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Combined PET/CT: the historical perspective

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The proposal to combine PET with CT was made in the early 1990s by Townsend, Nutt and co-workers. The concept originated from an earlier low-cost PET scanner design (Figure 1a) that comprised rotating banks of bismuth germinate (BGO) block detectors that was developed by Townsend and coworkers at the University of Geneva in 1991 [1]. The gaps between the banks of BGO detectors (Figure 1b, arrow) offered the possibility to incorporate a different imaging modality within the PET scanner. A Swiss oncology surgeon, Dr Rudi Egeli, suggested adding something useful such as a CT scanner in the gaps that would provide anatomical information more familiar to surgeons at that time. Thus, the concept of PET/CT was born in 1991, in which the components of a CT scanner would be mounted in the gaps between the banks of BGO block detectors (Figure 1c). However, it was soon evident from the inspection of a typical CT scanner (Figure 1d) that such a concept would not be feasible owing to the density of x-ray components mounted on the rotating support. Thus, it was to be seven years before the first prototype combined PET/CT scanner was completed and installed in the University of Pittsburgh Medical Center. In 1993, Townsend moved to the University of Pittsburgh where, in collaboration with Dr Ron Nutt, then President of CTI PET Systems (CPS) in Knoxville, Tennessee, received NIH funding to begin the development of the first PET/CT prototype. This work followed the pioneering work of the late Bruce Hasegawa and colleagues at the University of California, San Francisco in the early 1990s where they developed the first combined clinical CT and SPECT prototype scanner [2].

The objective of the PET/CT grant was to develop a prototype that comprised both clinical CT and clinical PET and could acquire both data sets in a single scan session. A spiral CT scanner was obtained from Siemens and the PET components of the rotating scanner developed by Townsend and coworkers in Geneva in 1991 [1] were mounted on the rear of the CT assembly (Figure 2a). This approach overcame the problem of finding space on the front of the CT assembly for the PET components. The CT and PET components therefore rotated as a single assembly acquiring CT and PET data sequentially. The entire rotating assembly was housed within a single gantry cover (Figure 2b). The patient moved from one imaging modality to the other by a translation of the common patient bed. The CT and PET images were aligned to the extent to which the patient remained immobile between the two acquisitions. This design offered significant, and now well-documented, advantages over the acquisition of CT and PET images on different scanners followed by software alignment. The CT images were also used to generate the PET attenuation correction factors thus obviating the need to perform the usual

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This article is dedicated to the memory of the late Professor Bruce Hasegawa from the University of California, San Francisco who was a true pioneer of multimodality imaging devices. Bruce was a friend and colleague and an inspiration for our work.

lengthy PET transmission scan [3]. It is to be emphasized that the documented objectives of this development was to offer *clinical* CT and *clinical* PET scans from a single device; the intended purpose of the CT was to provide clinical patient information and not just used for attenuation correction and localization alone. Thus, the use of the CT for attenuation correction was a secondary objective to the main purpose of developing a clinical PET/CT scanner.

The first prototype PET/CT scanner thus became operational in 1998, designed and built by CTI PET Systems in Knoxville, TN (now Siemens Molecular Imaging) and subsequently clinically evaluated at the University of Pittsburgh. This first design incorporated a single-slice spiral CT scanner (Somatom AR.SP; Siemens Medical Solutions, Forchheim, Germany) and a rotating ECAT ART scanner (CTI PET Systems, Knoxville, TN) as shown in Figure 2a 4. Data processing included an algorithm to scale the CT images from x-ray energy to PET annihilation photon energy (511 keV) and generate the appropriate attenuation correction factors [3]. Over 300 cancer patients were scanned on the prototype and the findings presented in a series of peer-reviewed publications [5–7]. Figure 2c shows a transaxial section acquired in 1999 on the prototype through the head and neck of a patient with cancer; the study was performed with intravenous contrast emphasizing that the objective of the prototype was always to acquire a clinical CT and a clinical PET scan. The results from the prototype thus demonstrated the importance of high resolution anatomy accurately registered with functional data. The coregistered anatomy localized functional abnormalities and clarified equivocal situations, thus improving the accuracy and confidence of the scan interpretation. The use of a rapidly-acquired, low-noise CT scan in place of a lengthy conventional PET transmission scan reduced the overall scan duration.

The impressive results from the prototype stimulated a demand from radiology and nuclear medicine for a commercial PET/CT design. In the early discussions with industry, the debate centered on the appropriate CT configuration to combine with PET, and whether that configuration should be one fully adequate for diagnostic body imaging or one of the state-of-the-art designs being developed for cardiac imaging[8]. With the conclusion of this debate, the first commercial PET/CT scanner to be announced was the *Discovery LS* (GE Healthcare) in early 2001, a design that incorporated a 4-slice CT scanner, which was in fact the highest end CT scanner at the time in terms of number of detector rows. This was followed a few months after by the *Biograph* (Siemens Medical Solutions), and then somewhat later by the *Gemini* (Philips Medical Solutions). In all cases the CT scanners incorporated were in the mid to high level of detector row number and performance, fully capable of high level body imaging. In the past seven years, PET/CT designs from all vendors have evolved considerably. There have been important developments in CT scanners with the increase in the number of detector rows (slices) and shorter rotation times. These fast-acquisition designs are primarily for cardiac applications, although they have also been incorporated into the latest PET/CT scanners. Advances in PET scanners have paralleled the improvements in CT. The PET advances include the introduction of new fast scintillators such as LSO, improvements in detector spatial resolution and coincidence timing, increased scanner sensitivity through an extended axial field-of-view, and the introduction of statistically-based reconstruction algorithms with a system model that explicitly incorporates all data correction factor, and time of flight methods of image reconstruction. The fact that all commercial PET/CT designs maintain relative independence of the CT and PET hardware allows advances in each modality separately to be rapidly incorporated into the combined devices. The CT scanner in the PET/CT is typically a design that lags 9–12 months behind state-of-the-art high end CT, whereas ever since the disappearance of PET-only scanners, all advances in PET have been incorporated directly into PET/CT.

Currently, five vendors worldwide offer PET/CT designs: GE Healthcare, Hitachi Medical, Philips Medical Systems, Toshiba Medical Corporation and Siemens Medical Solutions.

Current PET/CT designs offered by Siemens Molecular Imaging, GE Healthcare and Philips Medical Systems are summarized in Figure 3. The specifications and performance of the PET components are vendor-specific, with the *Biograph* HI-REZ TruePoint (Figure 3a; Siemens Medical Solutions) offering good spatial resolution in 3D with 4 mm × 4 mm × 20 mm LSO crystals [9]; the original *Biograph* design was based on 6.4 mm × 6.4 mm × 25 mm LSO detectors. The *Biograph* is currently offered with 6, 40 and 64-slice CT scanners. The *Discovery LS*, the original PET/CT design from GE Healthcare, combined the Advance NXi PET scanner with a 4, 8 or 16-slice CT [10]. The *Discovery ST* (Figure 3b; GE Healthcare) has 6.2 mm × 6.2 mm × 30 mm BGO detectors in combination with a 4, 8 or 16-slice CT scanner; unlike the *Discovery LS*, the gantry of the PET scanner now matches the dimensions of the CT scanner. The higher resolution *Discovery STE* has 4.7 mm × 6.3 mm × 30 mm BGO detectors in combination with 8 or 16-slice CT scanners; the *Discovery VCT* is an STE configured with a 64-slice CT scanner. The *Gemini GXL* (Figure 3c; Philips Medical) comprises 4 mm (in plane) and 6 mm (axial) GSO detector pixels, 30 mm in depth; the *Gemini* is also an open design with the capability to physically separate the CT and PET scanners for access to the patient. The *Gemini GXL* incorporates a 6 or 16-slice CT scanner. The most recent addition to PET/CT designs is the *Gemini TF*, the first commercial Time-of-Flight (TOF) PET scanner [11]. The *Gemini TF* has 4 mm × 4 mm × 22 mm LYSO detectors and is combined with a 16 or 64-slice CT scanner. All designs other than the *Discovery LS* offer a 70 cm patient port for both CT and PET thus to some extent facilitating the scanning of radiation therapy patients in treatment position. The *Gemini* and *Biograph* acquire PET data in 3D mode only, whereas the *Discovery* series incorporates retractable septa and can acquire data in both 2D and 3D mode.

While the first commercial PET/CT scanner appeared in early 2001, by 2006 PET-only scanners were no longer obtainable as major medical centers and clinics opted for PET/CT to replace their PET-only scanners and newly-established diagnostic imaging centers went directly to PET/CT. By 2008, over 2500 PET/CT scanners are now operational worldwide. From 2002 onwards therefore, PET/CT has been one of the fastest growing medical imaging modalities, rivaling the growth of MR during the 1980s and 1990s.

With their combined imaging capability, PET/CT scanners offer considerable flexibility in the choice of appropriate protocols. In contrast to the objectives of the original prototype design, some centers choose to use the CT scan for attenuation correction and localization only, while others perform full clinical CT and PET on their patients. The best practice of using PET/CT scanners in the clinic, therefore, raises important issues and is the topic of this meeting that was held in Sonoma, California in April, 2008.

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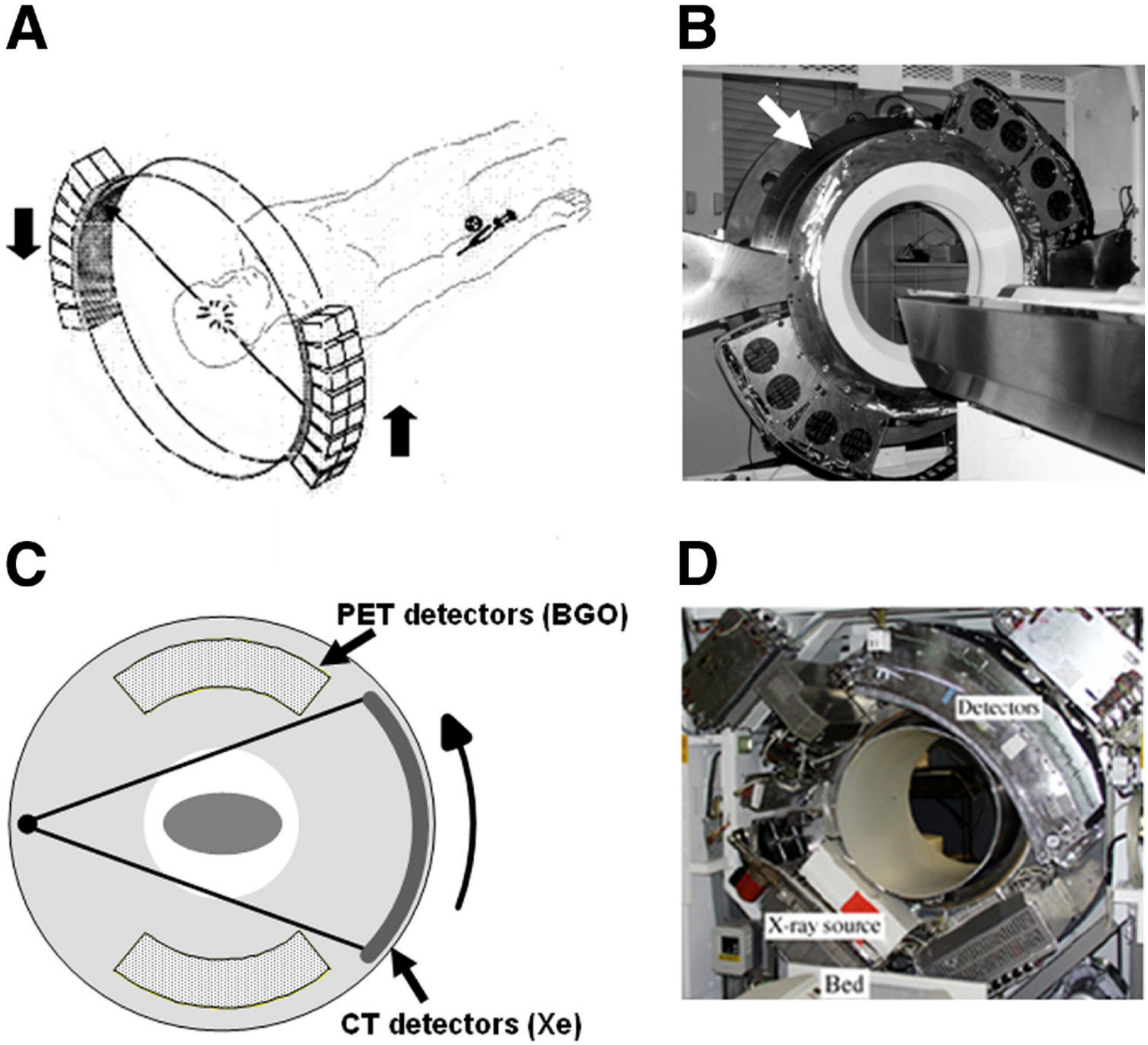

FIGURE 1.
The development of the PET/CT concept. The idea originated from the rotating PET scanner design (a) in which two banks of BGO block detectors are rotated around the patient. (b) The gaps between the detector banks provide space in which to mount the components of a CT scanner (arrow). (c) A possible schematic for a combined PET/CT scanner. (d) A typical CT scanner showing that the schematic suggested in (c) is not really feasible owing to the density of the x-ray components.

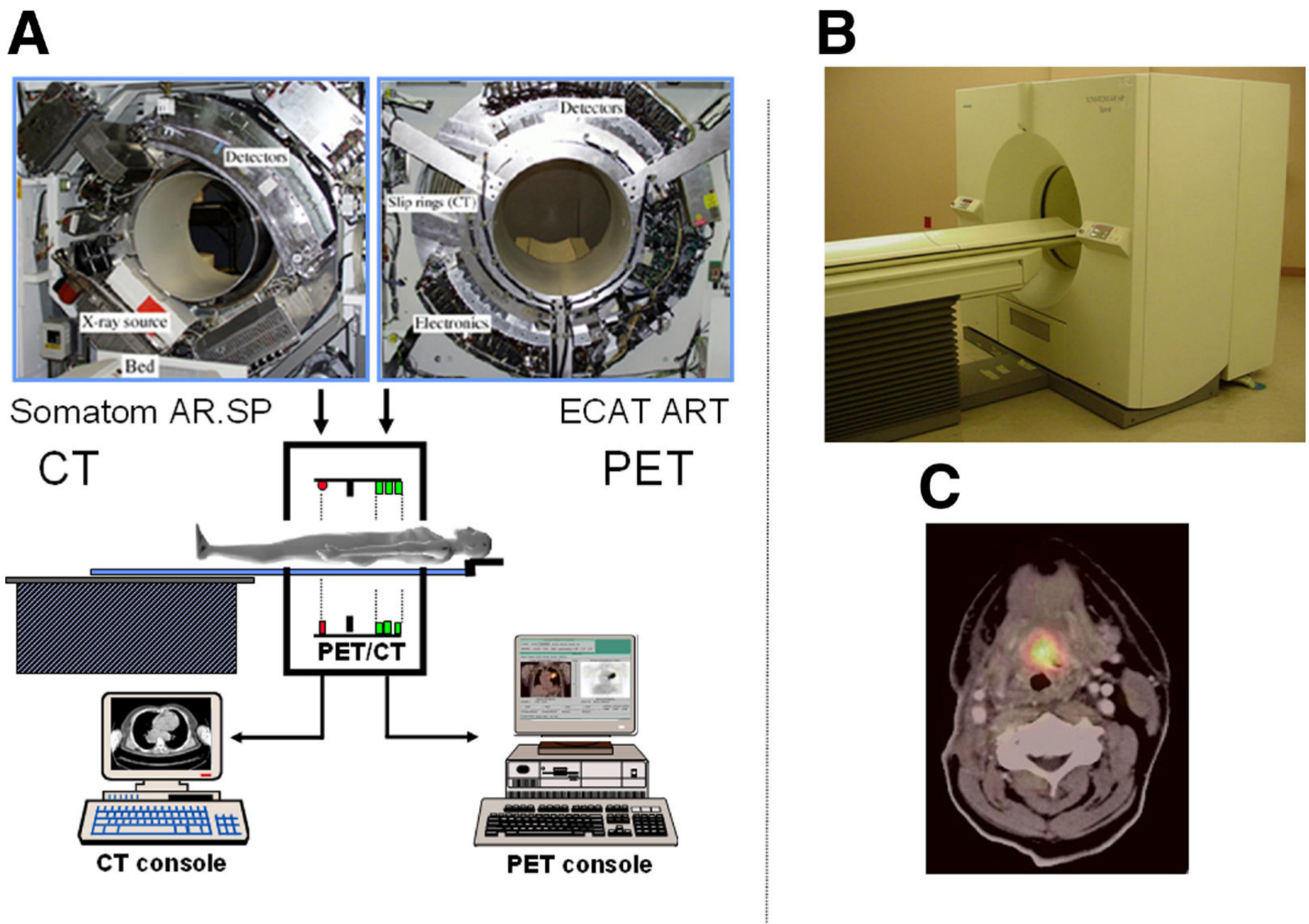

FIGURE 2.
(a) The first PET/CT prototype design evaluated clinically at the University of Pittsburgh. The CT and PET components were mounted on a single rotating support and the data acquired from two separate consoles; the CT images were transferred to the PET console and then used for CT-based attenuation correction and localization. (b) The original PET/CT prototype scanner at the University of Pittsburgh in 1998. (c) A transaxial section through a patient with head and neck cancer acquired on the prototype scanner in 1999; note that intravenous contrast has been administered showing that the prototype was used for clinical CT and clinical PET scans.

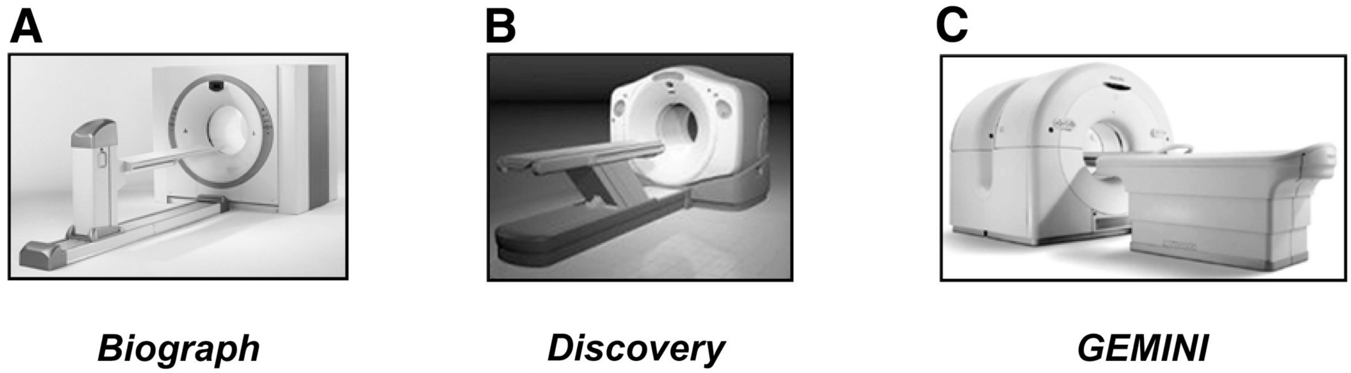

FIGURE 3.
Specifications of current PET/CT scanner designs from three of the major suppliers of medical imaging equipment: (a) the Siemens Biograph TruePoint, (b) the GE Healthcare Discovery range, and (c) the Philips Gemini series.