INVITED COMMENTARY

# New Developments in PET Instrumentation: Quo Vadis PET?

The growth of nuclear medicine at the end of the 20th century and the beginning of the 21st has been caused mostly by recognition of the clinical value of coincidence imaging, or PET. In the mid-1990s, hybrid SPECT–PET systems were developed along with a new generation of clinically oriented dedicated PET systems. More recently, new PET systems using lutetium oxyorthosilicate (LSO) and $Ge_2SiO_5$ (GSO) crystals have been developed. Furthermore, PET systems have now been combined with CT to provide CT transmission scans for attenuation correction and superior coregistration of PET and CT data. These developments were underscored by the 2001 annual meeting of the Society of Nuclear Medicine, in Toronto, where practically all vendors offered one or even several PET scanners, ranging from low- to very high-end. These new scanners tend to use more 3-dimensional (3D) imaging, and some work in 3D mode only.

The interesting article by Adam et al. (*1*) in this issue of *The Journal of Nuclear Medicine* describes the performance characteristics of such a clinically oriented PET scanner, C-PET, which works in 3D mode only, or without collimation. Up to now, most PET systems have had both options, that is, imaging in 2-dimensional (2D) or 3D mode. The article also gives insight into the National Electrical Manufacturers Association (NEMA) 2000+ standard, which, although not yet official, describes tests, phantoms, and evaluation procedures for 2D and 3D PET systems.

The principal advantage of 3D mode is significantly higher sensitivity, which can significantly reduce the tracer activity needed or shorten the acquisition time. 3D PET has been used mostly for brain imaging. An increase in sensitivity can also make cardiac gated studies possible, because in 2D mode, image quality is severely limited by the number of counts. However, compared with 2D mode, 3D imaging still has some disadvantages. Recently, the quality of 3D cardiac images was shown to be lower than (*2*) or, at best, comparable with (*3*) that of 2D PET images. Several reasons account for this finding. First, compared with 2D mode, 3D mode requires significantly more computer memory and significantly more time for reconstruction of images. Second, slice sensitivity along the axial field of view (FOV) in 2D mode is relatively uniform, except for the very edge of the FOV. In 3D mode, the same slice sensitivity varies greatly and is triangular (*4*). Therefore, C-PET, with an axial FOV of 25.6 cm, needs 8 bed movements to cover a 1-m length; that is, the scanner has a 50% overlap between 2 neighboring bed positions (*1*). Third and most important, 3D mode suffers from a high rate of scatter and random events.

To fully understand the differences between 2D and 3D PET imaging, one needs to know how PET data are acquired. PET systems acquire 2 channels, usually called the total prompt channel and the total delayed channel. The total prompt channel collects true, scatter, and random events that occur within the coincidence time window. The total delayed channel estimates random events, which are then subtracted from the total prompt channel to give true and scatter events. Each event is placed in a line of response in the sinogram. From the sinograms, reconstructed images are obtained.

The various available systems treat random and scatter events at different stages and in different ways. Therefore, in PET imaging, we cannot talk simply about counts. We have to specify whether we are talking about true, scatter, or random counts. This represents a significant difference between SPECT and PET. Therefore, when we speak of an increasing sensitivity of 3D PET, we should ask ourselves whether we are dealing with an increase in true counts, in scatter and random counts, or in a combination of all. The parameter that characterizes the relationship between true, scatter, and random events is the noise equivalent count (NEC) rate (*4,5*). Usually, the NEC rate is plotted as a function of activity concentration, which is expressed in kBq/mL (μCi/mL). PET systems, like gamma cameras, can be paralyzed. In other words, the NEC rate will reach a peak and then start declining as the system saturates at higher activity concentrations. DeGrado et al. (*5*), using a leading bismuth germanate (BGO) PET system, showed that the peak NEC rate is greater in 2D than in 3D imaging for a uniform phantom. The higher number of counts in 3D imaging does not necessarily mean a better image quality, because the increase in counts is mostly an increase in scatter and random events.

Resolution properties also differ between 2D and 3D PET imaging. Because of septa removal and exposure of more crystals, axial resolution is slightly worse in 3D imaging (*4*). However, this difference in axial reso-

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lution seems to affect image quality less than does the increased scatter in 3D mode. The 3D mode suffers not only from more scatter in the FOV but also from scattered activity outside the FOV. For this reason, almost all 3D clinical PET imaging has, until recently, been of the brain, which does not have a nearby hot organ causing a high level of out-of-FOV scatter.

Recently, an excellent article (*6*) addressed the problem of pileup in high-count studies. 3D PET imaging is especially sensitive to paralysis because of the high number of events involved. Also, the number of random events in 3D mode is high. The random rate increases as the square of the activity concentration, whereas the true counting rate increases linearly with activity concentration. Adam et al. (*1*) summarized this in their discussion: "The low [contrast recovery coefficients] also indicate that the scatter and random-event corrections need to be improved." Currently, this statement appears valid not only for C-PET but for all other PET systems.

Industry vendors are aware of the potential of 3D PET imaging. They are developing systems that use LSO and GSO crystals. The C-PET system described by Adam et al. (*1*) uses a NaI(Tl) crystal, which has the worst stopping power but the best light yield and good energy resolution. Most dedicated PET systems use BGO crystals, which, as opposed to NaI(Tl), have high stopping power, low light yield, and relatively poor energy resolution. LSO and GSO crystals have characteristics that fall between those of BGO and NaI(Tl). A higher energy resolution, such as is possible with a NaI(Tl) C-PET system, enables the lower level energy window to be raised from 350 to 435 keV and thus significantly decreases the amount of scatter (*1*). C-PET also has a shorter coincidence time window than do most of the other systems: 8 versus 12 ns. A shorter coincidence time window should improve counting characteristics. The significantly shorter scintillation decay time of GSO and LSO crystals (56 and 40 ns, respectively, compared with a crystal decay time of 230 ns for NaI(Tl) and 300 ns for BGO) can significantly improve the counting rate performance of the PET system and is particularly important in high-count 3D PET imaging.

Each crystal has certain advantages and disadvantages. Which has the best overall performance characteristics needs to be shown. Perhaps different crystals and different PET systems will perform best for different applications.

The NEMA NU-2 standard on performance measurements of positron emission tomographs (*7*) has not yet addressed 3D PET imaging. The new NEMA 2000+ proposal is still a draft. The study of Adam et al. (*1*) uses and describes the NEMA 2000+ standard and presents some recommended tests, phantoms, and evaluation procedures for 3D PET imaging. NEMA standards for 3D PET performance testing are extremely important as a guideline to purchasing, acceptance testing, and long-term PET quality control.

In summary, the full potential of 3D PET imaging will be achieved through more accurate random-event and scatter corrections, faster and better electronics, reduced coincidence time windows and improved counting characteristics, optimized crystal detectors, and improved reconstruction software and computer hardware. Prototypes of different PET systems, including 3D PET systems, are already available. To compare different PET systems objectively, we need applicable NEMA standards as soon as possible.

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