International advanced course on physics and engineering of medical imaging
Maratea (Italy) 23 Sep - 5 Oct 1984
CEA-CONF--7544

TIME-OF-FLIGHT POSITRON EMISSION TOMOGRAPHY (T.O.F. P.E.T.)

R. ALLEMAND

CEA - CENG LETI/MCTE - 85 X 38041 GRENOBLE CEDEX FRANCE

1 INTRODUCTION

Positron emission tomography (P.E.T.) consists in yielding images representing the spatial and temporal distribution of specific molecules labeled with positron emitting radionuclides (^{11}C, ^{13}N, ^{15}O, ^{18}F...). The goal of PET is to study organ physiology by detecting, in vivo, biochemical processes.

The basic concept of positron imaging consists in detecting the annihilation radiation limited to a transverse plane of the subject and reconstructing from these data the activity distribution image.

In the conventional method, each event is detected in measuring the time coincidence between the two 511 KeV annihilation photons emitted 180° apart with two opposing detectors. Thus, the position of each event is located on a straight line joining the detectors. In the reconstruction process, it means that each event is back-projected on the whole size of the image matrix.

Time-of-flight (T.O.F.) concept (1) (2) (3) consists in measuring the time difference between the arrivals of the two photons on the two detectors operated in coincidence. That method supposes that a very fast time measurement should be obtained since a time interval of 1 nsec. corresponds to a point source position variation of 15 cm. In measuring the time distribution of the events with a far greater accuracy than the transit time of a photon in the object, the gaussian spatial distribution of the events may be used. Therefore, in the T.O.F. reconstruction process, each event is backprojected on a length only a fraction of the image matrix resulting in a better signal-to-noise ratio than in the conventional technique. This statement represents the basic difference between the two methods (3) (4) (5).

2 T.O.F. TOMOGRAPHIC IMAGING CHARACTERISTICS

An imaging device can be characterized by three main parameters : the spatial resolution, the temporal resolution and the sensitivity.

The physical limitation of the spatial resolution is about a couple of millimeters, due to the non-colinearity of the two 511 KeV γ rays and the positron range inside the tissue. State of the art P.E.T. devices provides images with a spatial resolution of 5 to 10 millimeters. Large efforts are presently being invested in order to improve that characteristic.

The temporal resolution is a second important parameter for positron imaging. Random coincidences rate is proportional to the coincidence time. For dynamic studies with short life radionuclides, the random coincidence rate can reach the same level than the true events in conventional P.E.T. This leads to an image contrast degradation and to an error of quantitative activity measurements.

The sensitivity is the third major parameter of positron imaging. It is essential to detect the largest possible fraction of the events escaping of the organ in order to minimize the radiation dose for the patient.

2.1. Advantages of T.O.F. P.E.T.

2.1.1. Sensitivity

The advantage of signal-to-noise ratio improvement with T.O.F. technique has been extensively reviewed in published works (4) (5) (7). This advantage can be expressed in defining a sensitivity gain which is the ratio of the number of counts needed to obtain the same signal-to-noise ratio with the T.O.F. and conventional methods. For a typical time resolution of 500 psec. the sensitivity gain varies from 2 to 4, depending on the size of the object. That sensitivity gain definition is somewhat formal as it establishes the comparison between two identical devices as a function of the only time resolution parameter. It is clear that a real sensitivity comparison must take into account (as it will be seen later) other parameters and particularly the detection efficiency. The sensitivity gain G expression has the only goal to quantify the signal-to-noise ratio improvement due to the T.O.F. method.

These considerations can be summarized by the following relation (11) :

$$G = \frac{2D}{C\Delta t}$$

where C is the speed of light (3.10^{10} cm/s^{-1}), D is the diameter of the object and Δt is the timing accuracy in seconds.

2.1.2. Counting rate capability

Coincidence events rate represents only a few percentage of the total counting rate due to the important contribution of scattered radiation and accidental coincidences in the total number of detected events. It means that high counting rates ($\sim 10^5$ c/s) are obtained at the level of each detection probe in dynamic studies with short life radionuclides. For example, 50 to 60 mCi of O^{15} can be currently administrated, because the ^{15}O half life is only 2 minutes. No significant saturation effect due to pile-up of light in the crystal is observed with T.O.F. P.E.T. because of the very short light emission of the scintillators, well appropriate for T.O.F. (8) (10).

2.1.3. Response to the random coincidences

Random coincidence rate is proportional to the coincidence time. In the conventional method, the coincidence time is determined by the deadtime of the detectors (about 8 to 10nsec. for BGO crystals), while in the T.O.F. technique, the only limitation is given by the size of the object to be imaged (usually 3 nsec.). (5) (6) (8)

2.1.4. Further advantages

As each event is backprojected on a part only of the image matrix, the angular sampling condition for T.O.F. technique does not need such a large number of directions of projections as in conventional method. The practical result is that no angular motion is needed for T.O.F. P.E.T. device (12) (13).

Furthermore, the good rejection of random coincidences in T.O.F. P.E.T. allows to use a more intense transmission source than for conventional devices. It can be used either to get a better transmission measurements accuracy, or to obtain a shorter time exposure (11) (13).

2.2. Limitations of first generation T.O.F. P.E.T.

The label of "first generation" is devoted to T.O.F. P.E.T device using Cesium Fluoride (CsF) crystals as detection scintillator (6) (7) (8).

The two main criticisms (11) concern the spatial resolution and the sensitivity. These two points merit some comments.

2.2.1. Spatial resolution

The lack of commercially available small and fast photomultipliers was a major drawback in the first generation T.O.F. P.E.T. for achieving a spatial resolution competitive with conventional P.E.T. A typical resolution of 12 mm (FWHM) was obtained with the first generation T.O.F. P.E.T. using cylindrical CsF crystals and 1"1/8 in diameter fast phototubes. Several attempts have been investigated to overcome this technological limitation. They are reviewed in this paper in the second generation T.O.F. P.E.T. description.

2.2.2. Sensitivity

As mentioned above, the sensitivity gain expression given by T.O.F. technique does not take into account the detection efficiency parameter.

Table 1 gives the physical characteristics of different scintillators. For the first generation T.O.F. P.E.T. using CsF crystals the coincidence detection efficiency is significantly lower than for conventional P.E.T. using BGO scintillators, but this efficiency loss is compensated by the sensitivity gain which, for a typical time resolution of 500 psec, varies from 2 to 4, depending on the size of the organ.

3 - THE SECOND GENERATION T.O.F. P.E.T. PHYSICAL AND TECHNOLOGICAL CONCEPTS

Efforts have been invested by different groups in order to improve the quality of T.O.F. P.E.T. images. The technological developments have been focused on the two critical parameters which are the detection efficiency and the spatial resolution.

3.1. Detection efficiency

Barium fluoride (BaF_2) was suggested (6) (9) (10) in 1982 to be used as a new scintillator for T.O.F. P.E.T. designs. The light emission slow component (decay time $\sim$ 600 nsec.) was already wellknown and this crystal had been used as a conventional scintillator in applications where a non hygroscopic material is needed. The U.V. light emission fast component from high purity crystals was recently found (6) (10) and that new property raised up a large interest for fast timing measurements and particularly in the field of high energy physics and positron imaging.

Table 1 summarizes the main properties of the most interesting materials. BaF2 clearly appears as a much more suitable scintillator for T.O.F. P.E.T. than CsF. It exhibits a better packing fraction (non hygroscopic material), a higher detection efficiency, a faster timing, and also its lower price merits to be mentioned. Nevertheless, it has to be also noticed that a quartz window is required for the photomultiplier tube (PMT) as the light emission is located in the UV region (220 nm), it results an increasing of the PMT cost.

Table 1 : Main properties of scintillation materials for P.E.T.

	BGO	CsF	BaF2	
Density	7.1	4.6	4.9	
Linear attenuation coeff. at 511 KeV (cm^{-1})	0.9	0.42	0.44	
			fast**	slow
Scintillation decay time (nsec.)	300	2.5	0.8	630
Relative scintillation output	1	0.9	0.6	2.5
Wavelength emission (nm)	480	390	225	330
Hygroscopic	NO	YES	NO	
Detection efficiency*	0.77	0.50	0.60	

* Derenzo numbers : for a 20 x 20 x 40 mm^3 deep detector including packing fraction parameter (14)

** The two numbers correspond to the fast and slow light emission components

A factor of merit (FM) has been defined (14)

$$FM = \frac{\text{coincidence efficiency}}{\text{time resolution}}$$

where the (γ, γ) coincidence efficiency is the square of the single photon efficiency and where the time resolution roughly varies in the inverse ratio of sensitivity. Based on that FM definition, BaF2 is about twice better than CsF.

Large development efforts have been invested for the two last years by different companies in BaF2 manufacturing because of its very large interest in high energy physics, and now its technology and its characteristics are well controlled. Thus, curiously, the first goal (T.O.F. P.E.T. imaging) will take advantage of the new developments linked to the high energy physics market.

3.2. Spatial resolution

Technological efforts have been carried out by photomultipliers tubes (PMT) manufacturers in order to optimize the T.O.F. P.E.T. spatial resolution with BaF2 crystals. The first approach was to mount a quartz window on a fast 1"1/8 in diameter photomultiplier tube (Hamamatsu R 1398 PMT) and more recently, a small and fast phototube (Hamamatsu R 2076 PMT) was developed. It exhibits a good trade off between the size (3/4" in diameter) and the time response ($\sim$500 psec. FWHM with a 4 cm long BaF2 crystal).

Furthermore, several approaches have been investigated by different research groups for the two last years to improve the spatial resolution. All these efforts consist in coupling more than one crystal on each PMT and in proposing a localization method able to determine the triggered crystal.

Mullani group (15) suggests to couple two different crystals (one CsF and one BaF2) on each 3/4" in diameter PMT and the light decay time difference between the two crystals is used to find out the position.

Ter Pogossian group has studied a modular structure made of eight BaF2 crystals optically coupled to 5 PMT (3/4" in diameter). The geometrical arrangement allows to determine the impinged crystal by coincidence (or anticoincidence) measurements between two PMT's.

A third approach has been investigated by LETI group (13) (16) in taking advantage of the slow component of BaF2. The principle of the method is shown in fig. 1. Each PMT is optically coupled to two crystals. A pulse signal is triggered by the anode signal fast component and is applied at the level of the photocathode through an appropriate conductor. The electrical field generated by the pulse unfocuses the photoelectrons collection on the first dynode, and therefore a modification of the slow component shape is observed. The conductor positionning and the pulse amplitude are determined to have an unfocusing effect only under one of the two crystals, making thus the position determination. Very good results have been obtained with the two types of above mentioned PMT and that solution can be used now for the design of a complete machine. In a further step, that approach could be advanced in incorporating the sense conductor inside the PMT itself.

From the results of these new developments, it follows that the spatial resolution of the second generation T.O.F. P.E.T. will be strongly increased without involving a significant degradation of time resolution. Based on the laboratory experimental results, the expected values for a complete device are the followings :

- with 3/4" PMT = . spatial résolution : 5 - 6 mm
  . time resolution : ∿ 550 psec.
- with 1"1/8 PMT = . spatial resolution : 7 - 8 mm
  . time resolution : ∿ 500 psec.

These values are related to a transverse plane. It is important to notice that longitudinal resolution is much lower in all the devices (conventional or T.O.F.). That aspect needs to be pointed out because it can be the source of errors regarding some fundamental characteristics such as the sensitivity, the partial volume effects, etc... A positron image represents the activity distribution in each volume element (voxel) ; thus, in order to characterize a P.E.T. device, it is essential to normalize the physical performances by introducing the "voxel" notion.

4 SECOND GENERATION T.O.F. P.E.T. DESIGN

The label of "second generation" is related to high spatial resolution devices using BaF2 crystals.

Based on the above mentioned new developments, detailed designs have been carried out by different groups and now the realization of the first prototypes begins. The spatial resolution value which is usually announced varies from 5 to 6 mm for brain devices to 7 to 8 mm for whole body machines. In both cases, the time resolution is typically around 500 psec. The sensitivity values can change in a rather large ratio depending on several technical choices for the design:

ring diameter, slice thickness, shielding dimensions between slices and between crystals, scintillator packing fraction... Furthermore, large efforts have been invested to improve the reconstruction procedures (17) (18) and to make easier the operating conditions and maintenance :

- optimization of the hardware configuration of the data collection
- faster processing system
- implementation of software

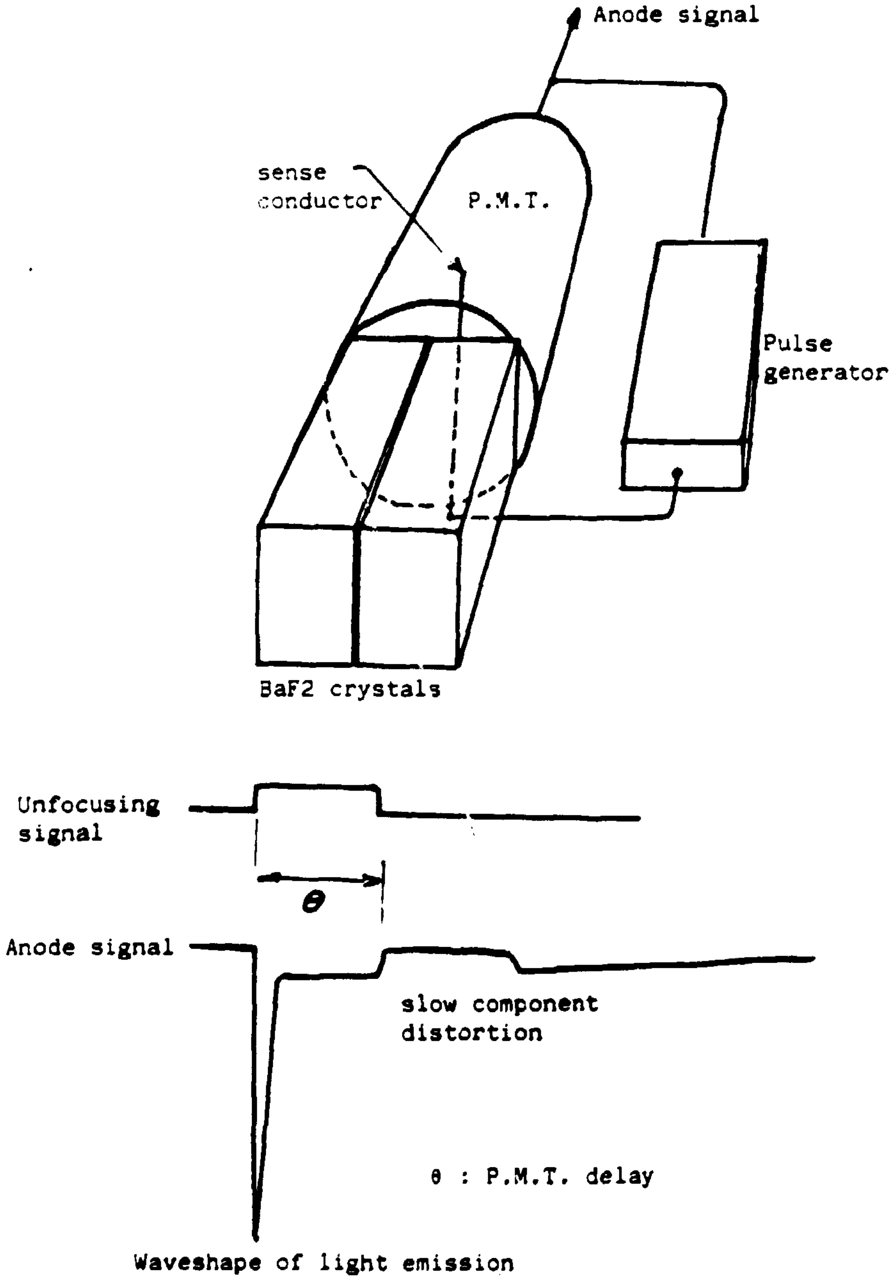
5 - CONCLUSION

A new important step has been made in the performances of the time-of-flight positron imaging for the two last years. It has been proved that a high spatial resolution can be obtained with the T.O.F. technique. It has also been shown that the overall sensitivity (taking into account the sensitivity gain and BaF2 detection characteristics) is quite close to the one of conventional methods.

On the other hand, the basic advantages related to the high counting rate capability, the random coïncidences rejection, etc... of course remain.

It is probably safe to assume that significant improvements can be expected if new technological efforts are invested. Unfortunately, P.E.T. is a complex and expensive tool which has been only used up to now in the research groups (about 50 centers in the world). The justification of new technical developments will be quite clear when this modality will be considered in the assessment of diseases and in clinical diagnostic applications.

Figure 1 : Identification system for high spatial resolution T.O.F. P.E.T.



REFERENCES

1. G.L. Brownell, C.A. Burnham and al. New development in scintigraphy and the application of cyclotron produced positron emitters. Medical Radioisotope scintigraphy - Vol 1 - Proceedings of a Symposium - Salzburg August 6-15, 1968
2. W.L. Dunn. Time-of-flight localization of positron emitting isotopes. Thesis in physics - Vanderbilt University- Nashville Tenessee, 1975
3. R. Allemand, C. Gresset, J. Vacher. Potential advantages of a Cesium fluoride scintillator for a time-of-flight positron camera. J. Nucl. Med. 21 (2) 153, 155 - 1980
4. R. Campagnolo, Ph. Garderet, J. Vacher. Tomographie par émetteurs de positrons avec mesure de temps de vol. Colloque international sur le traitement du signal - Nice - Mai 1979
5. R. Allemand, R. Campagnolo, Ph. Garderet, R. Gariod, C. Gresset, C. Janin, M. Laval, R. Odru, E. Tournier, J. Vacher. A new time-of-flight method for positron computed tomography. U.S.A. France Seminar on biomedical image processing. St Pierre de Chartreuse (France) - May, 26 1980
6. M. Laval, R. Gariod, R. Allemand, E. Cormorèche, M. Moszynski. The "LETI" positron tomograph architecture and time-of-flignt improvements. Workshop on time-of-flight tomography - May, 17-19 1982. Washington University - St Louis - Mo
7. M.M. Ter Pogossian, N.A. Mullani, D.C. Ficke, S. Murkham, D.L. Snyder. Photon time-of-flight assisted positron emission tomography. J. Comput. Assist. Tomogr. 5 (2) 227-239, 1981
8. M.M. Ter Pogossian, D.C. Ficke, M. Yamamoto, J.T. Hood. Design characteristics and preliminary testing of super PET 1. Workshop on time-of-flight tomography, May 17-19, 1982. Washington University - St Louis - Mo
9. M. Laval, M. Moszynski, R. Allemand, E. Cormorèche, P. Guinet, R. Odru and J. Vacher. BaF2 inorganic scintillator for subnanosecond timing - Nucl. Instr. and Meth.
10. J. Vacher, R. Allemand, M. Laval, M. Moszynski and R. Odru. New development on detection and fast timing on the time-of-flight LETI device. Workshop on time-of-flight tomography, May 17-19, 1982. Washington University - St Louis - Mo
11. T.F. Budinger. Time-of-flight positron emission tomography. Status relative to conventional P.E.T. J. of Nucl. Med. Vol 24 (1) - 73-78, 1983
12. E. Tanaka. Line-writing data acquisition and signal-to-noise ratio in time-of-flight positron emission tomography. Workshop on time-of-flight tomography May 17-19 1982. Washington University - St Louis - Mo
13. R. Allemand, JL. Lecomte. Methodology of positron emission tomography. An european workshop sponsored by EEC. London March 1984

14. S.E. Derenzo. Comparison of detector materials for time-of-flight positron tomography. Workshop on time-of-flight tomography - May 17-19 1982. p 63-69 - Washington University St louis Mo
15. W.H. Wong, N. Mullani and al. Characteristics of small barium fluoride scintillator for high intrinsic resolution time-of-flight positron emission tomography.
16. R. Allemand and al. Nouvelles perspectives technologiques pour la tomographie à positons par temps de vol. Symposium Liège 15-16 avril 1983.
17. D.C. Ficke and al. Recent developments in image reconstruction using a time-of-flight assisted positron emission tomography. IEEE Transactions on nuclear science, 1983, vol NS-31, Nb 1, p 605-609
18. D.G. Politte and D.L. Snyder. Results of a comparative study for a reconstruction procedure for producing improved estimates of radioactivity distributions in time-of-flight tomography. IEEE transactions on nuclear science, 1984, Vol. NS-31, Nb 1, p 614-620.