration causes blurring and defect smearing implying a much extensive disease compared to the motion-corrected images. In particular, heart motion due to respiration causes under-estimation of the tracer uptake mainly in the inferior and anterior regions of the LV myocardial wall. This was also reported in previous studies.\(^\text{3,4,7}\) The apical artifact observed in some figures is due to a solid-water square cross (0.5 cm side, 1 mm thickness) attached at the apex of the cardiac compartment to prevent the inner membrane touching the outer membrane during diastole.

Motion correction substantially reduces the motion-induced artifacts due to respiration observed in both SPECT slices and polar maps. In particular, images after motion correction result in more uniform uptake and reduction of motion blurring, a thinner appearance of the heart wall, especially in the inferior and anterior regions of the LV myocardial wall. An increase of the uptake values was also observed in the septal and lateral regions after motion correction but not as severe as that observed in the inferior and anterior regions. After motion correction, the percentage increase of the MPI uptake values in the anterior and inferior regions was 18% for normal and 35% for deep breathing, while the corresponding increase in the apical, septal, and lateral regions was 7% for normal and 9% for deep breathing. The quantitative analysis shows that after motion correction, there is major improvement in the inferior and anterior regions which are expected to be more affected by motion.

Figures 9 and 10 show SPECT images with (A) non-AC and non-MC, (B) AC and non-MC, (C) non-AC and MC, and (D) AC and MC, for the average male with small defects performing normal and deep breathing, respectively. Motion correction does not recover the uptake without applying attenuation correction. Applying only attenuation correction does not eliminate blurring in the anterior and inferior regions due to
motion. The extent of improvement depends on the amplitude of the heart motion.

Two physicians reported on the presence or absence of cardiac defects in AC-SPECT images, with non-MC and MC, for the normal and deep breathing modes. The physicians’ results were considered to be in very good agreement (Cohen’s Kappa coefficient: 0.86). Motion led to FP due to artifacts. For example, when no motion was present in phantoms with no defects, the physicians reported no defects, which led to a TP evaluation. However, when the phantoms with no defects performed normal and deep breathing, the physicians reported false

Figure 5. SPECT slices of short, horizontal long, and vertical long axis, obtained for the large female with no defects, performing normal breathing: (A) gate-1; (B) gate-2; (C) gate-3; (D) gate-4.

Figure 6. AC-SPECT slices of short, horizontal long, and vertical long axis, obtained for the average male with no defects, without motion (A) and performing normal (B, C) and deep (D, E) breathing before (B, D) and after MC (C, E).
defects in 4 out of 6 images and in 3 out of 4 images, respectively, which led to an FP evaluation.

The 12 large defects were correctly reported in all AC-SPECT images, that is, when the phantoms were in static, normal, and deep breathing modes. Only 4 out of the 8 small defects were reported in the AC-SPECT images, when motion was not present (Table 3). However, when the phantoms performed normal and deep breathing, all 8 small defects were reported in the AC-SPECT images. This is because the defects were located...
Figure 9. Slices of short, horizontal long, and vertical long axis obtained for the average male with small defects performing a normal breathing: (A) non-AC and non-MC; (B) AC and non-MC; (C) Non-AC and MC; and (D) AC and MC.

Figure 10. Slices of short, horizontal long, and vertical long axis obtained for the average male with small defects performing a deep breathing: (A) non-AC and non-MC; (B) AC and non-MC; (C) Non-AC and MC; and (D) AC and MC.
in the anterior and inferior regions in which the uptake values were mainly reduced due to motion-induced artifacts. This was also reported in a similar study with the NCAT phantoms. A combination of motion correction with attenuation correction enhanced the reduction of artifacts. Attenuation correction improved the uptake values in the basal segments, while motion correction improved the uptake values in the anterior and inferior regions and to a lesser extent in the lateral and septal regions. Applying motion correction on AC-SPECT images, the uptake values were increased in the anterior and inferior regions, in which the small defects were located, with the result 50% of the defects to be reported and evaluated as FN, as in the case of static phantoms. 

Table 3. Evaluation of physicians’ report (TP, FN) for the 8 small defects

<table>
<thead>
<tr>
<th>AC static</th>
<th>AC normal</th>
<th>AC+MC normal</th>
<th>AC deep</th>
<th>AC+MC deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>TP</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

AC and MC were applied on SPECT MPI data for phantoms in static, normal, and deep breathing modes.

A combination of motion correction with attenuation correction reduces artifacts in SPECT MPI. In AC-SPECT images, small defects located on the anterior and inferior regions of the myocardial wall of the left ventricle become more visible due to motion-induced artifacts. AC-SPECT images with and without motion correction should be simultaneously inspected to be able to report on small defects. The defects smeared by the respiratory motion implying a much extensive disease compared to the motion-corrected images leading to misleading interpretation. Therefore, motion correction is important for better diagnosis as it decreases the smearing effect. Motion correction does not fully recover the uptake without applying attenuation correction, provided that no misalignment between emission and transmission data is present or has been corrected for.

CONCLUSIONS

This study investigated the impact of respiratory motion correction on AC-SPECT MPI and on defect detection using a moving phantom assembly with cardiac defects. The inflatable lungs, and the ECG beating and moving LV during respiration, simulated normal and deep breathing. SPECT/CT data were acquired for each of the four respiratory phases, from exhale to inhale, in normal and deep breathing modes of the phantom assembly. These SPECT/CT images were used to generate the motion-corrected images. A non-linear registration algorithm was applied to register each of the four reconstructed respiratory phases to a reference gate to obtain the transformation fields and generate motion-corrected images. The quantitative analysis on AC-SPECT images and the physicians’ report on defect presence or absence, before and after applying motion correction, were evaluated.

Motion correction results in more uniform uptake and reduction of motion blurring, especially in the inferior and anterior regions. The extent of improvement depends on the amplitude of the heart motion displacement. A combination of motion correction with attenuation correction enhanced the reduction of artifacts. Respiration motion has more significant effects on the detection of small defects. In AC-SPECT images, small defects located on anterior and inferior regions become more visible due to motion-induced artifacts. AC-SPECT images with and without motion correction should be simultaneously inspected to be able to report on small defects.

This study is limited by the fact that it simulates only the cranio-caudal displacement of the heart during respiration. Also, defect detectability in the lateral and septal wall was not investigated. The respiratory phases were acquired sequentially and not continuously as observed in real patients. Further limitations may be due to phantom assembly (e.g., chest wall expansion, liver and heart twisting).

Future studies will investigate more realistic conditions of respiratory patterns and cardiac motion amplitudes as well as defects in other regions of the LV. Ultimately, such effects shall be studied in future by investigating real patient cohorts with respiratory-gated acquisition.
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Disclosure

The authors declared that they have no conflict of interest.

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