DEEP-OF-INTERACTION DETERMINATION IN NaI(Tl) AND BGO SCINTILLATION CRYSTALS USING A TEMPERATURE GRADIENT

Joel S. Karp and Margaret E. Daube-Witherspoon

Hospital of the University of Pennsylvania, Department of Radiology, Nuclear Medicine Section, 3400 Spruce Street, Philadelphia, PA 19104, USA

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A method for determining the depth of interaction in both NaI(Tl) and BGO crystals is investigated. This technique takes advantage of the relationship between temperature and decay time in a scintillation crystal. The depth of interaction is ascertained by measuring the decay time in a crystal with a uniform temperature gradient applied along its depth. The application of determining the depth of interaction in positron emission tomography scanners is discussed.

1. Introduction

The spatial resolution of positron emission tomography (PET) scanners has rapidly improved in recent years. State-of-the-art multislice whole-body scanners have a spatial resolution of 5–8 mm in the transverse plane [1, 2]. While this represents a significant improvement over scanners built just a few years ago, there is an interest in improving the resolution [3, 4] to its fundamental limit (2–4 mm), which includes the uncertainties of positron range in tissue and the angular deviation of the coincident gamma rays from 180° in the lab frame [5]. Large improvements in spatial resolution are now taking place using clever encoding schemes to determine the location of an event in the detector with great precision. Many of these schemes incorporate very narrow (3–6 mm) bismuth germanate (BGO) crystals which are coupled in groups to large photomultiplier tubes (PMTs) in ratios as high as 8:1 (see ref. [6]). The coupling schemes overcome the technological limitations of reducing the PMT size to match the size of the crystal, while still allowing multislice image capability. Another type of encoding scheme used at the University of Pennsylvania [7, 8], determines the location of an event in a continuous sodium iodide [NaI(Tl)] crystal much the same way as is done in an Auger camera.

Regardless of the encoding scheme used, the crystals must be thick enough, typically at least 2.5 cm, to stop the 511-keV gamma rays effectively. Since gamma rays may enter the crystals at oblique angles and interact at unknown depths in the crystals, there exists an uncertainty in the determination of the coincident lines along which the events are backprojected during image reconstruction. For PET scanners with a spatial resolution of about 5 mm, this parallax error caused by the uncertainty in the depth of interaction (DOI) in the crystal is one of the most important factors which limit the image quality. This error can potentially be eliminated by measuring the depth of interaction in the crystal.

In circular systems, which usually consist of narrow BGO crystals, the spatial resolution deteriorates preferentially in the radial direction at large radii (fig. 1a). This degradation occurs when oblique gamma rays either penetrate the first crystal but interact in an adjacent crystal, or else undergo Compton scattering in the first crystal and produce secondary gamma rays which pass through that crystal and interact in an adjacent crystal. The radial resolution, even with BGO crystals, which have a very high stopping power, is several millimeters worse near the edge of the field of view than at the center of the scanner [9–11]. This elongation can be reduced by inserting septa between the crystals [12]; however, this approach results in a reduced packing fraction and a lowered sensitivity. Another idea proposed by Wong [13] is to use a stratified ring with two or three thinner layers of crystals rather than one thick layer. This technique would allow determination of the DOI to one-half or one-third the total depth but would require a more complicated crystal PMT-encoding scheme, particularly for multiple rings. Wong calculates that the radial elongation with a three-layer system is significantly reduced and eliminates the need for septa between crystals.

The University of Pennsylvania PET scanner design uses six continuous NaI(Tl) crystals. The single-slice prototype [7] used one-dimensionally position-sensitive bar detectors, whereas the multislice scanner currently being built [8] uses two-dimensionally position-sensitive
area detectors. With hexagonal systems, all source locations, including the center of the scanner, will give rise to gamma rays which enter the crystals obliquely. Therefore, the effect of parallax error on the system's spatial resolution is seen throughout the field of view (see fig. 1b) but is less severe than with circular scanners.

2. Background

Making the crude assumption of uniform attenuation in the crystal with perfect spatial resolution, the uncertainty in the DOI results in a rectangular point spread function (PSF) at the detector with a width, \( \Delta x = t \tan \theta \), where \( t \) is the thickness of the crystal and \( \theta \) is the angle of incidence away from normal (see fig. 1c). For two detectors in coincidence, this would imply a triangular PSF with a fwhm of \( S/2 \), where \( S = \Delta x \cos \theta \). A more realistic description of the effect of DOI depends on the photon interactions in the crystal, which have been modeled for NaI(Tl) using a Monte Carlo simulation [14]. The result is the PSF in fig. 2a, which reflects the position uncertainty due to DOI for a given \( \theta = 15^\circ \). Convolving this function with a 5-mm full width at half maximum (fwhm) Gaussian PSF, which characterizes the intrinsic spatial resolution of our detectors, yields a function which is itself approximately Gaussian with a fwhm of \( \Delta x = 6.5 \) mm (see fig. 2d), which implies \( S = 6.3 \) mm. The response function at the midpoint between two detectors with Gaussian PSFs is also a Gaussian function with a fwhm of \( S/\sqrt{2} \). Therefore, if other effects are ignored, the spatial resolution at the center of the scanner increases from 3.5 mm with perfect DOI determination, to an average of 4.5 mm without knowledge of the DOI. With this difference in resolution, even a rough determination of the DOI would noticeably improve the image spatial resolution. If the uncertainty in the DOI were characterized by a Gaussian function with a fwhm of 12.5 mm (see fig. 2b), or half the crystal thickness, then the

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**Fig. 2.** The detector point spread function (PSF) depends on the uncertainty in the DOI. The top panels show the PSF with perfect spatial resolution with the following DOI determination: (a) none, (b) 12.5 mm fwhm (half crystal thickness) and (c) perfect. The bottom panels convolve a detector spatial resolution of 5 mm with the same DOI determinations: (d) none, (e) 12.5 mm and (f) perfect.
The image PSF resolution (fwhm) as a function of the distance from the center with the following DOI determination: none (×), 12.5 mm fwhm (+), perfect (○). The image space reconstruction algorithm (ISRA) was used [15] with four iterations.

In order to study the effect of the DOI on the image quality more rigorously, a computer simulation which models the emission and detection properties for our PET research scanner was used to generate images with and without DOI uncertainty. Simulated data were reconstructed using the image space reconstruction algorithm (ISRA) [15], based on the maximum likelihood principle. Fig. 3 shows the dependence of the image of a point source with distance from the center of the scanner, with and without DOI determination. The degradation of resolution ranges from 1 to 2 mm. With a DOI determination of 12.5 mm, the image resolution loss is reduced about a factor of 2. The effects of positron range and the angular uncertainty, which are not included in this calculation, will add about 1 mm to these values of image resolution for low-energy beta-emitters such as $^{11}$C or $^{18}$F. The degradation of image resolution caused by DOI uncertainty and the resultant loss of contrast, were examined by simulating a realistic brain phantom. With this phantom the effects of uncertainty in the DOI are not too severe if the phantom is placed in the center, since the maximum radial extent is only 7.5 cm. Even so, the loss of resolution is noticeable. Fig. 4a shows a simulated image of the Hoffman brain phantom with an assumed 5-mm detector resolution and no depth-of-interaction determination. Fig. 4b shows the image resulting from perfect depth-of-interaction determination.

In our design, the lateral position of the interaction in the crystal is determined by calculating the centroid of the light distribution [14]. In a continuous detector, the spatial resolution depends on the width of the light response function (LRF). By machining grooves on the front surface on the crystal, we are able to sharpen the LRF and improve the spatial resolution. Normally, the LRF is narrower for events closer to the PMTs. This dependence was utilized by Cook et al. [16] in a 2-in. thick Anger camera to determine whether an event had occurred in the front or back half of the crystal. Because of the ½-in. light guide and grooved crystal in our detector, the LRF dependence with depth is somewhat reduced. We found that an interaction taking place in the front of the crystal could be discriminated from one in the back of the crystal with about 75% confidence [8]. In addition, the DOI determination depends on the location of the scintillation along the crystal due to a position-varying LRF. Because of this position dependence, this method of depth determination was not considered further.

![Image ofgebung 3](image3.png)

**Fig. 3.** The image PSF resolution (fwhm) as a function of the distance from the center with the following DOI determination: none (×), 12.5 mm fwhm (+), perfect (○). The image space reconstruction algorithm (ISRA) was used [15] with four iterations.

![Image ofgebung 4](image4.png)

**Fig. 4.** Simulation of the Hoffman brain phantom with 5 mm (fwhm) detector resolution with (a) no DOI determination and (b) perfect DOI determination. The ISRA was used with 32 iterations.
In this paper a new method for determining the depth of interaction is discussed which depends on introducing a temperature gradient across the crystal. This idea was first suggested by White and Persyk [17]. Since this method does not rely upon the LRF in a continuous crystal, it is applicable to both continuous NaI(Tl) and small BGO crystals.

3. Theory

The scintillation efficiency and fluorescence decay time are both temperature dependent for inorganic scintillation crystals, including NaI(Tl) and BGO. For NaI(Tl), Startsev et al. [18] report a linear decrease in the luminescence of only 0.12%/°C between 0 °C and 270 °C, with incident γ-ray radiation. The relationship between temperature and decay time is of primary interest here, since it can be exploited by introducing a temperature gradient from the front to the back of the crystal. Both Schweitzer and Zeihl [19] and Schneid et al. [20] report a temperature variation of decay time which monotonically decreases as the temperature increases with a rate of about 5 ns/°C between 0 °C and 25 °C, at which point the decay constant is 240 ns. Above 25 °C, the decay time decreases more slowly, reaching a minimum of about 100 ns at 180 °C. With a temperature gradient present, the DOI of an event taking place in the crystal can be determined by the decay time of that event. An event which undergoes Compton scattering in the crystal would be characterized by an average depth which depends on the amount of energy lost (light output) at each depth.

Since we are using NaI(Tl) crystals in our PET scanner, a technique is needed which will determine the decay time of NaI(Tl) with precision, so as to minimize the temperature gradient needed, and which is compatible with the other requirements of our detectors. Schweitzer and Zeihl [19] determined the time constant of NaI(Tl) by the rise-time and the time-to-peak of the voltage pulse, which required between 500 and 1000 ns. Their experimental precision of 10–20% resulted in a decay time resolution (fwhm) of about 30 ns and a magnitude of the gradient which can be applied to a crystal is limited by the interface between the crystal and PMT, which may include a light guide, and the hermetically sealed housing which is necessary for hygroscopic crystals such as NaI(Tl). Since the determination of position in our crystals depends on finding the centroid of the light distribution, large variations of scintillation efficiency would probably affect the spatial resolution. However, the temperature variation of efficiency is not very strong [18], and so a moderate temperature gradient should not cause a significant loss of intrinsic spatial resolution. Between 25 °C and 50 °C, we only expect the luminescence to vary about 3%. Also, our large continuous detectors must be able to count at very high data rates, so we need to determine the time constant within as short a time as possible, preferably less than 500 ns. Finally, we would like to employ the same digital electronics to determine the decay constants that are currently used to determine the position of the event [8].

In our scheme, the pulse from NaI(Tl), which has a decay time of 240 ns at room temperature, is shortened with a 60-ns delay line. This pulse-clipping should bring the signal back to the baseline after 120 ns, although due to the finite rise time of the PMT and preamplifier, the pulse actually returns to the baseline between 150 and 200 ns (see fig. 5a). The pulse is smoothed, digitized every 40 ns and then integrated for 240 ns (adding six samples). Since the pulses are digitized continuously, the start of the integration period is only known to within 40 ns. Therefore, an integration time somewhat longer than the width of the pulse is used to insure that both the rise and fall of the pulse are sampled. The data are sent to a VAX computer for processing. With this technique we obtain a detector spatial resolution of about 5 mm, which little degradation below 2 million counts per second (Mcps). If the pulse decays with a time constant less than 240 ns, then the pulse will overshoot the baseline (see fig. 5a); whereas, if the decay is slower, then the pulse will undershoot the baseline. Using two integration time windows, the tail part of the pulse, \( N_2 = \int_{t_2} v(t) \, dt \), divided by the main part of the pulse, \( N_1 = \int_{t_1} v(t) \, dt \) can be used as a measure of the relative decay time, where \( v(t) \) is the amplitude of the delay-line-clipped pulse. For short decay times, the ratio \( R_N = N_2/N_1 \) will be negative and for long decay times it will be positive, as shown in fig. 5b.

BGO has a decay time of 300 ns at room temperature and a light output which is only about 1/3 the output of NaI(Tl). The temperature variation of efficiency and decay time are both stronger for BGO than for NaI(Tl). Melcher et al. [21] report a linear decrease in efficiency of about 1%/°C near room temperature (about 0 °C to 50 °C) and a decrease in the decay constant with temperature with a rate similar to that of NaI(Tl) below room temperature and about twice as fast above room temperature.

The low light output of BGO implies a yield of only a few photoelectrons per ns, which is not enough to determine the pulse shape accurately on an event-by-event basis. Therefore, the pulse-shortening technique will not work well. Also, in a BGO PET scanner geometry, one is usually not limited by the countrate capability of the detector, since each of the detectors subrends
Fig. 5. (a) Calculated pulse-shortened signals with a fixed 60-ns delay lines and 40 ns rise time as a function of scintillator decay time: $\tau = 180$ (- - -), 240 (——), 300 (---) ns. The signal is integrated during two different time windows, $I_1$ and $I_2$, both 240 ns long. $I_2$ is delayed by 180 ns relative to $I_1$. (b) $R_N$, the ratio of the integrated signal during $I_2$ to that during $I_1$, is negative for small $\tau$ and is positive for large $\tau$.

Fig. 6. (a) Calculated unshortened pulse shapes for $\tau = 180$ (- - - - -), 300 (---) ns, with an assumed rise time of 40 ns. The signal is partially integrated for 200 ns and almost fully integrated for 1 $\mu$s. (b) $R_B$, the ratio of the integrated signal for $I_1$ to that during $I_2$, approaches unity for small $\tau$.

4. Experiment

4.1. Sodium iodide

It is difficult to introduce a well controlled temperature gradient across a standard NaI(Tl) crystal because it is not thermally coupled at the gamma ray entrance face. Therefore, the pulse-shortening technique described above was used to determine the magnitude of the temperature difference which would be needed to determine the DOI in the crystal. The crystal was studied at temperatures ranging from about 15°C to 50°C. A 2-in. diameter crystal directly coupled to a 2-in. PMT was placed in an oven for the data taken above room temperature and in a refrigerator for the...
data taken below room temperature. Time was allowed for the assembly to achieve thermal equilibrium. In this temperature range, we did not measure a change in the light output, which was determined by integrating the signal without delay-line pulse shortening as a function of temperature. This measurement does not correct for the temperature and spectral response of the photomultiplier tube. Fig. 7 shows the pulse-shortened signals at several temperatures, above and below room temperature. Even at room temperature, with $\tau = 240$ ns, there is some overshoot due to a slight impedance mismatch at the input to the preamplifier.

The signal from the PMT was split and sent into two preamps. Pulse 1 was delayed by 180 ns and pulse 2 was not delayed. The integration trigger signal was delayed so that $N_1$ represented the integral of the main part of pulse 1 while $N_2$ represented the integral of the tail part of pulse 2. The ratio $R_N$, which characterizes the decay constant, was formed by taking the ratio $N_2/N_1$. The baseline value was first subtracted from both integrals before taking the ratio in order to make the ratio independent of amplitude and thus insensitive to the small variation of the PMT gain with temperature. Since an integration time of 240 ns is normally used to achieve good spatial resolution, this was not varied in determining the decay constant, nor was the 180 ns delay time changed. As is evident by the curves in fig. 8a, the integration windows $I_1$ and $I_2$ should be optimized to the decay time in order to get the best results for $R_N$.

Fig. 8 shows the results at several temperatures. The resolution of the measurement is about 7.5°C or 20 ns (fwhm) so that with a 15°C temperature difference, we can clearly resolve the decay times of 240 ns at 23°C and 200 ns at 38°C. Although the decay constant changes more rapidly with temperature below room temperature than above, $R_N$ changes slower, so that there is an advantage to heating the crystal rather than cooling it.

Since the NaI(Tl) crystal is canned, a controlled temperature gradient cannot easily be applied across the
crystal. To do so would require modification at the factory to couple thermally across the front face but insulate at the sides. Instead, it was decided to show the feasibility of applying a temperature gradient with BGO, which does not need to be canned.

4.2. Bismuth germanate

With BGO, we formed the ratio of the integrated light output after 200 ns to the integrated output after 1 μs, rather than using the rise-time or time-to-peak of the voltage pulse, as done by Melcher et al. [21]. Their decay time resolution, near room temperature, was about 60 ns fwhm. In our setup, the PMT signal was pre-amplified and then split into two amplifiers, with integration constants of 200 ns and 1 μs. The peaks of each output, $B_1$ and $B_2$, were digitized and then divided to form the ratio $R_B$.

Before applying a temperature gradient to BGO, we heated the crystal uniformly in the oven to compare this measurement of decay time with the pulse-shortening technique used with NaI(Tl). Because of the lower light yield of BGO and greater statistical fluctuations, a larger temperature difference is needed to discriminate the decay constant. The results are shown in fig. 9a. Between room temperature (23°C) and 53°C, we obtain good discrimination of the decay constant, which changes from 300 ns to 180 ns. Our experimental resolution is about 75 ns or 19°C. Therefore, with BGO, we need about 30°C or twice the temperature difference that we needed with NaI(Tl) to resolve the decay constant clearly, even though the decay constant of BGO changes more rapidly with temperature.

The experimental setup to study the feasibility of measuring the DOI using a temperature gradient across a 25-mm-thick BGO crystal had the following features. A collimated source illuminated the BGO crystal from the side at specific depths (0 mm and 25 mm) with a NaI(Tl) detector placed in coincidence with the BGO detector. The back surface of the BGO crystal (at a depth of 25 mm) was coupled to a PMT and heated by an RTV light guide with embedded resistive wire. The front surface of the BGO crystal was kept at room temperature by circulating air. With this setup a temperature gradient of about 30°C was achieved. The results of these experiments are shown in fig. 9b. Although a 30°C temperature difference was measured between the front and back surfaces of the crystal, the temperature difference determined from the two measurements was somewhat less, since each one averaged the effects of scattered radiation and broadening in the crystal due to Compton scattering. Also, despite insulation surrounding the crystal, heat loss through the sides of the crystal probably resulted in nonuniformities in the temperature gradient near the crystal boundaries. The two peaks are well resolved despite these sources of error.

With the BGO crystal, we measured 17% energy resolution at room temperature. With a temperature gradient of 30°C, the light yield varies by about 30% over the depth of the crystal and, therefore, the average energy resolution of the crystal is poor. In a PET scanner with a one-to-one PMT/crystal coupling, this energy variation would introduce a nonuniform sensitivity and problems in correcting for scattered radiation unless the lower-energy threshold, which is normally
fixed at about 300 keV, varied with the measured DOI. More recent PET scanner designs employ PMT/crystal coupling schemes with as many as eight crystals coupled to one PMT. In this case, the light output affects the accuracy of coding the correct crystal. Therefore, one might choose to cool the back surface of the crystal instead, since the technique for determining the decay time (and DOI) should work well with temperatures above or below room temperature.

Also, a decrease in temperature generally increases the sensitivity of the photocathode and decreases the leakage current of the PMT [22]. However, cooling the back of the detector and PMT to improve the efficiency would increase the decay time but slightly degrade the time resolution. It is important in a PET scanner to have good coincidence timing resolution, since a narrow timing window is needed to reject random coincidences. The time resolution between the BGO and NaI(TI) detectors was measured with constant fraction timing discriminators and a time-to-amplitude converter. At room temperature the resolution was 5 ns, fwhm. With the temperature gradient across the crystal and an uncollimated source to illuminate the crystal uniformly, the coincidence timing resolution was measured to be 6 ns.

5. Summary and conclusions

In PET scanners, the scintillation crystals must be thick enough to detect 511-keV energy gamma rays efficiently. In order to reduce the parallax error which results from gamma rays hitting the crystals at oblique angles, a technique was investigated to determine the depth of interaction in the crystal. This technique takes advantage of the relationship between the temperature and the decay time constant of a scintillation crystal. By applying a temperature gradient across the thickness of the crystal, one can measure the decay time constant on an event-by-event basis to determine the depth of interaction for each event. This technique can be applied to both continuous NaI(TI) crystals, used in our PET scanner, and to discrete BGO crystals, used in many other PET scanners.

With NaI(TI), the decay constant is determined by measuring the change in shape of the delay-line-shortened pulse. Since the pulse is delayed by 180 ns and integrated for 240 ns, a second pulse coming within 420 ns of the first pulse may interfere with the spatial resolution and the determination of $R_N$. This decreases the countrate capability of the detector somewhat, since without DOI determination, a second pulse can arrive 240 ns after the first pulse without interference. It may be possible, however, to integrate for a somewhat shorter time and to delay the pulse less in order to maintain high spatial resolution, DOI determination, and high countrate capability simultaneously.

It was found that a modest $15^\circ C$ temperature difference from room temperature is sufficient to resolve clearly the decay constant with NaI(TI). Since the resolution in the DOI determination is $7.5^\circ C$ the DOI would be determined to 12.5 mm fwhm, or one-half the crystal thickness, if this temperature difference were present across the thickness of the crystal. This amount of depth discrimination is expected to reduce the parallax of our PET scanner significantly, as shown in fig. 3. Of course, the resolution loss could be reduced even further by using thinner crystals; however, that approach would also reduce the sensitivity. Alternatively, the sensitivity could be increased by using thicker crystals with DOI determination to control the degradation of resolution. It is not known how difficult it will be in practice to obtain a uniform temperature gradient on a large canned crystal, such as NaI(TI). The detector would need to be modified so that the front face of the crystal was thermally conductive to the aluminum can, while the sides were thermally insulated. Then the back face of the crystal could be heated through a thin light guide, with embedded heated wires, while the front face was kept at room temperature with either circulating air or water. This idea was demonstrated with a small BGO crystal; it was also shown that the DOI can be measured in BGO as well as NaI(TI). Since a larger temperature difference is needed with BGO than with NaI(TI) to resolve the decay constant, a temperature gradient of $30^\circ C$ was applied across the crystal to achieve the same discrimination as with a $15^\circ C$ temperature difference in NaI(TI). Although the energy resolution of the BGO crystal is significantly degraded with a temperature gradient, the time resolution is not. It was noted that it might be better to heat the front face and keep the back face (and thus the PMT) at room temperature, or alternatively, to keep the front face at room temperature and cool the back face.

In conclusion, the temperature characteristics of both NaI(TI) and BGO can be exploited to yield information about the depth of interaction in the crystal. A practical implementation of this technique does not seem to have any fundamental problems and needs only modest additional electronics. Also, the incorporation of a temperature gradient on the crystals in a PET scanner need not be expensive or complicated.

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