New and Emerging Techniques: PET/MR

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Highlights

- Following PET/CT and SPECT/CT, PET/MR is the newest hybrid cardiac imaging modality.
- Attenuation correction (AC) and motion correction (MC) of PET data are current hot topics in PET/MR hybrid imaging research.
- Cardiac PET/MR is currently under investigation for assessment of cardiac function and viability, for diagnosis of cardiac inflammatory diseases and timorous diseases.

INTRODUCTION

Following PET/CT and SPECT/CT, PET/MR hybrid imaging is the most recent addition to the palette of hybrid cardiac imaging modalities. PET/MR synergistically combines the excellent soft tissue contrast and detailed image resolution of MR with metabolic information provided by PET. Integrated PET/MR systems furthermore offer the ability to acquire hybrid imaging data simultaneously (1). Beyond exact co-registration of PET and MR data this can be applied for MR-based motion correction of PET data. These features open up several cardiac applications, e.g. evaluation of cardiac function and viability, diagnosis of cardiac inflammatory diseases and tumorous diseases. To fully assess the diagnostic potential of PET/MR, however, several technical challenges have to be considered: attenuation correction (AC) of the patient tissues in PET/MR has to be based on MR-images and is currently hampered by a limited number of tissue classes and undercorrection of bone tissue. Cardiac radiofrequency (RF) coils and ECG gating equipment are currently not considered in AC. Consequently quantification of PET data therefore might be biased. The clinical workflow is rather complex and needs to be tailored to cardiac examinations. Few research groups currently explore this new hybrid imaging modality in selected cardiac applications.

TECHNICAL CONSIDERATIONS

Integrated PET/MR System Technology

To achieve a full integration of an MR and PET imaging modality in one whole-body system, numerous physical and technical preconditions and challenges had to be overcome (1). 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 required technical solutions such that PET hardware and PET signals are not disturbed by any of the electromagnetic fields of MR. Equally, for full and unlimited MRI system performance, PET must not disturb any of these electromagnetic MR fields and signals (2).

One current example of an integrated whole-body PET/MR system is the Biograph mMR (Siemens Healthcare Sector, Erlangen, Germany) (Fig. 1) (1-3). This hybrid system comprises a 3.0 Tesla whole-body MR system with a length of 199 cm (magnet length 163

cm) that hosts a fully integrated PET detector in its magnet isocenter providing a 60 cm diameter patient bore. Maximum gradient strength is 45 mT/m in all three axes and maximum slew rate is 200 mT/m/ms. The PET unit comprises a total of 56 LSO-APD detector blocks, each consisting of 64 crystal elements with a block area of 32 x 32 mm^2. The blocks are aligned circumferentially to form one PET detector block ring (Fig. 1). Eight detector block rings form the full PET detector unit, spanning a field of view of 25.8 cm in z-direction (2).

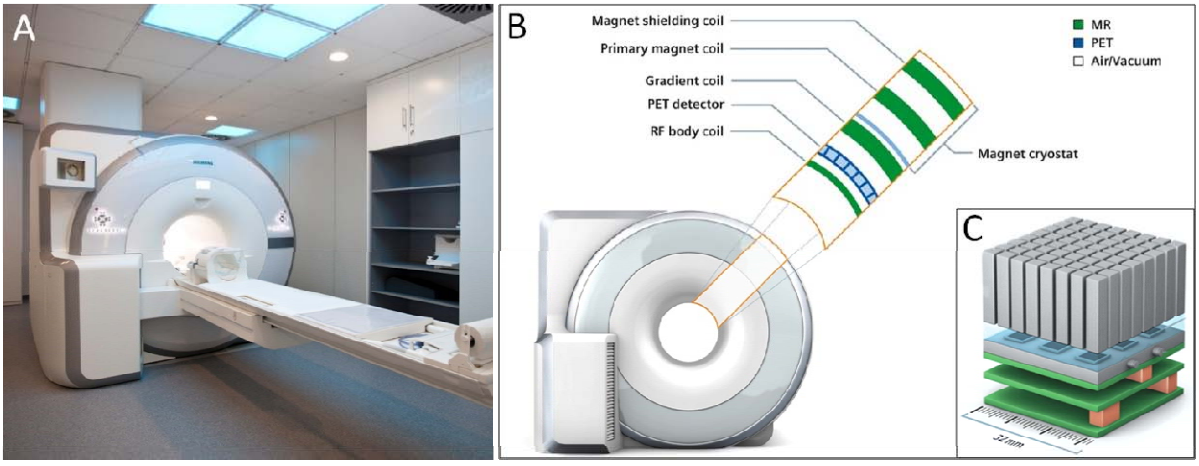

Figure 1: **(A)** Integrated PET/MR System (Biograph mMR, Siemens AG, Healthcare Sector) installed at the Institute of Medical Physics, University of Erlangen, Germany. **(B)** Schematic drawing showing the integration of the PET detectors in the MR hardware structure. From the inside to the outside: RF body coil, PET detector, gradient coil assembly, primary magnet coil, and magnet shielding coil. **(C)** PET detector assembly where 64 Lutetium Oxyorthosilicate (LSO) crystals form one detector block.

Attenuation Correction (AC)

PET data needs to be attenuation corrected in the reconstruction process in order to provide a valid quantification of tracer activity distribution in the human body (1). Scanner hardware components (e.g. table top, RF coils, ECG, etc.) as well as patient tissues within the FOV of the PET detector during data acquisition attenuate the number of true annihilation events and consequently lead to false results without AC. Depending on the relative position of the heart in the patient's body, the associated gamma quanta experience different attenuation on their way through different body tissues to the PET detector. Non-AC PET data generally shows underestimation of the tracer activity deep in the patient's body and in the heart. Since the PET/MR hybrid system cannot measure linear attenuation directly as in PET/CT hybrid imaging, AC here needs to be performed differently.

Human Tissue AC

Attenuation correction of human soft tissue is necessary to correct for the individual patient anatomy. Since no linear attenuation coefficient-based CT information is available in integrated PET/MR hybrid imaging, tissue specific AC has to be based on MR information which is based on proton density and relaxation properties (e.g. T1 and T2 relaxation times), rather than on the attenuation of X-rays in tissue. Both air and solid bone lack signal in MRI, thus these fundamentally different tissue classes are difficult to separate. In the current implementation of integrated PET/MR systems, tissue attenuation and scatter correction is performed using a 3D Dixon-VIBE technique, providing two sets of images where water and fat are "in phase" and "out-of phase" (Fig. 3) (4). This allows reconstruction of fat-only, water-

only and fat-water images and results in tissue segmentation of air, fat, muscle, and lungs in the reconstructed and displayed μ-maps (Fig. 2) (4). Cortical bone is currently not being accounted for in the Dixon-based AC approach. Bone is here classified as soft tissue and thus the exact magnitude of PET signal attenuation of bone might be underestimated (5).

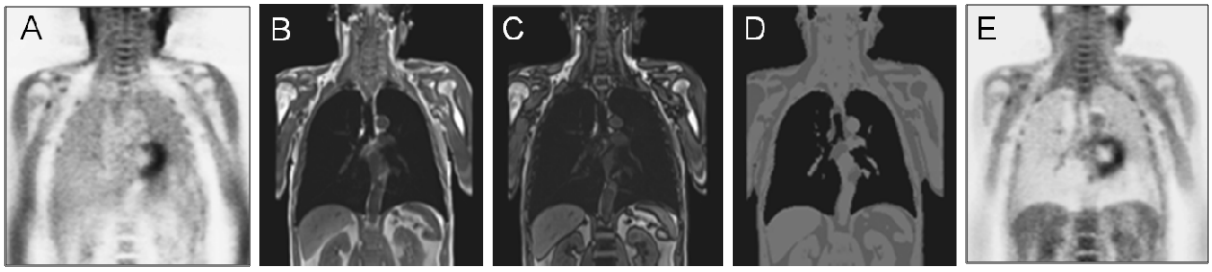

Figure 2: Soft-tissue attenuation correction (AC) based on MR imaging. (A) Uncorrected thorax PET scan showing relative activity enhancement in the lungs and along the outer contours of the patient. (B and C) 3D Dixon-VIBE MR sequence providing separate water/fat "in-phase" and "opposed phase" images that serve as basis for soft-tissue segmentation. (D) Segmented soft tissue groups (air, fat, muscle, lungs) that can be assigned to a 3D PET attenuation map. (E) Resulting attenuation corrected PET scan of the initial data set (A). Note: Bone signal is assigned as soft tissue values in this MR-based approach for AC.

Hardware Component AC

Radiofrequency surface receiver coils are a technical precondition for high resolution MR imaging and are well established in clinical MRI. In integrated PET/MR cardiac imaging, the patient is placed on top of a rigid phased-array spine RF coil. For anterior signal detection a second body phased-array RF surface coils is placed on the thorax of the patient during simultaneous MR and PET data acquisition (Fig. 3). Thus, all RF surface coils used in the PET field-of-view during simultaneous PET data acquisition have to be optimized for PET-transparency, i.e. such coils should attenuate gamma quanta only minimally (6-9).

The PET signal attenuation of rigid and stationary equipment such as the RF spine array and the RF head/neck coil can be compensated for by straightforward AC methods. After scanning this equipment by using CT, a 3-dimensional (3D) map of attenuation values can be generated. This data can then be converted into a 3D representation of the 511 keV attenuation values, the so-called "μ-map". By linking the RF spine – or RF head coils position to the patient's table position, the corresponding AC μ-map for each table position is automatically selected by the system for PET image reconstruction.

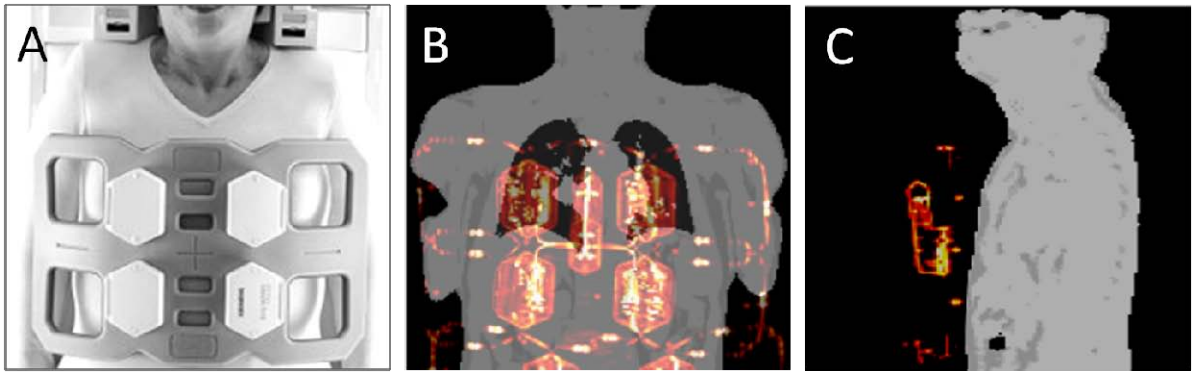

Figure 3: (A) 6-channel thorax radiofrequency coil that can be used for MR signal reception during simultaneous cardiac PET/MR data acquisition. Images (B and C) show MR-based attenuation maps of the patient tissues that were acquired with a 3D Dixon sequence. The hardware attenuation correction map of the flexible RF coil (orange/red color) here was automatically co-registered with non-rigid registration to the patient tissue AC map using visible markers. Such attenuation maps represent the geometric distribution of PET signal attenuating hardware and soft tissue structures in the PET field-of-view during simultaneous PET and MR data acquisition.

For flexible surface RF coils like the 6-channel RF body phased-array (Fig. 3), the AC is performed differently. Because the design is flexible, the individual position and shape of this RF coil during a patient examination is not known. Thus a pre-acquired rigid 3D CT template cannot directly be co-registered (8). Here visible markers can be used to perform an automatic non-rigid co-registration of the pre-acquired 3D CT attenuation template to the individual position and shape of the flexible RF during the cardiac PET/MR examination (10).

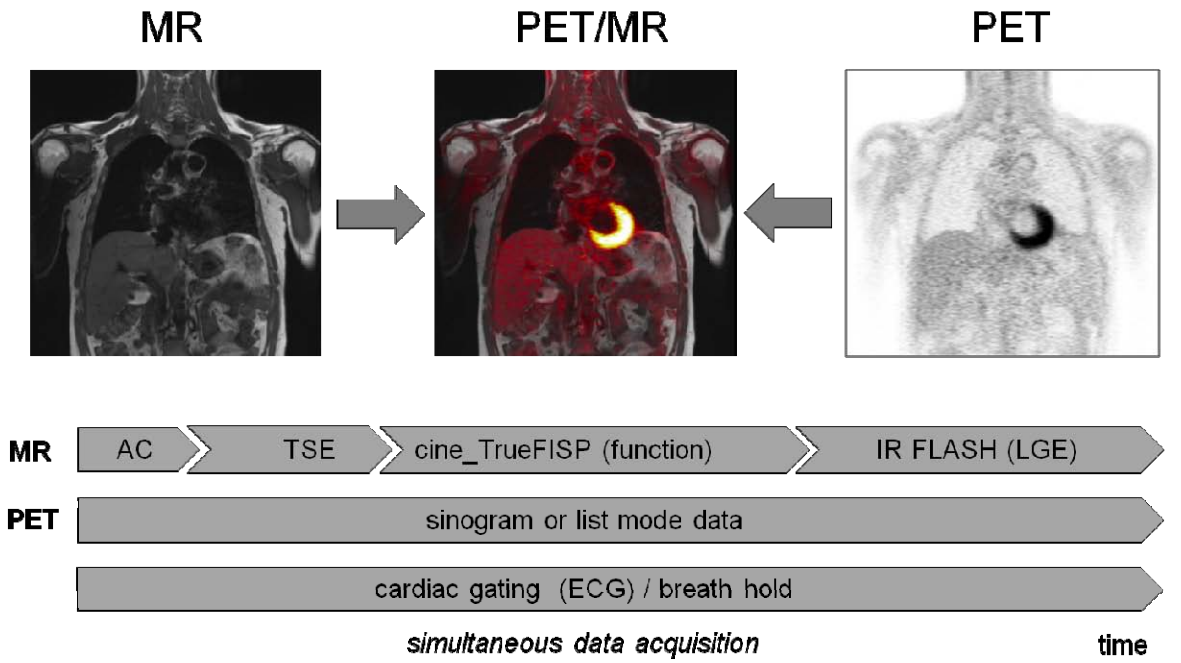

Figure 4: PET/MR simultaneous cardiac imaging workflow. MR (left) and PET (right) data acquisition is performed simultaneously. A standard cardiac MR examination encompasses e.g. sequences for attenuation correction (AC), TSE for anatomic reference, and cardiac gated cine-TrueFISP sequences for assessment of cardiac function. Late gadolinium enhancement (LGE) reveals cardiac infarction that then can be correlated to the metabolic information of simultaneously acquired FDG-PET.

Motion Correction (MC)

Integrated PET/MR systems provide the inherent advantage of simultaneous PET and MR data acquisition. In view of motion correction (MC) this is an inherent advantage over PET/CT that is currently being further explored (11,12). While in PET/CT the CT data is static and for dose considerations is acquired only once at the beginning at a typical hybrid examination, the MR data in PET/MR is acquired simultaneously to PET data acquisition and this applies to data acquisition in each bed position. This inherently leads to less deviation and less gross motion between both imaging modalities when compared to PET/CT imaging. Furthermore, real-time MRI data and 4D MR data of breathing motion can be used to retrospectively motion correct PET data to provide improved fusion of PET and MR data sets (11,12). This may potentially lead to improved lesion visibility in the lungs, upper abdomen, and liver and may also result in better quantification of activity in the myocardium since all structures are depicted with sharper contours and less smeared over a larger volume which otherwise leads to reduced standardized uptake values (SUV) of regions subject to motion (12).

CLINICAL APPLICATIONS

Cardiovascular Disease

Integrated PET/MR appears an attractive diagnostic tool in cardiovascular disease since it combines the strength of MR imaging in providing anatomic, functional, flow, and perfusion information and the strength of PET imaging in quantifying physiologic and metabolic processes in vivo (13). Potential clinical applications in cardiac imaging have been identified, such as the detection of myocardial viability (13) where the unique strengths of each modality could potentially be combined to complement each other (14,15). In a recent simultaneous PET/MR feasibility study Nensa et al. investigated 20 patients with myocardial infarction. The results of the study demonstrated high correlation of ischemic myocardial segments in MR late gadolinium enhancement (LGE) and 18F-FDG (PET) (16). Schneider et al. in an initial study suggest PET/MR hybrid cardiac imaging for diagnosis, monitoring, and treatment of cardiac sarcoidosis (17).

Hybrid imaging with PET/MR may also find a role in atherosclerotic imaging. Initial experimental studies on atherosclerotic rabbits with PET/MR using ultra small particles of iron oxide (USPIO) for contrast enhancement in MR and 18F-FDG as PET tracer allowed for assessment of changes in the inflammation of atherosclerotic plaques (18). The authors concluded that 18F-FDG PET seemed more sensitive than USPIO MR to detect early changes in plaque inflammation (18).

With the heart being subject to cardiac and breathing motion during PET and MR data acquisition, it is expected that the further development and application of advanced triggering, non-rigid motion correction and attenuation correction methods will have a substantial impact on PET/MR cardiac imaging in general and more specific in myocardial tissue quantification (19).

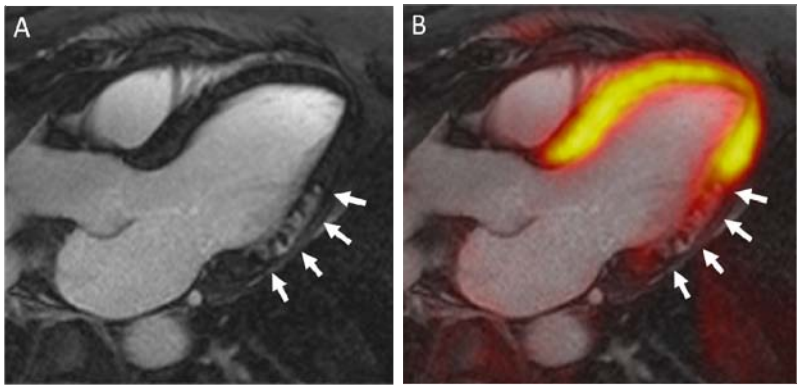

Figure 5: Simultaneous cardiac PET/MR with 18F-FDG after oral glucose loading in a patient with STEMI because of an acute occlusion of the left circumflex artery (CX). Imaging was performed 5 days after the event and subsequent interventional revascularization. The left image shows late gadolinium-enhancement (LGE) with transmural extend (bright area in the lateral wall, white arrows in **A**) and areas of microvascular obstruction (dark spots within bright area). The right image shows a fusion of the MR image on the left and the corresponding PET image. The fusion shows almost perfect agreement between LGE and reduced glucose uptake (white arrows in **B**). Courtesy of F. Nensa and T. Schlosser, University Hospital Essen, Germany).

CONCLUSION

While clinical experience with cardiac PET/MR hybrid imaging is still sparse, the great diagnostic potential of this new hybrid modality becomes increasingly visible. Unlike any other clinical PET/MR imaging application, cardiac PET/MR will benefit from further evolution and application of attenuation correction and motion correction algorithms to unveil its full diagnostic potential.

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