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REVIEW ARTICLE

Positron Emission Tomography/Computed Tomography–Imaging Protocols, Artifacts, and Pitfalls

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There has been a longstanding interest in fused images of anatomical information, such as that provided by computed tomography (CT) or magnetic resonance imaging (MRI) systems, with biological information obtainable by positron emission tomography (PET). The near-simultaneous data acquisition in a fixed combination of a PET and a CT scanner in a combined PET/CT imaging system minimizes spatial and temporal mismatches between the modalities by eliminating the need to move the patient in between exams. In addition, using the fast CT scan for PET attenuation correction, the duration of the examination is significantly reduced compared to standalone PET imaging with standard rod-transmission sources. The main source of artifacts arises from the use of the CT-data for scatter and attenuation correction of the PET images. Today, CT reconstruction algorithms cannot account for the presence of metal implants, such as dental fillings or prostheses, properly, thus resulting in streak artifacts, which are propagated into the PET image by the attenuation correction. The transformation of attenuation coefficients at X-ray energies to those at 511 keV works well for soft tissues, bone, and air, but again is insufficient for dense CT contrast agents, such as iodine or barium. Finally, mismatches, for example, due to uncoordinated respiration result in incorrect attenuation-corrected PET images. These artifacts, however, can be minimized or avoided prospectively by careful acquisition protocol considerations. In doubt, the uncorrected images almost always allow discrimination between true and artificial finding. PET/CT has to be integrated into the diagnostic workflow for harvesting the full potential of the new modality. In particular, the diagnostic power of both, the CT and the PET within the combination must not be underestimated. By combining multiple diagnostic studies within a single examination, significant logistic advantages can be expected if the combined PET/CT examination is to replace separate state-of-the-art PET and CT exams, thus resulting in significantly accelerated diagnostics. © 2004 Elsevier Inc. All rights reserved.

Key Words: PET/CT; Clinical protocols; Artifacts.

Introduction

Both, positron emission tomography (PET) and computed tomography (CT) are well-established noninvasive diagnostic modalities. Their application is wide, but no doubt the most dominant application are oncologic questions. Both modalities have their independent justification. CT images morphology and the diagnosis rely on structural changes. Therefore, CT is optimized to provide high-resolution images with as much contrast as possible. CT contrast is based on differences in X-ray attenuation between different tissues and these differences in contrast aid the diagnosis of pathology. Furthermore, morphologic imaging procedures depend on specific size criteria for detection of malignancy. These size criteria, however, have been shown to be an unreliable indicator for malignancy, which is most profound when assessing lymph nodes for malignant spread, applying a threshold of one cm for the differentiation of benign (< one cm) from malignant (> one cm) disease. Thus, previous studies have found up to 21% of nodes smaller than one cm to be malignant, while 40% of those larger than one cm were demonstrated to be benign.[1,2] Furthermore, malignant lesions, which appear isodense compared to their surrounding tissue may be indistinguishable from normal anatomy and, thus, be missed on CT evaluation. In part, this problem can be overcome

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by the use of oral and intravenous (IV) contrast agent agents, which increase the contrast between normal and diseased tissue. Due to the lack of functional information, however, the sensitivity of CT for the detection of early disease, as well as early detection of therapeutic response of a tumor are limited. PET is in many aspects complementary. Implicitly, this notifies a large variety of radiopharmaceuticals, which are sensitive to many different cellular aspects (e.g., receptors, metabolic pass ways, and milieu-dependent uptakes) and may detect a large spectrum of tumors or tumor characteristics. Speaking in mathematical terms, PET tests the differential change (in time) of the tumor, which makes the modality more sensitive to early detection both, of the tumor itself or of therapy response. This, however, presupposes the tumor to express the characteristics tested by the applied radiopharmaceutical. If that is not the case, even large tumors may be missed—although the diagnosis "no pathologic uptake" (receptor density, turn over, and so on) is made correctly. One of the major drawbacks of PET is the inability to determine the precise location of the lesion with respect to anatomical structures, which may result in the uncertainty of the tumor-bearing organ.

The combination of PET and CT images has several attractive aspects. The combination of two complementary modalities significantly increases the diagnostic accuracy compared to each of the two modalities, as well as the two imaging modalities viewed side-by-side.[3–7] The number of inconclusive PET findings will be reduced by accurate identification of the site of the activity accumulation. This finding may be due to pathologically increased (tumor) turnover, pathologically increased turnover in a nonmalignant process (e.g., inflammation, thyroid nodule), or increased but physiological uptake in an activated organ (e.g., fatty tissue, muscle, endocrine gland).

PET/CT Application Concepts

We define a PET/CT as the hardware-based combination of a PET and a CT scanner in which PET attenuation and scatter corrections are performed using the CT data. The development of PET/CT with rod sources is expected to be abundant in the future. PET/CT may be used in a variety of applications, which are based on different philosophies concerning the use of the combined modalities and which may require different imaging protocols. PET/CT may be used as a PET scanner (faster-PET) with built-in anatomical landmarking, or, alternatively as a device for both, diagnostic and high-quality PET and CT scans (diagnostic PET/CT).

The image coregistration of diagnostic CT with diagnostic PET data results in optimal image quality providing maximal diagnostic yield. Based on the well-known problems of retrospective image fusion of functional images with CT, faster-PET may not be upgraded to diagnostic PET/CT by the mere availability of a separate diagnostic CT scan. Apart from additional radiation exposure by the acquisition of two CT scans, the separate diagnostic CT and low-dose CT scan as part of the PET/CT, patient motion, differences in the breathing patterns, and different patient positioning during CT and PET/CT render image fusion challenging.

The two concepts, faster-PET and diagnostic PET/CT have to be justified. No doubt, local aspects in part influence them, for example by the attitude toward radiation exposure. In the faster-PET scenario, a rather high radiation exposure occurs by the CT, even though a low-dose CT is performed but only little information is extracted from these CT data. In diagnostic PET/CT, a full-dose CT is performed and this concept seems to be more efficient in terms of information/radiation dose than faster PET with a separate diagnostic CT. Furthermore, diagnostic PET/CT is more cost efficient than the separate PET and CT scanning considering a single examination procedure providing whole-body functional and morphologic staging in a single approach. Logistic efforts are reduced for the clinician as the patient needs only one appointment and only one report needs to be written by the evaluating physicians and reviewed by the referring physician, however, the integrated concepts require the cooperation of nuclear medicine physicians with radiologists, and, therefore, demand a higher organizational effort by the diagnostic departments. Both evaluating physicians must view PET and CT, as well as fused data, and a consensus must be found when writing the PET/CT report. Depending on the way the PET/CT device is used, different requirements for the protocols are needed and the spectrum of artifacts and pitfalls is different.

Clinical Protocols

The full diagnostic power of combined PET/CT is gained only, by avoiding separate CT investigations prior to the PET examination, which, in turn, requires additional education of the referring physicians. Figure 1 displays a decision tree for PET/CT indications at our hospital. By following this scheme we aim at avoiding unnecessary radiation exposure of the patient and costs from repeated CT investigations. The nuclear medicine physician makes the final indication for the PET, whereas the radiologist makes that for the CT. With both qualifications at hand a dual-modality trained physician may send a patient for a PET/CT study. The combined investigation is then performed under responsibility and supervision of the two specialists, who are responsible also for the technical and medical quality of the investigation.

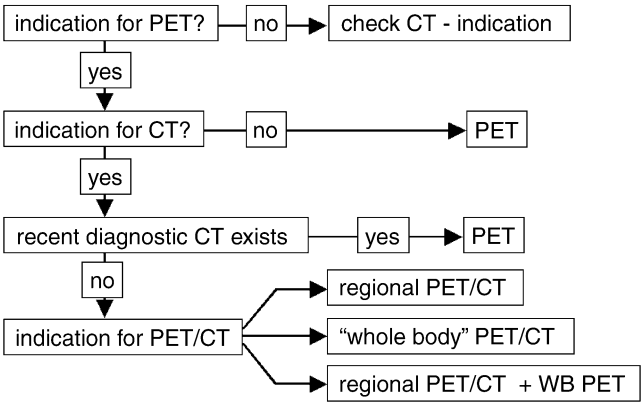

Figure 1. Decision tree for PET/CT referrals at the University Hospital Essen.

While the near-simultaneous execution of PET and CT scans in close spatial proximity minimizes residual mismatches, these mismatches are frequently not eliminated, and new challenges are introduced. Fortunately, most of these issues can be addressed by suitably optimized protocols (Table 1). In the following, we will illustrate the minimization of problems and artifacts using optimized protocols, which were developed from our own experience with clinical PET/CT.

General Patient Preparation Before Initiation of PET

The patient preparation for PET/CT studies is the same as for stand-alone PET. There is general agreement that patients preferably should be fasted overnight or at least for six hours prior to the injection of the 2-deoxy-2-[^{18}F]fluoro-D-glucose (FDG). Diabetic patients should be in a stable state of disease management (dietary, oral antidiabetic medication, or insulin), nevertheless, a reduced sensitivity for the detection of malignant disease in diabetics has been reported; insulin injections prior to the application of FDG do not help to overcome this limitation in many tumors entities.

Some PET centers advocate the hydration of the patients prior to the PET study and the application of a diuretic (e.g., furosemide) to flush the urinary collection system. However, depending on the duration of the PET data acquisition, the rapid filling of the urinary bladder has been seen as a problem by others.

Patient Preparation Prior to the CT Scan

No long-term preparation is necessary for a routine oncology CT examination, however, contraindications for the injections of IV contrast agents should be ruled out beforehand. Depending on the severity, thyroid disorder, such as hyperthyroidism or autonomous functioning thyroid tissue, may require premedication, that is, blocking of the thyroid gland with perchlorate, which competes with the iodine uptake into the thyroid cells, and/or thioamide derivatives, which block the intracellular iodine metabolism. Known allergic or anaphylactic reactions to iodinated IV contrast media may require a premedication, for example, with antihistamines and corticosteroids, or even prohibit the use of IV contrast agents.

To improve the delineation of the gastrointestinal tract oral contrast agents are administered at one hour prior to the CT scan. Since current implementations of the bilinear segmentation/scaling algorithm for CT-based attenuation correction are inadequate for correcting the attenuation of barium-based or iodine-based contrast agents, alternative CT contrast application schemes are preferable to avoid artifacts associated typically with high-dense CT contrast.[8] We have successfully evaluated the use of a water-based oral contrast agent based on solution containing 0.2% locust bean gum to increase viscosity and 2.5% mannitol, an osmotic agent. 1.5 L of this solution are given orally between the time of FDG injection and the begin of the CT scan.[9] This approach provides stomach and small bowel distension superior to that of water or barium and avoids high-Z artifacts in dual-modality PET/CT imaging (Figure 2).

Patient Positioning

Prior to the exam patients remove all metal (e.g., bracelets, dental braces, belt buckles, pants with zippers, etc.), which may lead to artifacts on the CT-transmission scan. On the scanner table patients should be supported with adequate positioning aids, that is, a roll to support the knees, an arm rest for all studies with the arms positioned over the head, and a head rest (Figure 3). Nevertheless, especially PET/CT studies involving the head and neck frequently suffer from local misalignment due to the relaxation of neck muscles within the 20-minute time delay between the CT and the PET acquisition in a standard whole-body protocol. Foam pallets or vacuum bags are suitable for immobilization of the head and neck area since no artifacts are typically introduced into the CT transmission data, and subsequently, into the corrected emission data. In case of special-built positioning aids, however, prepatient phantom studies need to be performed to validate artifact-free positioning.

Due to the comparatively high radiation sensitivity of the lens of the eye, this organ is often excluded from the CT examination, unless the top of the head is of particular clinical interest. In practice, a typical oncology PET/CT scan extends from the base of the skull to the symphysis (Figure 4).

Table 1. Acquisition parameters for PET/CT imaging in clinical routine and following a diagnostic imaging scenario

	Neg. oral contrast	i.v. contrast agent			CT		PET		
Protocol	**Volume [ml]**	**Volume [ml]**	**Flow [ml/s]**	**Delay [s]**	**Acquisition**	**Recon**	**Aquisition**	**Recon**	**Fixation**
Oncology whole body (venous phase enhancement)	1500	90 50	3 1.5	50	caudo-cranial 5 mm slice thickness 8 mm feed/rotat. 2.4 mm slice spacing 130 kVp, 140 mAs	abdomen lung	128^2 matrix 3–5′/bed	2 iterations 8 subsets 5 mm filter	knee support arms up with arm support head rest
Oncology thorax (arterial phase enhancement)		100	3	30	caudo-cranial 5 mm slice thickness 8 mm feed/rotat. 2.4 mm slice spacing 130 kVp, 140 mAs	abdomen lung	128^2 matrix 3–5′/bed	2 iterations 8 subsets 5 mm filter	knee support arms up with arm support head rest
Oncology abdomen (venous phase enhancement)	1500	100	3	50	caudo-cranial 5 mm slice thickness 8 mm feed/rotat. 2.4 mm slice spacing 130 kVp, 140 mAs	abdomen	128^2 matrix 3–5′/bed	2 iterations 8 subsets 5 mm filter	knee support arms up with arm support head rest
Protocol for combined whole body investigation including dedicated head & neck	1500								
Body part		120	3	50	caudo-cranial 5 mm slice thickness 8 mm feed/rotat. 2.4 mm slice spacing 130 kVp, 140 mAs	abdomen lung	128^2 matrix 3–5′/bed	2 iterations 8 subsets 5 mm filter	knee support arms up with arm support head rest
Head & neck part		70	3	30	cranio-caudal 3 mm slice thickness 2.4 mm feed/rotat. 1.5 mm slice spacing 130 kVp, 140 mAs	head & neck	128^2 matrix 5–6′/bed	4 iterations 8 subsets 4 mm filter	arms down vacuum mattress for shoulder, head & neck shoulder, head & neck

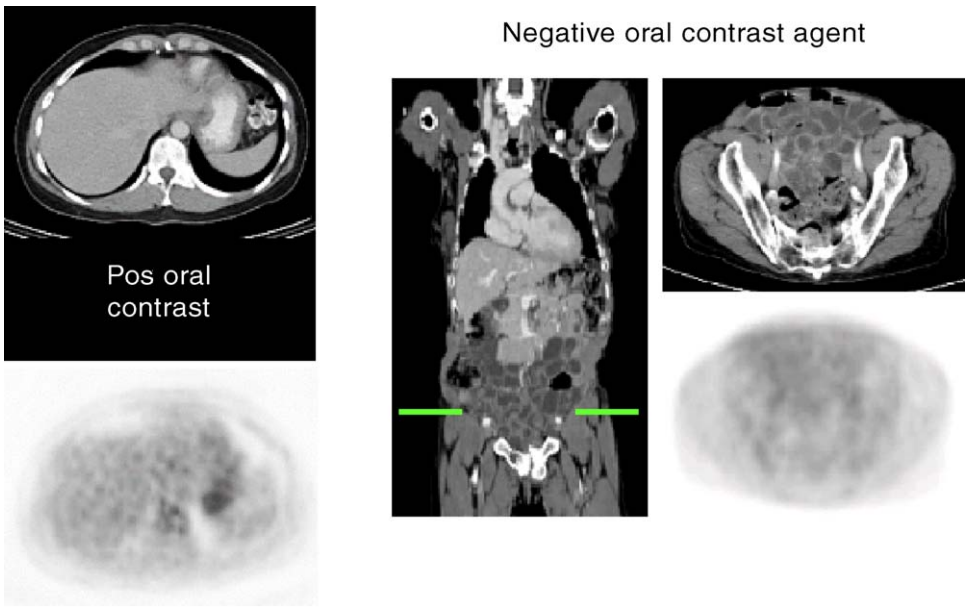

Figure 2. Positive oral contrast agents (left) may lead to high-density areas on CT (e.g., stomach, colon), which may further translate into artificial hot spots on corrected PET images. Using negative oral contrast agents (right) obviates the cause of these artifacts while providing good small bowel distention.[9]

CT Beam Hardening

In standalone PET imaging, the scan is usually performed with the patient's arms lying along the side of the body. This ensures whole-body imaging without increasing the axial scan length. Having the arms in the field-of-view (FOV) during a CT scan, however, causes serious beam hardening artifacts on the CT images due to the preferential absorption of the lower energetic X-ray components of the polychromatic X-ray beam, as well as scatter build-up (Figure 4). The resulting image quality is not acceptable if a state-of-the-art diagnostic CT study is desired. Furthermore, the resulting erroneous CT-based attenuation correction subsequently propagates the error to the calculated activity concentration in the PET image. Due to the fast total data acquisition possible with a combined PET/CT scanner, most patients will tolerate a PET/CT scan of the torso with the arms raised over the head, thus avoiding beam hardening artifacts in the body. However, special nonattenuating armrests are required to facilitate holding the arms in this position without movement. While optimizing the image quality in the torso, this approach compromises the images of the head and neck area. Therefore, split acquisition protocols should be utilized when this region of the body is of special interest, that is, an acquisition of the torso with the arms resting above the head and a second acquisition of the head and neck area with the arms resting alongside the body. The repositioning of the arms and the second acquisition only add less than five minutes to the total duration of the study compared to a single pass approach.[10]

Truncation

Obese patients, as well as patients with their arms down may extend outside the transverse FOV of the CT scanner (50-cm diameter in commercial PET/CT systems), resulting in inconsistent CT projection data, which cause truncation artifacts in the CT images. Furthermore, the transverse FOV of the PET scanner is larger (about 60 cm) than that of the CT scanner, resulting in missing data for the CT-based attenuation correction. The resulting discrepancy in imaging FOV results in artifacts of the corrected PET images, as well as in biased activity concentrations.[11] Modern algorithms extrapolate the inconsistent CT projections to mitigate the truncation errors within the FOV of the CT scanner, and reduce the bias in the attenuation corrected PET images (Figure 5).

External Radiation Therapy Planning

PET/CT imaging provides molecular information about a tumor in the spatial coordinate system utilized by the radiation treatment planning system. Recently, great hope has been expressed in the radiation oncology community that the resulting biological conformality may improve tumor control by radiation therapy.[12] Prior to using PET/CT images in the radiation therapy planning process, the data transfer between the diagnostic imaging device and the treatment planning system must be validated and quantitative accuracy of the displayed values should be verified. It is necessary, however, to perform the PET/CT scan in the exact patient position, which will be used later during radiation therapy. This necessitates the use of a flat radiation treatment pallet, as well as treatment specific fixation devices in the PET/CT scanner (Figure 6). Again it must be assured experimentally that the intended fixation devices will not cause artifacts.

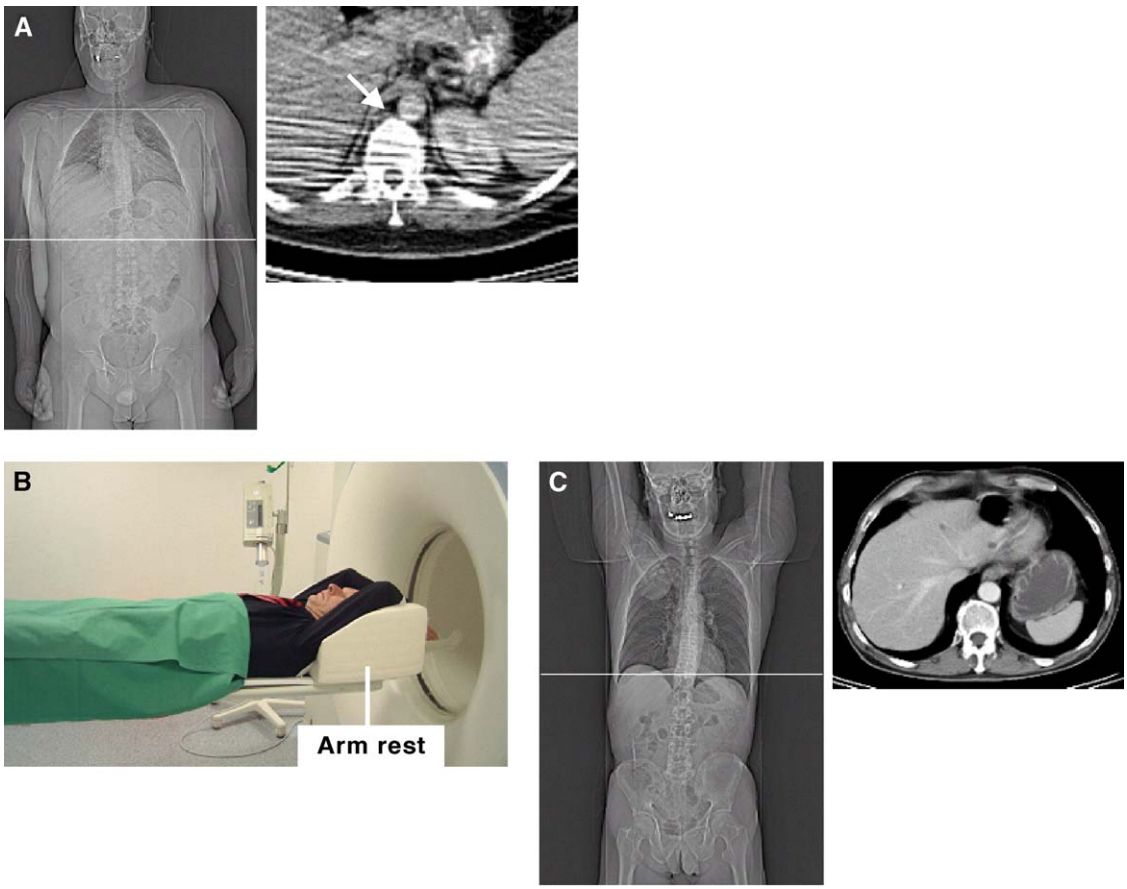

Figure 3. Positioning patients with their arms down leads to beam hardening and scatter artifacts, which present as streaks in the transverse CT images. The small lymph node (arrow) can be detected nevertheless. (A) Utilizing the fast-scan time capabilities of the combined PET/CT patients tolerate to being scanned with their arms raised above their head, (B) for better CT image quality.

Absolute Quantification of Positron Emitter Concentrations in the PET Study

PET imaging, which originated as a research tool, always had the potential for accurate *in vivo* quantitation of the activity distribution of a positron emitting radiopharmaceutical. Absolute quantitation requires accurate scatter and attenuation correction, and, for objects which are small compared to the system resolution, a size dependent recovery correction.[13,14]

Scatter and attenuation correction require an accurate attenuation map at a photon energy of 511 keV. Therefore, the use of the attenuation measured for X-rays (maximum energy of about 140 kV) for the attenuation and scatter correction of annihilation quanta with the energy of 511 keV presents a challenge.[15] For uniform materials of known composition, attenuation can be calculated precisely using well-established physical laws and material characteristics. However, this is no longer true, for unknown compositions, as the stopping power of material is proportional to Z^4 for electromagnetic radiation of X-ray energy. Therefore, a nonlinear relationship has to be considered, which is a function of the relative abundance of chemical elements in all voxels. Whereas the bilinear energy scaling algorithm used for the CT-based attenuation correction in today's PET/CT systems is adequate in soft tissue, bone, and lung, the presence of high-Z materials, such as contrast agents (e.g., iodine (Z = 53), and barium (Z = 56)), or dental fillings (e.g., mercury (Z = 80), gold (Z = 79)) violates the underlying assumptions of this algorithm, and leads to artifacts. While the CT-based attenuation map raises new challenges for attenuation and scatter correction, the availability of the high-resolution CT images facilitates the size determination of small lesions. This information may be used for the recovery correction. This is necessary for accurate quantitation in small objects of interest.

In tumor patients, quantitation the uptake typically is characterized by the standardized uptake value (SUV), which normalizes the activity concentration in the tumor to the injected activity and, for example, body weight, body surface area, or lean body mass.[16] This requires the calibration of the PET scanner and the dose calibrator used for measuring the syringe before and after injection.

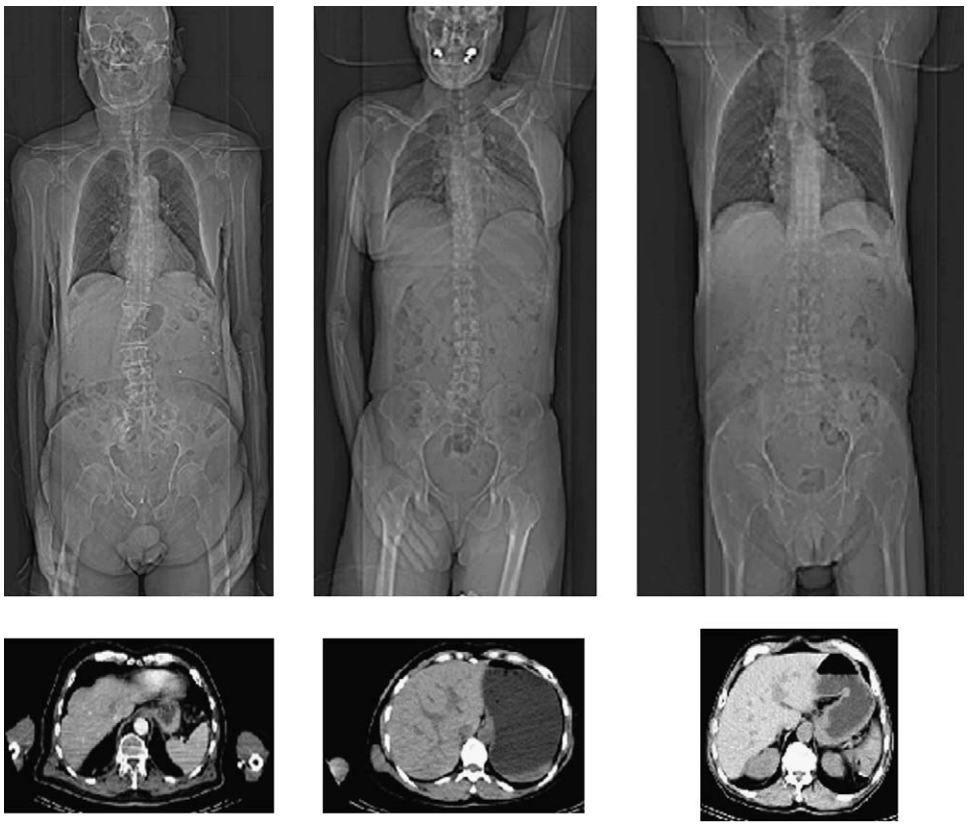

Figure 4. Topogram of patients with arms up and down. If the arms are raised above the head CT, beam hardening and scatter artifacts are minimized as seen on the transverse CT images below.

Protocol CT

IV Contrast

The acquisition of a long CT spiral in oncology PET/CT, which typically covers the body from the head to the symphysis, requires a contrast injection protocol, which is modified from the one used for the more familiar shorter spirals in single organ CT studies. For an optimization of the flow rate and the delay between injection and initiation of the CT scan the duration of the CT acquisition over the entire scan range, the direction (cranio-caudal versus caudo-cranial), and the desired peak enhancement in the main area of clinical interest must be taken into account.

To assure that vascular and parenchymal contrast in an oncology PET/CT study of the trunk is comparable to a standalone state-of-the-art CT scan, we usually inject 140 ml of an iodinated IV contrast agent containing 300 mg/ml iodine that are administered intravenously using a programmable automated injector. The initial

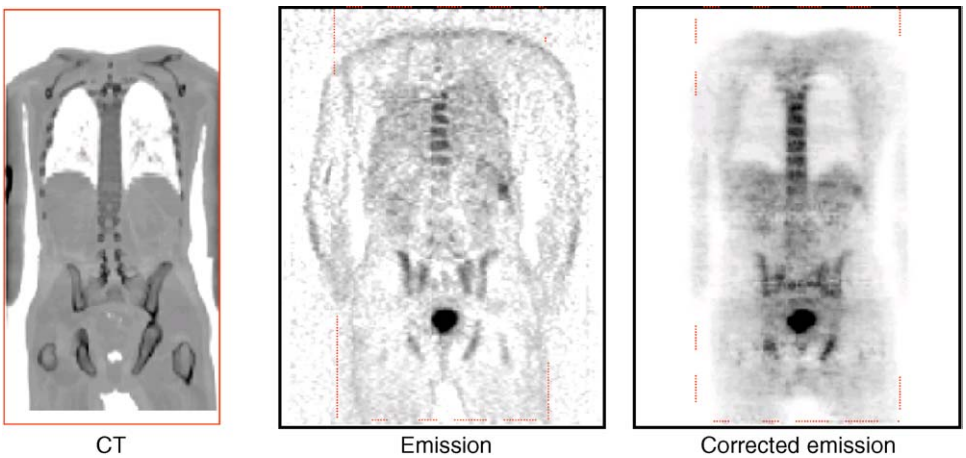

Figure 5. In large patients and patients with arms down the limited transverse FOV (50 cm) of the CT may cause truncation of the anatomy images (left). Truncation is usually not observed on the emission data (middle) with the 60 cm FOV of the PET. Using truncated CT images for attenuation correction introduces a masking effect onto the corrected PET images (right).

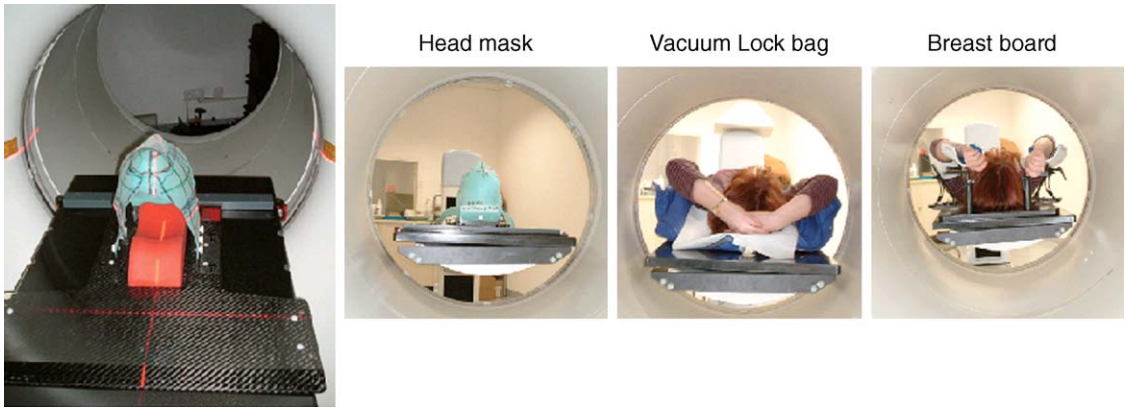

Figure 6. Positioning aids for radiation therapy patients, which can be used in conjunction with PET/CT tomography assuming a wide enough tunnel (70 cm and more).

flow rate is typically set to three ml/s for the first 90 ml and—in order to maintain good vascular enhancement during the later portions of the CT spiral—the remaining 50 ml are administered at 1.5 ml/s. This whole-body protocol assures good IV and parenchymal contrast in all examined body regions.[10] For the whole-body protocol the delay between injection and CT scan is 50 seconds. A dual-slice helical CT scanner is used to acquire the CT in the caudo-cranial direction. For PET/CT scans limited to the thorax the volume of IV contrast agent is reduced to 100 ml, which are injected at a flow rate of three ml/s; the CT scan in the caudo-cranial direction is initiated after a delay of 30 seconds.

The contrast injection schedule has to be modified further for split protocols, for example in head-and-neck studies, where two separate studies are acquired for the trunk and the head and neck region. Here the CT scan of the trunk is performed first, injecting 120 ml of IV contrast agent at three ml/s and starting the CT scan in the caudo-cranial direction after a delay of 50 seconds. Then the patient is repositioned and a second dose of 70 ml of IV contrast agent is injected at a flow rate of three ml/s; the cranio-caudal CT scan is initiated after a delay of 30 seconds.

The known limitations of the bilinear energy scaling algorithm for the CT-based attenuation correction algorithm in the presence of high-Z materials (e.g. dental fillings, not bone, which consists mainly of the medium Z calcium) result in CT artifacts, which are subsequently propagated to the PET image.[15] The contrast injection protocol described above minimizes but not completely eliminates significant CT enhancement in the upper thoracic vein with the enhancement being a function of the body mass index and the vascularity of the patient. Quantitative analysis of the maximal intravenous density revealed a mean density of up to 2,600 HU on the CT images and focally elevated activity concentrations in the attenuation corrected PET images; in regions without appreciable PET artifacts, for example, in the subclavian veins, the density measurements yielded 600 HU to 1,400 HU (Figure 7).[17] Advanced optimizations of the contrast injection protocol with the goal of further reducing the amount of undiluted iodinated contrast agent in the intrathoracic veins are conceivable, albeit with greater requirements for the injector system, and might require the use of an injection system with adaptive pressure or a saline flush after the injection of the contrast agents is completed.

In the majority of cases, however, a careful inspection of the coregistered CT and PET images helps to identify these artifacts unambiguously; thus preventing misinterpretation. In equivocal situations, however, the inspection of the PET images without attenuation correction—which are not affected by the high-Z artifacts caused by the attenuation correction algorithm—will provide further confirmation.

CT Acquisition and Reconstruction Parameters

The acquisition and reconstruction protocols depend in detail on the specific hardware and software used. We acquire all whole-body studies or partial studies of the torso with 5-mm slice thickness, 8-mm table feed per rotation, and a slice spacing of 2.4 mm with tube settings of 130 kVp and an effective tube current of 140 mAs, which is limited by the tube heat capacity in case of extended scan ranges. The CT images are reconstructed with a medium sharp filter and displayed in a soft tissue window. If the thorax was included in the study, an additional sharp reconstruction of the lungs is performed and the images are displayed in the lung window. For head and neck studies, we employ 3-mm

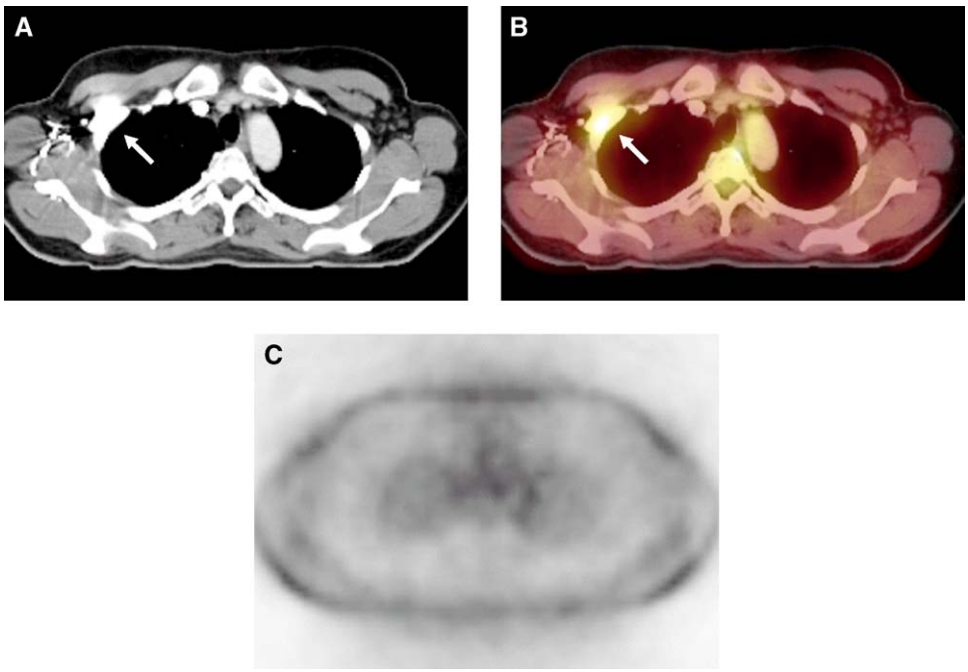

Figure 7. High-density artifacts in subclavian vein of a patient after bolus IV contrast injection with CT scanning in the cranio-caudal direction. The CT artifacts (A) translate into an artificial tracer uptake in the corrected PET (B), but cannot be seen on the noncorrected emission images (C).

slice thickness, 2.4 mm table feed per rotation, and a slice spacing of 1.5 mm with tube settings of 130 kVp and 140 mAs. The images are reconstructed with a medium sharp kernel and displayed in a soft tissue window.

PET-Acquisition Protocol and Image Reconstruction

In adult patients of nominal body weight (75 kg), we inject 350 MBq FDG one hour prior to the PET emission scan. During the uptake period the patients are kept relaxed in a comfortable chair in a softly lit room. Before being placed on the scanner bed, all patients must void. The typical acquisition time per bed position in three-dimensional mode on our system—based on the ECAT EXACT HR+ PET scanner—is three to five minutes with the shorter acquisition time being reserved for patients under 65 and the longer for patients more than 85 kg.[18] All PET studies, which include the abdomen, are acquired in the caudo-cranial direction in order to examine the pelvic region before the bladder fills up again.

After Fourier rebinning of the sinograms image reconstruction is performed into a 128^2 matrix with an iterative attenuation-weighted ordered subset expectation maximization algorithm (FORE+AW-OSEM) using a CT-based attenuation and scatter correction.[19] In the torso, we use two iterations, eight subsets, and a Gaussian apodization filter with 5 mm FWHM. Dedicated head and neck studies are reconstructed with a better resolution into a 256^2 matrix with 4 iterations, eight subsets, and a filter width of 4 mm. The quantitative images of the FDG activity concentration are then converted to SUV.

PET/CT Mismatches Despite Simultaneous Acquisition

Mismatches of breathing patterns in combined PET/CT examinations have been described as a source of artifacts in PET images following CT-based attenuation correction.[20,21] These artifacts are most severe, for example, when the CT scan is acquired during breath hold at maximum inspiration, that is, with the typical protocol for a standalone CT scan of the thorax. They are caused by the mismatch of the anatomy of the thoracic and abdominal organs at maximum inspiration versus the anatomy when averaging over many respiratory cycles during the PET study of the chest. The areas most affected by respiration are the anterior chest wall, the lower thoracic organs, and the liver (Figure 8). In the absence of routinely available respiratory gating options, the anatomy of the patient captured during the CT scan must be matched best to the PET images that are acquired over the course of multiple breathing cycles. Goerres and colleagues[20,22] have compared the quality of PET/CT image alignment in the thorax and abdomen for breath-hold and normal breathing. They found that in 53% and 27% of the cases normal expiration and free breathing respectively provided the best match in the thorax. CT and PET alignment accuracy for abdominal structures was similarly satisfactory when

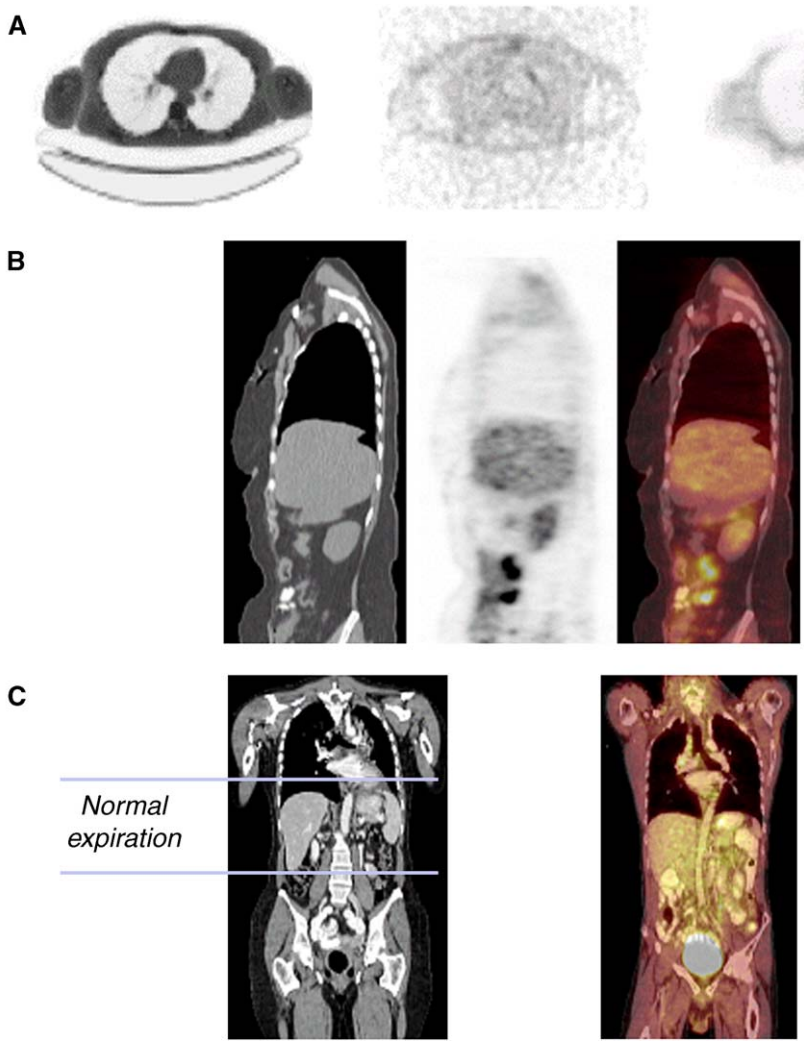

Figure 8. Full-inspiration CT in combination with free breathing PET acquisition may cause severe artifacts in the PET when corrected for attenuation with the available CT (A). Respiration mismatches are also seen when acquiring the CT in normal breathing (B). Using a limited breath-hold technique,[21] respiration artifacts can be limited and high-quality CT and PET without significant misregistration in the area of the diaphragm can be obtained (C).

acquiring the CT either in free breathing or in normal expiration. The applicability of the normal expiration breath hold protocol, however, is limited to PET/CT tomographs with very fast CT components. Still, acquiring the CT during breath hold in normal expiration over the entire imaging range is frequently not feasible when scanning uncooperative or respiratory compromised patients. Therefore, an alternative, a limited breath hold protocol has been suggested. Patients are asked to maintain breathing during the entire scan and only to hold their breath in normal expiration for the time the CT takes to cover the lower thorax and liver; this takes typically less than 15 seconds. Instructing the patient prior to the PET/CT exam on the breath hold maneuver is of essence to avoid serious respiration artifacts (Figure 8). If the respiration commands are not adequately followed by the patient, and respiration-induced misalignment persists and appears to introduce artifacts into the corrected PET images, the emission data should be reconstructed without attenuation correction and the two sets of fused PET/CT images carefully reviewed.

Metal Artifacts

Oncology patients frequently present with metal implants, such as chemotherapy ports, metal braces in the spine, artificial joints, or dental fillings. Unlike in standard PET transmission scanning, where metal implants cause little or no artifacts, they are often severe at CT energies (Figure 9). Just as for iodine-based contrast agents, this is due to the significantly higher photon absorption from high-Z materials (e.g., metals) compared to low-Z materials (e.g., soft tissues) at X-ray CT energies. This is not properly handled by the bilinear energy scaling algorithm currently employed for the CT-based attenuation correction. Several PET/CT users

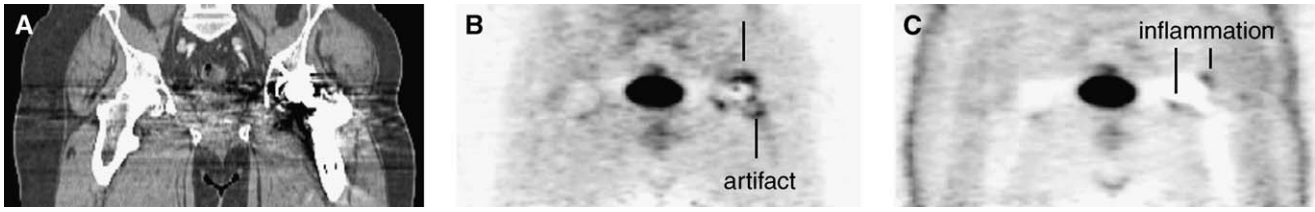

Figure 9. High-density metal artifacts, such as hip implants, cause streak artifacts on CT (A), which may translate into tracer uptake patterns on corrected PET images (B). These artifacts are not seen on the uncorrected emission images, which display residual activity only, likely to be caused by inflammation.

have reported metal artifacts in PET/CT studies around dental filling or implants, joint replacements, orthopedic metal implants, or chemotherapy ports.[23,24] These focal artifacts may mislead the diagnosis of the patient, particularly when true lesions may be present in the very vicinity of the high-Z structure, for example, head-and-neck tumors near dental fillings, tumor recurrences at the site of orthopedic metal implants, or lymph nodes near chemotherapy ports (Figure 10). In these situations it may be of vital importance to reconstruct PET images without attenuation correction.

PET/CT Reporting

The primary idea of PET/CT seems to be the transformation of the PET—functional information into the three-dimensional spatial coordinate system of CT. The second and attractive step is obviously to identify the PET finding with morphologic structures—normal or pathologic. Finally a joint report is necessary, which is an easy task in case of concordant findings. However, there is no accepted rule for dealing with contradictory PET and CT findings. We come to our conclusion depending on likelihood, which takes into consideration both sensitivity and specificity of the two modalities, as well as prevalence and other clinical information. The data are gained, however, with standalone PET and CT devices. A mathematical algorithm for decision-making needs not only the knowledge of the above-mentioned data but more over their statistical independence (or the knowledge of their dependence) that is no longer true in PET/CT. It will be a future task to gather this information in comprehensive clinical studies.

Conclusion

PET/CT combines the diagnostic power of PET and CT. The appropriate use of this new modality creates synergistic effects. Consequently, PET/CT is widely applied already shortly after its clinical introduction. The sources for artifacts and pitfalls have been identified. They will be reduced or avoided by ongoing technical developments as well as by the skillful use of the combined tomographs. The more integrated the use of the two modalities, the more dependent become their protocols from each other. Therefore, acquisition protocols have to be optimized with a thorough understanding of the physiologic and technical issues involved in PET and CT imaging. The judicious choice on an appropriate optimized protocol—matched to the clinical diagnostic task—avoids or minimizes artifacts. Although further development in the fields of technical/physical application and software is needed, for the future the

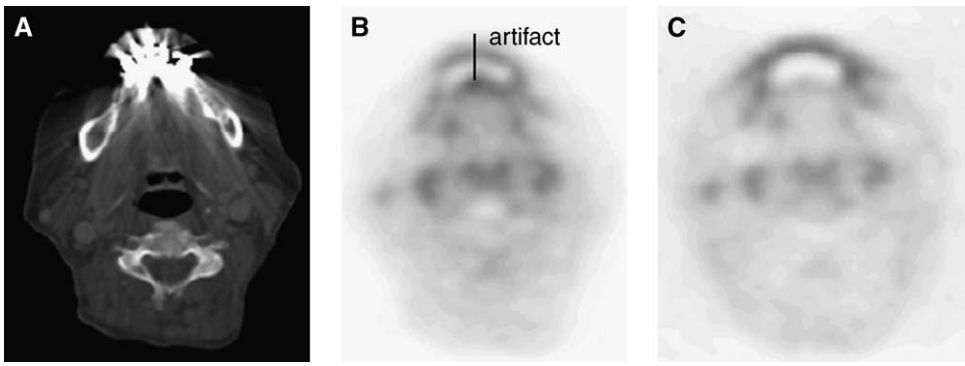

Figure 10. Diffuse FDG uptake in the vicinity of dental implants on corrected FDG-PET/CT images of the head and neck (B) correlates with CT artifacts (A) and is not present in the uncorrected emission images (C).

dominant field of development lies on the side of clinical application.

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