A flexible multicamera visual-tracking system for detecting and correcting motion-induced artifacts in cardiac SPECT slices

Joseph E. McNamara, P. Hendrik Pretorius, Karen Johnson,
Joyeeta Mitra Mukherjee, and Joyoni Dey
*Department of Radiology, University of Massachusetts Medical School, 55 Lake Avenue North,
Worcester, Massachusetts 01655*

Michael A. Gennert
Worcester Polytechnic Institute, 100 Institute Road, Worcester, Massachusetts 01609

Michael A. King^{a)}
*Department of Radiology, University of Massachusetts Medical School, 55 Lake Avenue North,
Worcester, Massachusetts 01655*

(Received 12 August 2008; revised 8 March 2009; accepted for publication 23 March 2009;
published 27 April 2009)

Patient motion is inevitable in SPECT and PET due to the lengthy period of time patients are imaged. The authors hypothesized that the use of external-tracking devices which provide additional information on patient motion independent of SPECT data could be employed to provide a more robust correction than obtainable from data-driven methods. Therefore, the authors investigated the Vicon MX visual-tracking system (VTS) which utilizes near-infrared (NIR) cameras to stereo-image small retroreflective markers on stretchy bands wrapped about the chest and abdomen of patients during cardiac SPECT. The chest markers are used to provide an estimate of the rigid-body (RB) motion of the heart. The abdomen markers are used to provide a signal used to bin list-mode acquisitions as part of correction of respiratory motion of the heart. The system is flexible in that the layout of the cameras can be designed to facilitate marker viewing. The system also automatically adapts marker tracking to employ all of the cameras visualizing a marker at any instant, with visualization by any two being sufficient for stereo-tracking. Herein the ability of this VTS to track motion with submillimeter and subdegree accuracy is established through studies comparing the motion of Tc-99m containing markers as assessed via stereo-tracking and from SPECT reconstructions. The temporal synchronization between motion-tracking data and timing marks embedded in list-mode SPECT acquisitions is shown to agree within 100 ms. In addition, motion artifacts were considerably reduced in reconstructed SPECT slices of an anthropomorphic phantom by employing within iterative reconstruction the motion-tracking information from markers attached to the phantom. The authors assessed the number and placement of NIR cameras required for robust motion tracking of markers during clinical imaging in 77 SPECT patients. They determined that they were able to track without loss during the entire period of SPECT and transmission imaging at least three of the four markers on the chest and one on the abdomen bands 94% and 92% of the time, respectively. The ability of the VTS to correct motion clinically is illustrated for ten patients who volunteered to undergo repeat-rest imaging with the original-rest SPECT study serving as the standard against which to compare the success of correction. Comparison of short-axis slices shows that VTS-based motion correction provides better agreement with the original-rest-imaging slices than either no correction or the vendor-supplied software for motion correction on our SPECT system. Comparison of polar maps shows that VTS-based motion-correction results in less numerical difference on average in the segments of the polar maps between the original-rest study and the second-rest study than the other two strategies. The difference was statistically significant for the comparison between VTS-based and clinical vendor-supplied software correction. Taken together, these findings suggest that VTS-based motion correction is superior to either no-motion correction or the vendor-supplied software the authors investigated in clinical practice. © 2009 American Association of Physicists in Medicine.
[DOI: [10.1118/1.3117592](https://doi.org/10.1118/1.3117592)]

Key words: cardiac SPECT, motion tracking, patient motion correction

I. INTRODUCTION

Patient motion is an ever-present potential cause of artifacts that can limit the accuracy of diagnostic imaging. The problem is especially significant for imaging modalities such as

SPECT and PET, which require the patient to remain motionless for protracted periods of time, and multimodality imaging, where patient alignment between the modalities is essential. For cardiac imaging, motion includes cardiac

contraction which is important for assessing function,¹ respiratory motion which results in a blurring of the superior and inferior heart walls,^{2,3} and voluntary patient movement of their body as a result of discomfort and other causes. In cardiac SPECT imaging, body motion has been reported to occur about 25% of the time and it is significant enough to cause artifacts which can mislead diagnosis in about 5% of cases.^{4,5} Only a small amount of motion is needed to reduce diagnostic accuracy.⁶ Generally, it has been reported that motion of two or more pixels (~ 13 mm) was enough to create minor to moderate defects in the tomographic data.^{4,5,7} A number of approaches relying solely on SPECT data to detect and compensate for motion have been described.^{8–13} While these methods have been shown to be able to correct motion in clinical acquisitions, none have proved robust enough for routine clinical usage in cardiac SPECT without caution being exercised by the clinician.

The use of external-tracking devices provides additional information independent of SPECT data that might be expected to result in a more robust correction than using only emission data. Following the work of others for head motion compensation in SPECT¹⁴ and PET,^{15–17} our group has been working toward developing a robust method to track and compensate for patient rigid-body (RB) and respiratory motions in cardiac SPECT.^{18–21} We have investigated employing infrared (IR) and optical cameras with their own source of illumination to track retroreflective markers on stretchy bands wrapped about the chest and abdomen of patients. These retroreflective markers are imaged with high contrast regardless of room lighting. Our motion-correction strategy is to isolate the body and respiratory motion components from the marker motion-tracking data to allow correction of both forms of motion. To this end, we have developed adaptive algorithms for the separation of these components.^{22,23} For the chest markers the component of interest is body motion. Its separation from respiratory motion is facilitated by the magnitude of respiratory motion being small even in the vertical direction for chest markers and respiratory motion being repetitive in nature. Thus respiratory motion is treated as a noise term which is smoothed out for the chest markers. A singular-value decomposition (SVD) is applied to the body motion components of the chest markers to obtain an aggregate six-degree-of-freedom (6-DOF) RB motion estimate which is employed to correct RB motion within iterative reconstruction.²⁴ The vertical motion of abdominal markers is used to obtain a signal employed in the correction of respiratory motion. This selection was based on the vertical motion of abdominal markers always exhibiting the largest effects of respiration. The abdominal marker with the largest respiratory component in the vertical direction after removal of body motion is used to amplitude bin list-mode SPECT data. These binned projection sets are then reconstructed with correction of RB motion and the 3D respiratory motion between the bins determined by registration of the heart in the slices.^{25,26} With the respiratory motion between the bins thus estimated, a second pass through reconstruction is performed resulting in a single set of slices with combined correction of body and respiratory motions.

Dependable marker viewing during SPECT imaging is limited by the detector heads rotating closely about the patient and patient anatomy masking the markers from being viewed. This has ultimately limited the clinical usage of the previous marker-tracking systems we have investigated, which have viewed patients from a single end of the SPECT imaging bed.^{18,19,21} We found better, but still less than ideal, operation when two independent tracking systems configured with two cameras each in a fixed geometry viewed patients from each end of the SPECT gantry.²⁰ We hypothesize that using more cameras which could be flexibly positioned and which acted together to provide stereo-tracking of the markers would further improve the robustness of marker tracking.

Herein we report on our adaptation to SPECT motion tracking of the Vicon MX system (Vicon Motion Systems, Los Angeles, CA) which meets these criteria, and thus theoretically offers the possibility of more robust tracking of patients. The system consists of MX3 cameras, an MX Ultraneet control box, and Vicon Nexus software. Each camera has an array of surface mounted LEDs, which emit a flash of near infrared (NIR) which is reflected back to the camera by the retroreflective coatings on the markers. This visual-tracking system (VTS) is flexible in that it allows the independent placement and alignment to the tracking volume of up to eight MX3 cameras per control box, with the combined usage of a number of control boxes as an option. This VTS is also flexible in that at any given time only two cameras need to see a marker for it to be tracked in 3D. That is, viewing the marker by any one out of all possible stereo-pairs is all that is required for 3D tracking. If more than one stereopair tracks the marker, the system automatically reports the location using all available pairs. In the following we describe the marker and camera configurations investigated, system calibration and stability, tests of the accuracy of spatial and temporal tracking, a clinical investigation of the number and placement of cameras needed for robust tracking, and the results of motion correction in ten cardiac SPECT studies.

II. MATERIALS AND METHODS

II.A. Retroreflective marker configuration

We tried a number of configurations for the markers used to track patient motion subject to several constraints. One constraint is that we need a design which is easy for a technologist to use so that there is no significant time penalty associated with use of motion tracking. Also, the markers must be held tightly against the patient body so that it is the patient and not the patient-independent movement of the marker which is being tracked. Further, the marker belt should not restrict patient breathing by being too binding. Finally, for infection control reasons, the design must be such that the portion which touches the patient is disposable and thus also inexpensive.

The configuration we arrived at mounts the markers on small carbon fiber posts which hold them approximately 1 cm off the patient's body surface. The markers and posts were obtained as a special order from Northern Digital, Inc. (Waterloo, ON, Canada). The 1 cm offset results in better

FIG. 1. Shown are the two belts of markers used in our patient studies for tracking rigid-body (chest markers) and respiratory (abdomen markers) motions. The chest markers are labeled c1–c4 and the abdominal markers a1–a4 for future reference when we discuss the ability of the VTS to track individual markers. Note during SPECT imaging patient arms are over their head and not at sides as shown here.

viewing of the markers by the VTS than when they were not raised from the patient surface and causes no change in how our technologists set up the camera orbit for acquisition of SPECT studies. Four of these assemblies were attached by Velcro to each of two 5-cm-wide stretchy self-adhesive bandages. We found that the posts, markers, Velcro, and bands caused an attenuation of approximately 2.5% for Tl-201 photons. Figure 1 illustrates two stretchy bands with four markers on each wrapped about the chest and abdomen of a volunteer. Using four markers per band provides some redundancy as we only need three noncollinear markers to calculate 6-DOF RB motion for the chest^{22,23} and one marker from the abdomen belt to monitor respiratory motion.

II.B. Setup of Vicon visual-tracking system

We mounted five Vicon MX3 cameras on the walls of the room out of the way of technologists and patients (Fig. 2), with three cameras viewing from the head end of the gantry and two viewing from the foot end. The goal of our setup was to raise the cameras viewing from the head end such that they could observe the markers on the chest of the patient unobstructed by the patient's head and arms. In cardiac perfusion SPECT imaging, the arms are typically raised above

FIG. 2. The three Vicon MX3 cameras facing the head end of SPECT/patient and the two MX3 cameras facing the foot end of SPECT/patient in our clinic.

the patient's head to keep them from being between the patient's heart and the detector heads. With three MX3 cameras at the head end we could still track a marker on the chest even if one of these cameras and both of the foot-end cameras were unable to view it. Elevating the MX3 cameras at the head end also allowed personnel to walk around that end of the imaging table as needed for patient care without interfering with the motion tracking. Raising the MX3 cameras at the head end does limit how far under the rotating gamma-camera heads they can view markers; the higher the cameras, the steeper the view angle, and thus the more restrictive the view of the markers. The two MX3 cameras on the wall at the gantry foot end allow viewing the markers on the patient's abdomen. These cameras are slightly elevated to enable the markers to be viewed over the patient's feet. They offer the possibility of also seeing the chest markers depending on the patient's anatomy.

The MX3 cameras were aligned to the desired viewing volume between the heads of the SPECT system by placing a reflective marker in the center of this volume and then adjusting the camera mounts manually until the marker was seen at the center of the 2D image recorded by each of the five cameras. The mounts holding the cameras were then locked in place to minimize the chance of moving. We selected manual alignment as opposed to computer-driven control of camera pan and tilt based on our past experience with such control in stereo-imaging where we observed drift over time and nonreproducibility of camera orientation even when the computer instructs the cameras to return to the same pan and tilt.²¹

II.C. Calibration of stereoinaging for motion tracking

The MX3 cameras map locations in the 3D world they are imaging onto 2D camera images. Modeling this process necessitates the determination of a number of parameters intrinsic to each camera and the extrinsic parameters of the camera pose in some coordinate system.^{27,28} Calibration is the process of determining these parameters such that stereo-mapping of the 3D volume viewed by the VTS can be accurately performed.

Calibration for motion tracking of the MX3 cameras of the VTS consists of two steps. In the first step, a three-marker wand (Fig. 3, left) of known marker geometry is waved throughout the tracking volume as snapshots are taken with all connected cameras. All of the camera parameters, including any nonlinear lens effects, are calculated.²⁹ This process takes only a couple of minutes and is carried out each morning before the Vicon VTS is employed for motion tracking.

At the end of the wand calibration step, the Vicon VTS tracks motion relative to the center of the image plane and camera axis of one of the five MX3 cameras. In the past, we have applied a coordinate transformation to map locations measured by VTS systems to the coordinate system we use for SPECT with the origin as the center of the field of view for the lateral, vertical, and axial axes of the reconstruction volume.^{18,19,21} This transformation was determined via

FIG. 3. At the left is shown the three-marker wand which is waved throughout the tracking volume for 1–2 min to calibrate the Vicon VTS system. At center is shown the seven-sphere phantom used to determine the transformation to map VTS coordinates to SPECT coordinates. At the top of each rod is a small well into which Tc-99m is added and then the retroreflective marker is screwed onto the rod so that the activity is positioned approximately at the center of the marker. At the right is shown an “L-marker” tool rigidly mounted out of the way of the technologists and patients on the back side of the SPECT gantry. Once the coordinate transformation between the VTS and SPECT systems has been initially determined from the seven-sphere phantom, the L-marker tool is used thereafter by the Vicon system to automatically map the reporting of markers such that they are in SPECT coordinates.

SVD³⁰ analysis based on the location in 3D of seven markers containing a small amount of Tc-99m at their center when measured by the VTS and the SPECT system (Fig. 3, center). The Vicon VTS enables this second step of calibration to be performed such that all locations it reports are in the coordinate system of our SPECT camera. To do this one images with the Vicon VTS a tool with four markers in a plane arranged in the shape of an “L.” Three markers of this tool form the longer side of the L and the fourth forms the bottom portion of the L which is perpendicular to the axis of the other three markers. We have rigidly mounted the L-marker tool on the back side of the gantry of our SPECT system in a location which is stationary during SPECT imaging. This location is on a portion of the gantry which is never removed during servicing of the system and out of the way of the patient’s feet so as not to be disturbed (Fig. 3, right). The location of these four markers in the SPECT coordinate system is obtained once by determining the transformation between the native Vicon coordinate system and the SPECT coordinate system using the seven-marker phantom. The L-marker tool is then imaged by the Vicon VTS, and the VTS to SPECT transformation is applied to the L-marker VTS determined locations. The SPECT locations of these markers are stored in a parameter file for use by the Vicon VTS. Each morning the L-marker tool is imaged by the Vicon VTS. The Vicon then uses these locations of markers to report in the SPECT coordinate system all subsequent measurements.

II.D. Stability of VTS determination of spatial locations over a 6 month period

We investigated the stability of VTS determination of spatial location over a 6 month period by determining the locations of the four markers of the L-marker tool once per month. The locations were recorded in the native VTS coordinates just after using the wand to calibrate the system. During this period of time two to four of the cameras were

removed several times from their wall mounts, used for motion tracking with other medical-imaging systems, and then returned to the wall mounts.

II.E. Investigation of accuracy of motion tracking

We investigated the accuracy of motion tracking in both the vertical and axial directions by imaging with both SPECT and the VTS a phantom consisting of seven retroreflective spherical markers each containing a small amount of Tc-99m at their center (Fig. 3, center). The phantom was placed on the imaging table of the SPECT system and the table moved using the hand controller in increments of about 1 cm in the axial and vertical directions. The SPECT slices were reconstructed with filtered backprojection with no attenuation or scatter compensation. The locations of the sources were calculated from the SPECT data as the center of mass (COM) of counts within a small volume about each sphere location and compared with sphere locations reported by the Vicon VTS.

We also checked the ability of the Vicon system to accurately track more complex motions of the phantom consisting of both translations and rotations by acquiring three SPECT and Vicon VTS acquisitions of the seven-marker phantom with the phantom moved an arbitrary amount by hand between them. The 6-DOF RB motion of the phantom for these two movements was obtained from the locations of the seven spheres as determined by SPECT and with the Vicon VTS.^{18,21}

II.F. Temporal synchronization with list-mode data collection

Since SPECT acquisition and Vicon motion tracking take place on separate computer systems it is essential to establish temporal synchronization between the two systems. On our Philips Medical Systems IRIX SPECT system, time is recorded during list-mode acquisition as a series of timing marks spaced 10 ms apart for the data acquired at each projection angle. However list-mode acquisition is enabled solely for step-and-shoot acquisition on our system and no timing marks are written during the 1–2 s when the gantry rotates from one projection angle to the next. Also the value of the series of numbers stored as timing markers is reset to zero at each new angle. Thus a method is needed to synchronize the data acquired at each projection angle with the Vicon VTS. We utilized a method similar to what we had previously used to synchronize list-mode acquisition with other motion-tracking systems.^{19,21} We start by activating a common remote start switch to initiate acquisition on both systems. Then we take advantage of the capability of our SPECT system to record in the list-mode file a repeating transistor-transistor logic (TTL) signal with a period of 10 s. This wave train is generated by the Vicon VTS when acquisition is activated. The missing parts of this signal are used to determine when the list-mode acquisition on the SPECT system actually started (typically about 2 s after activation) and for how long the SPECT system stopped acquiring during each gantry rotation in the step-and-shoot acquisition. The

10 s period of the wave train was selected to enable us to calculate both the initial delay and the periods of dead time when the SPECT heads rotate. The Vicon VTS acquisition typically starts within one frame (1/30 s) after being triggered and is taken as the reference time as there are no gaps in its recording.

We tested the accuracy of synchronization with a small amount of Tc-99m in a sealed vial with a marker attached. The vial was placed on the imaging table of the SPECT system and was moved twice in the axial direction while being imaged via both systems. Using software that our group developed, the list-mode data were converted into 100 ms SPECT projections. The time point relative to the start of acquisition at which the COM of counts changed indicating motion of the markers as observed by the SPECT system was determined from these projections. These time points of motion occurrence were then compared to the time at which the Vicon VTS reported changes in the position of the marker.

II.G. Phantom study of correction of motion during SPECT acquisition

We investigated the use of the motion-tracking information provided by the Vicon VTS to correct for the motion of a data spectrum anthropomorphic phantom. The heart wall, liver, and background compartments of the phantom had Tc-99m added to yield concentration ratios of 1:1:0.1, respectively, simulating clinical localization of activity within the phantom. Three retroreflective markers were attached to the top of the phantom in positions which could be viewed by the Vicon VTS when the phantom was in position for SPECT imaging. Two SPECT acquisitions of the phantom were performed following our standard clinical protocol which acquires images with two of the three SPECT camera heads at 102° relative to each other. Each head rotated through 102° and acquired 128 × 128 projections with 4.67 mm pixel size at 3° gantry rotation intervals using step and shoot and a circular camera-head orbit. Each frame was acquired for 26 s using a 15% photopeak window centered about the 140.5 keV emission energy of Tc-99m. Beacon transmission imaging using scanning Ba-133 point sources was performed subsequent to emission imaging for use in attenuation correction.³¹ The location of the markers was measured by the VTS during both of the SPECT acquisitions. The first SPECT acquisition was acquired without moving the phantom to serve as the reference for correction of the second SPECT acquisition during which the phantom was moved twice. The change in location as a function of projection angle was used to correct the RB motion of the second acquisition during reconstruction using our previously described methodology which incorporates 3D Gaussian interpolation in the projector/backprojector pair.²⁴ In this method, 3D Gaussian interpolation moves the current emission estimates and attenuation maps in the global coordinate system to locations in the rotating coordinate system to which the patient moved. It then moves back to the original location the backprojection of the ratio of the measured projections to the projections of the current estimate. Reconstruction was by

OSEM with attenuation and ESSE scatter compensation.³² Since transmission imaging was subsequent to emission imaging, the transmission images from the first acquisition were used to attenuation correct both the initial motion-free study and the study during which the phantom moved.

II.H. Robustness of tracking during clinical operation

To investigate robustness of clinical operation we acquired with IRB approval motion-tracking data from 77 patients (39 males and 38 females) undergoing SPECT cardiac perfusion imaging. The goal was to investigate various combinations of the five MX3 cameras to determine if fewer could be used clinically. This would decrease the expense of the system and advert reflections of NIR from one camera interfering with imaging by another camera. Unfortunately, the Vicon software did not allow us to perform stereo-analysis of marker tracking for less than the number of cameras employed in the original acquisition. Doing repeated imaging of the same patient with different combinations of cameras was out of the question. Thus, we determined for each patient which of the eight markers were seen in the Vicon acquisitions during our SPECT acquisition. Noting that viewing by two or more cameras is necessary for stereo-tracking, we then determined for each marker which combination of cameras resulted in the marker being seen all the time by at least two of the cameras. This can underestimate the system's ability to perform stereo-tracking when there are three or more cameras in the combination being considered because there is the possibility that different cameras may fail to record markers at different times. Thus we also determined the fraction of the time motion tracking was successful for the entire period of imaging for each marker.

II.I. Motion correction in ten patients undergoing cardiac SPECT imaging

With IRB approval we are motion tracking with the Vicon VTS patients during their resting Tl-201 cardiac perfusion studies and immediately after the completion of transmission imaging during a second-rest study. In this study, patients intentionally move a small amount, simulating motions we have observed clinically. Herein we report the results of motion correction in the first ten patients. The original-rest study during which they did not undergo significant voluntary body motion as measured by the Vicon VTS serves as the standard for determining the extent to which we were able to correct patient motion. Except for the radionuclide being Tl-201, acquisition and reconstruction were similar to the phantom study, although we did not perform scatter or attenuation correction during reconstruction. Short-axis (SA) slices were formed under user guidance for each set of transverse slices. Maximum-count circumferential-profile polar maps³³ were created from the SA slices to allow visual assessment of the relative perfusion in the left ventricular (LV) walls of second-rest study with and without motion compensation in comparison to the original-rest-imaging study. Quantitative assessment of the impact of motion and its correction in these maps on relative perfusion of the walls was performed

TABLE I. Monthly change in position relative to the first month for the four L-frame markers (in millimeters) along the X, Y, and Z directions. Note that the values listed are the average change in position of the four markers at each time point. The bottom row is the standard deviation of the change in position for the individual four markers compared to their position the first time they were measured.

Month	Ave. X (mm)	Ave. Y (mm)	Ave. Z (mm)
Second	0.000	-0.008	0.010
Third	0.009	-0.004	0.008
Fourth	-0.009	-0.017	0.025
Fifth	0.008	0.003	0.024
Sixth	0.009	-0.015	0.026
Standard deviation	0.058	0.430	0.093

by dividing the polar maps into 17 segments as recommended by current guidelines of the American Society of Nuclear Cardiology.³⁴ The quantitative comparison was performed by first normalizing the counts in each polar map such that the maximum in the map was 100. The average count within each segment of each map was then determined. The average of the absolute values of the difference in segment counts between the first- and second-rest-imaging studies for each segment was determined and averaged over the ten patient studies. The correction strategies compared were the second-rest study with no-motion correction, the second-rest study with motion correction using the motion estimates from the VTS system, and the second-rest study corrected by our research nuclear medicine technologist using the clinical motion-correction software available in our clinic.¹⁰ Analysis of variance was used to determine if there was a statistically significant difference between the average absolute values of the differences for these strategies, and Scheffe's multiple comparison test was employed to determine which of the pairwise comparisons of the differences were significant.³⁵

III. RESULTS AND DISCUSSION

III.A. Stability of VTS determination of spatial locations over a 6 month period

As shown in Table I, the marker averaged location of the L-marker tool was very stable showing virtually no net change in the location of these markers after system calibration over a 6 month period. All axes exhibited small standard deviation in marker location; the Y (vertical) direction was largest at 0.43 mm. For comparison, the noise level for tracking an individual stationary marker is approximately 0.2 mm. Thus, the system is shown to robustly report spatial locations reproducibly even when cameras have been removed and replaced on their wall mounts.

III.B. Accuracy of motion tracking

We found excellent agreement between the change in position of the seven-sphere phantom as assessed via Vicon tracking and the COM of counts in SPECT slices for eight

FIG. 4. VTS position versus SPECT position for the Tc-99m labeled seven-sphere phantom moved along the axial and then vertical directions. Linear regression lines fitted to the data and the squares of the correlation coefficient are shown.

axial and ten vertical steps of approximately 1.0 cm (Fig. 4). This figure shows the location for each of the seven spheres at each of the eight or ten positions as determined from the SPECT slices and by the Vicon VTS. Included on the plots are the linear regression lines which have slopes of almost identically 1.0 and offsets of nearly zero. Also shown are the square of the correlation coefficients between the two sets of measurements which are essentially 1.0 in each case. In the axial direction, we found a mean disagreement of 0.26 mm and a maximum disagreement of 0.78 mm between SPECT and Vicon measured displacements. In the vertical direction, the agreement was slightly better with a mean of 0.20 mm and a maximum difference of 0.61 mm.

Besides the studies of repeated motions in the axial and vertical directions, we also used the seven-sphere phantom to assess the 6-DOF agreement between Vicon and SPECT for determining arbitrary rotations and translations. These results are reported in Table II as the rotation angles of the three principal axes (α, β, γ) and translations in the X, Y, and Z directions. These values were calculated using SVD from the coordinates of the initial and final positions. Notice that the

TABLE II. 6-DOF results for an arbitrary rotation and translation of the Tc-99m labeled seven-sphere phantom as calculated from SPECT versus Vicon coordinates.

	SPECT	VICON
Rotation (α, β, γ)	1.24°, -17.71°, 3.62°	1.23°, -17.69°, -3.68°
Translation (x, y, z)	-2.01, 0.47, -2.09 (cm)	-2.01, 0.44, -2.06 (cm)

TABLE III. Results from two synchronization experiments for a single Tc-99m labeled marker moved twice during list-mode SPECT and Vicon acquisitions.

	First move (ms)	Second move (ms)
Exp. 1 SPECT/VICON	67,010/67,000	198,470/198,500
Exp. 2 SPECT/VICON	66,990/66,966	193,150/193,233

maximum difference in the angles estimated was 0.06° , and for translation the maximum difference was 0.03 cm.

The results of the above two paragraphs show that the motion measurements made by the Vicon VTS agree very well with those obtained by SPECT imaging of isolated point sources in air. We are unable to say whether the SPECT or Vicon measurements are the more accurate. The results in any case indicate that there is not much difference between them. The advantage of VTS over SPECT motion tracking of markers for patient studies is that the significant photon attenuation and “background” counts originating from the patient limit the accuracy of tracking multiple point sources in 3D at the acquisitions rates needed for correction of body and respiratory motion by SPECT but not the VTS.

III.C. Accuracy of temporal synchronization with list-mode data collection

Data from two experiments with a single Tc-99m filled vial with marker attached moved twice in the axial direction during each acquisition showed temporal agreement within 100 ms for all detected motions as shown in Table III. Since the list-mode SPECT data are in 100 ms bins, we can only say that the agreement is within that value even though it appears to be better in some cases. We acquired the marker data at 30 fps which is the slowest rate the Vicon VTS provides for acquisition and results in 33.3 ms per frame or 1/3 of what we use for binning the SPECT data. The timing of the start of the SPECT frames is to the nearest 10 ms in Table III. This is due to the time delay of the start of SPECT acquisition after the start of Vicon acquisition and the time lost during rotation between projection angles. Both of these are determined from the missing portion of the Vicon wave train which is recorded every 10 ms in the list-mode file.

III.D. Phantom study of correction of motion during SPECT acquisition

The Vicon VTS was used to estimate the change in position of a data spectrum anthropomorphic phantom which was moved twice during SPECT acquisition. The estimated 6-DOF changes in position relative to the initial position were computed using the three markers. We calculated the first motion as having translations in X , Y , and Z of 0.7, 0.6, and -30.7 mm relative to the initial position and the second motion as having translations of 3.0, 0.2, and -11.6 mm, again relative to the first position. The motions resulted in rotations about the three principal axes of the SPECT coordinate system of 2.20° , 0.19° , and -0.05° in the first case

FIG. 5. SPECT SA slices of the data spectrum anthropomorphic phantom reconstructed with OSEM over 204° with scatter and attenuation compensation for (top row) rigid-body motion of the phantom at two time points during acquisition with no VTS correction, (middle row) with VTS motion-correction, and (bottom row) motion-free references slices.

and 0.90° , -4.97° , and 0.08° in the second case. These estimated motions were used within iterative reconstruction to compensate for RB motion within reconstruction as we have previously detailed. The top row of Fig. 5 shows SA slices reconstructed without correction for the RB motion, the middle row shows the corresponding SA slices reconstructed with correction of the motions as estimated by the Vicon VTS, and the bottom row shows the motion-free reference SA slices from the reconstruction of a SPECT acquisition acquired with the phantom in the initial position. From Fig. 5 it is clear that the slices with RB motion and no-motion correction have significant motion-induced artifacts, while the corrected slices look similar to the motion-free slices. One would not expect them to be identical as the moved data have a different noise realization and correction included interpolation. This thus documents that the effects of RB motion can be greatly reduced using motion estimates obtained from the Vicon VTS markers.

III.E. Robustness of tracking during clinical operation

Motion tracking was performed with minimal impact on clinical imaging adding at most 1–2 min in total for wrapping and removing the bands with the markers about the patients. The results of analyzing these studies to determine the number and placement of cameras necessary for robust SPECT imaging are shown in Fig. 6. In terms of whether less than all five cameras can be used for motion tracking it can be noted in Fig. 6 that the removal of the center camera at the head end (camera 2 of Fig. 2) would degrade chest-marker tracking by 8% or more, but it would have only a small impact on the abdominal markers. The use solely of the three cameras at the head end does not appear to be sufficient to track the motion of the markers on the abdomen. Similarly, it appears that use of just the two cameras at the

FIG. 6. Data from clinical SPECT acquisitions tracking motion of 77 patients with four chest and four abdomen markers. The labels associated with each marker are as shown in Fig. 1 and the camera numbers are as identified in Fig. 2. Completely tracked means that there are no gaps in the 2D marker trajectories for at least two of the cameras. Also shown is the success rate for 3D marker tracking with all five cameras.

foot end would not be sufficient to track motion of the markers on the chest. Note, however, that the presence of the three cameras at the head end did increase the percentage of the patients in which the abdominal markers could be tracked throughout SPECT imaging, and the same is true for the two cameras at the foot end, increasing the percentage of the time the markers on the chest can be tracked. This illustrates the utility of using whatever stereo-pairs are available to track motion, even those from cameras on opposite walls of the room.

The use of all five cameras thus provided the greatest success in marker tracking, as might be expected. However, even with all five cameras we were not able to see any of the markers all the time with any two of the cameras for 100% of the patient studies. Shown at the bottom of Fig. 6 is the percentage of patients for which each marker was actually tracked throughout the entire period of SPECT imaging. It is equal to or greater than the percentage of time predicted from our analysis of the 2D NIR images. So long as any two cameras are seeing a marker its motion will be tracked even if it is not the same set of cameras which see the marker all the time. Thus the above result is not surprising.

With all five cameras the percentage of the time tracking was successful varied from 95% to 84% with the chest markers in the ninety percent and the abdomen markers in the eighty percent. This indicates the addition of a sixth camera at the foot end of the gantry may further improve our success rate in marker tracking for the abdomen. However, for motion correction of the heart we currently anticipate using the abdomen markers solely to provide a signal related to respiratory motion, and only one marker is required for this. In analyzing our studies we determined that we could track at least one marker on the abdomen belt all the time in 92% of the patient studies. We investigated whether there was a difference between males and females in terms of tracking at least one marker on the abdomen and determined that we were successful in 35 out of 38 females (92%) and 36 out of

39 males (92%). Thus no difference due to gender was observed. For correcting RB motion of the heart we need only any three of the markers to be able to be tracked all the time. We determined that we were able to track three markers all the time in 94% of the patients with the current configuration of markers on the chest band. We were successful in tracking at least three of the chest markers in 36 of 38 females (95%) and 36 of 39 males (92%). Thus again no significant gender difference was observed. Based on this analysis we are considering the addition of a third foot-end camera placed between and above the two currently there to further increase the robustness of tracking the abdominal markers.

Our conclusions as to the number and placement of VTS cameras are specific to the actual placement of our cameras tested and the large multiheaded SPECT system we employed in these investigations. We did preliminary studies with the cameras mounted on tripods using volunteer members of our group lying on the table of our SPECT system before arriving at the configuration we investigated clinically. However, it is still possible that different positionings of the cameras would have changed the robustness of tracking and thus conclusions as to the number of cameras needed. The application of our VTS for motion tracking with the smaller cardiac-dedicated SPECT systems will need investigation to determine the optimal number and arrangement of VTS cameras for them, especially when patients are imaged in a more upright position. The advantages of the Vicon system in this regard over past systems we have used are the flexibility of camera placement, the ease of calibration once the cameras are in place, and the adaptability of tracking markers using whichever of the cameras can view each marker at a given instant. Although there will definitely be variations in camera placement and possibly number, highly robust marker tracking should be achievable with these cardiac-dedicated SPECT systems.

FIG. 7. SPECT SA slices of two male and two female patients who volunteered for a second-rest study in which they were asked to perform specific movements. The raw data were reconstructed with OSEM over 204° but with no attenuation or scatter correction. The slices shown are from (leftmost) the first-rest study with no motion, (second column) second-rest study with no-motion correction, (third column) the VTS motion correction of the second-rest study, and (right most) the clinical correction of the second-rest study performed as a reference. The top row is for a male who performed a large axial shift, next is a female who performed a small twisting motion, third row is a female who was asked not to move during the second-rest study, and the last row is for a male who made a small axial shift.

III.F. Motion correction in ten patients undergoing cardiac SPECT imaging

Shown in Fig. 7 are SA slices from four of the first ten patient studies we have acquired in which the patient was asked to perform specific movements during the second-rest study. The motion they were asked to perform is listed in Fig. 7 along with the gender of the patient. One of the ten cases was asked to not move during the second-rest acquisition to serve as an example of how the different correction strategies affected studies with little or no motion. The correction strategies compared for the second-rest studies were no correction for motion to illustrate image degradation in the absence of motion correction (second column of slices in Fig. 7), correction with the VTS estimated RB motion during reconstruction (third column), or correction pre-reconstruction for motion by our research technologist using the clinical motion-correction software on our system (fourth column). Note that with the exception of the patient asked not to move during the second-rest imaging, the VTS-based motion-corrected slices look much closer to the first-rest slices than the uncorrected slices. Similarly, in each case the VTS corrected slice looks closer to the original-rest-imaging slice, sometimes much more so, than does the slice corrected using the vendor-supplied software. Thus qualitatively VTS-based motion correction is seen to be doing a very good job of correcting patient motion, better than the clinical software. Note that the VTS software returns the heart in the second-rest study to approximately the same location as that of the

FIG. 8. SPECT polar maps created from the SA slices for the same four patients. The slices shown are from (leftmost) the first-rest study with no motion, (second column) second-rest study with no-motion correction, (third column) the VTS motion correction of the second-rest study, and (rightmost) the data-driven clinical correction of the second-rest study performed for comparison.

first-rest study as illustrated by the difference of the vertical location of the heart within the slice for the first patient study shown.

The polar maps presented in Fig. 8 are for the same four patients as the SA slices shown previously. We note that the polar maps of the second-rest studies corrected with VTS looked closer to the no-motion first-rest studies than did the clinical software corrections for all four cases. The clinical correction performed worst for the male patient with a large axial sliding motion and the female patient who was asked not to move during the second-rest study. Our VTS correction did little to change the female no-motion second rest in which its polar map looks very similar to the first-rest and the uncorrected second-rest polar maps. The polar map for clinical software correction of this female patient shows significant artifacts compared to the other three. We note that there are other software packages on clinical systems which may have fared better in this comparison.¹² We tested only the software package available clinically at our site.

The results of the quantitative analysis of the polar maps for each of the three motion-correction strategies used in reconstructing of the second-rest slices are shown in Table IV. The numbers shown in the table can be thought of as the

TABLE IV. The average over the ten patients of the absolute values of the differences in relative counts in the 17 segments of the polar maps between the no-motion first-rest studies and the second-rest studies with no correction, our VTS-based correction, and the software correction on our clinical SPECT system. By Scheffe's multiple comparison test the difference between VTS correction and clinical correction is significant at the $p=0.05$ level. The other pairwise comparisons of differences are not significant at this level.

Polar map segment	No correction	VTS correction	Clinical correction
Apical	7.11	7.49	7.71
Apical anterior	6.84	8.08	8.31
Apical lateral	8.73	7.99	7.10
Apical inferior	7.32	6.91	7.44
Apical septal	6.92	6.18	8.02
Midanterior	7.99	8.00	5.88
Midanterolateral	6.90	6.47	6.57
Midinferolateral	6.80	5.90	7.49
Midinferior	6.50	5.56	8.62
Midinferoseptal	7.40	6.51	7.29
Midanteroseptal	7.74	7.05	7.73
Basal anterior	6.46	6.12	7.64
Basal anterolateral	6.05	5.79	7.24
Basal inferolateral	5.30	3.88	6.67
Basal inferior	5.85	5.30	8.18
Basal inferoseptal	7.09	5.74	7.38
Basal anteroseptal	6.35	5.02	6.98
Average	6.90	6.35	7.43
Standard deviation	0.82	1.15	0.68

average absolute value of the percentage difference in relative perfusion between the first rest and second rest for each of the 17 segments. Notice that the VTS correction on average results in the lowest difference and the clinical software correction results in the largest difference. Only the pairwise comparison between the VTS and clinical software correction was statistically significant at the $p=0.05$ level. The lack of a statistically significant difference between the VTS and no correction is likely in part due to the large SD of the segment average values with VTS correction. Also it should be recalled that in one of the ten cases the patient did not move so there should be little difference between the first rest, uncorrected second rest, and VTS corrected second rest. When one looks at the individual territories it can be noted that VTS correction results in a smaller absolute difference than no correction in 14 out of 17 segments. VTS correction also results in a lower absolute difference than the clinical correction software in 15 of the 17 segments. The clinical software correction resulted in better agreement with the first-rest study in only 5 of the 17 segments compared to no correction.

IV. CONCLUSIONS

We have determined that the Vicon VTS motion-tracking system provides sufficient spatial and temporal accuracy to enable motion tracking during cardiac SPECT imaging. The disagreement between Vicon- and SPECT-determined movements is submillimeter with subdegree differences in rota-

tion. Experiments showed that the Vicon and SPECT systems could be synchronized to within 100 ms. Motion tracking enabled us to considerably reduce motion artifacts as seen visually when reconstructing SPECT data from an anthropomorphic phantom. In the study of motion tracking in 77 patients, we determined that we can track most of the markers we attached to the stretchy bands wrapped about the patient chests and abdomens most of the time, especially for the chest markers. Finally we have shown in ten patient studies that we can correct for rigid-body patient motion such that the distortion resulting from motion is appreciably reduced visually. A visual comparison of the short-axis slices and polar maps for the four second-rest studies presented suggests that our VTS correction outperforms the clinical motion-correction software. This is confirmed quantitatively by the statistically significant improvement by VTS-based correction over clinical software correction in the analysis of the polar maps.

ACKNOWLEDGMENTS

This work was supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) Grant No. R01 EB001457 and by Philips Medical Systems. The contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Institutes of Health or Philips Medical Systems. The authors would like to acknowledge the assistance of the technologists within the Division of Nuclear Medicine with performing motion-tracking during clinical SPECT imaging.

^{a)} Author to whom correspondence should be addressed. Electronic mail: michael.king@umassmed.edu

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