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Feasibility of Stereo-Infrared Tracking to Monitor Patient Motion During Cardiac SPECT Imaging

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Abstract

Patient motion during cardiac SPECT imaging can cause diagnostic imaging artifacts. We investigated the feasibility of monitoring patient motion using the Polaris motion-tracking system. This system uses passive infrared reflection from small spheres to provide real-time position data with vendor stated 0.35 mm accuracy and 0.2 mm repeatability. In our configuration, the Polaris system views through the SPECT gantry toward the patient's head. List-mode event data was temporally synchronized with motion-tracking data utilizing a modified LabVIEW virtual instrument that we have employed in previous optical motion-tracking investigations. Calibration of SPECT to Polaris coordinates was achieved by determining the transformation matrix necessary to align the position of four reflecting spheres as seen by Polaris, with the location of Tc-99m activity placed inside the sphere mounts as determined in SPECT reconstructions. We have successfully tracked targets placed on volunteers in simulated imaging positions on the table of our SPECT system. We obtained excellent correlation ($R^2 > 0.998$) between the change in location of the targets as measured by our SPECT system and the Polaris. We have also obtained excellent agreement between the recordings of the respiratory motion of four targets attached to an elastic band wrapped around the abdomen of volunteers and from a pneumatic bellows. We used the axial motion of point sources as determined by the Polaris to correct the motion in SPECT image acquisitions yielding virtually identical point source FWHM and FWTM values, and profiled maximum heart wall counts of cardiac phantom images, compared to the reconstructions with no motion.

I. Introduction

Patient motion is a potential cause of artifacts that can limit the accuracy of diagnostic imaging. This is significant for imaging modalities such as SPECT and PET requiring motionless patients for protracted periods of time. Motion compensation strategies in SPECT imaging that rely exclusively on emission data itself, although commercially available, have not proved to be robust in clinical usage. We hypothesize that motion information obtained from a six-degree-

of-freedom stereo-infrared system can provide input for robust patient motion compensation as part of iterative reconstruction. We have selected the passive version of the Polaris Optical Tracking System from Northern Digital Inc., which uses infrared (IR) reflection from small spherical targets to provide real-time tracking of position and orientation. The targets can be grouped into “tools” of 3 or more reflective spheres with fixed geometry that may be tracked together with the Polaris system reporting the six translational and rotational degrees-of-freedom. By attaching a tool to the top of patient heads, the Polaris has successfully tracked motion in PET brain imaging [1,2]. Recently, reporting of the location in 3D of individual targets (spheres) has been provided. We investigated the feasibility of using this mode of operation of the Polaris system to monitor motion of patients in cardiac SPECT imaging. We see several advantages of IR motion tracking over the optical tracking which we have been investigating [3,4], including : 1) insensitivity to ambient lighting conditions, including shadows cast as camera heads rotate about the patient, 2) simpler human subject issues when recording motion vectors of IR targets and not optical images of patients, 3) substantially less disk space to store IR tracker output than optical image sequences, and 4) the Polaris is a commercial product with a stated 0.35 mm positional accuracy.

II. Methods

A. Viewing Area

The first matter to assess is whether Polaris can reliably view the chest and upper abdomen of patients being imaged by our Philips Medical Systems Irix SPECT scintillation camera (Fig. 1). The Polaris is located such that it sights through the tunnel of the gantry to view individual targets located on the anterior surface of patients. This keeps the Polaris out of the way of the patients and technologists. In this geometry, the Polaris can track targets at a distance of 1 to 3 meters. The distance between the Polaris and the center of its field-of-view is just over 2 meters, thus does not impose a restriction on patient tracking.

B. Calibration of Polaris and SPECT coordinates

To relate absolute Polaris position motion to changes in location as seen by SPECT it is necessary to calibrate the two systems. This is accomplished by determining the transformation matrix between Polaris and SPECT coordinates. This is the absolute orientation problem [5]. We solve it using the calibration tool with four targets shown in Fig. 2 that is imaged by IR and SPECT. We obtained plastic mounts for the IR spheres from the manufacturer. The 11 mm spheres snap onto the mounts which are in turn attached to a rigid plate to form the calibration tool. As manufactured, the mounts had a small hole extending downward a short distance from their tops where the spheres snap on. We enlarged these holes in four mounts and attached them to a thin Plexiglas plate to make a calibration tool. The enlarged holes serve as reservoirs to which a small amount of Tc-99m activity can be added. When the spheres snap onto the mounts, they lock the Tc-99m activity into place such that the activity is approximately centered within the sphere. This allows the location of the reflecting spheres to be determined by both the SPECT and Polaris IR systems, similar to our previous work with optical imaging [3]. A modified version of the software to calibrate targets in optical images with SPECT was employed to determine the transformation matrix between the reported locations of the four targets by the two imaging modalities.

As shown in Fig. 1, the Polaris was securely mounted on the room wall out of the way of traffic thus minimizing the chance of it being disturbed. During operation it is important to determine whether it is still reporting locations consistent with when it was calibrated so that application of the transformation matrix is still valid. This is determined by monitoring the location of 3 targets mounted on a disk (see Fig. 2) which attached to the back cover of the SPECT system such that it is always in line-of-sight of the Polaris. Since this cover is only removed when the

system is serviced, it provides a fixed location to determine if Polaris has moved and needs recalibration.

C. Synchronization with Irix Scintillation Camera

To employ the motion tracking information from the Polaris to correct SPECT acquisitions it is necessary to temporally synchronize the tracking information recording of the Polaris with the list-mode recording of events on our SPECT System. We have previously temporally synchronized the recording of optical images [4] and physiological signals [6] between the laptop computer used in data collection and the Irix SPECT scintillation camera by sending gate signals from the laptop to the Irix, which are then recorded in the list-mode file. We have altered our LabVIEW interface software to work with the Polaris.

D. Polaris axial and vertical correlation of motion with Irix

The accuracy and reliability of Polaris to report actual target positions in the SPECT environment was investigated as part of determining feasibility. The calibration tool (Fig. 2) with 4 spheres was positioned on the imaging table of the SPECT system and a SPECT acquisition performed to provide the location of the 4 targets in SPECT coordinates. The location of these spheres in Polaris coordinates was then recorded and the transformation from Polaris to SPECT coordinates determined. The SPECT table was then moved through a series of 10 axial offsets of approximately 1 cm. The location of the table in each case as recorded by the SPECT system to 0.1 mm was obtained from the header information of static acquisitions performed when the table was at each position. The Polaris determined location in 3D of the targets was recorded to the nearest 0.01 mm for each location, and these were transformed to SPECT using the determined transformation matrix. The process was then repeated for the table at an initial position and 10 offset locations of approximately 1 cm each in the vertical direction. The change in SPECT coordinates relative to the expected offset as determined in the axial or vertical directions was determined for each target in each case. The sphere average and standard deviation in these values was then calculated as an indication of the average disagreement from the offsets of the targets as recorded in the SPECT header versus those determined from the transformed Polaris measurements.

E. Comparison of Polaris respiration monitoring to “gold standard” measurement from pneumatic bellows

A two inch wide elastic belt was utilized with 4 Polaris reflective targets mounted at 50 mm spacing as shown in Fig. 2 to provide tracking of the location of the targets during respiration. The belt was placed around the mid-abdomen of a volunteer, along with a pneumatic-bellows belt-assembly (Fig. 2). The pneumatic-bellows sensed variation in pressure in the belt-assembly with stretching of the belt during respiration and was taken as the “gold-standard” measurement of respiration [6]. The pressure variations and locations of the targets were simultaneously recorded on two separate computer systems which were synchronized post data acquisition using a known data landmark.

The elastic band having the 4 Polaris markers was also utilized to provide tracking positional changes simultaneously with respiration. The intent was to determine if patient motion can be observed within Polaris data while a patient is breathing. Ultimately our goal is to provide correction for both respiratory and voluntary patient motion. As the volunteer was laying supine on the Irix SPECT patient bed, it was moved vertically by the hand controller of the SPECT system in approximately 2 cm steps. Additional data was gathered while moving the Irix SPECT patient bed into and out of the gantry using 2 cm steps during normal respiration.

F. Image Correction to compensate for Patient Motion

To verify that Polaris-reported positional changes in the axial direction could be used to correct an acquired image set an experiment was designed as follows. Technetium-99m was added to the cardiac insert of the Data Spectrum anthropomorphic torso phantom. The heart insert and the four Tc-99m point sources of the calibration tool were placed on the Irix patient bed. The Irix SPECT system was used to acquire a projection set of the heart phantom as well as the 4 point sources at a reference position. Note that no attenuation medium was present except that created by self attenuation of the phantom and that of the imaging bed. The SPECT patient bed was then moved 2 cm and a second SPECT projection set acquired. Both sets of data were acquired through 360 degrees into 120 projections of 256×256 , resulting in a pixel size of 2.335 mm. Before and after patient bed motion, Polaris values for the position of the 4 markers were established.

Three simulated motion projection data sets were created by combining the reference projection data set before table motion with that after the shift occurred. The first data set (Motion-1) has reference data until projection 30, with shifted data utilized from projection 31 through projection 120. Similarly, the second (Motion-2) and third (Motion-3) projection data sets utilized shifted data starting at projection 60 and 90 respectively. Each of these simulates patient motion as having occurred at different points in time during the SPECT acquisition.

The motion correction of these three projection data sets was accomplished by shifting projection image pixels corresponding to Polaris determined axial motion for the 2 cm indicated IRIX motion. The reference data as well as the simulated motion data were reconstructed using an ordered-subset expectation-maximization reconstruction (OSEM) algorithm without attenuation compensation. During reconstruction, 8 subsets and 5 iterations were employed. Due to the absence of major attenuation, image statistics were excellent and a 3-dimensional Gaussian post filter with a sigma of 1 pixel used.

The reconstructed heart data were re-orientated to the short-axis view for comparison. The reference heart phantom short-axis slices were visually compared to both the uncorrected and corrected reconstructed short-axis slices of the simulated motion data, and maximum count profiles of the heart walls determined to quantify the results. Additionally, the full width half maximum (FWHM) and full width tenth maximum (FWTM) values for the reference, uncorrected, and corrected point sources were determined in the X, Y and Z directions. Averages and standard deviations of these for the point sources were calculated.

III. Results and Discussion

A. Viewing Area

We can reliably and accurately track targets at distances of from 1 to about 3 meters, and also see the 3 target reference target tool which was mounted on the gantry surface facing the Polaris unit (about 1 m from Polaris). This agrees with vendor “pyramidal” volume dimensions. We chose the “pyramidal” volume rather than more limiting “silo” volume where the “pyramidal” provides a trackable volume centered at about 2 m axially from the Polaris.

Mid to lower abdomen placement of the “4 target” elastic band with 4 reflective targets was utilized due to Polaris system placement at the foot of the patient viewing through the gantry towards the head. Anatomical features such as large bellies or chest features, Fig. 3, can potentially limit the viewing rays from Polaris thus preventing direct viewing of an upper chest elastic band. Possible Polaris placement higher off the floor and angled down at a slightly larger angle may be able to view an upper abdomen respiratory belt to facilitate upper chest breather versus lower chest breather studies. Alternately, consideration of a second Polaris unit is possible to view an upper chest 4 target band from the patient head end, while the Polaris unit

positioned at the feet will work well monitoring the lower 4 target stretchy band. While it initially seems that directly facing Polaris IR units would not work due to IR emissions of one blinding the other, preliminary vendor testing has proved this may be feasible since Polaris works in pulse mode and opposing units will generally be out of synchrony much of the time. Thus each unit would function independently with minimal interference from the other. The conclusion is that opposing “Face towards Feet” and “Feet towards Face” units would be feasible. However the requirement to be between 1 meter and 3 meters from the reflective targets will require careful placement of the unit at the patients head end to not interfere with Irix SPECT bed and patient positioning.

B. Agreement of Polaris and SPECT estimates of motion

Fig. 4 shows the results of testing the correspondence of axial offsets of target locations, and Fig. 5 shows the results for the vertical offsets.

In these it can be seen that there is excellent agreement in each case with slopes of the regression lines between the SPECT recorded and transformed Polaris measured locations of essentially 1.0 and R^2 of 1.0. The average disagreement in offset for the four spheres between the values obtained from the SPECT system and those obtained by Polaris was -0.02 mm with a standard deviation of 0.09 mm for the axial offsets, and 0.12 mm with a standard deviation of 0.81 mm for the vertical offsets. In the case of the axial offset test, the average variation in the horizontal direction was -0.11 mm with a standard deviation of 0.03 mm and in the vertical direction the average was 0.04 mm with a standard deviation of 0.20 mm. Similarly, in the case of the vertical offset test, the average variation in the horizontal direction was -0.70 mm with a standard deviation of 0.09 mm and in the axial direction the average was 0.11 mm with a standard deviation of 0.06 mm. These results show that Polaris faithfully recorded the lack of motion in the directions where no motion occurred. Our results are in line with the Polaris having a 0.35 mm accuracy with 0.2 mm repeatability as stated by the manufacturer.

C. Comparison of Polaris respiration monitoring to bellows pressure variation monitoring

The Polaris and bellows comparison of Fig. 6 illustrates the ability of the Polaris to show respiratory motion of the targets on the belt with excellent temporal correlation to respiratory motion indicated by changes in pressure measured by the bellows. Note the excellent agreement in timing of maximum inspiration and expiration time points between the two recordings. Also note the scale of Polaris and Bellows are different. We have already developed [7] and applied clinically [6] a respiratory motion correction strategy which alters the detected location of counts axially as a function of the phase (or magnitude) of the respiratory cycle measured using bellows about patients. Since we have demonstrated herein that the Polaris measured motion of targets on an elastic belt correlates with the bellows signal, we believe we should be able to correct for the respiratory motion of the heart using the Polaris to estimate the timing of respiration.

Also shown in Fig. 6 is the ability of the Polaris to sense a change in the vertical location of the volunteer which goes undetected by the bellows. Thus the Polaris system is able to report both respiratory motion and patient body motion. Since both types of motion are mixed together as seen in the Figure we are currently working on developing an Artificial Neural Network which will be able to separate the quasi-periodic respiratory motion of targets from that of actual body movement of patients. The idea is to use the residual motion of the targets after subtraction of the respiratory motion to predict the motion that a rigid body would have undergone as predicted by the targets. It is anticipated that much of the non-rigid body movement of the targets relative to each other due to being attached to a stretchy belt will be subtracted as part of the respiratory motion of the targets. Any remaining non-linear component

to motion will be removed by fitting rigid body motion to that of the targets in the least-squares sense.

D. Image Correction to Compensate for Patient Motion

Sample short axis slices of the reference heart (Fig. 7 (a)) and Motion-2 before and after motion correction are given in Fig. 7. The un-corrected image in Fig. 7 (b) clearly shows a significant motion artifact in the antro-septal and inferior regions of the heart consistent with the axial motion of the bed. The corrected heart phantom slice can be seen in Fig. 7 (c), and demonstrates that motion corrected projection data successfully re-positions the phantom and reduces the blurring in the reconstructed image.

The maximum counts obtained from a circumferential profile of the heart wall are shown in Fig. 8. The quantification of the degree to which the image has been corrected is evident. The maximum wall counts for the “Corrected-2” image (Fig. 7 (c)) are very nearly the same as for the “Original” image (Fig. 7 (a)), with the “Motion-2” image (Fig. 7. (b)) showing a significant reduction in counts.

Table I shows the values for the FWHM and FWTM. This table shows averages of the FWHM and FWTM values for 4 point sources and associated standard deviation (S.D.) in the reference image, Motion induced images at 3 different projections (i.e. frame 30, 60, and 90 on out of 120), and corrected images for the same 3 projection sets. The FWHM and FWTM values for the point sources are significantly better after motion correction than before in the axial direction which was where the 2 cm shift was introduced.

IV. Conclusions

We have shown that the Polaris system is able to accurately track the location of targets attached to objects resting on the bed of our SPECT imaging system. We have also demonstrated that the motion of reflective targets mounted on an elastic belt about the abdomen of volunteers agrees with respiratory motion as sensed by a pneumatic bellows about the abdomen of the volunteers. We are currently investigating the separation of the respiratory motion component of target motion from that of rigid-body motion of patients. Based on the agreement between Polaris and bellows indices of respiratory motion we anticipate to then be able to correct for respiratory motion of the heart in list-mode SPECT acquisitions [6,7]. Following respiratory motion compensation of the SPECT data, we propose to employ the Polaris measured motion of the targets on the body surface of patients to correct for rigid-body motion of the heart by an adaptation of the data-driven method of Kyme, et. al. [8]. That is, we will use the Polaris measurements to group the SPECT data into sub-sets of projections acquired when the patient was stationary. Starting with the patient positioned as per the largest sub-set we will search for the transformation of the SPECT projections which minimizes a cost function using the Polaris measured motion of the patient between each sub-set and that of the largest sub-set as the starting point for the search. This process will be continued until all sub-sets have been motion corrected. Thus we plan to use a combination of Polaris measures of motion with a data-driven approach to hopefully provide a clinically robust compensation of patient motion.

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V. References

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Fig. 1. The Polaris system is seen on the far right mounted on the wall. This system is able to view IR reflecting spheres (targets) placed on the anterior surface of patients. In this figure two elastic belts are worn, one on the mid-abdomen and the other on the chest of the volunteer. The white spots on the belts are the attached IR reflecting spheres.

Fig. 2.
Shown: 1) 4 target calibration tool in upper left, 2) gantry mounted 3 target reference tool upper right, 3) stretchy belt with 4 targets in middle, and 4) bellows style respiration device at bottom.

Fig. 3. Views of a very large body size and potential Polaris viewing limitations of chest which could result. (Body model supplied courtesy of Dr. Brian D. Corner, U.S. Army Natick Soldier Center, Natick, MA.)

Fig. 4. Plot of Axial axis comparison showing Polaris SPECT mapped positions versus SPECT header indicated patient table positions.

Average SPECT Vertical Axis Test (Markers 4 -7)

Fig. 5.
Plot of Vertical axis comparison showing Polaris SPECT mapped positions versus SPECT header indicated patient table positions.

Fig. 6.

Trace showing Bellows respiration and Polaris target positions. Note the identical respiratory waveforms and the added Polaris capability of showing positional shifts (simulated motion) which bellows cannot.

Fig. 7.

Showing: (a) Reference heart phantom image before simulated motion, (b) Heart Phantom image after approximately a 2 cm simulated motion shift before correction, and (c) Heart Phantom image after correction.

Fig. 8.
Circumferential Profile of Heart Wall for: a) Original, b) Motion-2, and c) Corrected-2 images.

TABLE I
COMPARING ORIGINAL, MOTION AND CORRECTED IMAGES

	FWHM			FWTM		
	Trans-Axial	Trans-Axial	Axial	Trans-Axial	Trans-Axial	Axial
	X(mm)	Y(mm)	Z(mm)	X(mm)	Y(mm)	Z(mm)
Reference	14.87	16.24	16.14	29.30	29.42	30.53
	0.43	0.44	0.29	0.49	0.68	0.47
Motion-1	13.85	14.56	23.93	25.22	27.13	45.01
	1.28	0.76	6.43	2.84	1.37	2.04
Motion-2	14.50	15.86	29.74	28.06	28.73	47.26
	1.05	1.15	6.22	1.49	2.02	0.96
Motion-3	15.01	16.27	27.22	30.42	29.80	45.05
	3.22	0.49	4.34	4.61	1.19	0.86
Correct-1	14.94	16.25	16.15	29.13	29.37	30.50
	0.59	0.66	0.40	1.03	0.83	0.40
Correct-2	14.97	16.29	16.16	29.38	29.52	30.59
	0.52	0.50	0.34	0.64	0.71	0.51
Correct-3	14.81	16.25	16.19	29.31	29.53	30.65
	0.33	0.42	0.27	0.53	0.75	0.40
Key: Avg						
S.D.						