Whole-Body MR/PET Hybrid Imaging: Technical Considerations, Clinical Workflow, and Initial Results

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MR/PET – Advent of a new hybrid imaging modality

These days we are eyewitnesses to an exciting new hybrid imaging modality to enter the clinical arena, namely simultaneous whole-body MR/PET imaging. Envisioning the combination of the excellent soft tissue contrast, high spatial and temporal resolution, and functional tissue parameters that MR provides with the high sensitivity of PET, different technical approaches have been pursued by researchers and by the industry to work on the integration of two formerly “non-integrable” imaging modalities. With the recent introduction of the Biograph mMR, Siemens has launched a 3.0 Tesla whole-body MR hybrid system that hosts in its isocenter a fully integrated PET detector and that with its 60 cm patient bore enables whole-body simultaneous MR/PET imaging.

Researchers, radiologists, and nuclear medicine physicians have been waiting and actively been working on the advent of this hybrid imaging modality for a long time [1–3]. A detailed overview about the pre-clinical developments, the rationale to combine MR and PET as well as the steps which were necessary for integrating these imaging modalities to allow simultaneous scanning can be found in the article by Beyer et al. “MR/PET – Hybrid Imaging for the Next Decade”, published in the supplement of issue 3/2010, RSNA edition of MAGNETOM Flash. Note that whole-body MR/PET has entered clinical practice, we have a starting point to evaluate the full clinical potential of the modality, to research for and to validate new imaging applications, and to ultimately establish this imaging modality in early diagnosis of oncologic, neurologic, cardiology, and many more diseases. As more and more research and clinical sites come on board during the months and years ahead, let’s take a first look into the technology and explore what specific an integrated MR/PET hybrid system brings with it. We will then also explore the workflow of a MR/PET whole-body hybrid exam and present first image examples from clinical findings.

Technical integration of MR and PET

The Biograph mMR hybrid imaging system fully integrates the MR and the PET imaging modality into one imaging system. In order to ensure such a high level of integration, we have to overcome numerous physical and technical preconditions and challenges. The potential physical interactions of both modalities in both directions – PET on MRI and MRI on PET – are manifold. Full integration of a PET system into an MRI environment requires technical solutions for three groups of potential electromagnetic interaction:

1) The strong static magnetic $B_0$-field for spin alignment,
2) the electromagnetic changing fields of the gradient system ($G_{xyz}$) for spatial signal encoding, and
3) the radiofrequency (RF) $B_1$-field for MR signal excitation and MR signal readout.

PET hardware and PET signals must not be disturbed by any of these fields. Equally, for full and unlimited MRI system performance, PET must not disturb any of these electromagnetic MR fields and signals. Numerous technical solutions were thus required for PET integration into an MRI system. The most important key technology enabler was the development of detectors and photo diodes that are able to detect the 511 keV PET gamma quanta following an annihilation event inside of a strong magnetic field. What worked well in established PET and in hybrid PET/CT systems in the form of scintillation crystal blocks read out by photomultiplier tubes (PMT), had to be replaced for the MR/PET integration since the PMTs are very susceptible to magnetic fields. The current detector solution for simultaneous MR/PET is a combination of Lutetium Oxyorthosilicate (LSO) crystals and Avalanche Photo Diodes (APD). 9-channel preamplifiers and driver boards as well as integrated water cooling completes each detector block. This detector assembly is characterized by its small size, can be designed free of magnetic components, and performs in strong magnetic fields. 56 such blocks form one detector ring. 8 rings form the PET detector assembly in the Biograph mMR that spans a longitudinal field-of-view (FOV) of 25.8 cm.
How has the integration of the PET detector unit into the MR environment been performed technically? Seen from the perspective of the signals emitting patient, the hardware layer structure of the hybrid system is as follows: The innermost layer in the magnet bore is formed by the signal transmitting and receiving RF body coil with its RF shield, shielding the RF coil towards the other structures in the bore. The PET detector rings are located behind the RF coil and its RF shield. The layer behind the PET detector unit is formed by the gradient coil assembly encompassing gradient coils for spatial MR signal encoding. The PET detectors require stable temperatures over time of around 20°C temperature, which has been achieved by implementing water cooling into the APDs (Fig. 1). Analog electrical signals and water cooling are conducted from the PET detector in the isocenter of the magnet bore to the back end of the MRI PET system. All PET detector electronics are hermetically shielded by copper elements in order not to emit RF signals that potentially could disturb the weak MR RF signals or contribute to increased overall RF noise, leading to decreased signal-to-noise-ratio (SNR) in MRI measurements. With regard to potential interaction with the three groups of electromagnetic fields in an MRI surrounding, all components of the PET detector electronics must be absolutely non-magnetic and ‘gradient transparent’ in order to not disturb the linearity of the fast switching gradient fields. The PET detectors require stable electrical signals that can be explored and verified in numerous systematic technical and phantom testing experiments. This requires testing in both directions to answer the following questions: Is PET performance influenced by the RF? MR performance influenced by the RF? PET MR testing encompasses testing for potential interactions with RF, B0, and Gx,y,z field homogeneity and artifacts [5]. Figure 3 shows RF noise testing – a routine system performance test in MRI. In this test, the RF receiver chain is set to a high receiver gain and then stepped in steps of 10 kHz through a varying bandwidth ranging from -250 kHz to +250 kHz around the Larmor center frequency in intervals of 10 kHz. The panel in (A) shows a selection of 4x4 images, each representing a frequency range of 10 kHz. The individual noise images here show neither increased noise nor any other discrete enhancement. Zoom-in (B) demonstrates the effect of disturbing RF noise, image (C) shows a single measurement disturbed by a discrete RF signal (vertical stripe on the right side of the image) that has been provoked by opening the two doors of the RF cabin during measurement.
sequences providing anatomical and functional tissue information simultaneously with a combined data acquisition with PET. Diffusion-weighted imaging (DWI), diffusion tensor imaging (DTI), arterial spin labeling (ASL), functional MRI (fMRI), MR-spectroscopy, time-of-flight angiography (TOF-MRA), dynamic cardiac acquisitions, etc., to name only a few. Finally the PET system performance has also to be tested for the potential influences of the strong magnetic field by gradient fields, or by RF interactions. Such testing performed according to NEMA standards [5] twice outside and inside of the MRI system and during system integration testing did not reveal any deviations from the PET performance without MRI surrounding.

Siting specifics

With this new hybrid imaging systems generation, combining the non-radiating imaging modality MRI with the nuclear medicine imaging modality PET, a couple of technical and logistical particularities have to be considered when it comes to siting of such a hybrid system. The high degree of system integration in case of the Biograph mMR helps to reduce the space that is required for system installation. This holds true for the scanner room as well as for the technical equipment room. The installation only requires a minimum of 33 m² of installation space for the scanner, electronics and console room. Figure 4 shows the Biograph mMR installation at the Institute of Medical Physics (IMP), University of Erlangen, Germany. When compared to the installation of a conventional standalone MR system, the MR/PET hybrid system does not require additional space in the scanner room and only requires one additional cabinet in the technical equipment room (Fig. 5).

Water cooling infrastructure is shared for both the gradient system and for the PET detectors. The additional cabinet in the technical equipment room contains the PET electronics and computers for signal processing and image reconstruction, respectively. Another requirement for the MR/PET hybrid system installation is a second filter panel in the RF cabin to feed the PET signals and associated cables through the wall between the system room and the technical equipment room. During the MR/PET systems installation at the Institute of Medical Physics, University of Erlangen, a second RF shielded door was installed in the RF cabinet. Although not a necessity, this installation at the IMP enables a patient to be brought directly from the ‘active waiting’ controlled area into the scanner room which then becomes a temporal control area and thus not affecting the operator room with radiation at any time. Thus personnel, researchers and potential visitors can stay in the operator room while switching patients in the scanner room.

RF coils and associated attenuation correction

Like its MR-only siblings, the Biograph mMR MR/PET hybrid system is equipped with a full set of RF coils and associated RF architecture – the well established Tim technology (Tim, Total imaging matrix, Siemens Healthcare). The Tim RF system provides seamless coverage of the patient’s body with integrated surface coils from head to toe (Fig. 6). The coils are each equipped with multiple RF coil channels providing a high coil element density for high SNR gain as well as parallel imaging capabilities with high acceleration factors in three spatial dimensions. While this integrated RF surface coil concept today is well established in MRI, its use in a combined MRI/PET hybrid imaging system is a novelty and prerequisite for seamless whole-body MR/PET acquisitions. The RF surface coils that cover the patient’s body for optimal MR signal performance are at the same time in the FOV of the PET detectors. Thus all RF surface coils now have to be also optimized towards PET-transparency, i.e. such coils should attenuate gamma quanta to only a minor extent, for optimized PET performance. This also holds true for all other hardware equipment – MR or PET related – that potentially accompanies the patient’s body when traveling through the PET-FOV, e.g. RF surface coils, the patient table, cables, connectors, patient monitoring equipment, etc. [6]. Here one can differentiate between ‘rigid and stationary’ equipment such as the patient table, the RF spine array coil as well as the RF head coil, and between ‘flexible and non-stationary’ equipment such as the flexible RF Body Matrix array coils. ‘Rigid’ here means stable in its form and geometry. ‘Stationary’ in this context means non-moving relative to the patient table whose position is known to the imaging coordinate system at any point in time when moving in the scanner bore.

The PET signal attenuation and scatter of rigid and stationary equipment can be compensated for by straightforward attenuation correction (AC) methods. For example, the RF head coil (Fig. 7A) is scanned in a CT (computed tomography)
system once and a 3-dimensional map of attenuation values $\mu$ thus generated (Fig. 7B). X-ray-based CT attenuation values in general are in the energy range of about 70–120 keV and thus have to be converted to the 511 keV energy level of the gamma quanta emitted in PET. A 3D graphical representation of the obtained attenuation values ($\mu$-map) with 511 keV attenuation values is then generated (Fig. 7C). This CT-based registration of 3D attenuation values has to be performed once for each rigid hardware component and then the according $\mu$-map becomes part of the PET image reconstruction process. By linking the RF spine – or RF head coils – position relative to the patient’s table position, the relevant AC $\mu$-map for each table position is automatically selected by the system for PET image reconstruction. The flexible and non-stationary Body Matrix RF array coils covering the patient’s body cannot be attenuation-corrected in the same manner. Here the geometry and position of the coils attenuating structures depend on the patient’s individual anatomy and on the individual situation of the patient exam and thus cannot be easily predicted by MR imaging. Here the emphasis lies on designing flexible and moving RF coils as PET-transparent as possible. For the Bio-graph mMR system, the associated RF coils have been further optimized in this regard. Potential design parameters for RF coil optimization are the choice of materials, the geometry, and the overall assembly. The ultimate goal of such an RF coil design optimization process is to maximize SNR and signal performance for MR while not disturbing PET-imaging.

### Attenuation correction for tissue

A necessity in PET-based imaging is the correction for attenuation and scatter resulting not just from the hardware in the PET FOV (e.g. patient table, and RF coils as described above) but also from the patient’s body, i.e. the anatomic distribution of soft tissues, air, and bones in the individual patient. Such tissue AC in PET-only systems traditionally has been performed by rotation of radioac-

tive $^{68}$Ge 511 keV sources around the patient and detection of the attenuated transmission signals ‘behind’ the patient. From a number of projections, a topography of attenuation values ($\mu$-map) could be reconstructed. This was a relatively slow process since fast methods are hardly distinguishable, in CT and PET imaging on the other hand air and bone show minimal and maximal attenuation values, respectively. Different methods have been described in the recent literature, that deal with MR-based AC for tissue segmentation. Based efforts. In the latter, the gray values provided by selected sequences are registered to different tissue classes resulting in tissue segmentation. Depending on the sequence type used, air, lung, fat, muscle, and bones might be segmented and provided with according PET correction values. In the current implementation of the Biograph mMR system, tissue attenuation and scatter correction is performed twice. The head-neck region is attenuation-corrected with the help of a UTE (ultrashort echo time) sequence [10, 11] providing segmentation also of the bone which in this region takes a large percentage of the imaged volume. All other body parts are attenuation-corrected by a Dixon technique providing two images where water and fat are in ‘phase’ and in ‘opposed phase’. This allows for reconstruction of fat-only, water-only and of fat-water images and results in tissue segmentation of air, fat, muscle, and lungs (Fig. 8) [8]. Bone is not accounted for in this approach. Initial results in patient imaging have shown that this approach works reliably and provides results that are comparable to corrected images form PET/CT in the same individual. The ultimate impact of this and other MR-based AC methods on PET-quantification and determination of standard uptake values (SUV) has not yet been determined and is subject to current investigations and further research efforts.
MR/PET simultaneous imaging workflow. MR and PET data acquisition is performed simultaneously during a multi-step examination with 6–7 bed positions for whole-body coverage. Depending on the selection of MR imaging sequences, such a whole-body MR/PET hybrid imaging study is regularly completed in about 20–30 minutes.

Imaging workflow

From a procedural point-of-view the imaging workflow of a whole-body MR/PET examination on the Biograph mMR is very similar to a whole-body MRI examination. First, the patient is prepped on the patient table. For that purpose the earlier described dedicated mMR Tim RF coils (head and neck coil, spine coil, and up to four body matrix coils) are positioned underneath, on and around the patient’s body, respectively. In this context the Tim RF coil technology is a prerequisite for seamless whole-body imaging without RF coil replacement and patient repositioning. Following patient preparation a localizer scan is performed covering the region of interest; in contrast to PET/CT, the acquisition time necessary for MR imaging can be the limiting factor with respect to the total scan time of a mMR exam. However, the additional MR scan time is not lost: Further MR sequences may add to the acquisition time of a specific bed position. This additional time can then directly be used for longer PET data acquisition, translating not only into improved PET image quality but allowing a longer time-period. Combining PET data and multiple MR sequences will increase the amount of images and complexity of reading, not only for whole-body applications, but also for dynamic MR/PET studies of the brain, making use of the syngo software functionality the localizer scan, as well as any further MR scan can be loaded per drag and drop from a predefined list of protocols and can also be adjusted according the user’s specific needs and saved afterwards as individualized protocols, similar to customization of MR protocols. Based on the localizer scan the combined MR/PET scan then is planned. Figure 9 shows the user interface for examination planning. The yellow boxes in the graphical slice positioning section indicate the acquisition volume for the MR sequences used in the attenuation correction, the green and blue boxes indicate the acquisition volume of the respective PET bed positions. The overlap between the bed positions is variable. When the planning for the AC sequence is finished and the scan is started, automatically the simultaneous acquisition of the PET starts as well and – bed position per bed position – the simultaneous acquisition of PET, MR AC scan, and any further MR scan for anatomy and function is performed. Additional MR sequences (beyond the AC scans) for assessment of anatomy and function can be chosen individually for each bed position. For a typical MR/PET scan using 18F-FDG for tumor staging, the overall scan time is defined not necessarily only by the PET acquisition time per bed but also by the additional time necessary to cover the region-of-interest; in contrast to PET/CT, the acquisition time necessary for MR imaging can be the limiting factor with respect to the total scan time of a mMR exam. However, the additional MR scan time is not lost: Further MR sequences may add to the acquisition time of a specific bed position. This additional time can then directly be used for longer PET data acquisition, translating not only into improved PET image quality but allowing the collection of dynamic PET data (this includes also gating / triggering of PET data). The acquisition of single bed positions for simultaneous MRI and PET, e.g. for dynamic MR/PET studies of the brain, is clinically possible and it should be emphasized that this possibility is also a direct consequence of the large z-axis coverage by the PET detectors, allowing to scan the whole brain or the liver without the need of repositioning over a longer time-period. Combining PET data and multiple MR sequences will increase the amount of images and complexity of reading, not only for whole-body applications.

Therefore an intuitive and powerful tool for evaluating mMR examinations was developed in parallel to the scanner hardware. After the acquisition of the MR/PET data the dedicated mMR Reader supports reading and diagnosing by an MR expert (also on different days and in different rooms) in several regards including advanced findings navigation and also by automatically merging these individual findings into one joint report.
First clinical examples

An early study was initiated in 2010 at the Institute of Medical Physics (IMP), University of Erlangen, in cooperation with Siemens AG Healthcare Sector, Erlangen. This study aimed at system integration testing and at showing system performance and full operability by scanning first patients. For acquiring these images, the study was setup as follows: Patients referred to PET/CT scanning were recruited from the Nuclear Medicine Department of the nearby University Hospital Erlangen. Patients had been injected the radioactive tracer 18F-Fluorodeoxyglucose (FDG) and had already undergone their PET/CT examination immediately before participating in the MR/PET imaging examination. This study design thus also had the benefit that the preceding PET/CT examination could serve as a ‘gold standard’ comparison for subsequent MR/PET imaging. No additional FDG injection or increased radiation dose was necessary. Due to the scanning PET/CT first, however, patients involved in this study had their MR/PET examination on average about 120 min after the injection of FDG. This is about 60 min later than the PET scan would usually have been performed after 18F-FDG injection. With the given half life time of 108 min for 18F-FDG, this has the effect that activity and thus count rate have already decreased since the PET/CT examination and additionally, FDG has been metabolized during a longer time window than usual. In our study, the effect of decreased activity has been compensated for by longer PET measurement times per bed position (i.e. 6 minutes instead of 2–3 minutes per bed position).
Status and outlook

The long-awaited hybrid imaging modality enabling simultaneous whole-body MR/PET imaging has entered the clinical arena. On the physics and hardware level, this new hybrid imaging modality demands clinical evaluation especially given the wealth of new diagnostic information generated by the integration of both imaging modalities. Here a special area of interest will focus on the streamingline and optimization of the imaging workflow of simultaneous MR/PET imaging. The ultimate goal is to generate whole-body PET/MRI data. Brockmann H, Krohn T, Buhl A, Günter RB, Molltjau FA, Krombach GA. Eur J Nucl Med Mol Imaging. 2011; 38:138-52. Review.

Acknowledgements

The authors would like to thank Dr. Matthias Lichy, Dr. Jürgen Kampmeier, Dr. Michael Lell, all University Hospital Erlangen, Germany, for their PET-transparency is another research field. On the clinical imaging level, this hybrid imaging modality is intended for use in a whole-body PET/MRI scanner. Med Phys. 2010; 55:4361-74. Review.

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Introduction

Over the last decade, development of hybrid-imaging instrumentation has been among the innovations with the strongest impact on diagnostic imaging in clinical everyday routine. The driving force behind these developments is the considerable extent to which several different imaging modalities show complementary rather than redundant features. Consequently, it is logical to bundle the particular strengths of different modalities into one hybrid instrument. Hybrid PET/CT entered the market in around 2000 and became a major success, thereby quickly obviating the demand for PET-only scanners. This has been strongly driven by the demand for PET-only scanners. This includes the head and neck region, abdominal/pelvis. In contrast to CT, MR-imaging is required for MR-image acquisition is severely affecting the acquisition of the PET-signal. In particular, the conventional photomultiplier technique commonly used for obtaining the PET signal does not work properly in a magnetic field. To circumvent this limitation, platforms have been developed in which spatially separate MR- and PET-scanners are connected by means of a moving table. The patient is positioned on this table and undergoes first PET and then MR imaging, without having to get up from the table between the scans. However, these solutions do not allow simultaneous image acquisition and they are of course associated with lengthy examination protocols and with the risk of patient movement. With the introduction of the so-called APDs ( Avalanche Photodiodes) into PET-MR instrumentation this problem has been solved more elegantly: APDs function in strong magnetic fields and can be used to substitute conventional photomultipliers to acquire information in the MR-scanner. The advent of this technology has allowed the industry to produce a first generation of hybrid MR-scanners in which a true integration of both modalities in a single machine has been realized (see H. Quick ‘Whole-body MR/PET hybrid imaging’ page 88 in this issue of MAGNETOM Flash). This principle was first successfully demonstrated by means of small head-only PET-scanners (PET-insert) which have been installed in conventional MR-scanners (see T. Beyer et al. ‘MR/PET-hybrid imaging for the next decade’, MAGNETOM Flash #45 3/2010 Research Supplement). Several studies have been performed in this prototype system since and proved the practicability of the concept [1–4]. On the basis of this prototype, a dedicated whole-body MR/PET system has now been developed. In November 2010, the world’s first integrated clinical whole-body MR/PET scanner (Siemens Biograph mMR) was installed in the Department of Nuclear Medicine at the Technische Universität München (TUM), in Munich, Germany. The scanner is now operated by a consortium between the directors of Nuclear Medicine (Prof. Dr. Markus Schwaiger) and Radiology (Prof. Dr. Ernst Rüegg). The setup of the first scanner of this type in Germany (and of three identical scanners which were installed in 2011 in Essen, Leipzig and Tübingen) has been made possible by funding of the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft, Berlin). The Biograph mMR/PET-scanner is constituted by a head end 3T MR-scanner which harbours a fully functional state-of-the-art PET system within the gap. The PET-system covers a field of view (25.8 cm) which is larger than in any other existing PET-camera. This allows to obtain multimodal (MR&PET) image information simultaneously in an entire body with a limited number of bed positions in short time. For further technical details on the system see page 88 in this issue of MAGNETOM Flash.

Opportunities of the MR/PET-system

From a clinical point of view, this system offers a number of obvious advantages:

1. Reduction in examination time

In comparison to clinical CT-examinations, MR-scans can often be relatively time-consuming. The recently introduced whole-body MR/PET scanner now allows the acquisition of MR and PET information in a truly simultaneous approach, i.e. in regional alignment at exactly the same time, thereby reducing not only the number of examination appointments (i.e. the visits patients have to make to the imaging department) but also cutting the required examination time approximately in half (as compared to two separate examinations). This option of ‘one-stop shop’ examinations represents a major gain in patient comfort for patients requiring both MR and PET examinations and also reduces the required time of the medical personnel to acquire the requested imaging information.

2. Regional oncogery

The acquisition of PET and MR information in exactly overlapping anatomical positions also offers clear advantages. Precise coregistration of the PET-signal with the underlying anatomical information is assured as the risk of patient movement or changes in organ position (e.g. in bowel positions, different bladder filling status) between the acquisition of the two modalities is reduced and potential misalignment is minimized. Due to the lack of radiation exposure by the MR-image acquisition, anatomical scans can be added/repeated to achieve optimal anatomical information.

3. Simultaneity of acquisition

The newly introduced integrated MR/ PET scanner allows for a truly simultaneous acquisition of imaging information from two different modalities in the same region at the same time. This opens a completely new dimension in hybrid imaging. Even established PET/CT technology only allows the acquisition of CT and PET in the same system but not at exactly the same time and region, as the two modalities/acquisition procedures are cascaded one after the other. The simultaneous acquisition of MR and PET information opens the opportunity to address many new scientific questions, which may be translated into clinical application, e.g. to cross-evaluate the value of different imaging tests under identical examination conditions or to improve understanding of disease pathophysiology by shedding light on the interrelation between different pathological processes. Simultaneous acquisition may also allow the following of organ and/or patient movement over time allowing for motion correction [2] and also the combination of information on motility with other functional information provided by PET (e.g. information on viability/perfusion derived from PET-imaging with information on wall motion in cardiac examinations).

4. Exposure to ionizing radiation

Radiation exposure based on clinical imaging tests is currently a much-discussed topic. Compared to PET/CT, hybrid MR/PET offers the chance to reduce ionizing radiation exposure without loss of diagnostic information. The radiation exposure is determined by the combination of the respective radiation exposure for PET and MR imaging (see page 68 on details on the system). The overall exposure is strongly dependent on the patient characteristics (e.g. body build, body position in the scanner) and may be considerably reduced when compared to conventional PET/CT imaging.

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Integrated Whole Body MR/PET Imaging. First Examples of Clinical Application

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1. Attenuation correction

In PET/CT systems, low-dose CT scans are used to estimate the expected attenuation of the radiation emitted from a specific body region. In contrast to CT, MR imaging does not provide information on tissue-specific photon absorption, but rather on tissue type/class. However, it has been demonstrated that by means of a set of specific MR-sequences (Dixon imaging or chemical shift imaging) suitable attenuation maps can be calculated, which allow an approximation of 511 keV photon attenuation correction with sufficient reliability [8]. The dual point VIBE T1-weighted Dixon sequence used for attenuation correction in the Biograph mMR can be acquired quickly for each bed position (e.g. in the thorax during one breathhold), practically not increasing the examination time. However, the current approach of tissue classification with the Dixon sequence is not yet fully satisfying, as it prone to metal artifacts, attenuation by bones is not considered and truncation artifacts may occur due to the limited transaxial field-of-view of the MRPET scanner (particularly of the upper limbs). The compensation for these artifacts is currently a matter of ongoing research. Moreover, it can be anticipated that different sequences for attenuation correction will be used in specific areas of the body. For the head e.g., bone probably cannot be neglected completely for truly accurate AC, especially for the skull base. Therefore in this region, the application of ultrashort TE (UTE) sequences might be favourable, which allows for delineation of the bone, thus leading to more exact attenuation maps (μ-maps) as compared to the Dixon imaging approach.

2. Anatomical allocation of PET-findings

The low dose CT scan of the whole body as acquired in conventional PET/CT provides limited diagnostic information but it allows a rough anatomical allocation of suspect PET-findings with sufficient reliability in many cases. For precise attribution diagnostic contrast-enhanced CT scans can be acquired in very short time and provide excellent anatomical information. By contrast, MR-sequences can be comparably slow and it may not be feasible to always acquire whole-body MR-information with high resolution in due time. However, it seems likely that the Dixon-sequences used for attenuation correction of the PET-data also can be used for anatomical allocation of PET-findings with very satisfying results. These whole-body images can then be complemented by added high-resolution MR-sequences in particular regions of interest.

3. MR-specific diagnostic limitations

It is expected that MRPET will be inferior to PET/CT for indications which are commonly addressed with better diagnostic value by CT, e.g. small pulmonary lesions. It remains to be evaluated for which indications MRPET is superior or equal to PET/CT and for which indications PET/CT will remain the method of choice.

4. Workflow

The high costs for this type of imaging instrumentation will require elaborate logistics regarding patient flow, occupancy of the scanner, selection of examination procedures etc., to assure efficient utilization of the scanner. The combined acquisition of MR and PET information defines the need for specially educated medical personnel experienced with both modalities.

5. Design of suitable imaging protocols

The large number of available MR-sequences and of different PET-tracers exponentiates the number of potential combinations of imaging tests. This will define the need to develop optimized imaging algorithms for specific diagnostic questions, which ensure the selection of the most beneficial combinations.

Examples for clinical applications

1. Oncology

Case 1 Patient with a cervical Non-Hodgkin lymphoma.

A: Overview using the opposed phase of the MR AC Dixon sequence. B: Axial slice of the 18F-FDG-PET image, demonstrating tumor-suspect increased metabolism in two lesions (left and the right lateral). C: Axial MR (STIR sequence) demonstrating the high tissue contrast. Several cervical lymph nodes are apparent, some enlarged. D: Overlay of PET and MR, easily tumor-typical (red arrows) and non tumor-typical findings (green arrow) can be identified and allocated anatomically.
**Case 2** Patient with a Neuroendocrine tumor.

- **A**: Overview using the water image of the MR AC Dixon sequence. Note the area of intense focal tracer uptake in the right upper quadrant of the abdomen, projecting on the region of the terminal ilium. There is a small bladder diverticulum of the left lateral bladder wall with tracer retention as accidental finding.

- **B**: PET-findings with 68Ga-DOTATOC, a tracer binding to somatostatine-receptors which are expressed frequently on neuroendocrine tumors. An intense focal tracer-uptake can be found in the abdomen.

- **C**: MR-image, fat-suppressed coronal T1w breathold VIBE sequence.

- **D**: Fusion of PET and MR-findings. An excellent identification and anatomical allocation of the tumor is possible by combination of PET and MRI findings. No additional suspect lesions are apparent.

**Case 3** Patient with bone metastases of a prostate cancer.

- **A**: Overview of the 18F-Fluoride PET scan. PET-findings. MR-image, sagittal fat-weighted MR AC Dixon sequence.

- **B**: PET-findings. Fluoride-PET Bone Metabolism.

- **C**: MR-image, sagittal fat-weighted MR AC Dixon sequence.

- **D**: Fusion of PET and MR-findings. Upper row: sagittal slices, Lower row: axial slices. The Fluoride-PET scan shows a number of suspect lesions in the skeleton, likely corresponding to bone metastases of the prostate-cancer. On the MR- and the fusion-images it is apparent that in the region of the increased PET-tracer uptake, displacement of the bone marrow has occurred, underlining the suspicion of bone metastases.
2. Neurology

Case 4 Patient with a glioblastoma multiforme.

A: $^{18}$F-FET PET scan. The tracer FET represents a measure of the amino acid metabolism and allows the sensitive identification of brain tumor tissue which is characterized by high amino acid turnover, in contrast to healthy brain tissue. A strong tracer uptake is visible around a previous resection area, suspect for remaining/recurrent brain tumor tissue.

B: MR-image, axial FLAIR-sequence, demonstrating a region of hyper intensity around the area of resection, potentially representing edema and/or gliosis, but also vital tumor tissue cannot be excluded. Moreover, a left frontopolar hygroma is seen.

C: Fusion of PET and MR-findings, allowing excellent anatomical allocation of the vital tumor tissue in reference to anatomical structures and abnormalities in the MR-image.

D: Fibre-tracking based on a diffusion-tensor MR dataset, demonstrating the course of neuronal axons alongside the resection area.

Case 5 Patient with Alzheimer’s disease.

A: $^{18}$F-FDG PET of the brain, which represents a measure of neuronal function. Areas with reduced neuronal function in consequence of ongoing neurodegenerative processes are displayed in green-yellow (left temporoparietal cortex, see red arrow), healthy brain regions in orange-red.

B: MR-image, axial FLAIR-sequence. Brain anatomy can be displayed in high resolution, cerebral atrophy is apparent in widespread regions, predominantly on the left side.

C: In the MR/PET fusion regional allocation of hypometabolism and brain substance loss is possible.

D: Fibre-tracking based on a diffusion-tensor MR dataset, demonstrating the course of neuronal axons in the brain of the patient.
Conclusions
- First clinical imaging studies demonstrate successful clinical applicability of integrated whole body MR/PET.
- Attenuation correction of the PET signal using appropriate MR-derived attenuation maps appears to be feasible with sufficient reliability for most cases. Some problems (lack of accurate bone-detection, truncation artifacts) are a matter of ongoing research.
- From a diagnostic perspective, superiority of MR/PET compared to PET/CT can be foreseen for indications/body regions, which would preferably be approached by MRI rather than by CT, due to the superior soft tissue contrast of MRI. Examples are:
  - Oncology: Head and neck tumors, masses in the pelvis/abdomen (e.g. prostate cancer), carcinoma of unknown primary, whole-body imaging
  - Neurology: Brain tumors, epilepsy, dementia, stroke
  - Cardiology: Regional function (wall motion) and scar detection (late enhancement) versus myocardial perfusion and tissue viability
- It remains to be evaluated for which indications MR/PET is superior or equal to PET/CT and for which indications PET/CT will remain the method of choice. MR/PET will probably be inferior to PET/CT for indications which are commonly addressed with better diagnostic value by CT, e.g. pulmonary lesions.
- The expected high costs for this type of imaging procedure will require elaborate logistics regarding patient flow, examination procedures, occupancy of the scanner etc., to ensure efficient utilization.
- The large number of available MR-sequences and of different PET-tracers exponenstially the number of potential combinations of imaging tests. This will define the need to develop optimized imaging algorithms for specific diagnostic questions.

References

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