Collimator Interchange System for Adaptive Cardiac Imaging in C-SPECT

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Abstract

Compared to imaging the heart with conventional cameras, dedicated cardiac SPECT systems can achieve much higher performance through use of a small field of view. To realize this potential, however, the heart must be reliably placed in the appropriate small FOV prior to imaging, thus requiring a separate scout operation to locate the heart and estimate its size. Further-more, to achieve high performance across the general population, a system should provide several imaging configurations optimized for different size and location of the heart and the size of the patient. Because of the critical role the collimator plays in SPECT, it would be ideal if a dedicated collimator could be used for each of the different patient groups, as well as for the scout imaging. The ability to exchange collimators without moving the patient can also enable serial studies with different imaging options while preserving anatomic registration.

We developed a slit exchange system for the slit-slat collimator of the C-SPECT cardiac platform. The full-scale prototype, a precision link conveyor following a curved, body contouring path, allows four distinct transaxial collimation options. The collimators can be exchanged in 10 seconds without disturbing the patient, thus allowing adaptive clinical SPECT imaging. The positioning precision for all elements of the system is within 0.1 mm and has shown no degradation over 100,000 complete revolutions of the conveyor—twice the expected usage for a clinical system. We consider the rapid and precise operation allowing optimal collimation for different imaging tasks to be an important technological step for cardiac SPECT.

Keywords

Adaptive systems; biomedical imaging; collimators; single photon emission computed tomography

I. Introduction

IT is difficult to overstate the importance of cardiac imaging performed with single photon emission computed tomography (SPECT). The prevalence of coronary artery disease and the role SPECT plays in its diagnosis continue to keep cardiac SPECT an indispensable modality in cardiac imaging. The simple fact that cardiac SPECT accounts for more than half of all nuclear medicine procedures performed in the U.S. has made the development of dedicated cardiac SPECT systems economically justifiable. Dedicated systems have the potential to improve diagnostic value of SPECT since they can be optimized for imaging the heart; their smaller fields of view (FOV's) can increase the detector area available per unit

imaging volume. The resulting increase in the detection solid angle can lead to improvements in image quality, as well as enable and/or enhance capabilities for dynamic and gated imaging. The sensitivity increase also helps address the other pressures faced by nuclear medicine today: controlling cost, national radiation exposure, as well as radionuclide shortages.

To take full advantage of the image quality improvement potential inherent in small-FOV systems, two important issues need to be addressed. First of all, the heart needs to be reliably and reproducibly placed in the FOV. Secondly, no single imaging geometry is sufficient for producing high quality diagnostic images across the patient population, due to variation in patient size, as well as in the heart size and location. For highest performance, the system needs to be capable of first obtaining preliminary information about a given patient's anatomy, then changing the imaging configuration to best suit this patient. This is the essence of adaptive imaging, as described by Barrett, *et al.* [1]. To our knowledge, our work is the first attempt to implement collimator exchange to enable adaptive imaging in clinical SPECT. We do consider two recently available dedicated cardiac SPECT systems, GE Discovery NM 530c [2] and Spectrum Dynamics D-SPECT [3], to be important steps towards realizing the potential of cardiac-centric imaging. The GE system utilizes a medium-size FOV to accomplish imaging without any system motion. D-SPECT's scanning detector arrangement provides scout image capability and enables the reduction of the FOV to tightly surround heart, although it also limits dynamic imaging capabilities. Both systems achieve their notably high efficiency by the use of high-sensitivity collimators. High-sensitivity collimation shortens the time required for preliminary operations to place the heart into the small FOV; however, the same collimators must then also be used for the clinical studies. To achieve the necessary resolution performance, resolution recovery reconstruction (RRR) techniques [4] are implemented. These methods sharpen the images by incorporating collimator blur information into reconstruction algorithms. The degree of the effectiveness of RRR is a matter of current research. It is clear, however, that there is a limit to this effectiveness and that RRR cannot completely eliminate resolution degradation caused by high sensitivity collimators; otherwise, collimatorless SPECT systems would be possible. Conversely, RRR techniques can be applied to medium- or high-resolution collimators as well, further boosting their resolution. The ultimate resolution will be achieved by combining appropriate-resolution collimation with RRR methods. It is our strong belief that collimation is the major resolution-limiting factor of SPECT imaging, and for optimal imaging it is vital to utilize the collimator appropriate to the clinical task and patient anatomy. An exchange system would provide several collimation options within the same serial study and maximize the potential of the emerging resolution recovery methods.

II. C-SPECT

Our group is developing C-SPECT: a dedicated cardiac SPECT/TCT (transmission computed tomography) platform which has been described previously [5]. C-SPECT's overall design concepts are shown in Fig. 1. The goal of the system is improving clinical imaging by maximizing system geometric efficiency. When compared at the same collimator resolution, C-SPECT's geometric efficiency for imaging the heart will be 2–2.5 times higher than that of the systems described above. Coupled with resolution recovery algorithms, the system will reach significant advances in performance over present day systems. The keys to achieving this performance are C-SPECT's body-contouring geometry with a large area, high-stopping-power, high-packing-fraction detector coupled with a slit-slat collimator system designed around the concept of Pre-Determined Imaging Volume (PIV). A PIV is a small cylindrical FOV for which imaging is optimized by appropriate choice of slits which provide transaxial collimation. C-SPECT's collimator system contains several sets of discrete slit segments, with each set dedicated to imaging a specific PIV. The

sets of slits need to be exchanged for different imaging tasks precisely and rapidly, without disturbing the patient, to make C-SPECT's serial operations practical. These operations are summarized in Fig. 2.

In C-SPECT imaging, a scout scan, using a relatively large PIV with high-sensitivity collimation, is acquired first. Based on the scout scan, an appropriate PIV is selected from the available options, the patient is positioned by the Smart-Chair system to place the heart in the most appropriate PIV, and the corresponding slit set is moved into place for imaging. C-SPECT's typical imaging PIV will tightly enclose the heart and allow around 11–16 simultaneous non-overlapping projections. Possible truncation artifacts resulting from imaging with the small PIV can be largely mitigated in reconstruction by using the data from the large scout PIV [6]. The large number of simultaneous projections will enhance the capabilities for medium resolution fast or dynamic imaging without any system motion. For high-resolution imaging, additional sampling views can be acquired by translation of the slits or rotation of the patient on the Smart-Chair.

C-SPECT's collimator exchange system also enables TCT imaging for attenuation correction, while maintaining image co-registration. It is recognized that TCT-based attenuation correction can increase diagnostic accuracy of myocardial perfusion SPECT imaging [7]. In C-SPECT, immediately after the emission imaging, a set of thin vertical lead plates (V-Blinds) will replace the slits for TCT. The V-blinds block most of the photons emitted and scattered from the body, to avoid swamping the detector during TCT imaging. The latter will be performed using an integrated line source, with the patient rotated by the Smart-Chair system for adequate sampling.

In C-SPECT, the slats providing axial collimation will also be adjustable between high-resolution and high-sensitivity modes, without changing the PIV; the present work, however, focuses on the slit exchange system. The design goals were set out to achieve a positioning precision within 0.1 mm for all moveable elements of the collimator. This is two orders of magnitude below the combined spatial resolution range of the collimator and the detector. It is also at the lowest level of precision of any reasonable manufacturing procedure. To make C-SPECT operations practical, collimator exchange has to be accomplished in 10–20 seconds, without affecting the position of the patient. The system has to be able to function without degradation over the expected maximum lifetime for such an instrument. We estimate the maximum usage for a clinical C-SPECT system to involve 50,000 complete revolutions of the exchange mechanism. This is based on operating 250 days a year for 10 years, for studies on 10 patients a day with 2 full revolution of the system per study.

III. Materials and Methods

A. Slit Conveyor

The slits of C-SPECT's collimator will be located on discrete lead plate segments that form a closed loop wrapping around the slat stack and the detector, as shown in Fig. 3(a). The segments will be grouped in four sets, each of which is dedicated to a specific imaging task. These slit sets are brought to the front—the inner section of the loop—when needed for imaging. The slit exchange system is based on a precision link conveyor: effectively a constrained heavy duty chain. Together with Motion Index Drives, Inc. of Troy, MI [8], we designed and built a prototype, shown in Fig. 3(b). It consists of 113 aluminum links, with 31.75 mm pitch. Each of the conveyor's links is tightly constrained by means of three cam followers following tightly machined hardened steel tracks, as shown in Fig. 4(a). The conveyor is driven by an SEW Eurodrive [10] servo motor (which will be located below the C-SPECT gantry behind the patients back) through a 20:1 anti-backlash reducer. The motor

is controlled by an SEW Movidrive Servo Drive Unit by feeding back on a single absolute angular encoder (also SEW) on the motor shaft (4096 encoder pulses per shaft revolution). A full revolution of the conveyor chain corresponds to 272,263 encoder pulses, with steps as short as a single encoder pulse possible. The encoder measures the total rotation (including the number of complete revolutions) from its reference position ("zero"). No position information is lost in the event of a power shutdown. The encoder's "zero" position can be commanded to be reset at any point, for example, on completion of every full revolution or by use of another sensor. Throughout the 100,000 revolutions described in this work, the encoder was never reset, demonstrating the robustness of the control system. In our measurements, the conveyor was always operated by alternating clockwise and counterclockwise revolutions to evaluate motion in both directions and include effects of any possible backlash. The future clinical system will be capable of operation in either one direction only, or alternating directions.

In C-SPECT, the collimator plate segments containing the slits will be bolted to the conveyor links on one end only, as shown in Fig. 4(b). Each slit plate will be backed by a steel plate to maintain rigidity. The plates will utilize overlaps to prevent photon from "leaking" between the plates. For standard imaging operations, with 11–16 slits, the slit plates will alternate with dummy plates (without slits, overlaps only). Since the slit plates do not have to be centered over their corresponding conveyor links, thus, the available geometries for collimation are abundant. For the current testing, each link was loaded by a 1 lb lead plate (7×1×.875"), backed by a 1/4"-thick steel plate, to mimic the real situation (Fig. 3(c)).

B. Position Measurement Technique

The encoder on the conveyor's motor shaft is the only position sensor used for the slit exchange system operation. It is critical to ensure that there is always a one-to-one correspondence between the encoder reading and the position of every moving element of the collimator. Without that correspondence, it would be impractical to monitor the positions of all slit plates due to the large number of segments. Since modern SPECT systems rely on pre-calibrated system matrices for image reconstruction, reproducible and precise positioning is a high priority.

We tested the position repeatability of the system using a laser distance meter. The IDEC S62-Y sensor [9] was selected for its 10 micron nominal resolution at the 40–50 mm working distances used in this work. For repeatability measurements, the conveyor was commanded to stop at given encoder coordinates multiple times and actual position of one segment was measured with the stationary sensor for each stop. The conveyor was always driven through at least one complete revolution between successive measurements at the same encoder coordinate. All measurements were performed at the top of the lead plates, to include effects of any tilting or lead/frame deformation. Foam, cardboard or white plastic pieces epoxied to the lead plates were used to provide a diffuse reflecting surface for the sensor for several different types of measurements. The arrangement for measurements along the direction of travel is shown in Fig. 5. The foam surfaces are at about 30° angle to the direction of travel, thus all measurements along that direction were corrected by multiplying by $\cos 30^\circ$. To test the precision of the measurement apparatus, the sensor was aimed at one of the foam reflectors for 49 hours without actuating the conveyor. As shown in Fig. 6, the noise, resolution and drift of the measurement system add up to 0.1 mm peak-to-peak. There is some correlation between the observed drift and the ambient temperature; however, the nominal thermal drift of the sensor is smaller ($10\mu\text{m}/^\circ\text{C}$). Because of the differences in the observed drift between different links, we believe that much of the drift was caused by thermal contraction/expansion of the epoxied foam reflector.

IV. Results

A. Effects of Wear

Obviously, capital equipment as complex (and expensive) as a SPECT/TCT system must be capable of reliable operation for many years. For many types of instrumentation, effects of aging can be corrected by re-calibration; this is not the case for the conveyor described here. Since the system relies on tight tolerances to achieve its precision, wear could be problematic. To study effects of wear, the fully loaded conveyor was ran thru 97,200 revolutions (48,600 roundtrips), with three quarters of them at a high speed (8 seconds per revolution). Position of one of the lead plates was measured once during each roundtrip; the raw data for this measurement is shown in Fig. 7(a). The measurement was performed over the period of one month; concurrent ambient temperature in the lab is shown in Fig. 7(a). Approximately every other day the “accelerated aging” was stopped to perform the slower measurements involving all links; these stops/restarts are indicated by vertical lines in the plots. These measurements bring the accumulated number of full revolutions during the “aging” process to slightly above 100,000. The interruptions cause the apparent temperature discontinuities, since the measurement is restarted at a long time after it is stopped. This produces the “sharp transient” features in the position data, since the position data acquisition is restarted at a different temperature from the time when it was stopped. The rest of the data shows a reasonable correlation with ambient temperature. An exception can be seen centered at about 15,000 revolutions. The conveyor speed was increased prior to this aging interval; position measurement timing was not adjusted by mistake, causing the measurements to be acquired before the conveyor could come to a full stop, resulting in an offset and increased noise. Aside for this mistake, the observed position variations are within 0.1 mm.

The data acquired during the “aging” process was obtained by measuring only a single link. Unless described otherwise, the datasets presented from here on involve measurements of all of the conveyor’s links. With the sensor stationary, the conveyor was driven through 100 complete roundtrips, each consisting of one full clockwise and one full counterclockwise revolution. For each of the forward revolutions, the conveyor was stopped 113 times (as always, using the encoder for feedback) so as to place each of the plates in front of the sensor for measurement. Therefore, the standard data set, obtained over 16 hours, consists of 11,300 separate position measurements, with each link measured 100 times (with two full roundtrips between successive measurements of any given link, to include effects of backlash). One such set, obtained before conveyor “aging” is shown in Fig. 8. The 113 position traces, one for each of link are shown in Fig. 8(a), with arbitrary offsets for clarity. Subtracting the average from each of the link’s datasets collapses and superimposes the data so it can be seen clearly together as shown in Fig. 8(b). The measurements show the presence of a drift, likely thermal in origin as mentioned above. The histogram of the deviations of all measurements is shown in Fig. 8(c); it is consistent with a Gaussian distribution; the standard deviation and the full width at half maximum (FWHM) provide other convenient metrics of the conveyor’s precision. The measurements after the aging process are shown in Fig. 9. For this The precision of every link can be seen to lie within 0.1 mm, before and after “aging”, with no observed changes in the precision of the conveyor.

B. Different Locations and Measurement Axes

Following the completion of the wear testing, we performed experiments to test the precision of the system at several locations along the track, as well as along directions other than the direction of travel. The results are similar in all cases, with precision within 0.1 mm. Fig. 10 shows the results of the measurements performed at three different locations.

The slightly worse performance at one of the locations is related to the likely thermal drift during the measurement.

To test 3D positioning repeatability, distance measurements perpendicular to the direction of travel were also performed. Fig. 11 shows one of two arrangements for the measurement along the horizontal axis perpendicular to the direction of travel. Because the measurements are performed at the top of the mock slit plates, the effects of any possible tilting or bending along the measurement direction would be included in the results, along with any lateral translation. In addition, measurements at the leading and the trailing edges of the plates also provide an upper bound on any slit segment rotation around its vertical axis. To tighten this upper bound on rotation around the vertical axis, ten of the links were measured using 14" long reflectors as a baseline, as shown in Fig. 12. We also performed measurements along the vertical axis, with the set-up shown in Fig. 13.

Aside for the sensor position and reflectors, the measurements along the other axes were performed similarly to those along the direction of travel; they are presented similarly as well. Fig. 14 shows positioning precision of all links by measuring along the horizontal axis perpendicular to the direction of link travel. The results for both the leading and the trailing edges of the lead plate are shown together. The observed 0.1 mm positioning precision establishes an upper bound for any link rotation along a vertical axis at 0.46° . Measurements on 10 of the links using a longer baseline, shown in Fig. 15, tighten that upper bound for rotation to 0.06° . The data for the vertical axis, shown in Fig. 16, also show 0.1 mm precision.

C. Small Step Capability

The conveyor's motor/encoder combination allows for very small and precise translations of the links. This is demonstrated in Fig. 17. The data shown was taken during 300 (3×100) sequential full roundtrips of the conveyor. The sensor was moved after first and second hundred trips; the three sensor locations are shown in Fig. 10(a). During each of the roundtrips, the conveyor was stopped to perform a position measurement at seven encoder coordinates corresponding to small steps of 20 encoder pulses in length. Since the angular encoder is not linear, for small incremental steps the conveyor travel does not correspond linearly to encoder pulse count; this can be linearized in software if needed. Each of the three datasets in Fig. 17 corresponds to 100 repetitions obtained with the sensor at the three different locations; the datasets are offset vertically with respect to each other for clarity. The measurements show that for both the small incremental steps, as well as for full revolutions (in both directions) of the conveyor, the position of the links repeats within 0.1 mm.

V. Discussion

The precision of C-SPECT's slit exchange conveyor has been shown to be within 0.1 mm, with any slit rotation about the slit axes not exceeding 0.06° . These are upper bounds, since noise and drift of the measurement contribute somewhat to our measurements; however, there is no reason to believe that the real value for the precision is significantly smaller, since 0.1 mm lies at the limit of machining tolerances. Since we observed no degradation of performance with aging, we consider the research phase of the project to be complete. Additional minor refinements, particularly in the gantry contour, will be needed for the future clinical system, but these can be addressed closer to the manufacturing stage. The changes will include dimensioning gantry to optimally suit the majority of the target population, as well as opening up the patient area slightly for greater patient comfort.

C-SPECT is being designed as a platform with both present and future clinical requirements in mind. The collimator exchange system will accommodate various imaging options by providing dedicated collimator configurations for each in a single system. These options may include high-sensitivity configurations for fast and/or dynamic studies as well as high-resolution modes. This, in itself, is not an innovation, as any conventional system provides a choice of collimators. In C-SPECT, however, the collimators can be exchanged almost instantly without moving the patient. This allows different imaging modes to be used in the same clinical study sequentially, while preserving anatomic registration, leading to an unprecedented potential for image fusion and clinical protocols. An interesting possibility is combining acquisitions with multiplexed (overlapping) and non-multiplexed projections. Multiplexing can increase system sensitivity but creates ambiguities in image reconstruction. A recent study has shown the potential of mixing multiplexed and non-multiplexed projections to improve image quality [11]. An interchangeable collimator will allow separate acquisition of completely non-multiplexed and multiplexed sets of projections for optimal image quality. The exchange mechanism is not limited to slits; the slit segments can be replaced by pinholes and the slit stack dropped from the system. As the research into application of pinhole collimation for clinical imaging is advancing, an interchangeable pinhole system would provide solutions for problems of optimizing the imaging configuration for specific imaging tasks.

As presented, the collimator exchange system can accommodate four complete slit sets. Fig. 18 shows how two conveyors can be combined to increase the number of immediately available slit sections to six without increasing the footprint of the system. The system's precision is achieved with slit plates bolted only on one side; this allows the stacking of two conveyors as shown, with one on top and the other on the bottom. The chain of one of the conveyors will follow a track slightly wider than that of the other, except in the inner section of the loop where the two tracks will match. A section of each conveyor will be left empty to enable only a single section to be moved into place for imaging at any one time. In principle, more conveyors can be stacked following a similar scheme. A simpler way to increase capacity would involve adding more curved track length at the rear of the system, at the expense of footprint. Finally, also on a very practical side, the C-SPECT's collimation configuration can be upgraded simply by replacing individual slit plates.

It should be noted that it is not difficult to relate the slit exchange system's mechanical precision to future imaging performance. We do not expect the measured maximum 0.1 mm (0.07 mm FWHM) positioning uncertainty to lead to quality reduction of reconstructed images when added in quadrature to the 10 mm resolution of the proposed C-SPECT system. The fact that the measured precision of the system lies at the limit of machining tolerances would make any cost-effective improvements beyond the demonstrated conveyor unlikely. They are also likely not necessary, since the same mechanical constraints apply to all SPECT systems' moving subsystems; patient motion is typically a far more challenging concern. Imaging performance is, of course a necessary verification of an imaging system. In parallel with the collimator work, we are currently developing C-SPECT's high-resolution modular curved detector system to which will be used to test full imaging performance of the C-SPECT lab prototype, both to examine the impact of the exchange system's mechanical precision, as well as, as to test the effectiveness of the adaptive imaging approach to clinical SPECT.

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Fig. 1.

C-SPECT design concepts (a) Patient sits in motorized chair; X-ray source is integrated for TCT imaging. (b) A set of slits defines small imaging volume. Simultaneous views are acquired with large area detector. Slat stack provides axial collimation.

Fig. 2. C-SPECT Operations. (a) Acquire large-PIV scout image using high sensitivity collimation. (b) Select PIV appropriate for heart size and location. (c) Translate patient to place heart into the imaging PIV. (d) Exchange slit set and acquire image. (e) For larger patients, a slit set of a larger PIV can be used. (f) Switch collimation to V-Blinds and perform TCT imaging.

Fig. 3. Slit exchange system. (a) Rendering of C-SPECT collimator and detector systems. Different shading corresponds to separate collimation options. (b) Precision link conveyor; 36" ruler shown for scale. (c) Conveyor loaded for testing.

Fig. 4. Renderings of exchange system details. (a) Conveyor links and rollers used to constrain them on the tracks. (b) Collimator slit plates (darker shade), mounted behind steel frames (lighter shade) and bolted to conveyor links.

Fig. 5. Laser distance meter used for direct position measurements. (a), (b) Top and side view schematics of the set-up for measurement along the direction of link travel. Arrows indicate the axis along which the position is measured. (c) Photograph of the measurement set-up.

Fig. 6. Sensor/configuration characterization. (a) Distance measurement of static conveyor performed over 49 hours. (b) Corresponding ambient temperature.

Fig. 7. Conveyor aging. (a) Measurements of a single link during the aging process. (b) Corresponding ambient temperature.

Fig. 8.

Data processing for precision measurement of all links. (a) All 113 datasets (one for each link), shown offset for clarity. Data presented here was taken before conveyor “aging.” (b) Data for all 113 links, superimposed onto each other after subtracting the average from each link’s set. (c) Histogram of position errors for 11,300 measurements. Error is defined as the deviation from the average (over the 100 roundtrips) measured position of each link.

Fig. 9.

Effects of aging. Position repeatability measurements of all 113 links obtained after “aging” conveyor revolutions.

Fig. 10.

Measurements at different locations, indicated in (a). (b), (c), (d) Repeatability at locations 1–3.

Fig. 11. Measurement along horizontal axis perpendicular to the direction of travel. (a), (b) Top views of the measurement at opposite edges of the plate used to measure slit segment rotation. (c) Front view schematic. (d) Photo of the set-up.

Fig. 12.

Long baseline measurement along horizontal axis perpendicular to the direction of travel used to improve measurement of slit segment rotation (10 segments only). (a), (b) Top views of the measurement at opposite edges. (c) Front view schematic. (d) Photo of the set-up.

Fig. 13.
Measurement along the vertical axis. Side view and photo of the set-up.

Fig. 14.

Results for short baseline measurements along horizontal axis at right angle to direction of travel. The measurements at the leading and trailing edges of the reflector are combined (226 measurements per roundtrip).

Fig. 15.

Results for long baseline measurements of 10 segments along horizontal axis at right angle to direction of travel. Again, the leading and trailing edge data is shown together (20 datapoints per roundtrip).

Fig. 16.
Results of the measurements along the vertical axis.

Fig. 17. Small step precision. Repeatability datasets taken at the 3 different locations shown in Fig. 10(b)). Each of the three dataset consists of 100 sequences of 6 small steps followed by a near complete revolution of the conveyor to bring it back to same location a before the first step.

Fig. 18.

Two-conveyor configuration for adding capacity without increasing footprint. (a) Schematic top view of two conveyors, indicated by lines of different thickness, with three slit segment sections each. Dashed lines indicate conveyor links not loaded with slit segments, enabling the conveyors to pass and allowing collimation by a single section. (b) Two slit conveyors stacked on top of each other. The motor of the first conveyor will be located between the conveyor base plates or on top of the conveyor. (c) Future clinical C-SPECT system with 6 collimation options.