

## PET–MR imaging using a tri-modality PET/CT–MR system with a dedicated shuttle in clinical routine

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**Abstract** Tri-modality PET/CT–MRI includes the transfer of the patient on a dedicated shuttle from one system into the other. Advantages of this system include a true CT-based attenuation correction, reliable PET-quantification and higher flexibility in patient throughput on both systems. Comparative studies of PET/MRI versus PET/CT are readily accomplished without repeated PET with a different PET scanner at a different time point. Additionally, there is a higher imaging flexibility based on the availability of three imaging modalities, which can be combined for the characterization of the disease. The downside is a somewhat higher radiation dose of up to 3 mSv with a low dose CT based on the CT-component, longer acquisition times and potential misalignment between the imaging components. Overall, the tri-modality PET/CT–MR system offers comparative studies using the three different imaging modalities in the same patient virtually at the same time, and may help to develop reliable attenuation algorithms at the same time.

**Keywords** PET/CT · PET/MRI · PET/CT–MRI · Multi-modality imaging · Protocol evaluation

### Introduction of the specific concept of PET/CT–MRI

Integrated positron emission tomography (PET)/computed tomography (CT) has evolved into one of the major imaging procedures in oncology imaging and partly also in infection imaging.

However, PET/CT has several—technical as well as diagnostic—limitations. Thus, there is increasing interest in integrating PET with other imaging procedures like magnetic resonance imaging (MRI) [1–3]. Superior soft tissue contrast of MRI compared to CT and lower radiation exposure are the most obvious advantages. However, there are several technical and clinical challenges that have to be resolved before CT can be replaced with MRI in such a multimodal system. The current approach used in our hospital is a sequential PET/CT–MRI system composed of two major components: a 3T MRI system (Discovery 750w 3T, GE Healthcare, Waukesha, WI, USA) and a state-of-the-art TOF PET/CT (Time of flight, Discovery 690, GE Healthcare, Waukesha, WI, USA). Both systems can be connected with a dedicated shuttle system (see “Technical considerations,” Fig. 1a, b) which is based on a transferable board mounted onto a mobile shuttle system that links with the PET/CT and MRI from one side of the patient handling system via a floor-mounted docking station. The patient is first positioned on the transfer board on the fixed MRI table and subsequently, the MRI is performed. In order to limit the overall examination time for the patient, the MRI is performed during the uptake period of the PET tracer prior to the PET/CT examination. Following the acquisition of the MRI, the patient is transferred on the board to the shuttle system and redirected to the PET/CT. The shuttle system docks to the floor-mounted rails and the board is fitted on top of the PET/CT patient bed. Once the patient is moved and positioned inside the gantry, the

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PET/CT examination commences. The PET/CT study is performed with CT-based AC for PET-corrections in clinical routine. The acquired PET/CT and the MRI are retrospectively coregistered on a commercially available imaging workstation (Advantage Windows, GE Healthcare). Images can be displayed as PET/CT, PET–MRI, CT-only or PET-only. We always coregister the PET/CT with the MRI data. The MRI examination is typically performed as a whole-body examination due to current research trials comparing PET/CT and PET–MRI, or as a partial-body contrast-enhanced examination in the area of interest (head/neck, abdomen, pelvis, brain, see below for a more detailed discussion).

This paper will highlight some of the major issues and/or advantages of introducing this new hybrid technology into clinical routine, especially the advantages and disadvantages of simultaneous versus sequential PET/CT–MRI and PET/MRI, the related technical issues, as well as several research aspects which might arise in PET/CT–MR and PET/MR.

#### **Advantages and disadvantages of sequential PET/CT–MR and simultaneous PET/MR**

Several issues have to be addressed when evaluating a sequential PET/CT–MR versus the simultaneous PET/MRI approach. In our opinion, at the present state of the development of PET/MR technology, the advantages of a sequential PET/CT–MRI system outweigh the disadvantages. Currently there are only very few data available in the literature which demonstrate a potential advantage of PET/MRI over PET/CT in routine clinical oncological applications [1, 4–7]. So far, the majority of available data does not find statistically significant advantages of PET/MRI versus PET/CT concerning staging accuracy or detection of distant metastases [8–11]. One clear advantage of a sequential system is the flexibility in a routine clinical environment. Since both scanners can be operated separately, clinical PET/CT and MRI can be acquired at the same time in different patients. With the dedicated shuttle system, the patient can be shuttled back and forth between both systems. An overview over possible protocols in a clinical setting is given in Fig. 2.

Another key issue is how to achieve MRI-based attenuation correction (AC) and how to do adequate lung imaging in MR. Currently there are different approaches on how to perform MRI-based AC, e.g., template-based, atlas-based/pseudo-CT [12]. The first results of MR-based AC of PET-data using ultrashort echo time (UTE) sequences are promising, but to date are very time consuming, especially in large FOVs [13]. Another drawback in MR imaging is the difficulty of lesion detection in body regions presenting

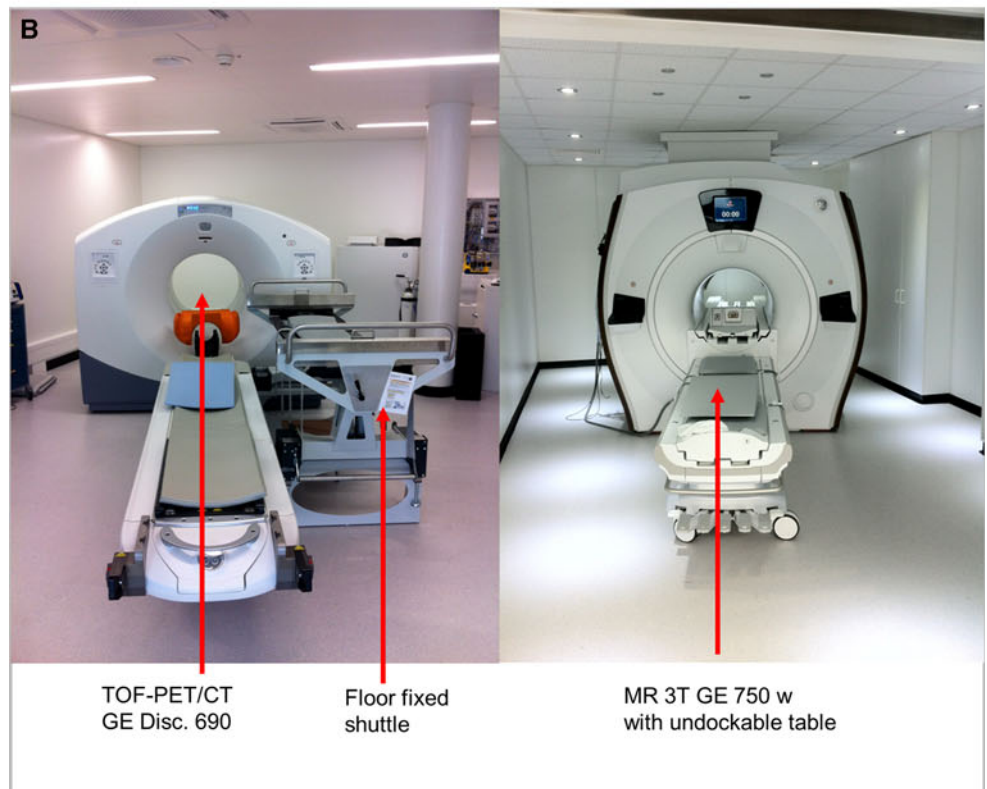
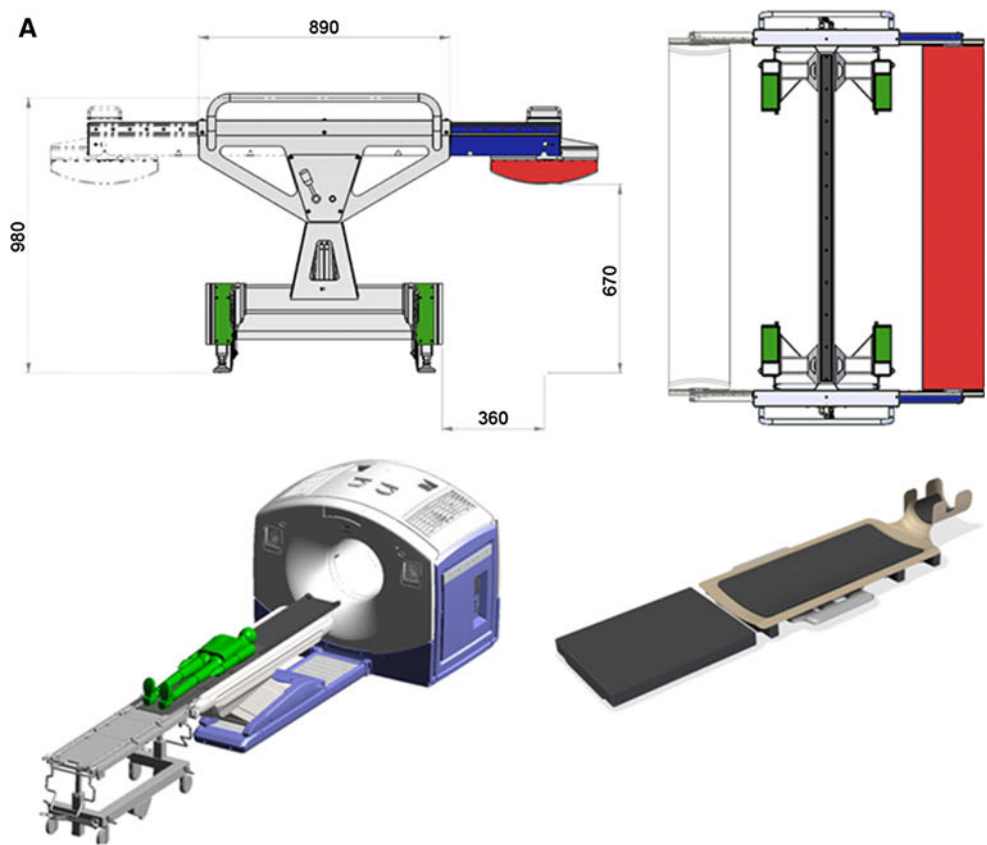
with large susceptibility changes, especially in the lung. Although MRI can be performed with gated sequences, those typically increase the acquisition time. Initial results with fast breath hold GRE-sequences may offer sufficient results in several cases [14, 15].

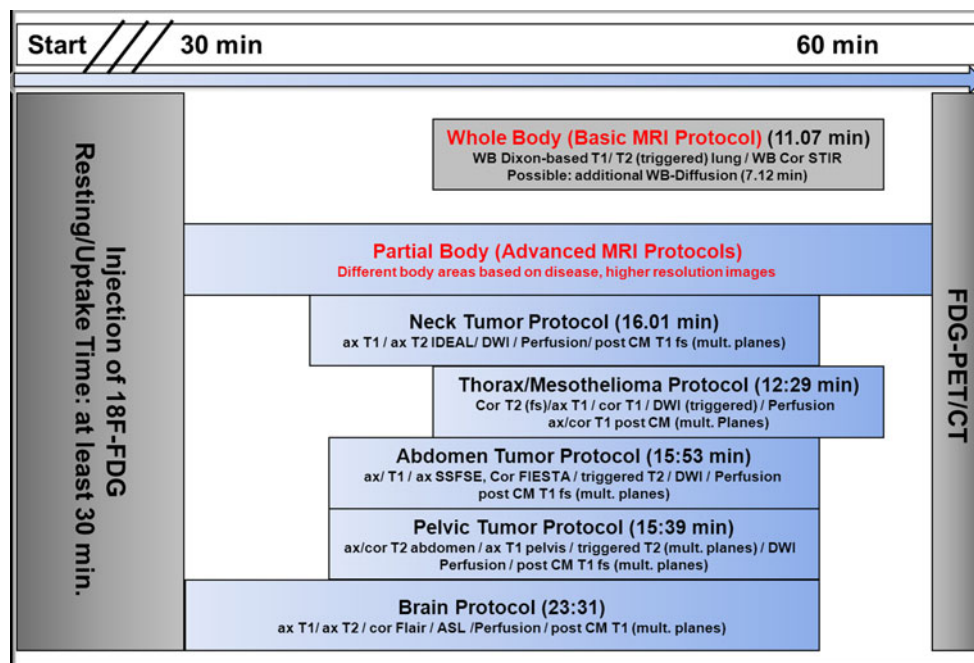
The development of an appropriate workflow for a PET/CT–MRI system as well as for a simultaneous PET/MRI remains challenging. Typically, whole-body PET/CT can be done in 10–15 min while a diagnostic MR of even a limited body region typically takes 25 min or more. Thus, a possible approach to an adequate and timely workflow might be similar to that of PET/CT, where a whole-body, low-dose scan is followed by a regionally focused full diagnostic CT. In PET/MRI, such a protocol would consist of a quick wholebody overview (e.g., possibly with a Dixon T1 GRE sequence) and a dedicated contrast-enhanced MRI in the region of interest. However, a major task for the future will remain the development of faster and more robust sequences to be used in PET/CT–MRI and combined PET/MRI.

Radiation issues have to be addressed when discussing the sequential PET/CT–MR solution. In principle, there is currently a clear advantage concerning radiation dose in simultaneous PET/MR systems because there is no additional CT-component. However, as long as the attenuation correction issues are not solved, this argument is moot [16–18]. Furthermore, much effort is applied to dose reduction in CT and PET/CT. Model based iterative reconstruction algorithms (MBIR) are already available in current commercially available scanners and upcoming advanced algorithms will reduce the CT dose even further. Thus, there is considerable potential that the radiation dose from PET/CT–MRI will be reduced by several factors in the near future.

One clear disadvantage of a sequential PET/CT–MR solution is the total scanning time for the patients because, no matter how short the MRI protocol might be, it is always an add-on to the PET/CT-examination. Although the overall patient stay time of PET/CT–MR might be the same in case the MRI is done during uptake time, patients might consider the “double-examination” as an extra burden. On the other hand, only the sequential solution currently offers the possibility to scan patients in a wide-bore MRI, which is more comfortable for claustrophobic and overweight patients. The lack of simultaneity is another disadvantage. Simultaneity can be important in interesting research applications such as dual neuro-activation or mapping studies or cardiac perfusion validation studies. Since nuclear imaging is usually done in a pseudo-steady-state tracer distribution, the meaning of simultaneity is currently unclear in such measurements. Although this approach (in neuro-imaging) currently does not have a relevant application in clinical routine, this might change with the installation of more simultaneous systems.

**Fig. 1 a** Top row Side-loading shuttle system in *frontal view* (left) and *top view* (right) consisting of a metal trolley with counter balance weights (60 kg) on each side (colored in green) and two arms (colored in blue) holding the glass fiber board (colored in red). The patient board can flexibly be slid either to the *right* or the *left* of the shuttle system, which permits loading the patient onto a scanner table from either side. *Bottom row* 3D schematic of the axial, front-loading patient transporter docked to the PET/CT table (left). When connected, the rail-guided transfer board (right) can easily be slid between the shuttle and the scanner. **b** Current design concept with a 3T MRI system and a TOF-PET/CT in two rooms directly adjacent to each other. The explanation of the shuttle mechanism and workflow is given in the “Introduction”





**Fig. 2** Overview over possible PET/CT–MRI protocols. For whole-body (WB) indications, PET/CT with additional basic whole body MRI might be applied (*grey* column). In more specific indications or diseases, contrast-enhanced MRI confined to the area of interest might be applied (partial body, PB) (*blue* column). For example, PET/CT can be done as a whole-body examination and the following (full diagnostic) MRI can be acquired, confined to the area of interest. Alternatively, the MRI can be acquired first in the desired area of interest (or whole body) during the uptake times. This concept holds

the advantage of not prolonging the total examination time since the patient has to wait anyway (at least for most  $^{18}\text{F}$  tracers) for approximately 1 h during the uptake period prior to PET. Imaging times given in the figure are scan acquisition times and may vary based on the medical status of the patient and ability to cooperate. The protocols given here are examples and are not a complete overview, as there are deviations of those protocols depending on the indication and clinical question

A significant disadvantage of current simultaneous PET/MRI in clinical routine is in MR lung imaging. Here, CT is still the best modality for nodule detection, evaluation of parenchymal texture, speed and robustness. Due to significantly longer imaging time, even with breath hold GRE-sequences, MRI has never matched the detection rates of CT. In a recent study from our group there is still a higher lesion detection rate in CT based on a lesion-by-lesion evaluation when compared to breath hold GRE Lava Flex T1 imaging, even when using the low-dose, limited axial resolution CT-component from routine PET/CT with tidal breathing [19]. However, in patient-based analysis, no statistically significant difference was seen in this preliminary study.

The current costs for simultaneous and sequential PET/MRI systems (one-room solutions) are approximately 5 millions euros (in Europe). The costs for the tri-modality system are comprised of the prize for a PET/CT, a MRI and the dedicated shuttle solutions. Thus, depending on the chosen components, we estimate that the total cost will be between €3.5–5 million, depending on the system configuration. Those costs do not include (in any case) the costs for staffing, floor space and service. The costs for the

procedure are comparable as well, of course depending on the local circumstances (supply costs, reimbursement).

### Technical considerations: patient transporter system

Multimodal imaging using separate, stand-alone PET/CT and MR scanners is based on the critical assumption of accurate multimodal image registration. Patient shuttle systems have been developed to avoid patient repositioning and minimize associated image misregistration, as well as to improve the overall workflow. Such a patient transporter system virtually connects the independent PET/CT and MR scanners into a single, sequential tri-modality PET/CT–MR imaging platform.

Conceptually, overall image misregistration can be decomposed into hardware and patient-induced errors. The former depends on the actual implementation of the shuttle system and its mechanical tolerances. Because of the rigidity of the patient shuttle, hardware registration errors can, to a good approximation, be described via rigid transformations. In comparison, patient-induced misregistration is of non-rigid nature, is dependent on patient

condition, anxiety and comfort, and tends to increase with increasing time span between the individual scans. Accurate and reproducible laser landmarking of the patient on both scanners practically eliminates registration errors along the axial direction. Misregistration along the lateral direction can be minimized via accurate table height adjustment (anterior–posterior direction) and guidance mechanisms (left–right direction).

In a recent patient study, the mean offset between PET/CT and MR was assessed to be well below 1 cm [20]. Image registration can be further refined via a subsequent software registration step available on dedicated multi-modal image viewing platforms, such as the Advantage Workstation (GE Healthcare, Waukesha, WI, USA) that we used. Assuming accurate geometric calibration of the PET/CT, image registration is most naturally done by registering the MR data towards the CT.

In collaboration with industrial partners, two prototype patient shuttles have been developed: (1) a lateral side-loading shuttle and (2) an axial front-loading shuttle, both depicted in Fig. 1a. The custom-built side-loading shuttle (Fig. 1a, top row) was developed in collaboration with a prototype engineering company (Innovation Design Center, Thalwil, Switzerland) and consists of a metal trolley and fiberglass transport board (colored in red). The board carrying the patient is held by two supporting sliding arms (colored in blue) and can flexibly be slid either to the left or to the right. After sliding the board over the scanner table, the table is elevated until the board is entirely supported. Subsequently, the board is released from the arms. After image acquisition, the shuttle is again positioned next to the scanner table and the arms are slid underneath the transport board. By lowering the scanner table, the patient is transferred back onto the shuttle and to the other side to the undocked MRI table. The board with the patient is then released.

There is also the possibility of using an axial front-loading shuttle prototype (Fig. 1b). However, this was used in a first trial phase, and currently only the side-loading shuttle is used.

### Technical considerations: quantification in PET/CT–MR versus PET/MR

PET/MR imaging is still at an early phase of development, with one of the key issues being PET quantification; in particular the correction of attenuation- and scatter-induced signal variations and artifacts and, to a lesser extent, standard calibration and quality control measurements [21]. In PET/MR imaging, the PET attenuation information has to be derived from the MR data. This is challenging because unlike CT, MR data is not easily transformed into

PET attenuation maps. Solid materials like bones and RF coils, the relative nature of MR signal, spatial signal variations induced by RF shading, and truncation artifacts due to MR field-of-view limitations, which is typically below 50 cm, all cause problems. A number of MR-based PET attenuation correction strategies have been developed, especially: the segmentation of MR images into discrete tissue classes (e.g., background/air, lung, fat and water-based tissue) with corresponding assignment of average PET attenuation values [22], atlas or template registration to account for more tissue classes, especially bone and/or RF coils [23–25], ultra-short TE-based MR imaging methods for direct bone depiction [13, 26], as well as maximum-likelihood methods for simultaneous estimation of activity and attenuation from PET data only [27]. These methods all have their strengths and weaknesses depending on the anatomy of interest. For whole-body coverage, including the head and RF coils, typically a combined approach has to be used.

Obviously, in tri-modality PET/CT–MR the standard CT-based PET attenuation correction can be used, which is an important advantage in terms of accurate and robust PET quantification. Furthermore, the sequential approach allows selective presence of RF coils during MR scanning and as well as their removal during PET/CT scanning without moving the patient. This is an important advantage considering that bulky RF head coil structures can cause significant attenuation artifacts with loss of intrinsic count rate of up to 50 % [26]. To avoid repositioning of the patient during the selective placement or removal of RF coils, the posterior coils ideally need to be integrated into the MR scanner table. Similarly, for the head coil a dedicated head holder is required which tightly fits into the coil structure. Flexible anterior coils can easily be removed from the patient.

In effect, the tri-modality PET/CT–MR system can use standard CT-based PET attenuation correction and it can effectively be used for the development and evaluation of MR-based PET attenuation correction methods as well as for clinical evaluation of PET/CT versus PET–MR [28, 29].

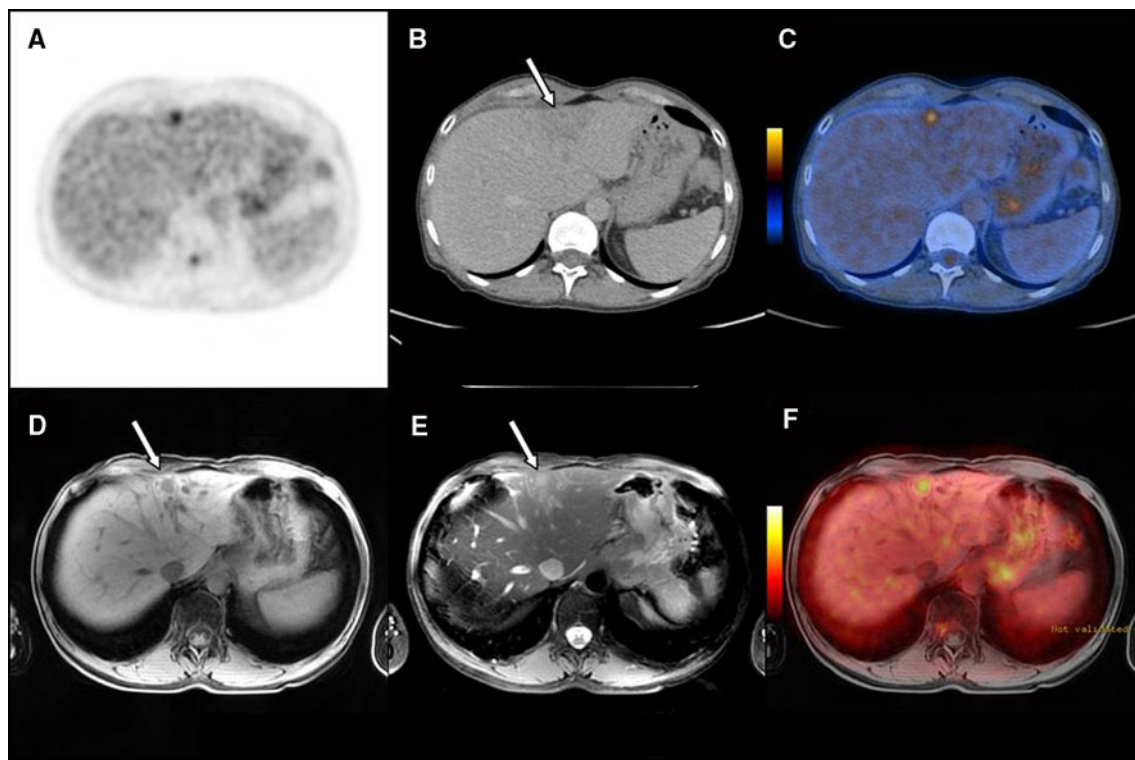
### Clinical motivation, clinical experience and objectives

The clinical motivation for PET/CT–MRI and simultaneous PET/MRI is based on the observation that in several clinical oncological indications the value of PET/CT is limited. Generally N-staging and M-staging is not impaired but it can be difficult to assess different tumor entities with regard to T-staging. This is based on the PET/CT's intrinsic lower soft tissue contrast compared to high-resolution MRI, even with state-of-the art CT-components.

In whole-body applications, such as for lymphoma, several publications compared PET/CT with MRI [30]. There are conflicting results in the literature concerning the agreement of DWI–MRI and PET/CT [31, 32]. DWI–MRI within PET/MRI holds the advantage of using a lower radiation dose when compared to PET/CT–MRI. However, because DWI–MRI currently does not match the diagnostic accuracy of PET/CT, a sophisticated imaging concept would be for example, having a PET/MRI for initial staging and DWI–MRI for follow-up because several papers point out this as a strength of DWI. Other whole-body indications are myeloma and melanoma. In multiple myeloma, PET/CT currently is considered the gold standard for therapy follow-up in this specific patient population. WB–MRI on the other hand is able to visualize especially lytic bone marrow lesions much better than CT, while CT has advantages in the detection of cortical lesions. Thus, PET/CT–MRI might provide useful concurrent information in myeloma patients, especially in therapy follow-up settings where the PET-component can be negative [33, 34]. In melanoma patients it has already been proven in multiple publications that MRI is superior to FDG–PET/CT in detection and characterization of brain metastases [35, 36]. However, it is well known that FDG–PET/CT is not well suited for detection of brain metastases.

Here,  $^{18}\text{F}$ -FET or  $^{11}\text{C}$ -methionin are examples of much better tracers for brain tumors, and PET and comparisons with MRI should be done using these tracers.

Several publications also investigated the superiority of MRI versus  $^{18}\text{F}$ -FDG PET/CT in liver lesions, and only very few so far have compared PET/CT and PET–MRI [37]. This is mainly based on the high background activity of the liver in PET and the intrinsic lower soft-tissue contrast provided by CT compared to MRI. Admittedly, very few studies actually compare cePET/CT (contrast-enhanced PET/CT) with MR for this purpose. However, a large meta-analysis showed that MRI and  $^{18}\text{F}$ -FDG/CT are not statistically significantly different in lesion detection [38]. Our own experience in an initial comparison of cePET/CT versus non cePET–MRI showed that (based on the PET-component) all lesions within the liver were detected on both multimodal imaging methods. However, lesion conspicuity was significantly better on the MRI component evaluated within a PET/CT–MRI system when compared to the ceCT component, especially when using T1 and T2 sequences [7] (Fig. 3). Additionally, when comparing the standard low-dose PET/CT versus PET–MRI in liver lesions, lesion conspicuity was again significantly better on PET–MRI when read by two independent readers. Lastly, several liver metastases (e.g., from uveal melanoma,



**Fig. 3** Enhanced lesion detection with contrast-enhanced PET/CT + MRI in liver lesions. Patient with metastasizing colon cancer with a focal  $^{18}\text{F}$ -FDG-positive liver lesion in the left liver lobe, barely seen on the ceCT-component. Top row PET (a), ceCT

(b), PET/CT (c). Lesion conspicuity is significantly higher on non-contrast-enhanced T1 (d) and FIESTA (e). No difference in lesion detection is noted when compared between PET/CT (c) and PET/MRI (f)

metastases after therapy) as well as the majority of primary liver tumors can be FDG-negative in a significant number of patients [39]. Although there is currently no study available focusing on those patient groups, it is very clear that patients will benefit from the additional MRI within a PET/CT–MRI setting.

Two other abdominal indications will benefit from PET/CT–MRI. Diagnosis of neuroendocrine tumors (NET) of the gastrointestinal tract has been recently changed dramatically with the introduction of new tracers like 18F-DOPA or 68-Ga DOTA (TATE/TOC/NOC) into clinical routine [40–42]. The new NET-specific tracer based PET/CT has proven to be superior to all other imaging modalities available. Since NET of the GI-tract are typically very small lesions within the bowel wall with adjacent larger mesenteric lymph nodes, this indication will probably also benefit from a PET/CT–MRI approach.

A similar reasoning may apply for gastrointestinal infection imaging with PET/MRI, e.g., in Crohn's disease. MRI has become the main imaging modality used to image and evaluate affected bowel parts, and dynamic MRI is able to evaluate hypo-/akinetic sections and concurrent inflammatory activity [43, 44]. On the other hand, PET/CT already has proven to be a highly accurate imaging modality in low-grade infections [45–47]. Thus, the combination of both procedures might be beneficial by making it possible to arrive at a more exact diagnosis in determination of active versus inactive inflammatory lesions.

There are clear advantages of MRI compared to CT in anatomically challenging areas like the pelvis. Prostate imaging serves as a good example where the technical capabilities of MRI (e.g., DWI–MRI, spectroscopy) are able to differentiate tumor from prostate tissue, which is not possible with contrast-enhanced CT. 18F-and 11C-Choline-PET/CT on the other hand has become the mainstay in the restaging of prostate cancer patients, while primary staging is only conducted in high risk patients [48, 49]. The combination of PET/CT–MRI can serve in those cases as a one-stop-shop imaging tool, providing information about the local tumor status, the nodal status and distant metastases. While there is no simultaneity needed for the restaging scenario, primary staging might be a well suited indication for simultaneous PET/MRI because prostate MRI is frequently done with an endorectal coil.

Another area with advantages for PET/MRI will be head and neck cancer. In particular, the infiltration of tumors in surrounding tissues can be visualized with MRI in an unparalleled way, which is partly not achievable by contrast-enhanced CT. PET/CT has been proven superior in the detection of lymph node metastases based on the PET-component, when compared to morphological imaging modalities [50]. Hence, PET/CT and MRI are currently the staging tools of choice for surgical as well as radiotherapy

planning. Since both procedures are often performed for head and neck cancer, a combined PET/CT–MRI approach seems advantageous. The combination of PET/CT–MRI also has advantages in patients with metal artifacts in CT, as new MR sequences can minimize those artifacts. Thus, head and neck cancer is certainly one of the most promising indications for a PET/CT–MRI or simultaneous PET/MRI.

In neuroimaging, MR images are often a prerequisite for the processing and analysis of PET data. The morphology depicted by MR imaging helps to correctly interpret 18F-FET (Fluoro-ethyl-tyrosine) PET images in brain tumor patients, to evaluate potential cofactors in Alzheimer's disease, to allow for normalization of PET data into stereotactic space and hence automated image analysis, and to correct the PET data for partial volume effects. Quantitative analysis of brain pathologies is of major importance for the standardization of treatment and therapy assessment. PET is widely accepted as a reliable tool for the quantification of pathological processes, but MRI also offers a wide range of advanced techniques for quantitative imaging [51, 52], such as apparent diffusion coefficient (ADC) maps as a tool for the quantification of cellular density [53], arterial spin labeling (ASL) for measurements of blood flow [54], and dynamic contrast-enhancement (DCE) to assess the characteristics of tumor vasculature, including perfusion, blood vessel permeability, blood volume and extravascular extracellular volume fraction [55]. Therefore, the combination of PET and MRI has the potential to become a powerful tool for quantitative imaging and objective decision making. As the skull is a rigid object, reliable coregistration of PET and MR data is possible also from different imaging devices. Hence, integrated PET/MRI in this setting is likely “nice to have” but often not mandatory in clinical multiparametric neuroimaging.

### Perspective on clinical use in future and research perspectives

Concerning the value of PET–MR in terms of clinical use and utility, we are currently in favor of the tri-modality solution. It offers the possibility to compare PET/CT and PET–MRI in a clinical routine setting and an easy way to acquire patients for comparison trials. The MRI can be done during the uptake time without major restrictions concerning scan time—which is the case when MRI-sequences have to be adapted to the bed-positions in PET. The patient can be transferred with an aforementioned dedicated shuttle system to PET/CT. In this way, no differences in SUV between the first (or second) PET from PET/CT and the second (or first) PET from simultaneous

PET/MRI limit interpretation of data and quantification, and the comparison between follow-up studies is straight forward. A second unparalleled advantage is that PET/CT and MRI can be used as independent imaging modalities as discussed above.

Future indications used in clinical routine are primarily the above-mentioned oncological indications, where the additional MRI-component in addition to PET/CT offers important information for diagnosis, surgical or RT-planning. This is especially useful in head and neck cancer, liver lesion characterization and localization, pelvic tumors including prostate cancer, and neuroendocrine tumors. Also this multimodal imaging will have a role in inflammatory and infection-imaging.

Our primary goal in clinical neuroimaging is to combine quantitative PET and MR imaging and to establish this multimodal procedure in routine imaging of brain pathologies. To accomplish this goal, the PET–MR examination has to be integrated in a sequential or simultaneous imaging system. Only a locally and temporally combined examination permits that PET/MRI is perceived as a simultaneous entity by the patient and the referring physician. Therefore, PET/MRI as well as PET–MR imaging protocols have been established, combining MRI with different PET-tracers such as  $^{18}\text{F}$ -FET for brain tumors,  $^{68}\text{Ga}$ -DOTATATE for therapy evaluation in meningioma patients,  $^{18}\text{F}$ -DOPA and  $^{11}\text{C}$ -Raclopride for characterization of movement disorders,  $^{11}\text{C}$ -Pittsburgh compound B as well as  $^{18}\text{F}$ -FDG in Alzheimer's disease or other neurodegenerative disorders, and  $^{15}\text{O}$ - $\text{H}_2\text{O}$  for cerebrovascular diseases (Fig. 4).

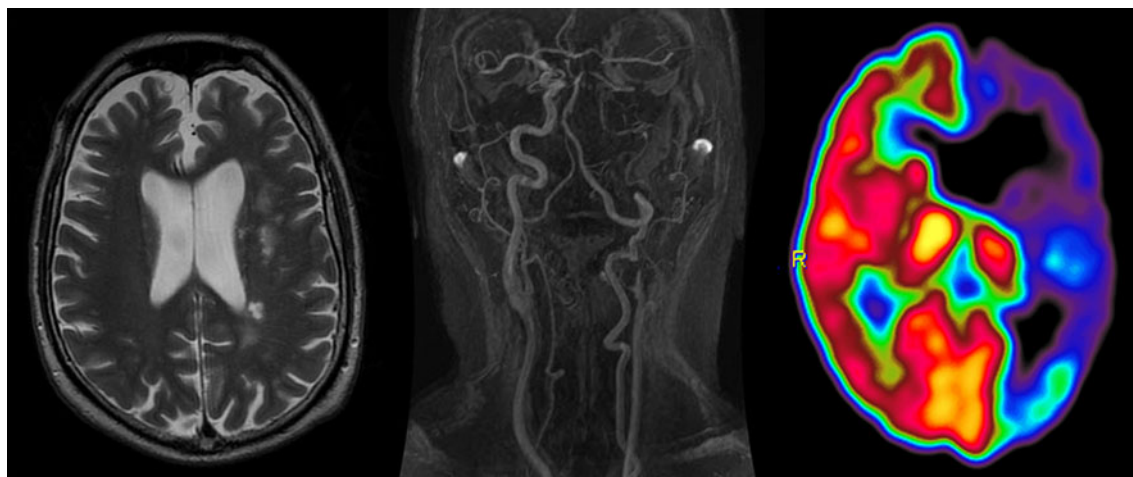
There are several research perspectives for a PET/CT–MRI system, which are not accessible by a simultaneous system, and vice versa. One example is multiparametric imaging which integrates information from different

modalities into one value or diagnosis, an approach which is increasingly gaining interest. Multiple options are possible with a sequential system: the integration of CT-perfusion into PET/CT has already been accomplished in several trials and has proven in part to provide additional information on the glycolytic state of the tumor [56, 57]. The PET/CT–MRI system now offers the possibility to acquire PET/CT with integrated CT-perfusion and additional MRI-perfusion data with a negligible time gap and good coregistration. Thus, generally such a tri-modal system offers the possibility of integration of more modalities than a simultaneous system—however, for the price of non-simultaneity.

Even non-contrast-enhanced perfusion sequences (ASL, arterial spin labeling) [58, 59] can be acquired, compared, and possibly integrated for several body oncology and neuroradiological indications in the near future. One major task will be the adaption of MRI-sequences within PET/CT–MRI and simultaneous PET/MRI to the PET-emission time and the PET-FOV. Current MRI-protocols—especially for whole body—as well as neuro-applications are not well suited, based on their rather long examination times.

## Conclusion

PET/CT–MRI is currently a valuable tool for investigating the value of adding MRI rather than CT to PET in clinical routine and offers the added value of clinical flexibility due to the two-room, tri-modal concept. This way, the selected indications discussed above, in which a simultaneous PET/MRI is possibly needed, can be evaluated and the value of these modalities established for clinical routine. The costs for a tri-modal system are generally comparable to a



**Fig. 4** In cerebrovascular pathologies, a combined approach with MRI, MR-angiography and quantitative PET perfusion measurement is helpful in assessing the extent of the disease. From left to right: T2 weighted MRI, subtraction MR-angiography and  $^{15}\text{O}$ - $\text{H}_2\text{O}$  PET



simultaneous system, however, it offers more flexibility concerning the choice of components. PET/CT–MRI, as well as simultaneous PET/MRI offer major research possibilities in body as well as in neurological applications to learn about tumor characteristics, evaluate new therapy follow-up strategies, enhance patient comfort and reduce radiation dose burden at the same time.

## References

- Schwenzer NF, Schmidt H, Claussen CD (2012) Whole-body MR/PET: applications in abdominal imaging. *Abdom Imaging* 37(1):20–28
- Beyer T, Freudenberg LS, Czernin J, Townsend DW (2011) The future of hybrid imaging—part 3: PET/MR, small-animal imaging and beyond. *Insights Imaging* 2(3):235–246
- Ratib O, Beyer T (2011) Whole-body hybrid PET/MRI: ready for clinical use? *Eur J Nucl Med Mol Imaging* 38(6):992–995
- Park H, Wood D, Hussain H, Meyer CR, Shah RB, Johnson TD, Chenevert T, Pierr M (2012) Introducing parametric fusion PET/MRI of primary prostate cancer. *J Nucl Med* 53(4):546–551
- Jambor I, Borra R, Kemppainen J, Lepomaki V, Parkkola R, Dean K, Alanen K, Arponen E, Nurmi M, Aronen HJ, Minn H (2012) Improved detection of localized prostate cancer using co-registered MRI and (11)C-acetate PET/CT. *Eur J Radiol*. Feb 17 (Epub ahead of print)
- Appenzeller P, Mader C, Schmidt D, Schmid D, Veit-Haibach P (2012) Low-dose PET/CT vs. fast body coil PET/MRI—how low can you go?. In: Proceedings of the 14th scientific meeting, Asean Oceanen Congress of Radiology, Sydney, New South Wales, Australia, EPOS 364.00
- Assiri Y, Kuhn FP, Pietsch C, Schmidt D, Veit-Haibach P (2012) Contrast-enhanced PET/CT vs. non-contrast enhanced PET/MRI in abdominal oncological lesions—initial results. In: Proceedings of the 14th scientific meeting, Asean Oceanen Congress of Radiology, Sydney, New South Wales, Australia, p 23
- Eiber M, Martinez-Moller A, Souvatzoglou M, Holzappel K, Pickhard A, Loffelbein D, Santi I, Rummeny EJ, Ziegler S, Schwaiger M, Nekolla SG, Beer AJ (2011) Value of a Dixon-based MR/PET attenuation correction sequence for the localization and evaluation of PET-positive lesions. *Eur J Nucl Med Mol Imaging* 38(9):1691–1701
- Pfannenbergs C, Schraml C, Schwenzer N, Werner M, Muller M, Bares R, Claussen CD (2011) Comparison of [68 Ga] DOTA-TOC-PET/CT and whole-body MRI in staging of neuroendocrine tumors. *Cancer Imaging* 11(Spec No A):S38–S39
- Yong TW, Yuan ZZ, Jun Z, Lin Z, He WZ, Juanqi Z (2011) Sensitivity of PET/MR images in liver metastases from colorectal carcinoma. *Hell J Nucl Med* 14(3):264–268
- Drzezga A, Souvatzoglou M, Eiber M, Beer AJ, Furst S, Martinez-Moller A, Nekolla SG, Ziegler S, Ganter C, Rummeny EJ, Schwaiger M (2012) First clinical experience with integrated whole-body PET/MR: comparison to PET/CT in patients with oncologic diagnoses. *J Nucl Med* 53(6):845–855
- Hofmann M, Pichler B, Scholkopf B, Beyer T (2009) Towards quantitative PET/MRI: a review of MR-based attenuation correction techniques. *Eur J Nucl Med Mol Imaging* 36(Suppl 1):S93–104
- Keereman V, Fierens Y, Broux T, De Deene Y, Lonnew M, Vandenberghe S (2010) MRI-based attenuation correction for PET/MRI using ultrashort echo time sequences. *J Nucl Med* 51(5):812–818
- Schwenzer NF, Schraml C, Muller M, Brendle C, Sauter A, Spengler W, Pfannenbergs AC, Claussen CD, Schmidt H (2012) Pulmonary lesion assessment: comparison of whole-body hybrid MR/PET and PET/CT imaging—pilot study. *Radiology*. doi: 10.1148/radiol.12111942
- Vogt FM, Herborn CU, Hunold P, Lauenstein TC, Schroder T, Debatin JF, Barkhausen J (2004) HASTE MRI versus chest radiography in the detection of pulmonary nodules: comparison with MDCT. *AJR Am J Roentgenol* 183(1):71–78
- Samarin A, Burger C, Wollenweber SD, Crook DW, Burger IA, Schmid DT, von Schulthess GK, Kuhn FP (2012) PET/MR imaging of bone lesions—implications for PET quantification from imperfect attenuation correction. *Eur J Nucl Med Mol Imaging* 39(7):1154–1160
- Beyer T, Weigert M, Quick HH, Pietrzyk U, Vogt F, Palm C, Antoch G, Muller SP, Bockisch A (2008) MR-based attenuation correction for torso-PET/MR imaging: pitfalls in mapping MR to CT data. *Eur J Nucl Med Mol Imaging* 35(6):1142–1146
- Schramm G, Langner F, Hofheinz F, Beuthien-Baumann B, Platzek I, Petr J, Kotzerke J, Steinbach J, van den Hoff J (2012) Quantitative accuracy of attenuation correction in the Philips Ingenuity TF whole-body PET/MR system: a direct comparison with transmission-based attenuation correction. *Magn Reson Mater Phys*. doi:10.1007/s10334-012-0328-5
- Stolzmann P, Veit-Haibach P, Chuck N, Rossi C, Frauenfelder T, Alkadhi H, von Schulthess GK, Boss A (2012) Detection rate, location, and size of pulmonary nodules in tri-modality PET/CT–MR: comparison of low-dose CT and Dixon-based MR imaging. *Invest Radiol* (in press)
- Samarin A, Kuhn FP, Crook DW, Hodler J, Von Schulthess GK, Schmid DT, Wiesinger F, Wollenweber S (2011) Image registration accuracy of a sequential, trimodality PET/CT + MR imaging setup using dedicated patient transporter systems. In: Proceedings of the 97th Radiological Society of North America 2011 scientific assembly and annual meeting. Chicago IL, SSK13-08
- Zaidi H, Hasegawa B (2003) Determination of the attenuation map in emission tomography. *J Nucl Med* 44(2):291–315
- Martinez-Moller A, Souvatzoglou M, Delso G, Bundschuh RA, Chef d’hotel C, Ziegler SI, Navab N, Schwaiger M, Nekolla SG (2009) Tissue classification as a potential approach for attenuation correction in whole-body PET/MRI: evaluation with PET/CT data. *J Nucl Med* 50(4):520–526
- Hofmann M, Bezrukov I, Mantlik F, Aschoff P, Steinke F, Beyer T, Pichler BJ, Scholkopf B (2011) MRI-based attenuation correction for whole-body PET/MRI: quantitative evaluation of segmentation- and atlas-based methods. *J Nucl Med* 52(9):1392–1399
- Hofmann M, Steinke F, Scheel V, Charpiat G, Farquhar J, Aschoff P, Brady M, Scholkopf B, Pichler BJ (2008) MRI-based attenuation correction for PET/MRI: a novel approach combining pattern recognition and atlas registration. *J Nucl Med* 49(11):1875–1883
- Malone IB, Ansorge RE, Williams GB, Nestor PJ, Carpenter TA, Fryer TD (2011) Attenuation correction methods suitable for brain imaging with a PET/MRI scanner: a comparison of tissue atlas and template attenuation map approaches. *J Nucl Med* 52(7):1142–1149
- Catana C, van der Kouwe A, Benner T, Michel CJ, Hamm M, Fenchel M, Fischl B, Rosen B, Schmand M, Sorensen AG (2011) Toward implementing an MRI-based PET attenuation-correction method for neurologic studies on the MR-PET brain prototype. *J Nucl Med* 51(9):1431–1438

27. Rezaei A, Nuyts J, Defrise M, Bal G, Michel C, Conti M, Watson C (2011) Simultaneous reconstruction of activity and attenuation in time-of-flight PET. Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) Valencia, Spain, pp 2375–2382
28. Qian H, Shanbhag DD, Kaushik S, Thiruvankadam S, Novak G, Lonn A, Wollenweber SD, Wiesinger F (2012) Whole-body PET/MR attenuation correction on a sequential, tri-modality PET/CT and MR imaging setup combining image segmentation, truncation completion and atlas-based skull segmentation. In: Proceedings new paradigms in molecular imaging conference, Elba, Italy, Tuesday 29th May
29. Shanbhag DD, Thiruvankadam S, Kaushik S, Mullick R, Wollenweber SD, Wiesinger F (2012) Automated workflow for MR-PET attenuation correction in a tri-modality system using Dixon fat-water imaging based tissue classification. In: Proceedings of the international society of magnetic resonance in medicine, Melbourne, Australia, p 4371
30. van Ufford HM, Kwee TC, Beek FJ, van Leeuwen MS, Takahara T, Fijnheer R, Nievelstein RA, de Klerk JM (2011) Newly diagnosed lymphoma: initial results with whole-body T1-weighted, STIR, and diffusion-weighted MRI compared with 18F-FDG PET/CT. *AJR Am J Roentgenol* 196(3):662–669
31. Pauls S, Schmidt SA, Juchems MS, Klass O, Luster M, Reske SN, Brambs HJ, Feuerlein S (2012) Diffusion-weighted MR imaging in comparison to integrated [(1)(8)F]-FDG PET/CT for N-staging in patients with lung cancer. *Eur J Radiol* 81(1):178–182
32. Chen W, Jian W, Li HT, Li C, Zhang YK, Xie B, Zhou DQ, Dai YM, Lin Y, Lu M, Huang XQ, Xu CX, Chen L (2010) Whole-body diffusion-weighted imaging vs. FDG-PET for the detection of non-small-cell lung cancer. How do they measure up? *Magn Reson Imaging* 28(5):613–620
33. Lin C, Luciani A, Itti E, Haioun C, Rahmouni A (2007) Whole body MRI and PET/CT in haematological malignancies. *Cancer Imaging* 7(Spec No A):S88–S93
34. Lutje S, de Rooy JW, Croockewit S, Koedam E, Oyen WJ, Raymakers RA (2009) Role of radiography, MRI and FDG-PET/CT in diagnosing, staging and therapeutical evaluation of patients with multiple myeloma. *Ann Hematol* 88(12):1161–1168
35. Dellestable P, Granel-Brocard F, Rat AC, Olivier P, Regent D, Schmutz JL (2011) Impact of whole body magnetic resonance imaging (MRI) in the management of melanoma patients, in comparison with positron emission tomography/computed tomography (TEP/CT) and CT. *Ann Dermatol Venereol* 138(5):377–383
36. Aukema TS, Olmos RA, Korse CM, Kroon BB, Wouters MW, Vogel WV, Bonfrer JM, Nieweg OE (2010) Utility of FDG PET/CT and brain MRI in melanoma patients with increased serum S-100B level during follow-up. *Ann Surg Oncol* 17(6):1657–1661
37. Kuhn FP, Crook DW, Mader CE, Appenzeller P, von Schulthess GK, Schmid DT (2012) Discrimination and anatomical mapping of PET-positive lesions: comparison of CT attenuation-corrected PET images with coregistered MR and CT images in the abdomen. *Eur J Nucl Med Mol Imaging* [Epub ahead of print]
38. Niekel MC, Bipat S, Stoker J (2010) Diagnostic imaging of colorectal liver metastases with CT, MR imaging, FDG PET, and/or FDG PET/CT: a meta-analysis of prospective studies including patients who have not previously undergone treatment. *Radiology* 257(3):674–684
39. Strobel K, Bode B, Dummer R, Veit-Haibach P, Fischer DR, Imhof L, Goldinger S, Steinert HC, von Schulthess GK (2009) Limited value of 18F-FDG PET/CT and S-100B tumour marker in the detection of liver metastases from uveal melanoma compared to liver metastases from cutaneous melanoma. *Eur J Nucl Med Mol Imaging* 36(11):1774–1782
40. Veit-Haibach P, Schiesser M, Soyka J, Strobel K, Schaefer NG, Hesselmann R, Clavien PA, Hany TF (2011) Clinical value of a combined multi-phase contrast enhanced DOPA-PET/CT in neuroendocrine tumours with emphasis on the diagnostic CT component. *Eur Radiol* 21(2):256–264
41. Schiesser M, Veit-Haibach P, Muller MK, Weber M, Bauerfeind P, Hany T, Clavien PA (2010) Value of combined 6-[18F]fluorodihydroxyphenylalanine PET/CT for imaging of neuroendocrine tumours. *Br J Surg* 97(5):691–697
42. Ambrosini V, Tomassetti P, Franchi R, Fanti S (2010) Imaging of NETs with PET radiopharmaceuticals. *Q J Nucl Med Mol Imaging* 54(1):16–23
43. Narin B, Ajaj W, Gohde S, Langhorst J, Akgoz H, Gerken G, Ruhm SG, Lauenstein TC (2004) Combined small and large bowel MR imaging in patients with Crohn's disease: a feasibility study. *Eur Radiol* 14(9):1535–1542
44. Ajaj WM, Lauenstein TC, Pelster G, Gerken G, Ruehm SG, Debatin JF, Goehde SC (2005) Magnetic resonance colonography for the detection of inflammatory diseases of the large bowel: quantifying the inflammatory activity. *Gut* 54(2):257–263
45. Love C, Tomas MB, Tronco GG, Palestro CJ (2005) FDG PET of infection and inflammation. *Radiographics* 25(5):1357–1368
46. Stumpe KD, Strobel K (2006) 18F FDG-PET imaging in musculoskeletal infection. *Q J Nucl Med Mol Imaging* 50(2):131–142
47. Strobel K, Stumpe KD (2007) PET/CT in musculoskeletal infection. *Semin Musculoskelet Radiol* 11(4):353–364
48. Castellucci P, Fuccio C, Rubello D, Schiavina R, Santi I, Nanni C, Allegri V, Montini GC, Ambrosini V, Boschi S, Martorana G, Marzola MC, Fanti S (2011) Is there a role for (1)(1)C-choline PET/CT in the early detection of metastatic disease in surgically treated prostate cancer patients with a mild PSA increase <1.5 ng/ml? *Eur J Nucl Med Mol Imaging* 38(1):55–63
49. Castellucci P, Fuccio C, Nanni C, Santi I, Rizzello A, Lodi F, Franceschelli A, Martorana G, Manferrari F, Fanti S (2009) Influence of trigger PSA and PSA kinetics on 11C-Choline PET/CT detection rate in patients with biochemical relapse after radical prostatectomy. *J Nucl Med* 50(9):1394–1400
50. Veit-Haibach P, Luczak C, Wanke I, Fischer M, Egelhof T, Beyer T, Dahmen G, Bockisch A, Rosenbaum S, Antoch G (2007) TNM staging with FDG-PET/CT in patients with primary head and neck cancer. *Eur J Nucl Med Mol Imaging* 34(12):1953–1962
51. Gore JC, Manning HC, Quarles CC, Waddell KW, Yankeelov TE (2011) Magnetic resonance in the era of molecular imaging of cancer. *Magn Reson Imaging* 29(5):587–600
52. Dhermain FG, Hau P, Lanfermann H, Jacobs AH, van den Bent MJ (2010) Advanced MRI and PET imaging for assessment of treatment response in patients with gliomas. *Lancet Neurol* 9(9):906–920
53. de Bondt RB, Hoerberigs MC, Nelemans PJ, Deserno WM, Peutz-Kootstra C, Kremer B, Beets-Tan RG (2009) Diagnostic accuracy and additional value of diffusion-weighted imaging for discrimination of malignant cervical lymph nodes in head and neck squamous cell carcinoma. *Neuroradiology* 51(3):183–192
54. Detre JA, Rao H, Wang DJ, Chen YF, Wang Z (2012) Applications of arterial spin labeled MRI in the brain. *J Magn Reson Imaging* 35(5):1026–1037
55. Yankeelov TE, Gore JC (2009) Dynamic contrast enhanced magnetic resonance imaging in oncology: theory, data acquisition, analysis, and examples. *Curr Med Imaging Rev* 3(2):91–107
56. Bisdas S, Spicer K, Rumboldt Z (2008) Whole-tumor perfusion CT parameters and glucose metabolism measurements in head and neck squamous cell carcinomas: a pilot study using combined positron-emission tomography/CT imaging. *AJNR Am J Neuro-radiol* 29(7):1376–1381
57. Veit-Haibach P, Treyer V, Strobel K, Soyka JD, Husmann L, Schaefer NG, Tschopp A, Hany TF (2010) Feasibility of integrated CT-liver perfusion in routine FDG-PET/CT. *Abdom Imaging* 35(5):528–536

58. Bokkers RP, Hernandez DA, Merino JG, Mirasol RV, van Osch MJ, Hendrikse J, Warach S, Latour LL (2012) Whole-brain arterial spin labeling perfusion MRI in patients with acute stroke. *Stroke*. doi:[10.1161/STROKEAHA.110.589234](https://doi.org/10.1161/STROKEAHA.110.589234)
59. Pedrosa I, Rafatzand K, Robson P, Wagner AA, Atkins MB, Rofsky NM, Alsop DC (2012) Arterial spin labeling MR imaging for characterisation of renal masses in patients with impaired renal function: initial experience. *Eur Radiol* 22(2):484–492