Review

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Progress and perspectives in total body PET systems instrumentation

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Abstract: Total body positron emission tomography (PET) systems are being developed by different groups worldwide. These systems have potential to change the number of applications in which molecular imaging is used. The change from a short axial field of view (FOV) to a longer one is however associated with a linear increase in the cost of these systems. This may limit their application to a small number of centers (capable of obtaining sufficient research funding). Therefore it remains interesting to see if lower cost systems can be developed and bring total body PET to the clinic for an acceptable budget. The wider availability of this low cost system can also enable more researchers to further optimize and explore the full potential of total body PET.

Keywords: PET; PET-CT; sensitivity.

Introduction

The current clinical positron emission tomography (PET) systems [1] are based on detector modules [2, 3] (combination of scintillation material, light detector and electronic readout). These are grouped in complete detector rings and a system is then composed of a certain number of detector rings (typically 3–5 rings of each 3–5 cm axial length). Most recent systems are time-of-flight (TOF) PET systems [4, 5] which measure the time difference of both photons. More recently the readout with large conventional photomultiplier tubes has been replaced with solid state silicon photomultipliers (SiPMs) [6, 7].

The concept of total body PET is now to further extends the system with multiple rings (up to 1–2 m). These long axial field of view (FOV) systems have been extensively simulated by several groups [8–10] to optimize the design before building them. One of the conclusions from these studies is that for a single organ sensitivity is not much increasing after 70 cm length. The further extension is particularly helpful to boost the sensitivity in cases where we are imaging a long object (like the patient body or at least the torso). This type of studies (full or partial body) is what is done in about 90% of the clinical studies and therefore there is also interest in total body PET for clinical routine. In this manuscript we will first give an overview of current technology and then go into detail on different possible scenarios for further optimization of total body PET.

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Overview of recent developments

The first clinical total body PET system (so called Explorer [11]) has been aiming for a maximization of the solid angle coverage. When the full body should be imaged this seems a logical choice as no patient motion is required anymore [12]. Without any doubt this is the also the most interesting configuration for researching the potential of total body PET. There are also three disadvantages:

(1) The long bore may create claustrophobia in some patients. This effect may be limited as we are typically using short duration exams.
(2) The footprint of such a system is clearly higher than other clinical PET-CT systems. This may limit its integration in existing clinical PET centers which are often space constraint.
(3) The long axial FOV is associated with a very high total cost.

An alternative configuration has been designed by UPENN [13] and Siemens based on the Vision system. The first UPENN system has a length of 140 cm and the second has a length of 106 cm. The associated sensitivity reduction (due to reduced axial length compared to Explorer) is compensated by an improvement in TOF (from 400–500 ps to 200–250 ps) resulting in an increase in the so-called effective sensitivity.

This does however not solve the limited axial length of the patient seen in one bed position. In most of the current nuclear medicine studies the imaging range is however limited from head to thigh.

Future directions for total body PET

These three total body PET systems outperform current PET-CT systems with an increase in sensitivity of 20–40 for body imaging (at the expense of a much higher cost). Compared to current technologies one can further improve these systems by enhancing TOF resolution (towards 100 ps) and improving system spatial resolution (towards 2 mm). Improvements in photodetectors, time estimation algorithms and other detector configurations like monolithic detectors [14] have been investigated by different groups and can improve the next generation of TB-PET systems [15].

While the much higher sensitivity of current TB-PET system is surely interesting for serving all research demands (ultra-low dose, new paradigms, novel tracers, brain body interactions) one can question whether this large increase is required for all nuclear medicine physicians interested in TB-PET. The associated high costs of these systems (3–4 times higher than a current PET-CT) seem also a barrier for most departments to even consider a TB-PET system.

For a lower cost TB-PET system different options are available:

We will first explain how one can reduce the costs for the hardware. PET detectors are the most expensive components in PET systems as they are composed of expensive scintillation crystals, typically L(Y)SO in current systems, costly SiPMs and readout electronics [1].

The first option to reduce the cost per detector unit is to reduce the crystal thickness, as PET works in coincidence mode the sensitivity will drop roughly quadratically by reducing the thickness of the detector by 50%. In a simulation study [16] systems with different axial lengths from 20 to 75 cm and constant total scintillator volume were simulated. The optimal thickness (with LYSO) was 10 mm and an axial length of 36 cm. In general however thinner crystals will also have better TOF performance, so some compensation will occur via the gain in effective sensitivity.

A second method to reduce the cost is to reduce the number of readout channels and SiPMs with techniques like sparse SiPM coverage and multiplexing of the data. A third method is to introduce gaps in the detector cylinder and reduce the total amount of detectors. This can be done inside each transverse ring or by omitting rings in the axial direction. One of the advantages of the recent PET scanners is their TOF capabilities. This additional TOF-information per measured event makes the reconstructed image less sensitive to missing data. Sensitivity loss is always determined by the number of detected coincidences and therefore sensitivity will drop by a factor of 4 when deleting e.g. half the rings or half the number of detectors. A fourth method is to use alternative detector technologies, like readout at axial or replace the expensive scintillators with plastic scintillators [17].

A third hardware method is to design a detector that is specifically designed for total body PET. One idea is to use radially oriented crystals [18]. These are long crystals along the main axis of the scanner. Less readout would be needed as it is only required at the axial ends. A similar approach but based on plastic scintillators is proposed by the group in Krakow [19–21]. Besides reducing the number of detectors one can also reduce the cost of scintillator: cost per volume is about 80 times lower than L(Y)SO.

Besides working on the “hardware” one can also improve the images (and indirectly reduce the cost of the system) for a given amount of counts with “software”. PET has a relatively high sensitivity and image reconstruction and postprocessing can further improve the quality. The first method is introducing prior information in PET reconstruction. Different papers have shown that this can lead to a significant noise reduction for a given count level. These methods can also be combined with total body PET systems and may compensate for lower count levels in alternative designs. Besides reconstruction also a second method, so called post reconstruction deep learning based denoising can be used [22]. The estimate is that a possible reduction with a factor of 4 in counts is possible and may be applied to total body PET scanners. Deep learning was also used to derive full-dose PET images from 1/10th dose PET images [23].

Conclusions

Total body PET is being introduced recently in research and clinical centers. Up to now it has fulfilled all promises (Ultra-low dose, late imaging, ultrafast imaging). While the first systems are aiming at ultra-high sensitivity (with the downside of high acquisition and maintenance costs), there are clearly alternatives with other detector configurations investigated for lower cost total body PET (somewhere in-between the current 20–30 cm axial FOV clinical PET-CT and the first high end total body PET). Several iterative reconstruction and deep learning denoising

methods have the potential to enhance the image quality of such "reduced" Total Body PET systems.

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References

1. Muehllehner G, Karp JS. Positron emission tomography. Phys Med Biol 2006;51:117–37.
2. Lewellen TK. Recent developments in PET detector technology. Phys Med Biol 2008;53:287.
3. Peng BH, Levin CS. Recent development in PET instrumentation. Curr Pharmaceut Biotechnol 2010;11:555–71.
4. Karp JS, Surti S, Daube-Witherspoon ME, Muehllehner G. Benefit of time-of-flight in PET: experimental and clinical results. J Nucl Med 2008;49:462–70.
5. Surti S, Karp JS. Advances in time-of-flight pet. Phys Med 2016; 32:12–22.
6. Britvitch I, Johnson I, Renker D, Stoykov A, Lorenz E. Characterisation of Geiger-mode avalanche photodiodes for medical imaging applications. Nucl Instrum Methods Phys Res Sect A Accel Spectrom Detect Assoc Equip 2007;571:308–11.
7. Roncali E, Cherry SR. Application of silicon photomultipliers to positron emission tomography. Ann Biomed Eng 2011;39:1358–77.
8. Surti S, Karp JS. Impact of detector design on imaging performance of a long axial field-of-view, whole-body PET scanner. Phys Med Biol 2015;60:5343–58.
9. Schmall JP, Karp JS, Werner M, Surti S. Parallax error in long-axial field-of-view PET scanners—a simulation study. Phys Med Biol 2016;61:5443–55.
10. Eriksson L, Townsend D, Conti M, Eriksson M, Rothfuss H, Schmand M, et al. An investigation of sensitivity limits in pet scanners. Nucl Instrum Methods Phys Res Sect A Accel Spectrom Detect Assoc Equip 2007;580:836–42.
11. Cherry S, Karp J, Moses W, Qi J, Bec J, Berg E, et al. In: Proceedings of IEEE nuclear science symposium and medical imaging conference; 2013. M03–01.
12. Badawi RD, Shi H, Hu P, Chen S, Xu T, Price PM, et al. First human imaging studies with the explorer total-body pet scanner. J Nucl Med 2019;60:299–303.
13. Karp JS, Vishwanath V, Geagan M, Muehllehner G, Pantel A, Parma M, et al. Pennpet explorer: design and preliminary performance of a whole-body imager. J Nucl Med 2020;61: 136–43.
14. Stockhoff M, Decuyper M, Van Holen R, Vandenberghe S. High-resolution monolithic LYSO detector with 6-layer depth-of-interaction for clinical PET. Phys Med Biol 2021;66:155014.
15. Vandenberghe S, Moskal P, Karp JS. State of the art in total body PET. EJNMMI Phys 2020;7:35.
16. Surti S, Werner M, Karp J. Study of pet scanner designs using clinical metrics to optimize the scanner axial fov and crystal thickness. Phys Med Biol 2013;58:3995.
17. Moskal P, Stępień EŁ. Prospects and clinical perspectives of total-body PET imaging using plastic scintillators. Pet Clin 2020;15: 439–52.
18. Beltrame P, Bolle E, Braem A, Casella C, Chesi E, Clinthorne N, et al. The ax-pet demonstrator design, construction and characterization. Nucl Instrum Methods Phys Res Sect A Accel Spectrom Detect Assoc Equip 2011;654:546–59.
19. Moskal P, Salabura P, Silarski M, Smyrski J, Zdebik J, Zieliński M. Novel detector systems for the positron emission tomography. Bio Algorithm Med Syst 2011;7:73.
20. Moskal P, Rundel O, Alfs D, Bednarski T, Białas P, Czerwiński E, et al. Time resolution of the plastic scintillator strips with matrix photomultiplier readout for J-PET tomograph. Phys Med Biol 2016;61:2025.
21. Moskal P, Kowalski P, Shopa RY, Raczyński L, Baran J, Chug N, et al. Simulating NEMA characteristics of the modular total-body J-PET scanner – an economic total-body PET from plastic scintillators. Phys Med Biol 2021;66:175015.
22. Catana C. The dawn of a new era in low-dose pet imaging. Radiology 2019;290:657–8.
23. Kaplan S, Zhu YM. Full-dose pet image estimation from low-dose pet image using deep learning: a pilot study. J Digit Imag 2018: 1–6.