The biograph: A Premium Dual-Modality PET/CT Tomograph for Clinical Oncology

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Introduction

Cancer is the second leading cause of mortality in the Western world. Efficient treatment planning depends largely on early diagnosis and accurate therapy follow-up. Disease processes, such as cancer begin as changes at the molecular level. By the time the number of affected cells is sufficiently large to result in recognizable anatomical changes, the disease may well have progressed beyond the stage where it can be successfully treated. Conversely, morphological change is not necessarily indicative of malignancy. Today, most of the diagnosis and staging of cancer, as well as the assessment of therapy response, relies on imaging modalities such as CT and MRI, which detect only anatomical changes in lesions. Increasingly, however, molecular imaging techniques, such as Positron Emission Tomography (PET), that are sensitive to functional changes in tissue are playing a role in the diagnosis and staging of disease [1, 2]. The emergence of ^{18}F-fluoro-2-deoxyglucose (FDG) as a sensitive tracer for PET imaging of malignancy [3], and the possibility of using PET to survey the entire body with a single dose has established whole-body FDG PET scanning as an effective procedure for these purposes. However, FDG PET images themselves typically contain little anatomical detail. Other, more tumour-specific PET tracers exhibit even less physiological uptake, and hence essentially no anatomic information at all (Fig. 1). The need to place such functional images in an anatomical context is obvious. Thus CT and PET are complimentary imaging modalities whose combination promises to be far more powerful than either imaging technique is alone [4, 5].

A number of computer algorithms are available to register image sets from different modalities such as CT and PET *retrospectively* [6]. Retrospective image alignment works best for a rigid organ such as the brain. Success in other regions of the body is less certain since in most cases the patient must be moved between the two machines and repositioned on different beds, with the

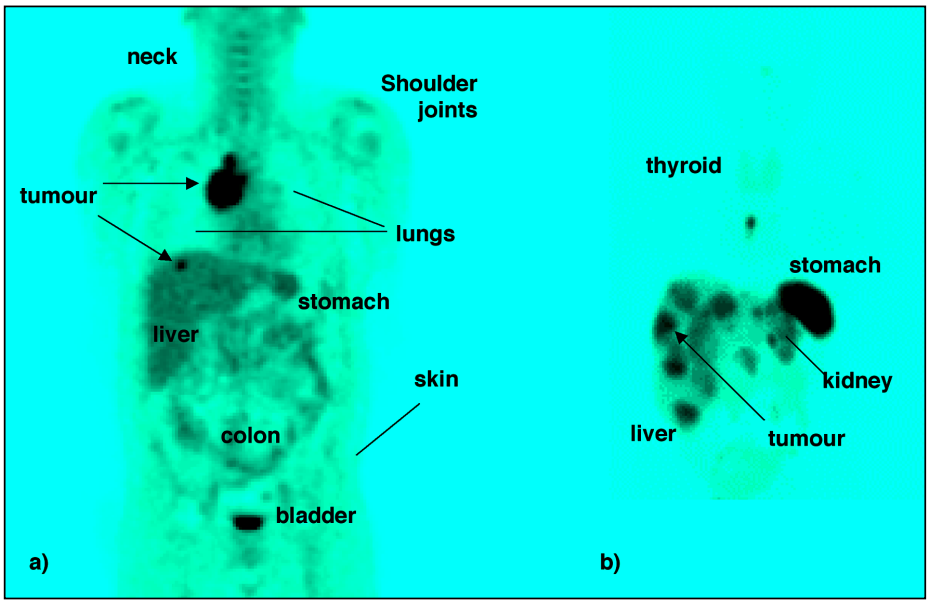


Figure 1
Anatomical detail seen in PET images: FDG PET images (1a) exhibit a fair amount of anatomical detail due to the non-specific, physiologic uptake of FDG in addition to its accumulation in malignancies.

In comparison, more specific tracers, e.g. ^{68}Ga-DOTATOC (1b) reveal less anatomical detail, and correlating functional information with a morphological reference is more challenging.

^{68}Ga-DOTATOC MIP image courtesy of Dr. Hofmann (Hannover, Germany).

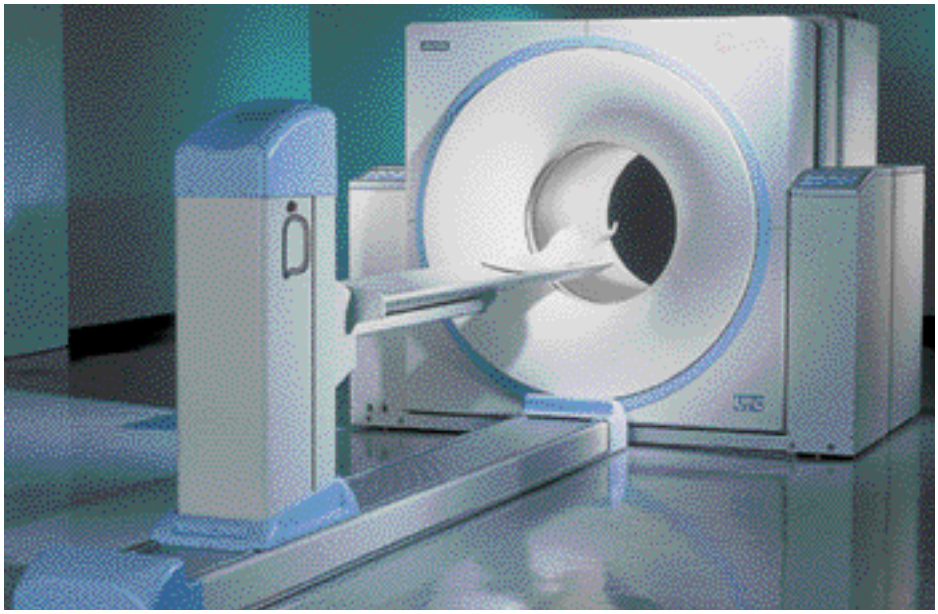


Figure 2
The **biograph** PET/CT system combines highest-performance PET and high-performance CT technology in a single, combined gantry. A fixed fulcrum, fully cantilevered patient handling system allows efficient patient positioning in the scanner, and avoids any relative deflection and mis-registration between the CT and the PET acquisition.

The combined tunnel diameter matches the CT gantry opening to allow for easier patient handling and increased patient comfort.

two scans perhaps even being performed on different days. This inevitably leads to mis-registration due to differences in patient position and physiological state, scanner bed profile, and the uncontrollable movement of internal organs. Even with the use of reference markers retrospective alignment procedures can be labour-intensive [7, 8], making them less attractive for routine clinical use in high-throughput scenarios.

An alternative to the software approach is a scanner that acquires both functional and anatomical information during a single imaging session to minimize the temporal and spatial differences between the two imaging modalities. We have previously reported on a combined dual-modality prototype PET/CT tomograph for clinical oncology [9]. This PET/CT tomograph was developed at the University of Pittsburgh (UPMC) in collaboration with CTI PET Systems Inc. Knoxville, USA and Siemens Medical Solutions, Iselin, NJ, USA [10]. Financial support of the first PET/CT development was given by the National Cancer Institute (Grants CA 65856 and CA 74135). The prototype was installed in the PET Center in Pittsburgh in May 1998. Since then more than 300 cancer patients have been scanned with the PET/CT prototype. Already with the first clinical data it was shown that the use of complementary functional and diagnostic images greatly improves diagnostic accuracy [11, 12].

The widespread interest in PET/CT imaging created by the results from the UPMC prototype has stimulated intense commercial activity. Now several major vendors of medical imaging equipment offer combined PET/CT scanners, but with significant differences in design choices among them [13]. Following on our previous report, this article will briefly review the next generation PET/CT tomograph (named **biograph**™) that has been designed based on the experience gained with the prototype system. In continuation of a successful collaboration, the first **biograph** unit (manufctured by CTI PET Systems, Knoxville, USA and distributed by Siemens Medical Solutions Nuclear Medicine Group, Hoffman estates, USA) has been installed at the UPMC PET Center in mid-August of this year.

Materials and Methods

Design Concept

The **biograph** (Fig. 2), the first commercial PET/CT system, has been designed with routine whole-body, clinical oncology applications as the primary focus. A guiding principle has been that the PET component should have the highest possible performance in both sensitivity and spatial resolution in order to better match the capabilities of CT. The CT on the other hand should serve three functions: (a) provide the anatomical correlation for the functional information, (b) provide clinical diagnostic-quality CT images [13], and (c) provide the means for CT-based attenuation correction of the PET data [14]. The need to achieve repeatable co-registration with sub-millimeter accuracy dictated an entirely new concept for the patient handling system (PHS). Finally, the practical requirements of clinical workflow and high throughput demanded a fully integrated and streamlined software interface.

The Combined PET/CT Gantry

The **biograph** is based on the mechanical combination of existing high-performance PET and CT components: the ECAT EXACT HR+ and the SOMATOM Emotion,

PET	Detector material	BGO
	Crystal size [mm]	4.05 x 4.39 x 30
	Crystal rings	32
	Tunnel diameter [mm]	700
	Axial field-of-view [mm]	155
	Transverse field-of-view [mm]	585
	In-plane spatial resolution [mm]	4.6 (at 1 cm), 5.4 (at 10 cm)
	Sensitivity [cps/Bq]	6.6
	Peak NEC [kcps]	35 at 10 kBq/mL
CT	Detector elements	672, UFC (ceramic)
	Max. tube power [kW]	40
	Slice thickness [mm]	1, 2, 3, 5, 8, 10
	Tunnel diameter [mm]	700
	Transverse field-of-view [mm]	500
	Tube voltage [kVp]	80, 110, 130
	Tube current [mA]	30 - 240
	Time for full rotation [s]	0.8, 1.0, 1.5
	Max. continuous scan time [s]	100
	In-plane spatial resolution [mm]	0.32

Table 1
Key design and performance parameters of the **biograph**.

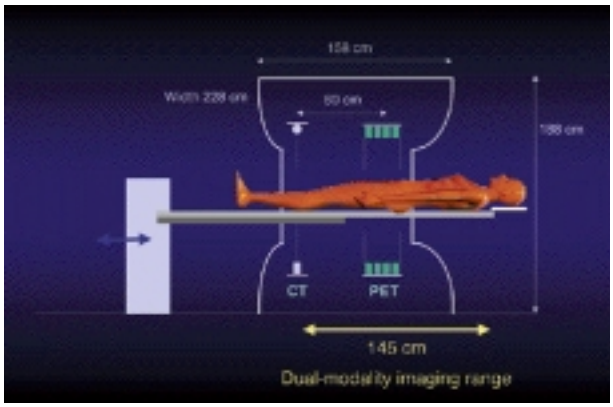


Figure 3
Design concept of the **biograph** PET/CT scanner.

The common patient support faces the CT in the front of the combined gantry.

The ECAT EXACT HR+ PET components are axially offset by 80 cm from the CT. The common tunnel is 70 cm in diameter.

The **biograph** allows for a 145 cm dual-modality examination range compared to 100 cm with the prototype PET/CT.

respectively. Mechanical isolation between both components was maintained to allow better serviceability compared to the prototype PET/CT system. The SOMATOM Emotion is a sub-second (0.8 s full rotation time) spiral CT with characteristics ideally suited for the PET/CT application, including its compact size, reliability, high image quality, efficient use of patient dose, and low cost. While the tilt option is disabled for the CT, the remaining range of functionalities is that of a stand-alone CT system.

The choice of the premium PET components was dictated by the need to provide the highest possible performance for lesion detection, in terms of both sensitivity (6.6 cps/Bq) and spatial resolution (4-5 mm). To accommodate radiation therapy pallets and appliances, as well as to increase patient comfort, the patient port of the ECAT EXACT HR+ has been expanded to match that of the SOMATOM Emotion, so that the combined PET/CT gantry has a uniform 70 cm diameter tunnel over its full depth. Operated in fully 3D acquisition mode, this modified ECAT EXACT HR+ achieves a maximum noise equivalent count rate of 35 kcps at 10 kBq/mL. Table 1 lists a number of key design and performance parameters of the **biograph** PET/CT system, and Fig. 3 illustrates the design of the **biograph**.

A major challenge in the design of the combined PET/CT system for clinical use is the patient handling system (PHS). In order to accurately assign the functional information obtained from the PET to the high-resolution background information from the CT the patient should be positioned with high vertical and axial precision, and with minimal relative deflection between the CT and the PET scan fields-of-view. The resulting PHS (Fig. 3) is a unique design involving a fully cantilevered carbon fiber pallet. The pallet is supported on a pedestal moving on a floor-mounted, high-precision rail system that is driven by a linear motor. Based on the design features, it is possible to achieve sub-millimeter intrinsic registration between the CT and PET, independent of the patient weight (max. 204 kg). The benefits of this co-registration accuracy have already been observed in patient scans at the first **biograph** site in Pittsburgh (see Clinical Studies).

Data Acquisition and Data Processing

One of the main advantages of the design of the **biograph** is the close integration of the CT and PET acquisition, processing and visualization interfaces. This integration has been achieved through the use of the cross-modality *syngo*® software platform (Siemens Medical Solutions, Erlangen, Germany) for all software components. A unified PET/CT whole-body protocol (Fig. 4) provides automatic PET acquisition planning based on the CT spiral scan definition. A key feature of the **biograph** is the ability to utilize CT-based attenuation correction for the PET data [14]. This eliminates the time required for a separate transmission scan, and provides a

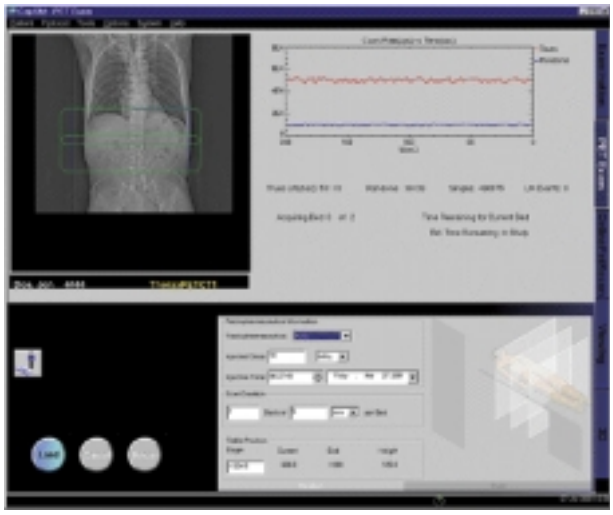


Figure 4
Unified, *syngo*-based user interface for PET/CT acquisitions with the **biograph**. The snapshot shows the PET acquisition task card of a whole-body PET/CT acquisition with two contiguous bed positions (outlined in green).

The emission countrates (upper right) are monitored during the acquisition.

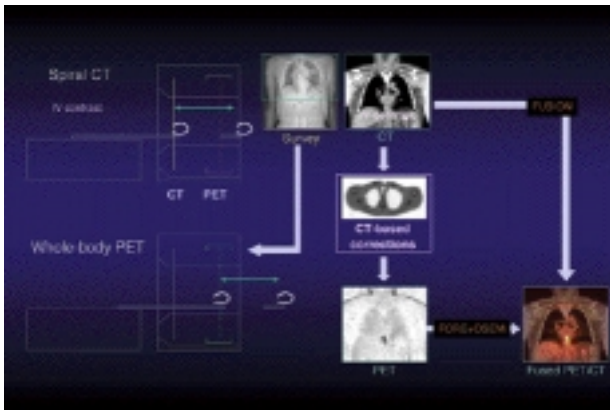


Figure 5
Standard PET/CT acquisition protocol.

correction that is essentially noiseless. Simulation-based scatter correction and iterative reconstruction of the PET data for individual PET emission scans occur in parallel with the ongoing acquisition of the remaining axial imaging range. Fully reconstructed and registered PET/CT whole-body image volumes are ready for viewing approximately 90 s following the completion of the last data acquisition. The software is fully DICOM compliant, and the image data may be stored in PET, CT or MR format to facilitate transfer to RTP and PACS systems.

Based on the close integration of the PET and CT components, data acquisition and processing are straightforward. A typical use case scenario is illustrated in Fig. 5. Standard PET/CT acquisitions begin following an uptake period of at least 60 min after the patient has been injected with FDG. First, the patient is positioned on the PHS and a topogram (scout scan) is acquired with the X-ray tube and the X-ray detectors stationary. The operator graphically defines one or more spiral ranges on the topogram, which are constrained in length to match an integral number of discrete bed positions (15.5 cm) of the step-and-shoot PET acquisition. The following CT and PET acquisition are fully automated as mentioned above, and corrected PET and CT images are ready for viewing by the time the patient leaves the scanner. If needed, the patient can be given IV or oral contrast agents prior to the CT exam.

The duration of the spiral CT scans depends on the axial imaging range and the CT scan parameters chosen, but typically does not exceed 60 s for a 70 cm examination range. The equivalent PET examination time is about 30 min, leading to a typical PET/CT whole-body examination time of just over half an hour. This represents a significant improvement in throughput compared to the prototype machine, where a comparable study, including image reconstruction, required at least two hours to complete. This improvement is due both to the enhancements in the performance of the PET and CT components in the **biograph**, and to the more streamlined and efficient workflow and data processing.

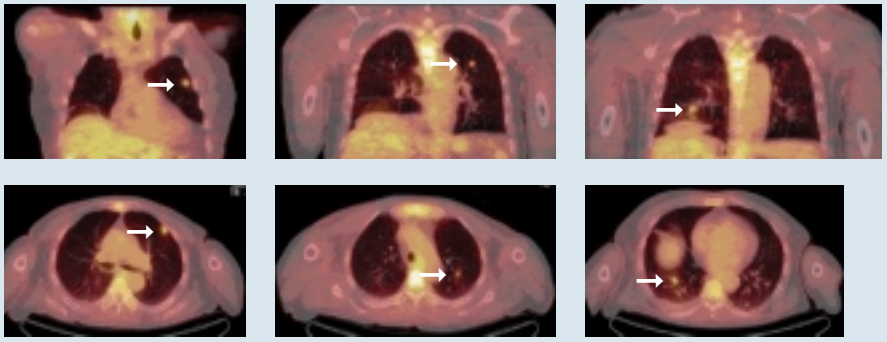
Clinical Studies

Three clinical cases are presented here to illustrate the imaging capabilities of the **biograph**. The CT parameters used for the PET/CT protocols were: 130 kV_p, 100 mAs, 5 mm slice width, and pitch 1.3. The CT images were reconstructed in axial intervals of 2.4 mm to match the axial sampling of the PET images.

Case 1 (Fig. 6)

A 74 year-old male with colorectal cancer diagnosed in 1999 following partial colorectomy. The patient was treated with radio- and chemotherapy. Colonoscopy and endoscopy were negative. A PET/CT scan was performed

Case 1

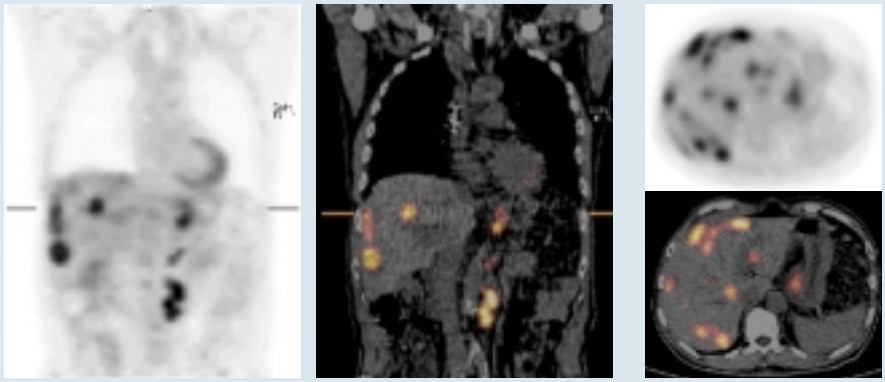


a) b) c)

Figure 6
Male with history of colorectal cancer.

Fused PET/CT images demonstrated multiple hypermetabolic foci in the left lung (6a, b) and in the right lung (6c), illustrated in coronal (top) and transverse views (bottom).

Case 2



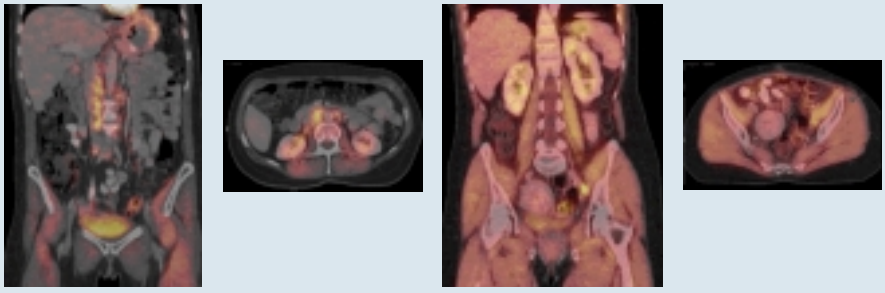
a) b) c) top, d) bottom

Figure 7
Male with history of colorectal cancer.

Coronal whole-body PET image (7a) demonstrated multiple FDG foci in the area of the liver and the lower abdomen.

Corresponding coronal (7b) and transverse (7d) PET/CT fusion images helped to localize the foci within the anatomical frame of the CT images. CT was acquired without the use of CT contrast agents.

Case 3



a) b) c) d)

Figure 8
Patient with cervical cancer post surgery, chemo- and radiotherapy.

PET/CT showed several foci of FDG accumulation corresponding to para-aortic lymph node involvement (8a, b).

In addition PET/CT showed a previously unknown left pelvic lymph node metastasis (8c, d).

following an injection of 390 MBq FDG at 130 min post-injection (pi). The fused images (Fig. 6) demonstrated several hypermetabolic foci in the left and right lung that went undetected in a clinical PET scan performed prior to the PET/CT study. Subsequent patient treatment was modified based on the PET/CT results.

Case 2 (Fig. 7)

A 60 year-old male with a history of colorectal cancer was scanned on the **biograph**. After an uptake time of 160 min following an injection of 370 MBq of FDG a PET/CT scan was initiated over an axial imaging range of 50 cm. Total emission scan time was 20 min. The PET/CT images showed extensive disseminated disease with involvement of the liver and para-aortic lymph nodes (Fig. 7 a, b). When appropriate thresholds were applied to the PET images, highlighting the malignant uptake only, FDG effectively played a role comparable to that of a CT contrast agent (d).

Case 3 (Fig. 8)

A 44 year-old female with cervical cancer diagnosed in 09/00 underwent total hysterectomy and oopherectomy. She recently finished chemo- and radiotherapy. A PET/CT scan was scheduled to evaluate further treatment with radiotherapy. Scanning was initiated 170 min pi of 400 MBq FDG. The CT was acquired with IV and oral contrast agents. The fused PET/CT images showed diffuse uptake in several para-aortic lymph nodes in addition to a left pelvic lymph node metastasis that was previously unknown.

Discussion

The **biograph** system is a dedicated, high-performance PET/CT tomograph for routine clinical oncology. The design of the first commercial version of a combined PET/CT system drew heavily from the clinical experience gained with the first PET/CT prototype operated at the University of Pittsburgh from 1998 until July 2001. Several aspects of the data processing of the **biograph** benefited from the methodological work carried out with the prototype tomograph (e. g. CT-based attenuation correction algorithm), of which we reported in an earlier issue of "electromedica" [9].

The sensitivity and countrate capabilities of the PET components allow for an emission examination time of about 30 min for an axial imaging range of about 70 cm, which is a typical exam length for most PET oncology studies. Nevertheless, the total examination time is dominated by the PET acquisition time, and while the use of multi-slice CT may offer a wider ranger of applications it will not reduce the total scan time appreciably.

Future PET/CT developments, however, may benefit from recent advances in PET detector technology, and in particular in the introduction of LSO (lutetium oxyorthosilicate, [15, 16]). Compared to widely-used PET scintillator BGO, LSO offers a ten times shorter scintillation decay time and a five times higher light ouptput. The first LSO-based whole-body clinical PET tomograph (ECAT ACCEL) produces quality whole-body images with PET emission scan times as short as 12 min for an axial imaging range of 70 cm [17].

Aside from the already existing diagnostic efficacy, PET/CT imaging could make major contributions to radiation therapy planning (RTP) and monitoring (Fig. 8). Currently RTP is based on tumour delineation on CT images that are correlated with the planning-CT on an RT unit. However, it has been shown in a number of retro- and prospective studies that PET may add valuable information to help optimizing the radiation treatment plan [18], thereby adapting the planning target volume more closely to the active tumour volume than would be possible based on the CT alone [19]. Last but not least, the availability of combined and intrinsically registered PET and CT information during the course of treatment management could help in adjusting the treatment plan to better account for the functional and morphological response of the lesions irradiated [20].

The range of different applications to which the PET/CT can be applied raises a number of methodological issues. In particular, the mismatch between a CT scan acquired with full inspiration breath-hold and a PET scan acquired with normal breathing will affect both the alignment of the images and the accuracy of the CT-based attenuation coefficients, especially for studies of the thorax and upper abdomen. It is unlikely that the duration of a PET scan will ever be sufficiently short to be acquired with breath-hold and therefore gating procedures will be required to minimize or reduce the mismatch. Solutions for this and other PET/CT methodology issues will hopefully emerge from current research projects.

Although the current PET/CT scanning protocols have certain limitations, some of which are described above, it is anticipated that the commercial availability of combined PET/CT scanners will help promote the development of optimal solutions to these challenges, and further extend the areas of application of dual-modality imaging. As more such systems are introduced into the clinical arena, questions such as the choice of appropriate whole-body protocols (for both PET and CT), the requirements for the CT with respect to image quality and speed, operational restrictions due to patient dose issues, and reimbursement for PET/CT studies, will have to be addressed.

While only a few of the possible applications of dual-modality imaging have yet been analyzed, it is already clear that fusing complementary imaging technologies in a single device is an accurate and cost-effective approach to medical imaging that will dramatically improve the diagnosis and treatment of disease.

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