GE Healthcare

CZT Technology: Fundamentals and Applications

White Paper

Abstract

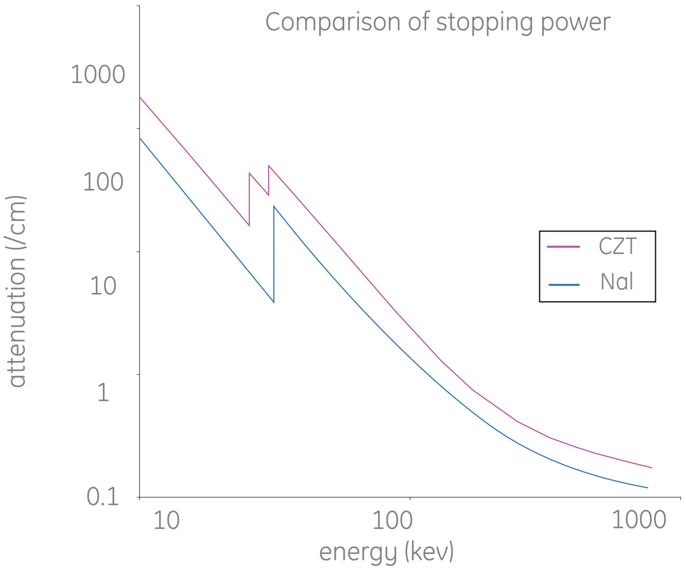
Nuclear Medicine traces its technology roots to the 1950's, and while it has continued to evolve since the invention of the Anger camera, the underlying principle of operation of the detector has not changed during this time, and this has set limits on the performance that can be obtained with a gamma camera.

The commercial availability of CZT (Cadmium Zinc Telluride) detectors has allowed gamma camera designers to challenge many of the traditional design constraints, and the result is a new generation of Nuclear Medicine equipment with previously unheard-of performance and clinical utility.

What is CZT

CZT is shorthand for Cadmium Zinc Telluride – a direct conversion semiconductor with a density of ~5.8 g/cm^3. Its density and high effective atomic number (Z_{eff} ~50) give it high stopping power for typical energies of interest in SPECT – with a linear attenuation coefficient greater than that of NaI, for example.

The zinc content varies from supplier to supplier, but a typical composition is $Cd_{(1-x)}Zn_xTe$ with x around 0.1 . It often contains trace amounts of other elements (dopants) that are used to improve the electrical properties. CZT is grown as a single crystal at a temperature of around 1100C in a hermetically sealed container to prevent chemical contamination. The crystal (known as "boule") is cut into wafers, polished, and metal contacts are deposited on the surface to extract the electrical signals from the detector. Finally it is bonded to electronics, and becomes a complete miniature detector.

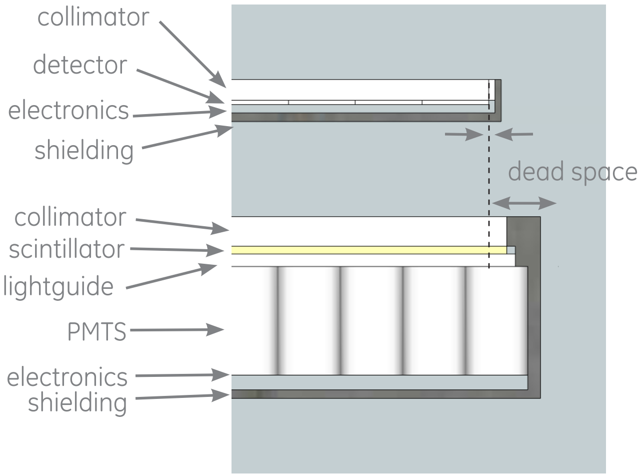


Linear attenuation coefficient of NaI and CZT showing that the latter has greater stopping power at these energies

Comparison with Anger camera

In a typical scintillator-based gamma camera, incident gamma rays deposit their energy in the scintillator where it is converted into visible (or near-UV) light photons. The number of photons generated varies with scintillator, but for NaI:Tl (thallium-doped sodium iodide, the "standard" scintillator for Anger cameras) the conversion rate is typically 38 photons/keV; thus, the 140 keV emission from ^{99m}Tc produces about 5300 photons. Two/thirds of these photons reach the photocathode of a photomultiplier (PMT), where about 25% of them are converted to photoelectrons. These photoelectrons are amplified by the PMT and turned into an electrical pulse with amplitude proportional to the deposited energy. The amplitude of the electrical signal observed for the same energy deposited is affected by many factors: variation in number of photons generated, variation in number of photons transported to the photocathode (depends on depth of interaction), variations in conversion efficiency of the photocathode, variations in the amplification properties of the PMT dynodes, and statistical fluctuations (Poisson noise); the latter is probably the most significant.

By contrast, in a direct conversion detector like a CZT the radiation deposits energy at some point in the crystal lattice where it results in the generation of pairs of charge carriers. By application of an electric field the charge carriers get swept to the cathode and anode of the device where they induce a current pulse that can be detected. The energy resolution for either detector is ultimately limited by Poisson statistics: the FWHM energy resolution can be no better than 2.355/sqrt(N), which sets a limit of 7% FWHM on NaI at 140 keV (with about 1000 UV photons detected) but less than 1.5% FWHM for CZT (with over 30,000 electric charges detected).



In practice the resolution obtained with NaI detectors is a little closer to the theoretical value (10% vs 7%) than for CZT (6% vs 1.5%). This reflects the many years of technical evolution of NaI detectors which has brought their performance close to the theoretical best; while for CZT detectors, there is still room for further improvement.

Dead space

One of the most striking things about the CZT detector is its size. Specifically, in an Anger camera it is difficult to resolve the position of events beyond the center of the last (edge) PMT. This results in a significant dead space all around the detector; the CZT detector, being direct-conversion based, has no such dead space. A CZT-based detector is also much thinner than an Anger camera since it contains no light guide or photomultiplier. The consequence of this is that the volume that needs to be shielded is much smaller for a CZT-based detector, which in turn means that the final assembly will be much lighter.

Intrinsic spatial resolution

The spatial resolution of today's CZT detectors is 2.5 mm independent of energy – a lot better than the 4.0 mm typically achieved with NaI at ^{99m}Tc energies (140 keV), and much better again than the resolution obtained with ^{201}Tl (5 – 6 mm). The reason is that the photons in a NaI crystal are diffused over a considerable distance before being detected, and the triangulation to their origin is done with PMTs that are several centimeters away from the location of radiation interaction. By comparison, in CZT a compact charge cloud is detected by a segmented anode that is only millimeters away – and an improvement in resolution can be obtained simply by making the anode pixels smaller and increasing the number of electronic channels. The practical limit on resolution, then, is given by the limits on the density of the electronics, and the associated power dissipation and cost; but detectors have already been successfully produced with 0.6 mm pixels for certain astrophysical experiments, showing that the practical limit on resolution is still some ways off.

System tradeoffs

The detector of a gamma camera is often considered separate from the collimator, yet the one cannot function without the other. For example, intrinsic resolution of a detector is an almost meaningless parameter unless considered in conjunction with the corresponding resolution in the collimator; similarly, sensitivity of a collimator does not matter unless the stopping power of the detector is taken into account. With this in mind, it is helpful to consider what is needed from a gamma camera system, and then work back to the detector requirements.

Ultimately, the goal of the gamma camera is to create an accurate representation of activity distribution in a body. Given the physics of nuclear medicine, this can be broken down into five fundamental requirements:

- Sensitivity: *get lots of counts*
- Resolution: *where did they come from?*
- Field of view: *am I looking at the right part of the patient?*
- Scatter & photopeak crosstalk rejection / correction: *are these events what I think they are?*
- Attenuation correction: *what am I missing?*

The first three of these requirements are subject to system trade-offs; the last two are patient dependent. The best-known of these trade-offs is between sensitivity and resolution: a high-resolution collimator views a very narrow column of activity from the patient, and therefore provides excellent spatial resolution at the expense of sensitivity. A high sensitivity collimator by contrast accepts radiation from a wider range of angles; this increases the sensitivity at the expense of resolution.

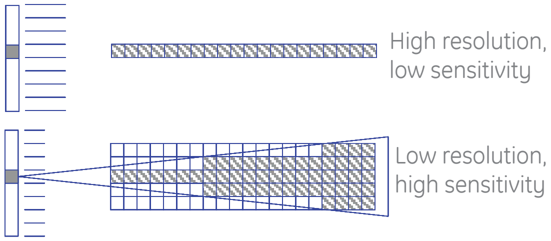


Figure 1a:- Resolution ←→ Sensitivity

It is also possible to get more sensitivity by sacrificing field of view

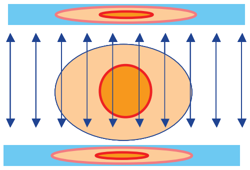
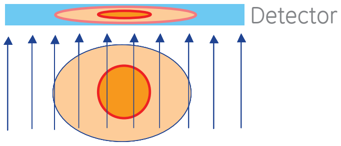
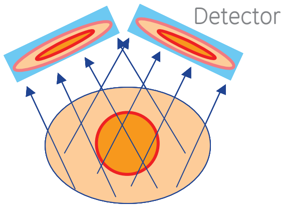


Figure 1b:- Detector surface ←→ Sensitivity

or by increasing the total detector area, as is shown in the diagram.



Parallel hole SPECT



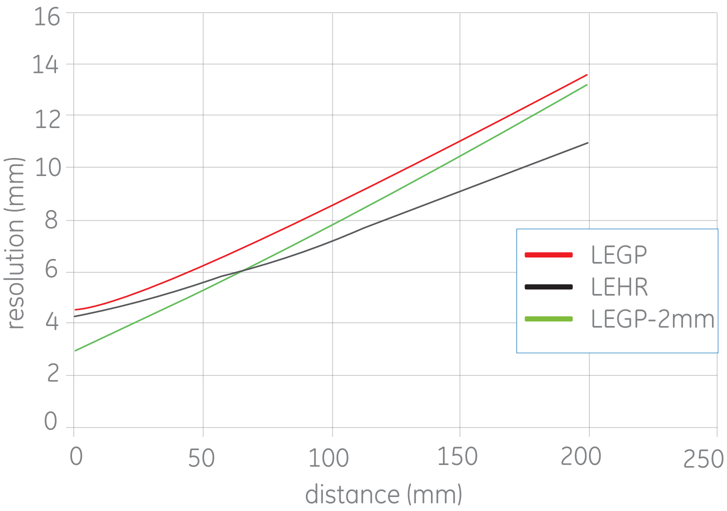
Two smaller detectors

Figure 1c:- Field of View ←→ Sensitivity

Resolution and sensitivity are important, but they are not the only things that matter. The fourth requirement addresses the question of scatter rejection and the rejection of photopeak crosstalk for multi-isotope imaging. These are achieved with good energy resolution in the detector. For an isotope with a single photopeak, like ^{99m}Tc, it has been shown that image quality improves until energy resolution of the detector reaches about 5%. At this resolution, image quality is improved without the need for scatter correction.

Patient distance

All other things being equal, a high-resolution collimator (LEHR) will have lower sensitivity than a general-purpose collimator (LEGP). However, image quality obtained with a LEGP collimator may well be better than the quality obtained with a LEHR collimator in the case where the latter is further from the patient. The following graphs demonstrate that the resolution of the system depends on the intrinsic resolution when the object is close to the collimator, but is dominated by the collimator at source distances greater than a few centimeters. For intrinsic resolution we compare typical values for intrinsic resolution of 4 mm (general purpose NaI based camera) and 2 mm (CZT).



System resolution degrades with object distance – more so for high sensitivity collimators. Intrinsic detector resolution hardly affects resolution at larger distance.

In the figure we plot system resolution as a function of object distance for three cases: LEGP (Low Energy General Purpose) collimator with 4 mm detector resolution; the same collimator with 2 mm detector resolution; and a LEHR (Low Energy High Resolution) collimator with a 4 mm resolution detector.

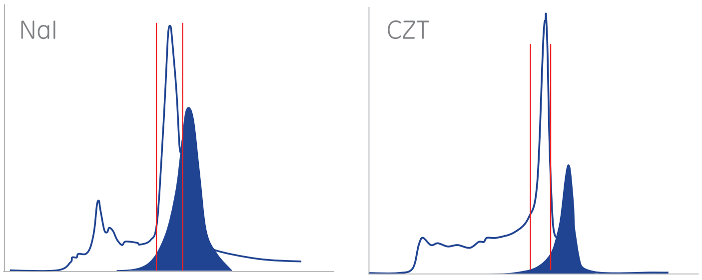
It can be seen that a high sensitivity collimator can outperform a high-resolution collimator when it is closer to the patient. The same is true even when the intrinsic resolution of one system is higher than that of another system: imaging performance comes about as a result of the interaction of all these factors, and imaging performance can be optimized only by taking a system approach.

At this point it is worth mentioning that recent advances in image reconstruction techniques using PSF (point spread function) modeling allow the reconstruction of images with higher resolution than is suggested by these curves; but even with these algorithms there is no "free lunch" and for equal count statistics the image quality obtained with higher resolution collimators will be superior.

Energy Resolution

The primary reason for wanting good energy resolution in a gamma camera is that it gives the camera the ability to distinguish scattered from unscattered radiation. The better the energy resolution, the narrower the acceptance window can be, and thus the smaller the fraction of scattered events that is accepted into the imaging window. The additional image quality benefit that can be obtained once energy resolution drops below 5% FWHM is small. However, when more than one photopeak is imaged at the same time -- whether because the isotope has multiple emission peaks or because the patient is being imaged simultaneously with multiple isotopes -- energy resolution improvements below 5% are still worthwhile as the degree of crosstalk diminishes linearly with window width. This is an exciting area of ongoing research for CZT-based gamma cameras.

As was mentioned above, dual isotope imaging is one of the most promising applications of CZT technology. We reproduce here the spectrum obtained with a conventional gamma camera viewing a mixture of ^{99m}Tc and ^{123}I, and a second spectrum of the same mixture obtained with a CZT detector. It is clear that in the CZT spectrum there is much less down-scatter from the 159 keV peak into the 140 keV window:



Overlay of ^{99m} Tc and ^{123}I spectra, showing greater crosstalk between the two peaks for the NaI detector with its poorer energy resolution and wider energy window.

Because there is less overlap between the peaks with the CZT detector, the correction that has to be applied to remove the downscatter is quite small; this in turn means that this correction will add little noise, and that the bias in the final image will be small.

Application of CZT in GE systems

At this point GE sells four different imaging systems based on CZT technology, while a fifth system is in the research phase. A quick look at these designs highlights some of the strengths of the CZT material as a gamma ray detector.

Pre-clinical SPECT

The first two systems are our preclinical SPECT imagers the explore speCZT and Triumph X-SPECT. The eXplore speCZT consists of a ring of 40 CZT detectors that are tightly packed all around the object of interest. The detectors are fixed but a set of slit/slat or pinhole collimators on a cylinder can rotate to give multiple views of the object. This system design follows all the principles outlined above: it leverages the high intrinsic resolution of the CZT in order to get excellent spatial resolution in the system, and takes advantage of the low dead space in order to maximize the amount of detector coverage all around the subject. The result is a system with high sensitivity over a large field of view – this is particularly useful for dynamic whole-body imaging in small animals.

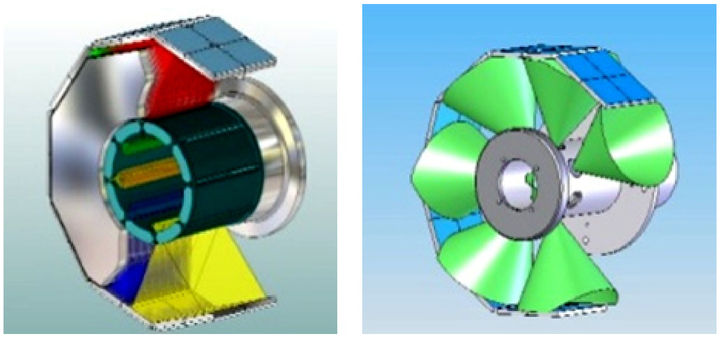
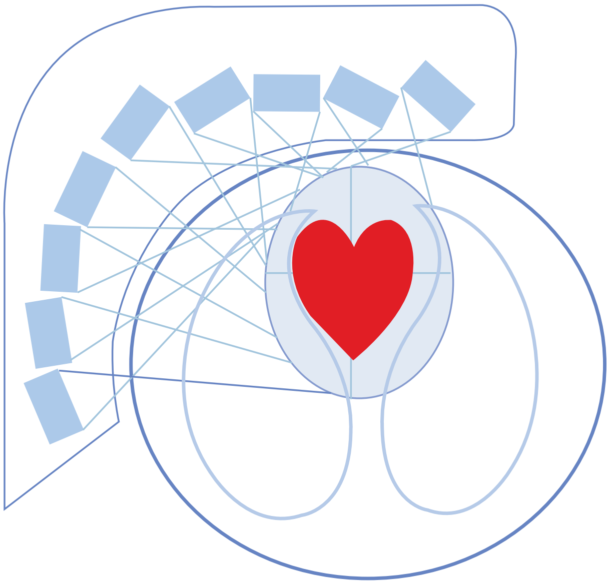


Diagram of preclinical SPECT scanner showing tight arrangement of detector modules and slit-slat (left) or
multi-pinhole (right) collimator

Alcyone Technology

The third and fourth GE systems to use CZT detectors are the the Discovery NM 530c and Discovery NM/CT 570c with Alcyone Technology dedicated cardiac cameras. The principle here is to get many detectors as close to the heart as possible in order to be able to image the heart without detector motion. Once again, the key characteristics of CZT that make this possible are the excellent intrinsic resolution (which permits the use of pinholes in the minifying configuration) and low dead space, which allows close packing of detectors. The energy resolution of the detectors is also good enough for the potential of simultaneous imaging of ^{123}I and ^{99m}Tc labeled agents which can be expected to lead to the development of more efficient imaging protocols and greater diagnostic accuracy.



Configuration of the detectors in the Alcyone system, showing how multiple detectors view the heart at the same time from different angles for high system sensitivity.

Molecular Breast Imaging: MBI

The fifth and final example of the use of CZT involves research effort into a system that could be capable of doing Molecular Breast Imaging. For breast imaging, spatial resolution and dead space are the key factors. With the compact form factor and minimal dead space of the CZT detector it is possible to make a gamma camera that can be positioned close to the patient, with potential for both CC and MLO views. At the same time, the smaller size could make the camera less intimidating for the patient. Further, since the detector can get so close to the breast, the collimator can be kept short, resulting in high sensitivity without sacrificing resolution. While more clinical evidence is needed, initial work with prototypes has shown great promise for providing additional diagnostic information especially for women with dense breasts.

Conclusions

CZT detectors have reached a level of maturity that permits their use in specific applications that take advantage of their unique properties: high spatial resolution, low dead space, and excellent energy resolution. Over the next few years further developments in detector technology can be expected to lead to additional improvements in performance. CZT technology will lead to a major transformation in the practice of Nuclear Medicine.

About GE Healthcare

GE Healthcare provides transformational medical technologies and services that are shaping a new age of patient care. Our broad expertise in medical imaging and information technologies, medical diagnostics, patient monitoring systems, drug discovery, biopharmaceutical manufacturing technologies, performance improvement and performance solutions services help our customers to deliver better care to more people around the world at a lower cost. In addition, we partner with healthcare leaders, striving to leverage the global policy change necessary to implement a successful shift to sustainable healthcare systems.

Our "healthymagination" vision for the future invites the world to join us on our journey as we continuously develop innovations focused on reducing costs, increasing access and improving quality and efficiency around the world.

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