Published in final edited form as:

IEEE Trans Nucl Sci. 2009 ; 56(5): 2614–2620. doi:10.1109/TNS.2009.2027903.

Monte Carlo Simulation Study on the Time Resolution of a PMT-Quadrant-Sharing LSO Detector Block for Time-of-Flight PET

Shitao Liu [Member, IEEE], Hongdi Li [Member, IEEE], Yuxuan Zhang [Member, IEEE], Rocio A. Ramirez, Hossain Baghaei [Member, IEEE], Shaohui An, Chao Wang, Jiguo Liu, and Wai-Hoi Wong [Member, IEEE]

Department of Experimental Diagnostic Imaging, University of Texas M.D. Anderson Cancer Center, Houston, TX 77030 USA

Shitao Liu: Shitao.Liu@mdanderson.org

Abstract

We developed a detailed Monte Carlo simulation method to study the time resolution of detectors for time-of-flight positron emission tomography (TOF PET). The process of gamma ray interaction in detectors, scintillation light emission and transport inside the detectors, the photoelectron generation and anode signal generation in the photomultiplier tube (PMT), and the electronics process of discriminator are simulated. We tested this simulation method using published experimental data, and found that it can generate reliable results. Using this method, we simulated the time resolution for a 13×13 detector block of $4 \times 4 \times 20$ mm³ lutetium orthosilicate (LSO) crystals coupled to four 2-inch PMTs using PMT-quadrant-sharing (PQS) technology. We analyzed the effects of several factors, including the number of photoelectrons, light transport, transit time spread (TTS), and the depth of interaction (DOI). The simulation results indicated that system time resolution of 360 ps should be possible with currently available fast PMTs. This simulation method can also be used to simulate the time resolution of other detector design method.

Index Terms

LSO detector block; Monte Carlo simulation; time-of-flight PET

I. Introduction

It has long been realized that signal-to-noise ratio (SNR) in position-emission-tomography (PET) images can be improved by incorporating the Time-of-Flight (TOF) information [1]–[3]. Recently, a growing interest in lutetium orthosilicate (LSO) [4], [5] and lutetium yttrium orthosilicate (LYSO) [6] in TOF PET has been observed. Their high light yield, short decay time, high effective atomic number and photoelectric fraction make it possible to build PET systems with high spatial and time resolution, and reasonable sensitivity.

The LSO scintillators timing properties have been studied by Moses and Derenzo [7]. Coincidence time resolution of 300 ps has been measured with two $3 \times 3 \times 3$ mm³ LSO crystals coupled with Hamamatsu R-5320 photomultiplier tubes (PMTs). However, the time resolution was degraded to 475 ps when two $3 \times 3 \times 30$ mm³ crystals were used instead. These authors attributed this degradation to two factors: a difference in the transport time between events with different depths of interaction (DOI), and time dispersion due to multiple reflections.

More recently, Moszynski *et al.* [8] recorded a time resolution of 196 ps when $4 \times 4 \times 20$ mm³ LSO was directly coupled to the center of the Photonis XP20D0 PMT [9], [10]. They also measured time resolution with an 11 mm-thick Lucite disc between the crystal and PMT as light diffuser, and observed a degradation of 224 to 287 ps while moving the crystal from the center to the edge of the PMT. This degradation was mainly caused by a reduction in the light collection. The results of these studies indicate that the time resolution is influenced by many factors, including the DOI, light transport, light collection, and PMT characteristics. Hence, understanding the effects of each individual factor would be useful in finding ways to minimize the time uncertainty.

Monte Carlo simulation is one of the effective tools to understand the detector system. It has been widely used to guide the design of TOF systems for high-energy colliders, which require time resolution of 50 to 100 ps (root mean square, RMS) [11], [12].

Our study had two goals: first, to develop a reliable Monte Carlo simulation method for TOF PET, and second, to use the simulation method to study the time resolution of our PMT-quadrant-sharing (PQS) detector design. In Section II, we will describe the physics model of the TOF measurements and the simulation program used. In the first part of Section III, we will compare the results obtained using our simulation method with the experimental results reported in [8]. In the remaining parts of Section III, we describe the simulation of a 13×13 LSO detector block using PQS design to study the effects of different factors on the block time resolution. The factors examined include the number of photoelectrons (PheNum), transit time spread (TTS), and the DOI. In Section IV, we discuss possible ways to improve time resolution.

II. Simulation Model and Method

Fig. 1 shows the three-part physics process involved in the TOF measurement: γ -ray interaction in detector; the scintillation light emission and light transport inside the detector and the photoelectron generation; and anode signal generation in the PMT and the electronics process which involves the time discriminator.

A 13×13 LSO detector block with $4 \times 4 \times 20$ mm³ crystals was simulated to study the effects of different factors on the block time resolution. The detector block was coupled to four 51 mm PMTs using PQS technology [13]. The polished surface was used for the top side of the crystal, while the ground surface was used for all the other sides. Optical coupling grease was used between crystals and between the PMT and the block. The detector structure is shown in Fig. 2. LSO crystals and reflectors are glued (using grease/glue) together to be a detector block. Then the detector block is coupled to PMT using PQS configuration by grease/glue. In the simulation model, the PheNum, the TTS and the DOI were examined.

A. γ -Ray Generation and Interaction in Detector

In GEANT/GATE simulation, 511 KeV γ -rays were generated from a point source 430 mm (radius of PET camera) away from the 13×13 LSO detector block. The time (t_{hit}) and energy deposition (E_{hit}) of each interaction in detector were recorded.

B. Scintillation Light Emission and Transport

The energy deposition data from GATE simulation were input to an optical transport simulation program for PET detector—DETECT2000 [13]. The scintillation light emission and transportation process in the detector were simulated with DETECT2000.

The scintillation light emission was described by the total light yield (average light output for a certain energy deposition in crystal), energy resolution (light output variation) and the emission time (t_{emit}) profile. For LSO, the light yield was set to 30000-photons/MeV, the

energy resolution was set to 14% and the time profile of the scintillation light was described as an ideal exponential decay with a decay constant τ of 40 ns [15]:

$$P(t_{emit}) = \frac{1}{\tau} \exp\left(-\frac{t_{emit} - t_{hit}}{\tau}\right). \quad (1)$$

During the light emission, the angular distribution of the emitted photons was isotropic. Hence, only a very small amount of photons could directly reach the PMT. Most of the photons arrived at the PMT after one or more reflections. The light transport process in PET detectors is very complicated, both because the pixilated detector structure greatly increases the number of surfaces involved and because the surfaces used in detector design are usually ground to improve light sharing.

After the light photons went through the detector and PMT glass window, the light arrived at the photocathode and generated photoelectrons according to quantum efficiency (QE) of photocathode. The time and location of each photoelectron were recorded in DETECT2000 simulation. Fig. 3 shows the light position distribution (on photocathode) of crystals at block corner and center. The light was localized on the photocathode. Hence, the time resolution degradation caused by non-uniformity of PMT photocathode could be corrected. So the non-uniformity of PMT photocathode was not considered in this simulation.

C. PMT Response

The PMT response is mainly determined by single photoelectron pulse and the TTS. Usually the TTS of PMT is specified using the single-photon transit time spread. In this paper, the term TTS means the full-width-half-maximum (FWHM) of the single-photon transit time spread. Each photoelectron has a corresponding pulse in the PMT anode. The time (t_{pe}) between the gamma interaction inside the crystal and the appearing of the single photoelectron pulse on the anode is:

$$t_{pe} = t_{emit} + t_{pro} + t_{TT} \quad (2)$$

t_{pro} = Photon transport time

t_{TT} = Transit time of the single photoelectron

The PMT response of single photoelectron is a current signal that can be described using a clipped Gaussian pulse [16]:

$$i_{pe}(t) = \frac{G}{\sqrt{2\pi}\sigma} \left[\frac{35}{32} \exp\left(-\frac{(t - 2.2166\sigma)^2}{2\sigma^2}\right) - \frac{3}{32} \right] \quad (3)$$

G = Parameter related to the gain of the PMT,

σ = Time constant that determines the width of the pulse.

The G varies according to 70% energy resolution of single photoelectron [17].

The anode output circuit can be considered as a parallel of a load resistor (R_L) and parasitic capacitor (C). The impulse response of this circuit is:

$$h(t) = \frac{1}{C} \exp\left(-\frac{t}{\tau}\right) \quad (4)$$

$$\tau = R_L C$$

The single photoelectron anode response (v_{pe}) was the convolution of the anode current and the output circuit:

$$v_{pe}(t) = \frac{G}{\sqrt{2\pi}\sigma C} \cdot \int_0^t \exp\left(-\frac{t-x}{\tau}\right) \cdot \left[\frac{35}{32} \exp\left(-\frac{(x-2.2166\sigma)^2}{2\sigma^2}\right) - \frac{3}{32} \right] dx. \quad (5)$$

The PMT output signal was the sum of the anode pulses of all the photoelectrons:

$$V(t) = \sum_{i=1}^{N_{pe}} v_{pe,i}(t - t_{pe,i}). \quad (6)$$

Fig. 4 shows a simulated LSO crystal signal of a 511 keV γ -ray event. The data includes the PMT output signal of a gamma ray event, the PMT response of single photoelectron (Phe), the photoelectrons time distribution on the photocathode and the normalized time distribution of photoelectrons. Here normalized means that the photoelectron distribution is divided by total number of PheNum.

D. Electronics

The electronics components include the discriminator and time to digital converter (TDC). Two types of discriminator, constant fraction discriminator (CFD) and leading edge discriminator (LD) are commonly used. The advantage of CFD is that the trigger time is not affected by the pulse height. On the other hand, it is more complicated, and usually implemented in application specific integrated circuits (ASICs). LD, on the contrary, is simpler in discriminator part, but requires the signal height/charge information to correct the time walk. LD with pulse height/charge correction is generally used in the TOF system for the high energy collider, where time resolution of 50 to 100 ps (RMS) is typically required [18]–[21]. In PET applications, the charge measurement is required for decoding, and the use of LD instead of CFD does not therefore carry additional costs. In the first commercial TOF PET/CT scanner, the Philips Gemini TF, LD is used to obtain time information [22].

In the simulation, the signal of every γ -ray event was discriminated by CFD/LD method to get its time. From the time profile of all events, we could get the time resolution of each crystal in the detector.

The block coincidence time resolution was determined in two steps: first, the coincidence time resolutions of one crystal with all 169 crystals in the detector block were calculated. The average of these 169 resolution values was taken to be the coincidence time resolution of this one block. Second, the coincidence time resolutions of all crystals were averaged to obtain the block coincidence time resolution.

III. Result

A. Single Crystal Simulation

Results from single-crystal simulations are compared with results from other experimental data [8] to validate the simulation program. For this study, the simulation used a Teflon-wrapped $4 \times 4 \times 20 \text{ mm}^3$ LSO crystal with a polished surface, a Photonis XP20D0 PMT, and three types of coupling schemes: one with the crystal coupled to the center of the PMT, another with the crystal at the center of an 11 mm-thick 52 mm-diameter Lucite disc coupled to the PMT as a light diffuser, and a third with the crystal at the edge of the diffuser.

The parameters of the XP20D0 were obtained from [8], [9], [23]–[26]. The single electron spectrum resolution was 70%. The TTS of the PMT was 520 ps with a high voltage of 2500 V. In the single-crystal time resolution test, the high voltage is between 1700 V and 1800 V, hence the TTS would be increased to about 610 to 630 ps. TTS of 610 ps was used in the simulation. The TTS was 900 ps with a high voltage of 1000 V.

Table I shows our simulation results along with the experimental results from [8, Table IV]. In Table I, the center and four edge positions (top/bottom/left/right) on the PMT photocathode are shown. Our simulation results are in good agreement with the experimental data.

B. Detector Block Simulation

The crystal pulse heights of all crystals were set as the light output; Fig. 5 show the result of the DETECT2000 simulation. On average 65% of light generated were collected.

The ratio between the minimal and maximal pulse heights is 82%, which is a typical pulse-height ratio for the PQS detector block [27]–[29]. A single crystal energy resolution of 14% was used for the random generation of the total PheNum.

The effects of each of the 4 factors, PheNum, light transport, TTS and DOI were analyzed. The TTS was scanned from 0.25 to 2 ns with 0.25 ns step size. The PheNum was scanned from 500 to 5000 with 500 step size.

C. Time Discriminator

The block coincidence time resolution comparison of CFD/LD discriminator is shown in Fig. 6. With different TTS and PheNum, the LD was always better than CFD. Hence, we used LD in the following simulation. The threshold of the LD discriminator was scanned to have the best result.

D. Light Transport

To investigate the effect of light transport, the block time with and without light transport was simulated. The TTS values used were set to 0.25 ns and 0.75 ns. The PheNum from 500 to 5000 was scanned with steps of 500. In Fig. 7, which shows the results of the simulations, the time resolution with light transport was worse in all cases than it was without light transport. The resolution curve with light transport process could be fit with function:

$$\delta t = \frac{f}{\sqrt{\text{PheNum}}} + 0.053. \quad (7)$$

The resolution curve without light transport process could be fit with function:

$$\delta t = \frac{f}{\sqrt{PheNum}} \quad (8)$$

where f is the fit parameter that was found to depend on TTS and $PheNum$ is the number of photoelectrons.

According to (7), a PMT with a larger TTS required a larger number of photoelectrons ($PheNum$) to achieve the same time resolution as could be achieved from a PMT with a smaller TTS. For example, to get 0.35 ns time resolution, 2156 photoelectrons were needed for a 0.25 ns TTS PMT; it would increase to 2928 for a 0.75 ns TTS PMT.

According to (7) and (8), the light transport process directly added a 0.053 ns constant factor on detector time resolution.

Under same TTS, the f values without light transport process were smaller than that with light transport process. On Average the time resolutions with light transport process was ~ 80 ps bigger than the time resolution without light transport process.

E. PheNum and TTS

The block coincidence time resolutions of different $PheNum$ and TTS were simulated (including light transport process). Fig. 8 shows the results from our simulation.

The time resolutions were better with smaller TTS and more photoelectrons. The dependence of f on TTS was found to be well-described by a polynomial of third order. The fitting result was reliable in the data range because f only had 1% or less relative fitting errors. f and their errors were shown in Fig. 9.

F. DOI

From crystal top to PMT window surface, the depths were set as 0 to 20 mm. The events at 1 mm, 5 mm, 9 mm, 15 mm, and 19 mm depth were picked to investigate the DOI effect.

The TTS is 0.25 ns. The time resolution difference caused by DOI was only 10 to 20 ps (see Fig. 10). The DOI effect was not obvious for the PQS detector when $PheNum$ was less than 4000. When the $PheNum$ was bigger than 4000, the time resolution was better than 300 ps, the DOI effect could be $\sim 8\%$ of the total time resolution.

G. Time Resolution of LSO With Several Available TOF PMT

We estimated the time resolution of PQS PET detector with several TOF-capable fast PMTs. According to [8], a $4 \times 4 \times 20$ mm³ crystal positioned on the center of a PMT with a blue sensitivity of 13.7 $\mu\text{A}/\text{lmF}$ can generate 3015 photoelectrons. In PQS design, the corner crystal also sits on the center of the PMT, so the $PheNum$ of a corner crystal in a PQS detector block would also be about 3015. This number will therefore be used as a reference to calculate the $PheNum$ for other PMTs.

Table II lists the estimated system resolution using PQS detector design with several fast TOF capable PMTs. Time resolutions of 330 ps could be achieved with R9800, R9979 and XP3060.

H. Noise

In the experimental signal of LSO + R9779, there is a 1 mV (standard deviation) white noise in it. This noise includes the noise and dark current of the PMT. After including the effect of

this noise, the coincidence time resolution of the detector (13×13 LSO PQS detector block + R9779 PMT) increased to 363 ps.

I. Transit Time and Gain Difference of R9779

Similar to the experiment in [30], we test the transit time and gain across the photocathode of a R9779 PMT. The result shows the maximum transit time difference is 109 ps and the maximum gain difference is 84% to 100% (This was similar to the gain test in data sheet).

J. LSO Background Radiation

LSO crystal has a background radiation from Lu-176. It is 241 cps/cc and has a wide energy spectra [31]. After the background was added in the simulation, the time resolution increased to 365 ps.

K. TDC

Time resolutions of 30 to 50 ps TDCs are available [32]–[34]. With a 30 ps time resolution TDC, the final time resolution will be 367 ps.

IV. Discussion

Among all the factors that affect the time resolution, PheNum is the most important one. When we use LSO crystal to build detector for PET application, the crystal light output of 511 keV γ -ray is fixed. In order to get more photoelectrons, we could improve the light collection in detector or choose a more sensitive PMT. In our PQS design, we have made continuous efforts to maximize light collection efficiency and increase the pulse-height ratio of the detector block by optimizing the light reflector mask [27]–[29].

Since the time resolution is mainly determined by the leading edge of the signal, other crystals with higher light yield and shorter decay time could also improve the time resolution. LaBr₃ (Ce) [35], CeBr₃ [36], and LuI₃ (Ce) [37] are some good candidates. On the other hand, their low photoelectric fraction and long attenuation length hurt the coincidence efficiency. Another approach is to increase the quantum efficiency (QE) of PMT. Photocathode with QE of more than 35% has been reported recently [38]–[40].

The TTS of PMT is another important factor. The value of f was doubled when TTS increased from 0 to 2 ns. The time resolution would be almost doubled. The f of 0.54 ns TTS was 10% more than f of 0 ns TTS. Hence, the time resolution would be degraded less than 10% when TTS was less than 0.54 ns. There are several 0.5 ns or less TTS PMT available on the market.

Since the TTS is inversely proportional to the high voltage, one way to lower the TTS is to increase the high voltage. The disadvantage of this method is that it also increases the PMT's anode current and excessive anode current causes fast gain loss. Another way to lower the TTS is to use dynode readout [41] instead of anode readout. However, because of the difference in DC voltage between the dynode and the ground, this method requires AC coupling. The AC coupling causes baseline drift, and requires real-time baseline restoration due to the fast changing radioactive dose during PET scan.

The effect of DOI was about 10 to 20 ps, which is negligible compared to the block time resolution of ~ 300 ps. One reason is that the number of counts follows an exponential decay along the depth; hence the time distribution is mainly decided by the events from the top part of the crystal.

The PMT gain/transit time difference and noise degrade the time resolution significantly. In this work, a $\pm 8\%$ gain difference, 109 ps transit time difference and 1 mV noise could degrade time resolution to 363 ps. PMTs with uniform photo-cathode should be used in a TOF camera. The noise must be controlled very well in the system to have good time resolution.

The LSO background and TDC time resolution are small factors in the time resolution; the time resolution only change by 1 to 2 ps in the simulation.

With GEANT4/GATE, DETECT2000 and following home developed Monte Carlo code, the result of this work (360 ps for PQS design LSO detector + R9779) is close to the result in [42] (330 ps for Anger-logic LaBr3 detector + XP 20D0, 660 ps for Anger-logic LYSO detector + XP20D0). Considering similar noise level was used. The main difference is the simulation tools and detector structure. The PQS detector design has better light transport control and more light output. This gives PQS detector better timing.

This simulation method could also be applied to other detector design method, because the physics processes of TOF measurement are same for all the detector design methods.

V. Conclusion

The agreement between our simulation results and experimental data proves that the MC simulation we used is reliable. A reliable Monte Carlo simulation would enable us to study the effect of each factor, which would help in understanding the detector system, and can be used as a reference for system design.

Although the PheNum is the most important factor, the TTS of the PMT is also important. Since the QEs of most PMTs are very close (Table II), improving the TTS becomes more important.

Our simulation also suggests the potential to use our PQS method in TOF PET. The high light collecting efficiency and good pulse height uniformity results in high number of photo-electrons and good time resolution. Our results indicated that system time resolutions of 360 ps should be achievable with LSO and currently available fast PMTs.

Acknowledgments

This work was supported in part by the National Institute of Health under Grant RO1 EB00217 and Grant RO1 EB001038, in part by the U.S. Army Breast Cancer Grant, in part by the John S. Dunn Foundation Research Grant, and in part by the Cobb Foundation for Cancer Research.

References

1. Ter-Pogossian MM, Mullani NA, Ficke DC, Markham J, Snyder DL. Photon time-of-flight-assisted positron emission tomography. *J Comput Assist Tomogr* 1981;5:227–239. [PubMed: 6971303]
2. Budinger TF. Time-of-flight positron emission tomography: Status relative to conventional PET. *J Nucl Med* 1983;24(1):73–78. [PubMed: 6336778]
3. Wong WH, Mullani NA, Phillipe EA, Hartz R, Gould KL. Image improvement and design optimization of the time-of-flight PET. *J Nucl Med Jan;1983* 24(1):52–60. [PubMed: 6600276]
4. Casey ME, Eriksson L, Schmand M, Andreaco MS, Paulus M, Dahlbom M, Nutt R. Investigation of LSO crystals for high spatial resolution positron emission tomography. *IEEE Trans Nucl Sci Jun;1997* 44(3):1109–1113.
5. Moszynski M, Ludziejewski T, Wolski D, Klamra W, Avdeychikov VV. Timing properties of GSO, LSO and other Ce doped scintillators. *Nucl Instr Meth A Mar;1996* A372(1):51–58.
6. Pepin, CM., et al. Investigation of the properties of new scintillator LYSO and recent LSO scintillators for phoswich PET detectors. 2002 IEEE Nucl. Sci. Symp. Conf. Rec; Nov. 2002; p. 655-660.

7. Moses WW, Derenzo SE. Prospects for time-of-flight PET using LSO scintillator. *IEEE Trans Nucl Sci Jun*;1999 46(3):474–477.
8. Moszynski M, Kapusta M, Nassalski A, Szczesniak T, Wolski D, Eriksson L, Melcher CL. New prospects for time-of-flight PET with LSO scintillator. *IEEE Trans Nucl Sci Oct*;2006 53(10):2484–2488.
9. XP20D0 Product Datasheet. [Online]. Available: www.photonis.com/data/cms-resources/File/Photomultiplier_tubes/spec/
10. Moszynski M, Gierlik M, Kapusta M, Nassalski A, Szczesniak T, Fontaine C, Lavoute P. New Photonis XP20D0 photomultiplier for fast timing in nuclear medicine. *Nucl Instr Meth A* 2006;567:31–35.
11. Nam JW, et al. A detailed Monte Carlo simulation for the Belle TOF system. *Nucl Instr Meth A* 2002;491:54–68.
12. Zhang L, Peng H, Zhang Z, Chen H, Shao M, Wu J. Simulation study for a single TOF scintillator using GEANT4. *Meas Sci Technol* 2004;15(7):N54–N57.
13. Wong WH. A positron camera detector design with cross-coupled scintillators and quadrant sharing photomultipliers. *IEEE Trans Nucl Sci Aug*;1993 40(4):962–966.
14. Thompson, RA.; Cayouette, F.; LeBlanc, J.; Zelakiewicz, S. A new surface parameterization for modeling thin layers of reflector material in the DETECT2000 optical modeling program. *Proc. 2002 IEEE Nucl. Sci. Symp. Conf. Record*; Nov. 2002; p. 846-849.
15. Derenzo SE, Weber MJ, Moses WW, Dujardin C. Measurements of the intrinsic rise times of common inorganic scintillators. *IEEE Trans Nucl Sci Jun*;2000 47(3):860–864.
16. Snyder DS, Thomas LJ Jr, Ter-Pogossian MM. A mathematical model for positron emission tomography systems having time-of-flight measurements. *IEEE Trans Nucl Sci Jun*;1981 NS-28(3): 3575–3583.
17. Philips Photonics Manual. Brive, France: Philips Photonics International Marketing; 1994. Photomultiplier tubes principles & applications; p. 2-8.
18. Chen C, et al. Front-end electronics for the CDF-II time-of-flight system. *IEEE Trans Nucl Sci Dec*; 2003 50(6):2486–2490.
19. Heng, Y., et al. The progress of TOF on BESIII. presented at the SNIC Symposium; Stanford, California. Apr. 2006;
20. Wu J, et al. The performance of the TOF tray in STAR. *Nucl Instr Meth A* 2005;538:243–248.
21. Kichimi H, et al. The BELLE TOF system. *Nucl Instr Meth A* 2000;453:315–320.
22. Surti S, Kuhn A, Werner ME, Perkins AE, Kolthammer J, Karp JS. Performance of Philips Gemini TF PET/CT scanner with special consideration for its time-of-flight imaging capabilities. *J Nucl Med Mar*;2007 48(3):471–480. [PubMed: 17332626]
23. Moszynski, M. Private Communication. Swierk, Poland: Soltan Institute of Nuclear Studies; Mar. 2007
24. Kapusta, M. Private Communication. Brive, France: Photonis; Mar. 2007
25. Lavoute, P. Private Communication. France: Photonis; Aug. 2007
26. Szczesniak T, Moszynski M, Nassalski A, Lavoute P, Dehaine AG. A further study of timing with LSO on XP20D0 for TOF PET. *IEEE Trans Nucl Sci Oct*;2007 54(10):1464–1473.
27. Kim S, et al. High resolution GSO block detectors using PMT-quadrant-sharing for small animal PET. *IEEE Trans Nucl Sci Feb*;2006 53(2):40–43.
28. Liu S, et al. New 9×9 and 10×10 BGO block detectors for human PET using PMT-quadrant-sharing design. *IEEE Trans Nucl Sci Feb*;2008 55(2):457–462.
29. Ramirez R, et al. High-resolution L(Y)SO detectors using PMT-quadrant-sharing for human and animal PET cameras. *IEEE Trans Nucl Sci Jun*;2008 55(6):862–869. [PubMed: 19946463]
30. Bauer F, Aykac M, Loope M, Williams CW, Eriksson L, Schmand M. Performance of the New Hamamatsu R9779 and Photonis XP20D0 fast 2 Photomultipliers. *IEEE Trans Nucl Sci Jun*;2007 54(6):422–426.
31. Huber JS, Moses WW, Jones WF, Watson CC. Effect of ^{176}Lu background on singles transmission for LSO-based PET cameras. *Phys Med Biol* 2002;47:3535–3541. [PubMed: 12408480]

32. Gerds EJ, Van der Spiegel J, Van Berg R, Williams H, Callewaert L, Wyckmans W, Sansen W. A CMOS time-to-digital converter IC with 2 level analog CAM. *IEEE J Solid-State Circuits* Sep;1994 29(9):1068–1076.
33. Raisanen-Ruotssalainen E, Rahkonen T, Kostamovaara J. An integrated time-to-digital converter with 30-ps single-shot precision. *IEEE Trans Nucl Sci* Oct;2000 35(10):1507–1510.
34. Yousif AS, Haslett JW. A fine resolution TDC architecture for next generation PET imaging. *IEEE Trans Nucl Sci* Oct;2007 54(10):1574–1582.
35. Glodo J, et al. Effects of Ce concentration on scintillation properties of LaBr₃:Ce. *IEEE Trans Nucl Sci* Oct;2005 52(10):1805–1808.
36. Shah KS, et al. CeBr₃ scintillators for gamma-ray spectroscopy. *IEEE Trans Nucl Sci* Dec;2005 52(12):3157–3159.
37. Shah KS, et al. LuI₃:Ce – A new scintillator for gamma ray spectroscopy. *IEEE Trans Nucl Sci* Oct; 2004 51(10):2302–2305.
38. Mirzoyan R, Laatiaoui M, Teshima M. Very high quantum efficiency PMTs with bialkali photo-cathode. *Nucl Instr Meth A* 2006;567:230–232.
39. Marmonier, C.; Dehaine, AG.; Bascle, P.; Lavoute, P.; Pierre, L. New Developments in Photomultipliers for Nuclear Medicine [Online]. Available: www.photonis.com/data/cms-resources/File/new/euromedi5.pdf
40. Photonic Devices – Electron Tube Devices and Applied Products Hamamatsu. 2007. [Online]. Available: http://sales.hamamatsu.com/assets/pdf/catsandguides/p-dev_2007_TOTH0014E01.pdf
41. De Vries J, Kelling FET. Fast timing with photomultiplier dynode pulses. *IEEE Trans Nucl Sci* Feb; 1988 35(1):392–395.
42. Kuhn, A.; Surti, S.; Shah, KS.; Karp, JS. Investigation of LaBr₃ detector timing resolution. *Proc. 2005 IEEE Nucl. Sci. Symp. Conf. Rec*; Oct. 2005; p. 2022-2026.

Fig. 1.
Simulation process of TOF measurement.

Fig. 2.
Detector structure in simulation.

Fig. 3.

Light distribution on the photocathode: (a) represents the light distribution of the crystal on the corner of the 13×13 PQS detector block, while (b) represents the light distribution of the crystal on the center of the 13×13 PQS detector block. The scale bars on the sides of the plots show the total electron numbers accumulated on the pixels (1 mm^2 size) after 80 events. The red circle in the figure is the radius boundary of half maximum counts.

Fig. 4. Sample signal: (a) Normalized time distribution of photoelectrons, (b) Photoelectrons time distribution on the photocathode, (c) PMT response of single photoelectron and (d) PMT output signal of a gamma ray event. Phe = photoelectron.

Fig. 5.
The single crystal pulse-height distribution. It reflects the PheNum in each crystal of the 13×13 array.

Fig. 6.

The block coincidence time resolution comparison of CFD/LD time discriminator. “TTS0.25” means $TTS = 0.25$ ns and “TTS0.75” means $TTS = 0.75$ ns; the “CFD” means the simulation using constant fraction discriminator; “LD” means the simulation using leading edge discriminator.

Fig. 7.

Block time resolution with and without light transport process. The circles and squares were the time resolutions with light transport process (“with-Trans”), and the triangles and diamonds were the results without light transport (“without-Trans”). Curves labeled “TTS0.25” show results for TTS = 0.25 ns, and those labeled “TTS0.75” are for TTS = 0.75 ns.

Fig. 8. Block coincidence time resolution versus PheNum for different TTS values. A time resolution of 0.35 ns is shown by the dashed line. “TTS0.00” shows results for TTS = 0.00 ns, etc.

Fig. 9.

The dependence of f on TTS was found to be well-described by a polynomial of third order. The bars ($\leq 1\%$) on the curve are the fitting error.

Fig. 10.

The block coincidence time resolution versus PheNum PheNum on different depths of interaction. We applied it to the simulation. The coincidence time resolution of the detector (13×13 LSO PQS detector block + R9779 PMT) increased to 363 ps.

TABLE I

Single Crystal Time Resolution With CFD

LSO Position	Light diffuser used	PheNum	Time resolution (ps)	
			Experiment [8]	Simulation
Center	No	305	196	191
Center	Yes	2250	224	230
5Edge	Yes	1620	271	272
		1610	272	274
		1530	277	281
		1410	287	294

Table II

Estimated System Time Resolution Using PQS Detector Design

PMT	R9800/R9420/R9779 Hamamatsu [40]	XP3060/XP20D0 Photonis [8,9,24,39]
Diameter (mm)	25/38/51	38/51
Typical Blue Sensitivity (uA/lmF)	11	13/12.5
Phe number	2421	2861/2751
Working voltage (V)	1300/1300/1500	1300/1000
TTS (ps)	270/550/250	500/900
Coincidence time resolution (ps)	330/352/329	326/376