Design Considerations for a New Solid-State Gamma-Camera: SOLSTICE

Daniel Gagnon, *Member, IEEE*, Gengsheng L Zeng, *Member, IEEE*, Jonathan M Links, Jerome J Griesmer, *Member, IEEE*, Frank C Valentino, *Member, IEEE*

***Abstract* - This paper presents an alternative to conventional gamma camera. The proposed system is based on the combination of a new detection material – CZT - and a new acquisition geometry – 1D detector with slat collimator. The slat collimator offers a better compromise to the usual sensitivity-resolution tradeoff. Solid-state detection offers significantly improved energy resolution. The combination of the two elements, and the development of better reconstruction tools, has the potential of bringing a new level of performance to nuclear medicine imaging. The targeted system performance includes a spatial resolution of 5mm FWHM at 10 cm from the detector surface and an energy resolution better than 5% FWHM, both at 140 keV. While the results are still preliminary and incomplete, they more than justify further investigation.**

I. Introduction

The Anger camera has truly established nuclear medicine as an important medical imaging modality. Since its invention in 1958, spatial and energy resolution have slowly and very gradually improved but are still limiting the global performance of gamma cameras. First, the spatial resolution is almost entirely determined by the characteristics of the collimator, which, in turn does not offer much hope for any significant improvement since the process of building collimators has been well optimized over the years. Changing the characteristics of the collimator to meet clinical requirements is also of limited interest since improvement in resolution is unavoidably accompanied by a substantial decrease in sensitivity. Alternative to parallel-hole collimation have been thoroughly investigated. Focusing collimators (either fan or cone beam) offer incremental improvement on the basic equation at the expense of field-of-view. A fan beam would typically improve by 20-30% the sensitivity for the same resolution, or improve by 1-1.5 mm the system resolution for the same sensitivity. Although desirable, these changes are not important enough to justify any departure from the parallel-hole application and generally offer similar clinical outcome.

Second, the energy resolution is defined by the scintillation crystal and the readout electronics (including subsequent data processing). This characteristic of the technology has seen more rapid progress over the years but has reached a limit that can no longer be pushed: thallium-doped sodium iodide can only produced so much light in converting a gamma-ray. Future improvement on this factor stems essentially in the possibility to harness the exquisite energy resolution of solid-state devices.

This paper presents a new imaging technology based: Solstice (**SOL**id **ST**ate **I**mager with **C**ompact **E**lectronics). It is based first, on a new sensitivity-resolution compromise offered by rotating slat collimators, and, second, on the performance of direct gamma ray conversion through solid-state detectors. The authors believe that no fundamental changes in nuclear medicine technology can happen if these two aspects are not considered simultaneously.

II. System Components

It is believed that the rotating slat hole collimator is the only viable way to change the sensitivity-resolution equation. Analysis of this kind of device can be found in [1, 2, 3]. The hypothesis is that the increase in the sensitivity of the device is enough to compensate for the additional reconstruction. The object of this paper is to establish that fact.

The various components of the system are complementary and should only be considered as part of the whole concept. For instance, the bias caused by the presence of scatter can generated unacceptable artifact in 3D images obtained from a rotating-slat systems; the essentially Compton-free nature of CZT imaging with 5% energy resolution eliminates this problem.

In the following sub-sections, the geometry of the imager will be described along with its major imaging characteristics. Then the properties of CZT will be summarized. The overall system performance along with images, will then be presented.

A. Spatial Resolution and Slat Collimator

The Solstice camera is defined (Figure 1) by a series of high-attenuation plates (W, Pb or equivalent) of dimension W_X, W_Y and W_Z. The distance, G, between each plate defines a plane A through the object. The activity in plane A is visible only through one slat of the assembly. Photons going between the plates will be detected by the solid-state detector on top of the slat assembly, C_Z thick and C_Y wide in a direction parallel to the slat. The whole assembly, slats and detector, of length L, rotates about an axis located in the center of the assembly. In this design, "L" defines the field-of-view, and for a given slat design, the sensitivity is mostly affected by changing C_Y.

Rotation about the axis of the detector creates a series of 1D projections (called spinograms); complete 3D information is obtained by rotating the whole detector around the object as usual.

- D. Gagnon, J.Griesmer, and, F.Valentino are with Philips Medical Systems, Nuclear Medicine Division, 595 Miner Rd, Cleveland, OH, 44143

- L.Zeng is with University of Utah, MIRL Radiology, 729 Arapeen Dr. Salt Lake City, UT, 84108

- J. Links is with Johns Hopkins University, School of Public Health, 615 North Wolfe St, Baltimore, MD, 21205

For correspondence, daniel.gagnon@ieee.org

The resolution component is relatively easy to compute and follows the known rules of (1D) collimation. There is, however a noteworthy difference between previously reported examples of rotating slat collimator and the Solstice design. With the use of pixelated (CZT) detectors matching exactly the pitch of the collimator assembly, the system resolution IS the collimator resolution. When combined with continuous detector, the intrinsic resolution of the detector needs to be added in quadrature. Tosswill [4] describes an arrangement similar to the Solstice using Ge detectors that would have the same characteristics in terms of resolution.

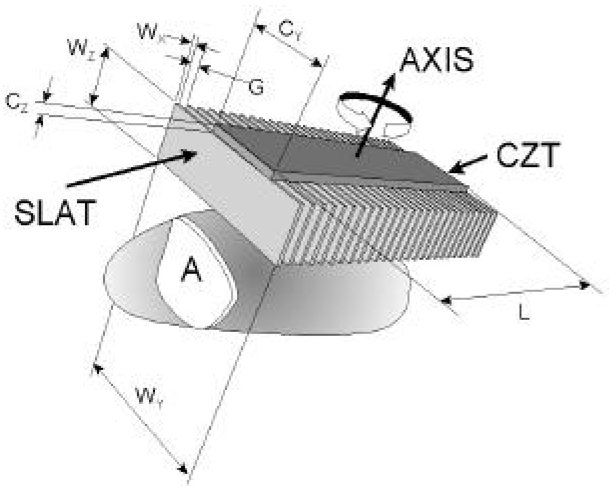

Figure 1. Representation of the Solstice geometry. The whole activity of the plane "A" defined by two consecutive slats is integrated by the CZT crystal along the whole length "C_Y". A 2D image is obtained by reconstructing the information collected while rotating the array.

Detection Material	CZT
Detector Thickness (**C_Z**)	5mm
Detector Width (**C_Y**)	56mm
Number of Imaging Channel	192
Collimation Material	W and Pb
Collimator Thickness (**W_X**)	300 um
Collimator Spacing (**G**)	1.5 mm
Collimator Height (**W_Z**)	40mm
Field-of-View (**L**)	345mm
Spatial Resolution @ 10cm	5mm

Table 1. Solstice Detector physical parameters. Individual variables can be found in Figure 1.

The Solstice detector used in this paper was built using the physical parameters contained in the Table 1. The overall system spatial resolution was set to be 5mm FWHM at 10cm distance for 140 keV photons.

B. Energy Resolution and CZT

Analysis and compensation for scatter contamination in nuclear medicine have generated a lot different techniques but none have been completely satisfactory. Elimination of scatter at the source – by using a better detection scheme – seems to be the only alternative. Solid-state detectors have been demonstrated to have a better energy resolution. For Solstice, the requirement is that each imaging channel have better than 5% energy resolution at 140 keV, and that the CZT detector maintain a good photopeak efficiency.

Figure 2 shows the exquisite performance of the CZT in the prototype arrangement. This typical pixel shows a 3.6% energy resolution for 122 keV (same as the average for the whole array of close to 3000 pixels), and simultaneously very high photopeak efficiency.

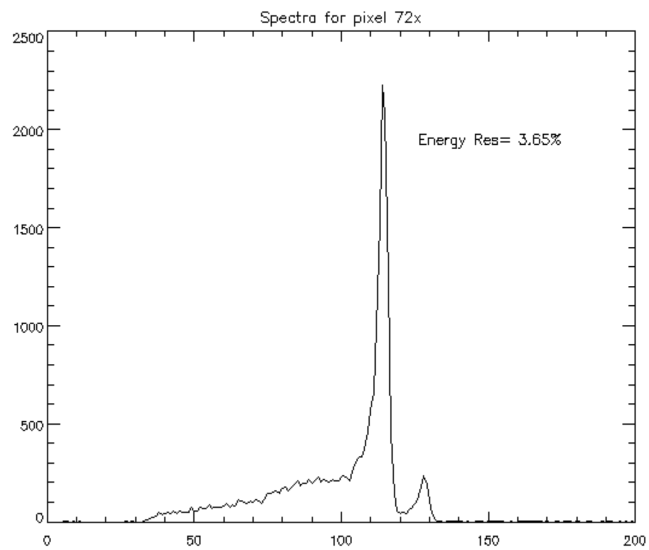

Figure 2. Typical energy spectrum from an individual pixel in the array. This particular spectrum clearly resolves the 2 peaks of Cobalt-57 and has been measured at 3.6% FWHM.

While improvement in energy resolution was definitely targeted, 3.6% FWHM at technetium for the average energy resolution exceeds our expectation and certainly establishes that the goal of better-than-5% is achievable for room temperature CZT.

III. Global Imaging Features

The performance evaluation of an imaging system is a complex task. We will review in this section some of the global imaging tests that have been performed using the Solstice detector described earlier. Those tests do not constitute a complete image quality assessment of the device, they are simply indicators of what can be obtained. More detailed work in a variety of clinical conditions is necessary to be more explicit in the following comments.

A. Spatial Resolution in 2D

Two dimensional images are obtained from the reconstruction of the spinogram. The number of spin angles has been set to 512 for ALL the images in this paper. The first example is the planar,contrast-resolution phantom (so called Rollo phantom). The Solstice image is compared with the standard NaI gamma camera. The two images have been produced with similar activity, similar geometry and the same imaging time.

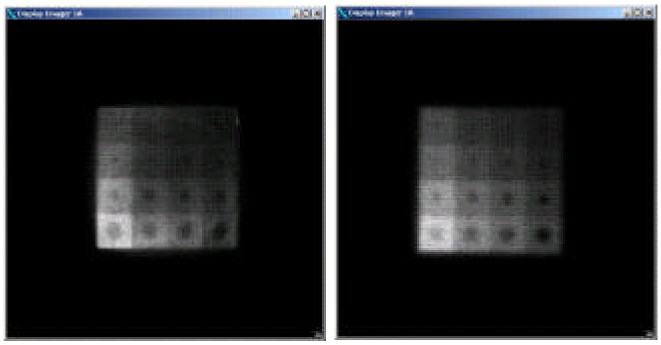

Figure 3. Planar contrast / resolution (Rollo) phantom of the Solstice image (left) and the standard gamma camera (right). While more quantitative analysis is required, the images already show the performance of the solid-state detector.

Analysis of this kind of images reveals interesting aspects of the imager. In particular, the ability of the Solstice detector to eliminate almost entirely the scatter contamination, should result in better contrast resolution.

B. Spatial Resolution in 3D

Obviously the 3D spatial resolution is of greater interest. We used the cold rod section of a Data Spectrum Deluxe phantom to demonstrate the performance of Solstice. The reader should have his/her own reference point for this kind of image and be able to recognize the quality of the Solstice reconstruction. The acquisition parameters were, 30mCi of ^{99m}Tc, 40 seconds per projection (spinogram), 180 projections over 360 degrees.

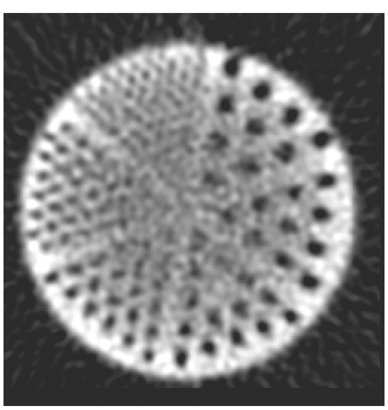

Figure 4. Cold rod section of the Data Spectrum Deluxe, imaged with 30 mCi total activity, 40 sec per projection and 180 projection over a complete 360 degrees rotation. Starting at the 1 o'clock position, the rods are 12.7, 11.1, 9.5, 7.9, 6.4 and, 4.8mm respectively.

C. Small Animal Imaging

Plane integral tomography exhibits a 1/r sensitivity dependence (where "r" is the distance to the detector) resulting in better performance as the object is put closer to the detector. This can be exploited for small animal imaging. The following image was obtained from a phantom that we developed for testing performance in small animal imaging situation. The phantom has 4 sections with hot rods of 4, 3, 2.5 and 2mm respectively (diameter and spacing). The cylinder matches the size of the heart insert of the Data Spectrum Torso phantom. A full 3D image has been obtained from the Solstice camera and from a standard gamma camera (able to accommodate very small radius of rotation).

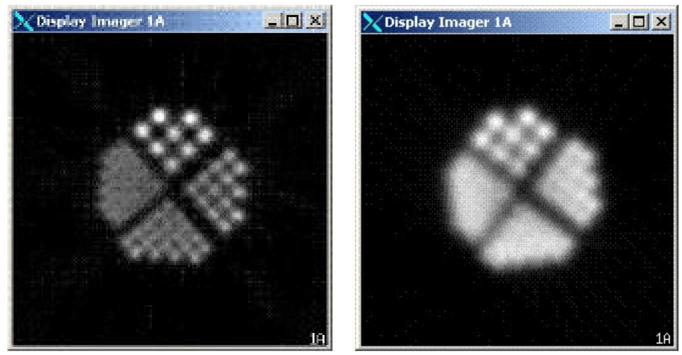

Figure 5. "Micro-Rod" phantom imaged with Solstice (left) and with a standard NaI camera (right). Acquisition included 180 projection over a complete 360 degrees rotation. Starting at the 12 o'clock position, the rods are 4, 3, 2.5, and, 2mm respectively (diameter and spacing).

D. Dual Isotope Imaging

Energy resolution is a critical feature of the Solstice imager and substantial improvement should be expected from this characteristic alone. A simultaneous dual isotope test was devised using the same (micro-rod) phantom as in the previous section in which every other hole was separately filled with either ^{99m}Tc (140 keV) or ^{123}I (159 keV). The total amount of Technetium was 10 times higher than the Iodine dose. Two energy windows of 13% each around the two peaks were defined and data acquired simultaneously from the two isotopes. A full 3D acquisition and reconstruction were then performed. Figure 6 shows the filling geometry and the spectrum.

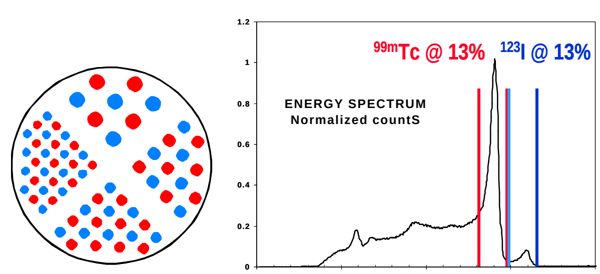

Figure 6. "Micro-Rod" filled with ^{99m}Tc (140 keV) and ^{123}I (159 keV). The total Technetium dose was 10 times the one of Iodine. Two energy windows were defined around the peak and imaged simultaneously.

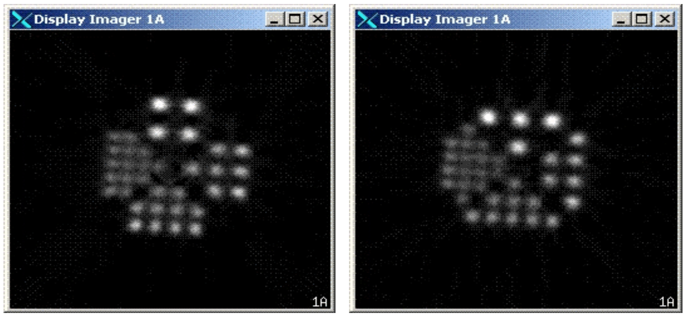

Figure 7. Resulting ^{99m}Tc (left) and ^{123}I (right) images for the "Micro-Rod" phantom. The images are virtually perfectly separated with no contamination from the low energy window into the Iodine.

The images in the Figure 7 show virtually perfect separation between the two isotopes.

E. Truncation

Finally, the plane integral geometry of Solstice will need to deal with truncation is almost all cases (where the object is larger than the detector itself). While it is beyond the scope of this paper to describe the details of the reconstruction techniques, early results showing the performance of a technique specifically developed to eliminate the truncation artifacts can be presented. In fact, the technique uses the very properties of the plane integral tomography to accomplish that goal. In order to test the performance of the algorithm, cardiac phantom from Data Spectrum was imaged with large "outside of field of view" activity ("bladder"). This outside bladder had roughly the same total activity as the part of the phantom in the field-of-view. (indicated on the image as the superimposed square).

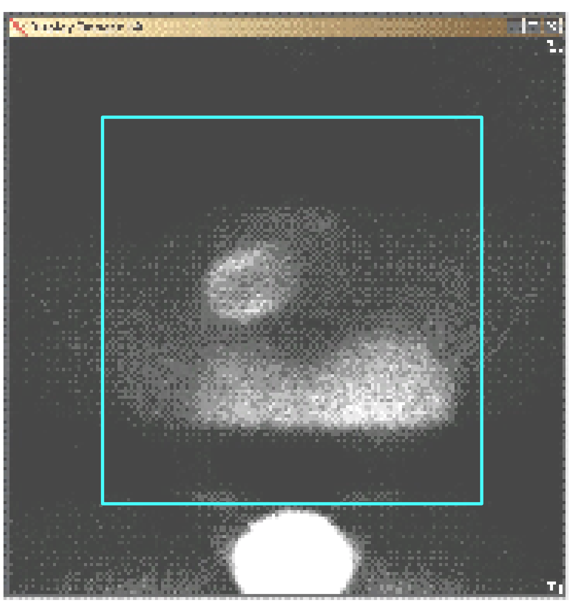

Figure 8. One view (projection) of the cardiac phantom. The box superimposed on the image represents the actual size of the Solstice field-of-view. The activity in the "bladder" was roughly the same as in the rest of the phantom.

The images reconstructed using the derivative approach described by Zeng [6] show an excellent reconstruction and seem to indicate that effects of truncation can be overcome. With the presence of such an intense object outside of the field-of-view, normal means of reconstruction (FBP or MLEM) are simply overwhelmed and produce very limited results.

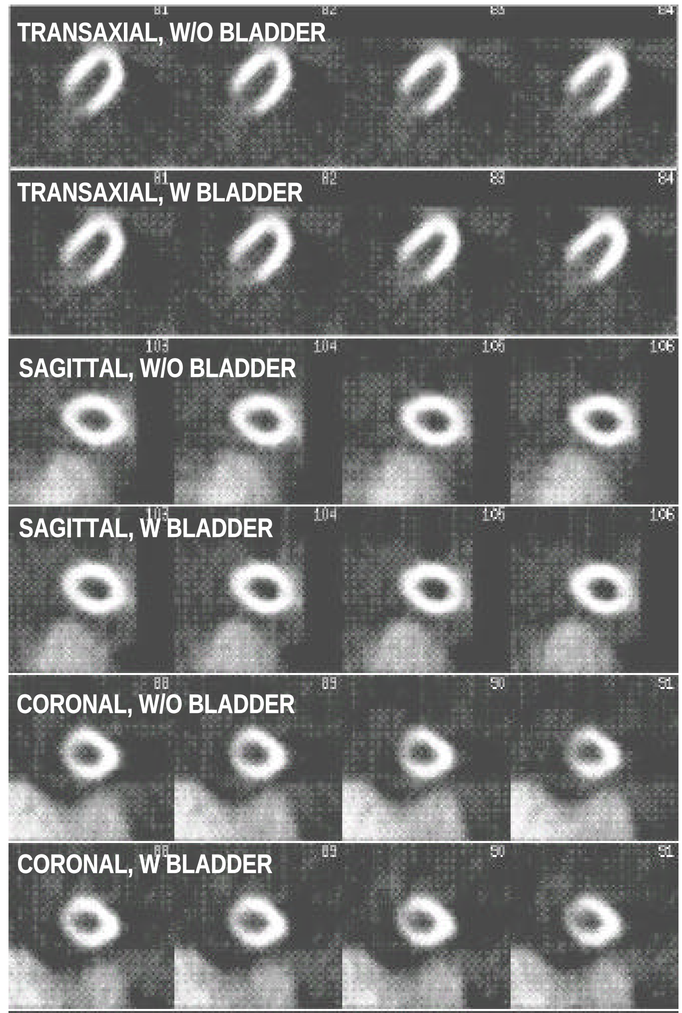

Figure 9. Reconstruction of the cardiac phantom. Transaxial, sagittal and coronal views of the phantom without the "bladder" (from top and alternate rows) and phantom with the "bladder" (second from top and alternate rows). They are identical to the limit of the quality of the print.

F. Other Features

One potentially interesting feature of the Solstice camera, which is consequence of the use of solid-state detector, is the count rate. The prototype design of 34cm field-of-view can easily handle several million counts per second before any dead time effect can be perceived. The only limitation at this point is the digital acquisition and framing hardware/software but can easily perform acquisition a 1 Mcps. For most of the images presented in this paper, acquisitions were made between 100 and 150 kcps in window (up to 500 kcps total spectrum depending on the object).

Later on, other features will progressively be described as more tests are being done and specific targeted applications identified.

IV. DISCUSSION

We have presented the early results of a new solid-state imager. The basic assumption in this work is that **both** spatial and energy resolution need to improve for any significant change in Nuclear Imaging to be made.

The use of a solid-state detector (CZT in our case) for improving the energy resolution is obvious although engineering and cost problems have so far prevented a wide use of this material in the main stream of Nuclear Medicine. The linear (or at least elongated) arrangement in Solstice substantially relaxed the cost constraints by requiring up to 8 times less material than the standard 2D approach of the same field-of-view. The fact that all pixels along a detection slat are combined to estimate the value of the plane integral also help cost by being more tolerant to dead or otherwise non-optimal CZT pixels.

The end result for Solstice is a superb 3.6% average energy resolution for the whole imaging array at room temperature without any special cooling devices. By virtue of the fact that each pixel can be considered as a small detector, Solstice can also operate at extreme count rates.

Spatial resolution and system sensitivity are more complex. The use of rotating slat hole geometry and acquiring data in a 1/r weighted plane integrals, although bringing a whole new series of challenges, seems to be the only approach to breaking the sensitivity-resolution limitation that the standard parallel hole collimators have imposed on Nuclear Medicine for years.

The system point spread function (resolution) is guaranteed by design. While essential, this is not sufficient to create a imaging system. Two points need to be addressed. The raw sensitivity and the truncation. Results presented in this paper show that we have a reasonable chance in both cases.

The plane integral design generates a much higher 'raw' sensitivity but we also know that more counts ARE needed because of the additional reconstruction. The raw sensitivity of the Solstice system, at 10cm, is around 800 counts / uCi / min (compared to 175-225 for a typical collimator). The sensitivity figure can be as high as 1600 at 1cm. The ratio between Solstice and the parallel hole collimator would be much higher if the same spatial resolution was needed from the classical collimator. Using the current technology, a collimator with 5mm FWHM at 10cm distance should have a system sensitivity of about 35 to 45 counts per uCi per minute. Under this new rule, Solstice has 20 times more (raw) counts for standard imaging, and up to 50 times for small objects. The images presented in this paper support, in an anecdotal way, that the Solstice sensitivity is sufficient to reconstruct useful images. In any case, thicker (C_Z) and/or wider (C_Y) CZT can be used to further increase the raw sensitivity.

Truncation is the other limitation and is addressed by reconstruction alone. Solstice samples the data in 1/r-weighted plane integrals ("r" being the distance between a point in the object to the detector). One possible method to deal with this kind of data, inspired from Grangeat cone-beam reconstruction algorithm [5], is to convert the derivative of the data into a derivative of parallel planar integrals, then consistent with the Radon transform [6].

V. CONCLUSION

We have established in this paper the main guidelines for the development of a new gamma camera based on solid-state detection and plane integral sampling and reconstruction. The tests performed so far seem to support the targeted system specification of an energy resolution better than 5% FWHM at 140keV and a (reconstructed) planar spatial resolution of 5mm FWHM at 10cm distance also at 140 keV. While much more is required to build an actual imaging system, the results are either in line or exceeding the target and justify more development effort in this direction.

VI. ACKNOWLEDGEMENTS

The authors would like to thank the important contributors to the system design team, Barry Kline from Philips Medical Systems and Joe Grosholtz and Kevin Parnham from eV Products, (Saxonburg, PA). Members of the engineering team also include, Austin Bowen, Bob Davis, Eric Dillen, Harry Smith, and Steve Vydrin from eV-Products, and Pat Bender, Kevin Mantey, Chris Matthews, Kevin McMahon, David Mercer, Jason Radachy, and Bob Zahn, from Philips Medical Systems

VI. REFERENCES

[1] Webb S, Flower MA, Ott RJ. *"Geometric Efficiency of a Rotating Slit-Collimator for Improved Planar Gamma-Camera Imaging"*, Phys. Med. Biol. vol.38, pp.627-638, 1993.

[2] Webb S, Binnie DM, Flower MA, Ott RJ. *"Monte-Carlo Modeling of the Performance of a Rotating Slit-Collimator for Improved Planar Gamma-Camera Imaging"*, Phys. Med. Biol. vol.35, pp.1095-11108, 1990.

[3] Lodge MA, Binnie DM, Flower MA, Webb S. *"The Experimental Evaluation of a Prototype Rotating Slat Collimator for Planar Gamma Camera Imaging"*, Phys. Med. Biol. vol. 40, pp.426-448, 1995.

[4] Tosswill GH. *"Imaging"*, US Patent, 4,090,080, 1978.

[5] Grangeat P. *"Mathematical Framework of Cone-Beam 3D Reconstruction via the First Derivative of the Radon Transform"*, in Mathematical Methods in Tomography, Editors Herman FT, Louis AK, Naterrer F, Springer Verlag, New-York, 1990.

[6] GL.Zeng, D. Gagnon, CG. Matthews, JA. Kolthammer, JD. Radachy *"Image Reconstruction Algorithm for Rotating Slat Collimator"* IEEE MIC 2001, San Diego, Nov. 2001.