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Beacon-S™: Non-uniform attenuation correction for SPECT imaging

The new medium-energy transmission device for AXIS and IRIX

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Transmission scan using a medium energy source

Today's gamma cameras are true multi-energy imaging devices. Not only must the camera image the traditional low energy isotopes ^{99m}Tc and ^{201}Tl, but it must also image medium energy isotopes such as ^{67}Ga and ^{131}I and positron-emitting isotopes such as ^{18}F. The challenge is to satisfy optimally the requirements for the low-energy application while addressing the needs for high-energy imaging.

The Beacon-S product addresses SPECT imaging needs and has the following features:

— Ability to upgrade to provide PET attenuation correction (Beacon-SP option) when used in conjunction with the γ-PET™ for the AXIS and IRIX.
— Beacon-S includes a 356-kev medium energy ^{133}Ba source with a 10.54-year half-life. This means that the transmission source will never have to be replaced for the effective clinical life of the system.
— The energy of the transmission source is such that enough radiation penetrates *through* the low energy collimators, making the selection of the collimators for emission independent of the transmission task.
— The higher energy of the gamma substantially improves the transmission contrast for larger patients by virtue of better penetration through the body.
— The medium energy source is electronically collimated in both the X and Y directions, thus fully utilizing the camera's intrinsic spatial resolution (since the collimator is not "visible" at that energy) resulting in high-resolution transmission scans.
— Since the energy of the source is above the emission energy, no emission downscatter from the object is present in the transmission data, resulting in high-contrast scans.
— The imaging principles of the medium energy source, combined with the location and functionality of the source holder, allow the device to be used in all the possible configurations of the AXIS and IRIX. The source and source holder stay permanently attached to the camera, minimizing handling and exposure to personnel.

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Transmission images and reconstruction

The first test for the medium energy source is to compare the quality of the transmission scan with its low energy counterpart (e.g. ^{153}Gd, ^{99m}Tc). However, the "real" test is to assess how the reconstruction of the object is improved by the use of a non-uniform attenuation map.

The advantages of the medium energy source in defining structure (delineation of the lungs, Figure 1) and contrast (spinal cord and bed structure, Figure 2) are obvious from these images (both 10 sec/projection total acquisition time using a Spectrum, Torso phantom). Note the improvement in detail and image contrast.

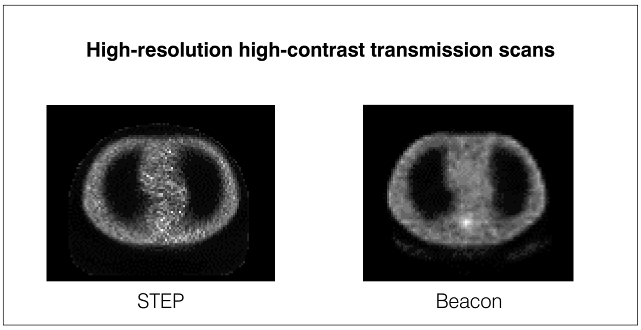

Figure 1. Comparison of STEP (Gadolinium source) and BEACON (Barium source) using comparable imaging protocol for resolution and imaging time per slice. The Beacon image better defines the shape of the lung and correctly locates the spine.

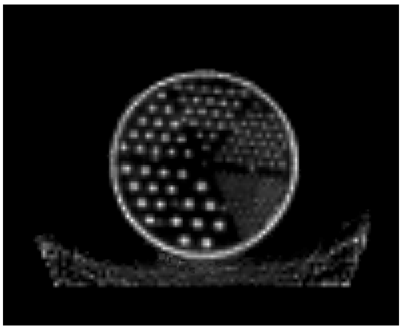

Figure 2. Beacon transmission image of the rod phantom (Data Spectrum Deluxe Model ECT/DLX/P). Largest rods are 12.7 mm in diameter. The fifth section is 6.4 mm and easily resolved. The last section, 4.8 mm is partially resolved with the level of counts.

Attenuation correction

Non-uniform attenuation of the object to be imaged is one of the most important problems in nuclear medicine. Knowledge of the actual attenuation map, on a patient-by-patient basis, has become part of the solution.

Attenuation maps

One possible way to compensate for the effect of the attenuation is to obtain an accurate description of the different media — in terms of shape and density — through which the gammas have to traverse before reaching the detector. With an appropriate map of the attenuating medium, it is possible to compensate for the effects of attenuation.

The attenuation map can be determined in different ways, such as prior knowledge or through direct transmission measurements. External radioactive sources have been used to generate those maps by collecting transmission information and doing the reconstruction more or less like that utilized by CT.

Attenuation coefficient

The actual attenuation coefficient is a characteristic of the attenuation medium and is dependent on the transmission energy. A correction needs to be applied when the energy used to measure the map differs from the emission energy. The following table shows the (total) attenuation for WATER and AIR at energies corresponding either to common imaging agents or to transmission sources.

Table 1

Energy (keV)		Attenuation (1/cm)	
		Water	Air
Americium	59	0.20	0.00022
Thallium	80	0.18	0.00019
Gadolinium	100	0.17	0.00018
Technetium	140	0.15	0.00015
Barium	356	0.11	0.00012
Positron	511	0.096	0.00010
Cesium	662	0.085	0.00009

From Table 1 we can see that using a transmission source with an energy below that of the imaging agent results in an overestimation of the attenuation and using a source with a higher energy results in an underesti-mation of the attenuation. In either case, compensation can be made and is of the same order of magnitude. For Beacon™, ^{133}Ba was selected because it is in the middle of the spectrum of useful isotopes, optimizing the characteristics for both low and high energy correction. Since a straightforward scaling can be made to convert attenuation coefficients from one energy to another, the real challenge is to extract the *shape* of the attenuator (patient outline and delineation of the internal organs). We will see that using a medium energy source will produce effective results.

Before describing the advantages of using a medium energy source, a few additional characteristics of ^{133}Ba will be given.

Half-life

With a 10.54-year half-life, ^{133}Ba is particularly well-suited as a *permanent* transmission solution. A permanent source simplifies the operation and presents important cost savings over the life of the equipment.

Beyond the financial savings, a greater impact of a longer half-life source is that it allows a stable imaging protocol to be established. In other common implementations, in which the 9-month half-life source ^{153}Gd is used, the source frequently has to be replaced, and as a result, the source activity varies substantially over short periods of time. Therefore, it is likely that the imaging protocol would need to be modified often as the source decays or one would need to accept a change in the performance of the device over time.

Table 2

^{133}Ba Energy-Spectrum		
Energy (keV)	Intensity (%)	
30.62	34.25	
30.97	63.42	Filtered out at the sourse
35.00	22.75	
53.16	2.14	
79.61	2.54	
80.99	**32.97**	
160.61	0.59	
223.23	0.45	
276.39	6.90	
302.85	**18.33**	**Contributing**
356.01	**62.05**	**Main Peak**
383.84	8.94	

Table 2 represents the gamma rays emitted by ^{133}Ba. Only three lines (in bold) have any significant effect on the design and use of the device. The main peak is 356 keV, and all the imaging considerations (penetration and shielding, for example) are based on this energy. Extra counts are available from the 302 keV line if the acquisition energy window is opened wider to include this line. The 81 keV line is not useful for Beacon™, and in fact this line

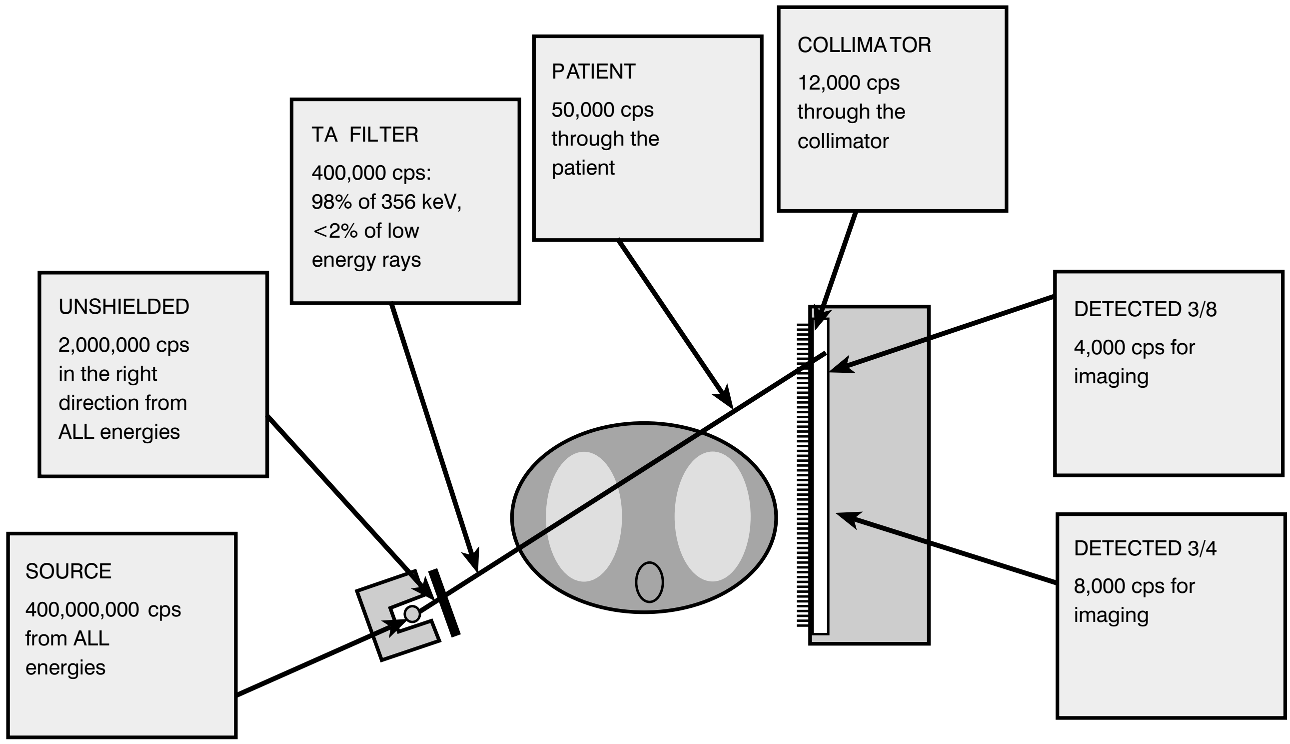

Figure 3

could interfere with Thallium imaging if proper measures are not taken. It is also desirable to filter out the low energy rays in order to reduce patient exposure during the acquisition. For this reason, a thin sheet of tantalum foil is placed over the exit slit of the source holder, which effectively blocks the low energy gammas (and Pb x-rays from the source holder) while not significantly attenuating the desired 356 keV gammas.

Activity

Another goal of the transmission source selection was to reduce the amount of activity required in an effort to reduce patient exposure without compromising the final map quality. To satisfy this goal, Picker has elected to utilize a moving point source, which is collimated in the axial direction. This results in excellent patient penetration through a fan beam geometry that, when combined with iterative reconstruction techniques, makes the use of lower level of activity possible. Therefore, the Beacon non-uniform attenuation correction device utilizes two 10 mCi point sources.

Shielding

Shielding of the source is required for three main reasons:

1. To reduce exposure to the technologist and patients during system use or storage.
2. To eliminate or reduce contamination of the transmission activity into the emission data.
3. To eliminate the need to remove the source holding device for storage during non-transmission based acquisitions.

The ^{133}Ba source addresses these issues favorably. The low activity (compared to several hundreds of millicuries for some devices) and the reasonable energy level of the ^{133}Ba gamma rays (compared to the 662 keV line source of ^{137}Cs) greatly simplifies the shielding task to the point where permanent shielding can be designed within the device itself.

Transmission imaging with a medium-energy source

It becomes obvious that the combination of long half-life, optimal energy, lower activity, and proper shielding create the most efficient transmission scanning device with very interesting imaging features.

Transmission *through* the low-energy collimator

Without any doubt the key feature of the Beacon-S product is the fact that the detected 356 keV gamma rays travel through the low-energy collimator during SPECT acquisitions. This means that the collimator geometry does NOT have to match the transmission source geometry, allowing the collimators to be optimized for emission energy, and, therefore allowing the use of a parallel hole collimator indifferently in 90° or 102° detector orientations without affecting the Beacon performance.

Full electronic collimation

The moving point in an "effective" fan beam geometry ("effective" because there is in reality NO fan-beam collimator) offers several advantages. It is a very efficient way to obtain full (X and Y) electronic collimation of the transmission information.

As one can appreciate from the graphical representation of the Beacon geometry (Figure 4) the position of the source is known at every point of its motion. Thus, every detected event can be associated with the source position, defining a very accurate path for the photon. In addition, since no mechanical collimation is used at the detector level, the precision of the positioning is only limited by the intrinsic resolution of the system.

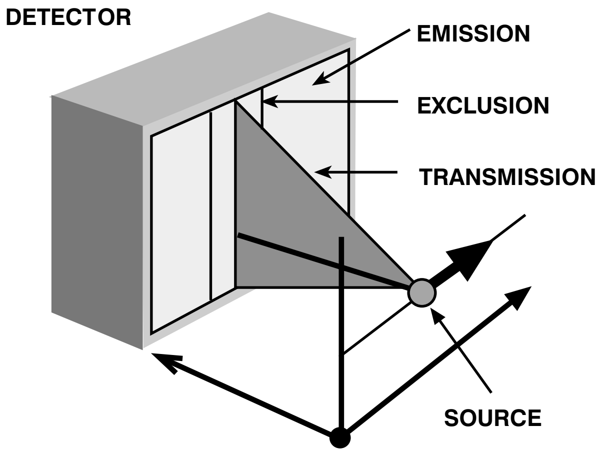

Figure 4

In practice, transmission counts from the source are acquired within a narrow spatial window exposed by the source, which moves along with the source.

Better contrast in large patients

One limitation in routinely applying transmission attenuation correction to real clinical situations is reduced count statistics for larger patients. At ^{153}Gd energy (100 keV) the gamma ray attenuation length is around 6 cm, meaning that the beam may have to traverse possibly more than five attenuation lengths, with obvious consequences for the number of counts available for detection and reconstruction. One expects for instance at least six times the number of counts through a 30 cm water cylinder using 356 keV photon instead of 100 keV. The poor count statistics are sometimes critical and the deficiency of the reconstructed attenuation map (contrast and noise) may *degrade* the emission reconstruction instead of improving it.

Medium and high-energy imaging

Transmission scans for attenuation correction of medium and high-energy imaging are in theory possible but will require the use of an asymmetric fan beam collimator that matches the geometry of the source.

Radiation protection issues

Before describing the imaging characteristics of the Beacon device, a few words on radiation protection issues might be useful. Advantages of the Beacon device over other transmission scan techniques can easily be identified. Here are some examples:

- No user manipulation for the life of the equipment and no need to fill liquid sources.
- Active area contained within a plane which itself is contained into a volume formed by the detector buckets shielded for high-energy imaging.
- Built-in park areas with additional shielding.
- Built-in permanent storage with additional shielding.
- Low activity.
- Better image statistics for larger patients, where increased imaging time was the only alternative.

The Beacon option comes with a sophisticated sensor system making sure that the position of the source-holder is consistent with the imaging task and does NOT interfere with any of the motion required for that particular acquisition. Messages are given to the user, through the P-Scope™ and using clearly visible LED indicators, that the source is out of its storage/shielded position and ready for imaging. The source drive mechanism also has a battery backup system so that the source is automatically returned to its safe (shielded) position even after a system failure or power outage.

The low activity of the sources produces a very low risk (2 to 3 mR per hour) to the patient and personnel, comparing advantageously to higher activity, lower energy and similar activity, higher energy devices.

Further readings

Nearly everything you wanted to know about physical data and constants can be found in a very convenient searchable form on the WWW. For instance, for all constants and attenuation cross-section data for pure elements and compounds, see:

http://physics.nist.gov/PhysRefData/

For characterization data on isotopes:

http://www.dne.bnl.gov/CoN/index.html/

More information on regulation for instruments containing radioactive sources and a list of registered instruments in the U.S. is available from the Nuclear Regulatory Commission:

http://www.nrc.gov/

Literature on attenuation correction in SPECT is abundant, in fact too abundant for an exhaustive review to be provided here. Key papers can be listed though. For instance:

B.M.W. Tsui et al, *Correction of non-uniform attenuation in cardiac SPECT imaging*, J Nucl Med 1989; vol. 28: 497–507.

The authors were among the first to identify the need for non-uniform attenuation correction using transmission information. The first description of a commercial apparatus performing simultaneous emission and transmission scan is due to:

C.H. Tung et al, *Non-uniform attenuation correction using simultaneous transmission and emission converging tomography,* IEEE Trans Nuc Sci 1992; Vol. NS-39: 1134–1143.

A thorough description of a complete validation procedure on the same device is available in:

G.T. Gullberg et al, *The design and performance of a simultaneous transmission and emission tomography system*, IEEE Trans Nuc Sci 1992; Vol. NS-45: 1676–1698.

Beekman describes the use of scanning point source in a fan- or offset fan-beam geometry in:

F.J. Beekman, et al, *Half-fan-beam collimators combined with scanning point sources for simultaneous emission transmission Imaging,* J Nucl Med 1998.

PET imaging technology was already using moving point to obtain transmission information. See for example:

J.S. Karp et al, *Singles transmission in volume-imaging PET with ^{137}Cs source,* Phys Med Biol 1995; Vol.40: 929–944.

Beacon-S imaging

This document describes the Beacon-S SPECT attenuation device. One of the main features of the device is its ability to be used for all the possible configurations of the AXIS and IRIX and the ability to be used for single photon and positron imaging for Beacon-SP is an integral part of the design.

Before going into the specifics of SPECT imaging, some general operating features of the Beacon device will be reviewed.

Non-interference with transform motions

In the parked mode, Beacon does NOT interfere with any of the gantry motions, including all transform motions (irising, conversion from/to any of the 90<, 180<,102<,120< modes), all manual and automatic tomographic orbit motions, and the collimator exchange motions. Special motions and configurations are enabled by manually deploying the Beacon device.

Blank scan

Transmission imaging is based on ratios (number of counts in a specific location WITH and WITHOUT the object). In theory, this ratio can be established in any configuration, however, in practice, it is necessary to limit the number of configurations as it is necessary to produce a blank scan in every imaging geometry and for every collimator. With the heads I and II in a fixed „L" arrangement (90° or 102°), it is possible to keep the relationship between the source and the opposite head constant while defining ANY kinds of orbits, thus allowing for optimal orbits to be defined. In all the other configurations (120° and 180°), it will be necessary to return to predetermine geometry for ALL transmission acquisitions including the blank scan.

Reconstruction and other corrections

The information generated by the transmission device is then going to be processed by Picker's advanced reconstruction package which utilizes an ML-EM central engine with options for ordered subsets, resolution recovery, and enhanced quality control feature. Scatter correction will be achieved by acquiring multiple energy windows and using a narrower window when quantitative accuracy is required (e.g. perfusion study) or a wider and less restrictive window when counts are more important (e.g. gated study). In the case of gated or dynamic study, the same attenuation map will be applied to all the time frames of the sequence.

Beacon imaging
AXIS/IRIX - Cardiac 102° Mode

Cardiac is one of the most important applications for attenuation correction. The variable geometry AXIS camera optimally acquires the emission and the transmission information. In 102< mode (for either the AXIS or the IRIX) one can still achieve parallel-beam geometry for the emission and asymmetric fan-beam for the transmission scan.

The combination of parallel hole collimator and the 102< geometry offers the best quality for the emission data as it eliminates the corner gaps, allowing for closer orbits. In addition, the large field-of-view of the AXIS and the asymmetry of the transmission beam eliminate any truncation of the transmission map. In the preferred protocol, the emission information is acquired first, followed by the transmission. Because of the very close orbit that can be defined using the 102° mode, it will be necessary to adjust the radius to be able to clearly define the inside portion of the body (portion close to the detector). The whole process is illustrated in Figure 5.

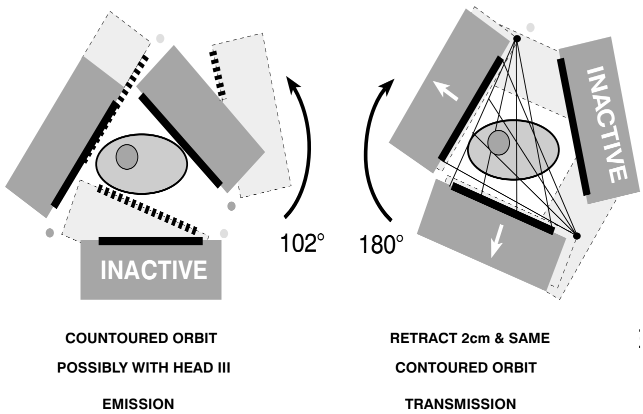

Figure 5. IRIX/102/120 - sequential 204 cardiac.

AXIS — General mode

For general 360° acquisition (180° rotation with the two detectors at 180° opposed), the Beacon geometry has to be adapted. In this mode, the emission data are acquired following any valid protocol, then the two detector heads with the sources will go to a predetermined radius so that the location of the source with respect to the opposite detector is the same as the one used for the blank scan. The whole detector-source combination is then shifted using the VT motion of the AXIS to cover the center of rotation and to define the external contour of the patient. One would note that the larger radius necessary to perform the transmission scan does not degrade the image quality (as it would for the emission part) since both the starting point (the source) and the end point (the detected position) are known for each event and the line of response can be determined exactly.

Figure 6 illustrates the General SPECT mode on the AXIS

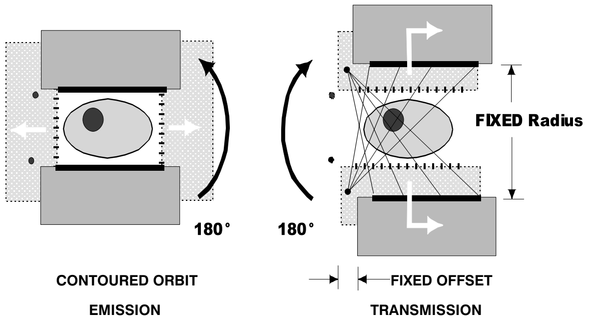

Figure 6. AXIS/180° - sequential 360° general mode.

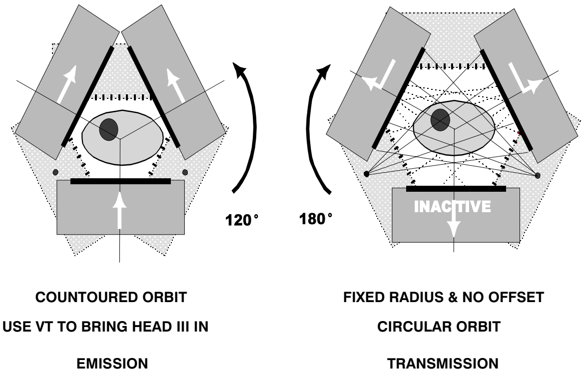

Figure 7. IRIX/120°/180° - sequential 360° cardiac & general mode.

Irix - general 360° spect

The same principles are used with the triple-detector gantry of the IRIX. In cardiac mode, different geometries are available for emission data whether one favors the 180< acquisition protocol or the full 360< protocol. However, with Beacon-S, the 102< configuration between Heads 1 and 2 still provides the best approach. In this mode, the third head can either be idle (for the 180< acquisition mode) or be contouring the patient at 120< from Head 2 and contribute to the collection of emission information. In all cases though, the detector number 3 does NOT participate in the acquisition of the transmission scan. In other words, the Beacon device is exactly the same for both the AXIS and the IRIX, using the same holder on the same two detectors, hence providing a simple upgrade path for AXIS customers.

A different mode is available for full 360° acquisition. With the three heads in the equilateral configuration, close contouring can be achieved by a combination of radial and tangential (VT) motion. After emission, the three heads are going back to their unshifted position, retracted to a predefined orbit to do the transmission part. As in the previous General 180° SPECT case, defining a known configuration is necessary to be able to compare the acquired transmission information to the blank scan. Figure 7 shows the two steps of this General 360° SPECT on an IRIX.