Feasibility of Sequential PET/MRI Using a State-of-the-Art Small Animal PET and a 1 T Benchtop MRI

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Abstract
Purpose: Combined PET/MRI studies receive increasing attention, as their combination allows deeper insight into disease progression. We evaluated a novel 1 T benchtop MRI scanner (1T-MRI) for its use in sequential PET/MRI studies.

Procedures: Phantom studies were performed, addressing the attenuation caused by the MRI coils. For in vivo studies, PET/MRI data acquired with the 1T-MRI were compared with data using a conventional small animal high-field MRI (7T-MRI) in combination with the same PET scanner.

Results: Phantom and in vivo measurements show that the animal beds have no negative impact on the PET scanner performance compared to the 7T-MRI animal bed. Representative images of various animal studies are shown, indicating a wide field for sequential PET-benchtop MRI applications.

Conclusion: Phantom and in vivo data indicate that sequential PET/MRI studies with this novel setup are comparable to sequential PET/MRI studies using a 7T-MRI in combination with a dedicated PET scanner.

Key words: Benchtop MRI, Small animal PET, PET/MRI, Multimodal imaging

Introduction

Over the past few decades, non-invasive in vivo imaging has provided detailed information on morphological, molecular, and functional properties and how they change with disease progression, thus improving healthcare and allowing the development of new strategies in basic biomedical science [1]. While each modality has its strengths, each also has inherent drawbacks. Therefore, a lot of effort has been devoted to combine different imaging modalities as positron emission tomography (PET) with X-ray computed tomography (CT) [2] or, very recently, PET with magnetic resonance imaging (MRI) [3–6]. The combination of the molecular information provided by PET or single photon emission computed tomography (SPECT) and the anatomical information provided by CT or MRI allows very detailed insight into disease progression in preclinical research [7, 8] and in the clinics [6, 9–12]. Specifically, in preclinical research, the advantages of combining PET and MRI are obvious, as MRI yields detailed anatomical information without requiring large quantities of contrast agents as in small animal CT [13]; however, one major restriction so far is the enormous effort required to install and maintain a high-field small animal MRI system, as often

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extra radiofrequency (RF) shielded cages, cryogenic cooling, and usually an extra room for the electronics are necessary. New permanent magnets with a field strength of 1 T make benchtop MRI systems feasible at costs between three and six times lower than a 7 T animal MRI scanner. With their negligible stray field, they may be placed near dedicated small animal PET scanners, enabling sequential PET/MRI studies, thus combining the advantages of both modalities and providing results comparable to a full-scale sequential PET and high-field MRI measurement, with few restrictions in MR image quality and animal handling. In this study, we evaluated the feasibility of sequential PET/MRI studies using a 1 T benchtop MRI and a dedicated PET scanner and compared the system with a sequential PET/MRI study using a 7 T high-field small animal MRI and the same PET scanner. This design was intended to allow a direct comparison of the differences in results arising from the differences in field strengths and animal handling, and their impact on small animal PET/MRI studies. Therefore, we provide image examples and quantitative results demonstrating that sequential PET/MRI studies have been successfully performed using the 1 T benchtop MRI and the PET scanner.

Materials and Methods

Imaging Hardware

**PET** All PET studies were performed on a small animal PET scanner [Inveon dedicated PET (DPET); Siemens Healthcare, Knoxville, TN, USA]. The scanner acquires the data exclusively in list mode, with a timing window of 3.432 ns and an energy window of 350–650 keV. In this setup, the reported spatial image resolution was 1.46 mm and the detection sensitivity was 5.75 % [14]. The scanner is equipped with a $^{57}$Co source that rotates around the object of interest to generate transmission data, allowing correction for attenuation of the 511 keV photons. All PET emission data were reconstructed using the OSEM2D reconstruction algorithm (matrix 128, zoom 1, 16 subsets, four iterations), yielding a voxel size of 0.8 mm$^3$; default methods for dead time correction, decay correction, and component-based normalization were applied to all datasets.

**MRI** MRI was performed on two dedicated small animal tomographs, a 1 T benchtop MRI scanner [Icon (1T-MRI); Bruker BioSpin GmbH, Ettlingen, Germany] and a 7 T MRI scanner [ClinScan (7T-MRI); Bruker BioSpin GmbH].

The 1 T benchtop MRI was installed within one working day, and it was placed less than 2 m from the dedicated small animal PET scanner. The system consists of a 1 T permanent magnet (without extra cooling required for the magnet) mounted on a 1.8 × 0.8 m$^2$ table, providing enough space for the operational electronics, an anesthesia system, and a host computer. Its gradient coil provides 450 mT/m. The scanner’s fringe field is enclosed in the entire footprint of the 1T-MRI, which is less than 2 m$^3$, although the recommended minimum floor dimensions are approximately 2.6 × 2.9 m$^2$ (according to Bruker BioSpin site planning information). As the external stray field is negligible, the operation of other magnetic-field-sensitive equipment in close proximity to the 1T-MRI is possible. An important issue was to ensure that the surface of the floor can bear the ∼905 kg/m$^2$ load.

After installation, the scanner is fully operational within less than 3 min. The user interface to control and operate the scanner is based on the Syngo software (Siemens Healthcare), which is also used to control and operate clinical MRI scanners. When referring to sequential PET/MRI studies, the terms “1T-setup” and “7T-setup” will be used, depending on which MRI scanner was used in combination with the DPET. An overview of the available dedicated small animal beds and RF coils of the 1T-MRI, as well as the 7T-MRI mouse whole-body bed and the corresponding whole-body RF coil, is presented in Supplemental Fig. 1.

The animal handling systems and RF coil “philosophy” are inherently different between the 1T-MRI and the 7T-MRI. For the 1T-MRI, the entire animal handling system with integrated anesthesia, animal warming, respiration trigger, and RF coils mounted onto or integrated into the bed allows the animals to be handled on the bed with accurate positioning of the coil, outside of the scanner with full control of the anesthesia and of the body temperatures, enabling a safe transfer between the scanners. Therefore, during sequential PET/MRI studies using the 1T-setup, the coil is already mounted for the PET measurements, increasing attenuation and scatter of the photons during the PET acquisition.

For the 7T-MRI, the RF whole-body coil is installed inside the scanner and the animal bed, including all connections for anesthesia, animal warming, and physiology monitoring is slid into it.

Phantom Studies

**Evaluation of the DPET Performance for PET/MRI Studies** To evaluate the PET performance in the combined PET/MRI studies, where RF coils and dedicated beds are required, a PET/MRI phantom study was performed using a single sphere with a volume of ~18 µl and a diameter of 3.2 mm, located in the center of a cylindrical phantom with a volume of ~10 ml, a diameter of 18 mm, and 40 mm in length. The phantom was placed on a 1T-MRI mouse whole-body bed, including the corresponding mouse whole-body coil, as this is the most frequently used setup in our laboratory. The results obtained allow a direct comparison with phantom measurements performed earlier in our laboratory, using the same phantom and addressing the performance of the same PET scanner under ideal conditions. Specifically in that study, there was no other material around the phantom that might attenuate the emission data or cause photon scatter [15]. The sphere was filled with $11.3±2.3$ MBq/ml of $^{18}$F and positioned in a background activity of $1.5±0.3$ MBq/ml, yielding a target-to-background ratio of ~8. MR images were acquired with the 1T-MRI using a T2-weighted anatomy multi-slice-muli-echo (MSME) protocol (Table 1) which yielded a signal-to-noise ratio (SNR) of 169 in the manufacturer’s standard