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# PET/MRI system design

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**Abstract**

*Introduction* The combination of clinical MRI and PET systems has received increased attention in recent years. In contrast to currently used PET/CT systems, PET/MRI offers not only improved soft-tissue contrast and reduced levels of ionizing radiation, but also a wealth of MRI-specific information such as functional, spectroscopic and diffusion tensor imaging. Combining PET and MRI, however, has proven to be very challenging, due to the detrimental cross-talk effects between the two systems.

*Objective* Significant progress has been made in the recent years to overcome these difficulties, with several groups reporting PET/MRI prototypes for animal imaging and a clinical insert for neurological applications being demonstrated at the 2007 Annual Meeting of the Society of Nuclear Medicine.

*Discussion* In this paper we review different architectures for clinical PET/MRI systems, and their possibilities, limitations and technological obstacles.

**Keywords** Positron emission tomography · Magnetic resonance imaging · Instrumentation · Equipment design

## Introduction

Following the extensive research effort dedicated to software coregistration in the 1990's, the introduction of combined positron emission tomography (PET) and computed tomography (CT) systems [1] was met with enthusiasm by the medical community. Nine out of ten PET scanners purchased today are combined PET/CT systems. The key to this success was not just the straightforward solution to the coregistration problem in most applications, but also the significant improvement in workflow from scanning the patient quasi-simultaneously and from avoiding a standard PET transmission scan. PET/CT is currently fully integrated into clinical routine, but although its advantages are many, CT still provides limited soft-tissue contrast and, when used for whole-body diagnosis, may expose the patient to high radiation doses (over 10 mSv) [2]. An alternative source of anatomical information would be magnetic resonance imaging (MRI) [3].

Combining MRI and PET, however, has proven to be very challenging, due to known and potential crosstalk effects. Indeed, the static magnetic field, rapidly changing gradient fields and radiofrequency (RF) signals from the MR affect the light yield of scintillator materials [5], prevent the normal operation of photomultiplier tubes (PMT) and induce interference in the front-end electronics of PET detectors. Conversely, the mere presence of the PET detector causes inhomogeneities in the magnetic field, which can lead to artefacts in the MR images. Furthermore, it can emit signals interfering with the RF and gradient coils, both due to its normal operation and to Eddy currents induced by the changing magnetic field.

However, in recent years, progress has been made in identifying scintillators with adequate magnetic properties [6], in developing suitable PET detectors which use optical fibres to guide the scintillation light away from the MR magnetic fields [4, 7–10] or that replace the PMTs by magnetic field-insensitive avalanche photodiodes (APD) [11, 12, 14–16], or design shielded PET electronics to avoid electromagnetic interference [17].

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Several research groups have successfully developed small PET/MRI prototypes for small-animal studies [13, 24–26]. One medical equipment manufacturer has introduced a human-sized prototype design for neurology applications [28]. However, there is still no consensus on what is the best configuration for a clinical PET/MRI system, especially for whole-body imaging. There are essentially three main approaches to combine a PET and a MRI system (Fig. 1):

1. A first approach would be to combine them in the same manner as current commercially available PET/CT systems, i.e. to place both modalities in tandem and physically separated. This mandates only minimal modifications to the existing PET and MRI systems.
2. A second approach involves a removable PET insert, which is placed within the bore of the MR system. While only minimal modifications are required for the MRI system the PET system has to be redesigned completely.
3. A third approach would be to integrate the PET detector ring within the MR. This is the technologically most challenging approach, requiring significant changes to both systems.

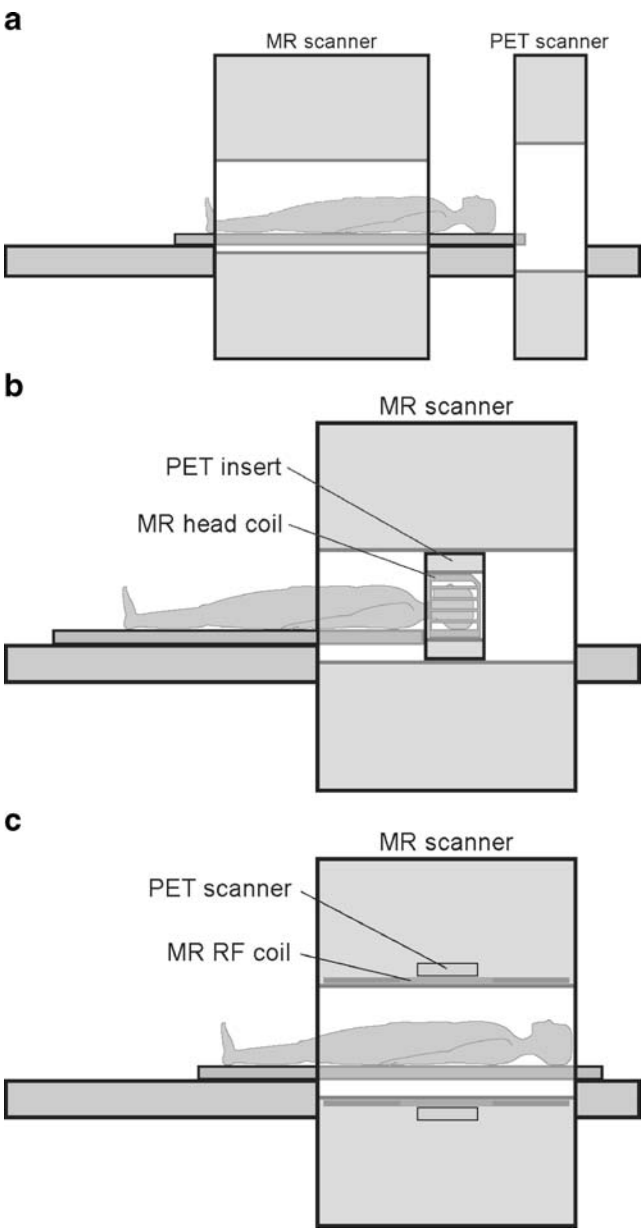


**Fig. 1** Integrated design for combining PET and MRI systems: **a** sequential, **b** insert, **c** integrated

In this paper we discuss the advantages and disadvantages of the above approaches. We provide an overview of the different set-ups investigated by the various groups that have reported on working PET/MRI prototypes.

## PET/MRI system designs

### Sequential architecture

The most straightforward way to create a combined PET/MRI system would be to adapt existing PET and MRI technology to work in a coplanar, tandem configuration. This is the design used in all the existing PET/CT systems. In this approach, the patient is placed on a common mechanical bed that slides through the MR and PET field-of-view (Fig. 1a).

An evident advantage of this configuration is that it minimizes the degree of adjustment of the individual system components. This could lead to a short product development time since many existing modules developed for stand-alone PET and MRI could potentially be used in a combined system.

Naturally, the presence of the magnetic field means that even this simple architecture involves more than merely placing two existing scanners side-by-side and networking them. Either significant separation and shielding [18] or magnetic field-insensitive photodetectors must be employed. Measures must still be taken to prevent interference both from and with the field, although the separation between the two components makes electromagnetic shielding a much easier task. Furthermore, increased physical separation has occasionally been advertised as a way to reduce patient claustrophobia and to improve physical access to the patient during the examination.

From the software and front-end point of view, this approach would also require minimal modification of the existing packages, needing little more than the introduction of a tool to define the scan sequence and automate the bed displacement.

However, a disadvantage of this first design concept is the inability to perform true simultaneous PET/MR imaging. Performing PET and MRI sequentially instead may potentially lead to unacceptably long total examination times in whole-body imaging, which may become a major disadvantage for clinical users. Furthermore, coregistration errors due to physiological activity and patient motion during the scan transition could be challenging to correct retrospectively. Finally, tandem system configurations come at a cost in terms of room size. If the bed is to move the full length of the patient through both systems and to cover the coaxial displacement, medical centres intending to replace existing facilities should consider carefully if their magnetically shielded rooms have the necessary extra space.

## Insert architecture

The main idea behind this concept is to build a removable PET insert capable of working within the bore of a conventional MR, while leaving most of the associated electronics in a separate location with lower magnetic flux density next to the MR gantry (Fig. 1b). The main technical challenge of this approach with respect to the tandem configuration is the introduction of electronic circuits in the magnetic field. Several issues therefore need to be taken into account for the insert to function properly:

- The magnetic susceptibility of the used materials must be such that the disturbance to the magnetic field is minimized.
- The devices used for the scintillation light readout and amplification must either be insensitive to the magnetic field or sufficiently separated from the MR.
- All electronic parts must be shielded to prevent the changing gradient field and RF signals from causing induced electromagnetic interference.

Cherry's group at UCLA [10] was the first to develop MR-compatible PET detectors. The detector principle was based on the use of 4-m long optical fibres to guide the light from the scintillator crystals to position-sensitive PMTs situated where the magnetic field dropped below 10 mT. Based on this technology, the first simultaneous PET/MR phantom images were obtained using a 38-mm diameter LSO ring within a 0.2-T scanner [19]. Artefact-free simultaneous PET and MRI was demonstrated with a similar prototype and various MR acquisition protocols [20]. This kind of design, however, leads to poorly performing PET, partly due to the signal loss in the long light guides [8].

APDs have been used instead of PMTs to avoid having to guide the scintillation light outside the magnetic field [15, 21]. APDs are compact, have higher quantum efficiency than PMTs, require a lower supply voltage and above all, are capable of operating in high magnetic fields. On the other hand, ADP-based measurement are noisier than those based on PMTs, which has a detrimental impact on energy and timing resolution. In addition, APDs have a relatively low gain, and, thus, require more powerful preamplifier electronics and close temperature monitoring [22].

Electronic considerations set aside, this architecture has a very important limitation in the fact that once the insert is fitted within the bore of the MR scanner, there is little space left for the patient. This fact, however obvious, has important consequences both for the insert design and its applications. For one, limiting the radial extent of the insert means limiting the length of the scintillator crystals, and thus the detector sensitivity. Heat management is also complicated by size restrictions. From the applications point of view, the available field-of-view will, for the time being, restrict this architecture to small animal studies and either neurological or limb explorations in humans.

Despite these technical challenges, the insert offers a unique feature that constitutes its main advantage with respect to sequential architectures, which is the option to perform simultaneous PET/MR acquisitions. This not only leads to a reduction in the overall acquisition time, but, more importantly, opens the way to a whole range of novel applications, such as simultaneous fMRI/PET, kinetic studies, etc. The simultaneous acquisition of PET and MR data guarantees a perfect geometrical coregistration of the two examinations.

The acquisition of simultaneous PET and MR imaging as well as MR spectroscopy for small animals was first reported by Carson et al. [23] who used optical fibres to couple the scintillators to an external detection module (Fig. 2a). A similar system with two opposite detector heads instead of a full detector ring was also described Raylman et al. [24].

More recently, a nonmagnetic version of the APD-based RatCAP tomograph was described by Schlyer et al. [25] (Fig. 2b). Here the PET detector ring is mounted on the animal head and not attached to the MR unit.

A collaborative effort between the University of California Davis and the University of Tübingen has led to the development of two different PET insert prototypes which are fitted inside the bore of an animal MR system. In one design short optical fibre bundles are used [12, 13] (Fig. 2c), while the second approach uses direct coupling to the scintillators [26] (Fig. 2d). So far, the only example of such a system for human imaging is an APD-based PET insert for 3-T MRI that was first demonstrated at the 2007 Society of Nuclear Medicine Meeting [27, 28].

All things considered, this architecture offers clinical centres already equipped with an MR system a rather cost-effective access to PET/MRI without major modifications of their existing facilities—other than the unavoidable

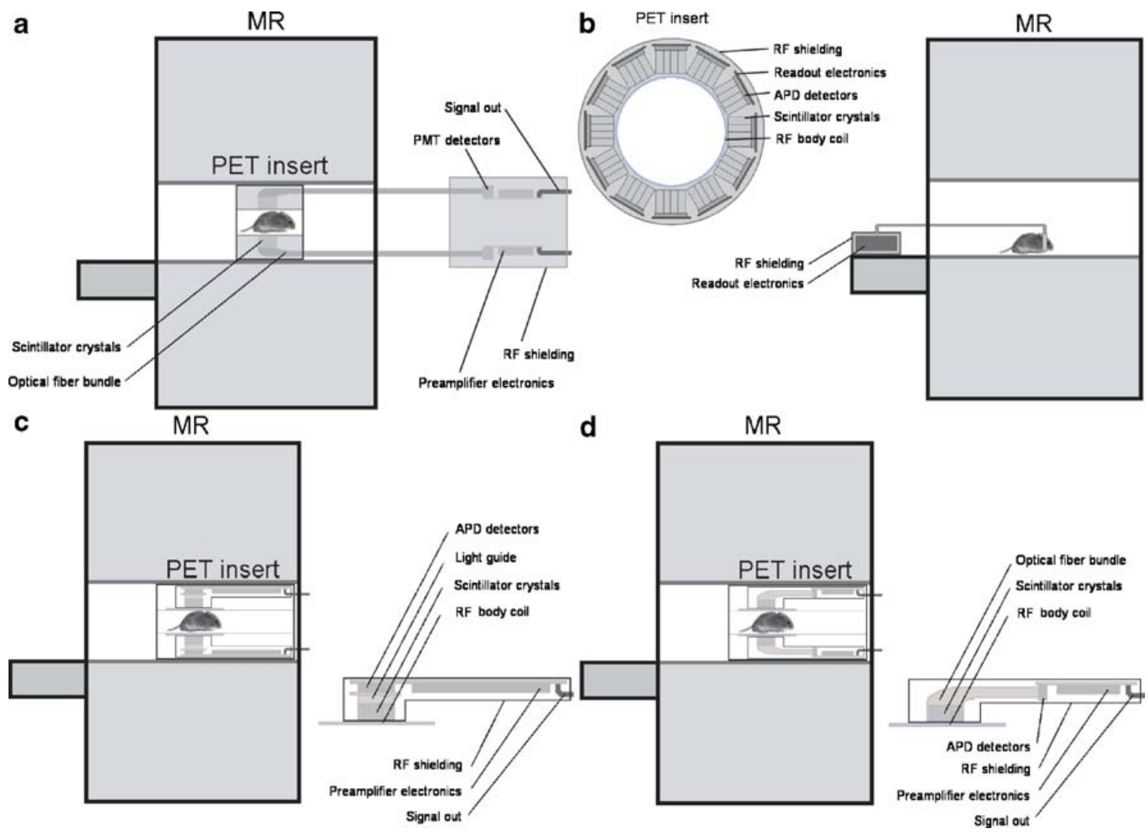


**Fig. 2** Small-animal PET/MR imaging: **a** based on photomultiplier detectors linked to the scintillator via optical fibres array; **b** based on a nonmagnetic version of the RatCAP tomograph [25]; **c** based on APD detectors linked by optical fibres to the scintillator array; **d** based on APD detectors directly coupled to the scintillator array

radiation protection certification. Furthermore, the possibility of removing the insert to perform conventional MR acquisitions provides great flexibility to centres that cannot afford a dedicated PET/MRI system. The existing PET insert, for instance, can be installed or removed in a couple of minutes.

## Integrated architecture

This approach aims at whole-body PET/MRI scanning while retaining the possibility of simultaneous acquisition. The way to achieve this is the complete integration of the PET detector and electronics within the MR system (Fig. 1c). From a technical point of view this is naturally the most challenging approach. However, the inherent potential for new diagnostic and research applications would be a big advantage of this architecture.

The designs currently being investigated rely on the use of a split superconducting magnet [7], on the use of field-cycled MR [29] or on the insertion of the PET detector ring between the gradient and body coils of the MR (Fig. 3).

In the first case the MR superconducting coil is built in two separate elements, leaving between them an axial space of several centimetres in which a PET scintillator ring can be accommodated. The scintillation light is guided by radially distributed fibre optic bundles to PMTs situated outside the 1-mT fringe field. Such a system is currently being tested for preclinical imaging at the Neuroscience Department of the University of Cambridge [7]. This design requires a low-field magnet and specialized gradient set, which probably restricts this approach to small-animal imaging.

In the case of field-cycled acquisition, two separate and dynamically controllable magnets are used for polarization and readout. This enables interleaving in the acquisition of MR data certain temporal frames free of magnetic field, in which the PET acquisition can take place. This design, like the previous one, is for the moment restricted to preclinical imaging.

In the last case both the scintillator crystals and the associated photodetectors are located between the RF and the gradient coils of the MR. Naturally, the limited space available leads to severe constraints on the PET geometry. For example, the radial extent of the scintillator crystal needs to be shortened, thus, reducing the detection efficiency. The diameter of the detector ring has to be adapted as well, thus, resulting in a smaller ring compared to standard geometries. Heat management in such a reduced space is also a challenge, yet critical if APD technology is used.

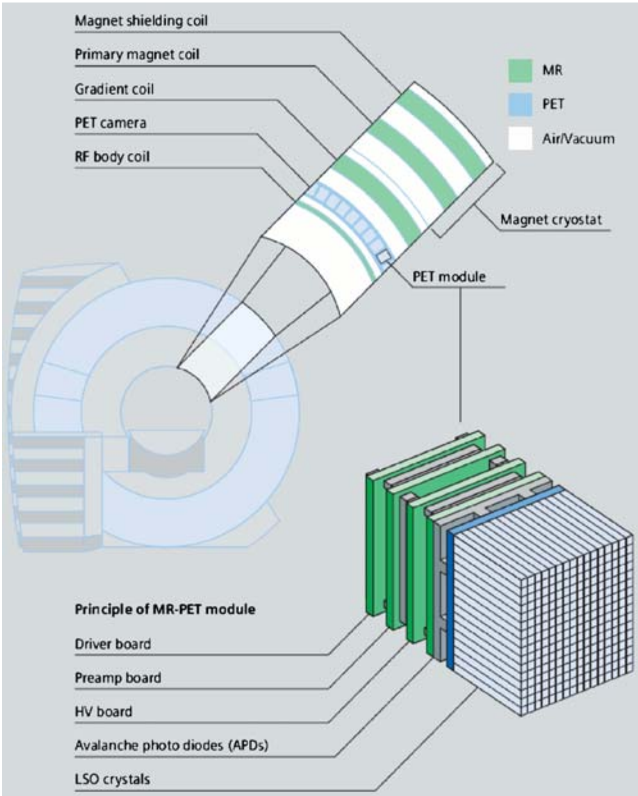


**Fig. 3** Integrated system architecture for PET/MRI in humans. Reproduced with permission of the authors [35]

An additional approach has been proposed recently within the context of the European FP7 project. The project "Hyper Image" (www.hybrid-pet-mr.eu) seeks to construct PET/MRI system based on a split gradient coil to provide extra space for the PET ring. This would considerably simplify the integration, allowing a larger portion of the processing electronics to be directly coupled to the detectors, thereby making the output signals more robust to interference. At the time of writing, this project is at a very early stage and no prototype is yet available to study the effect of such a design on MR image quality.

## Performance characteristics of integrated PET/MRI

For the last couple of years our own group has been using Monte Carlo simulation techniques to investigate the performance that can be expected from an integrated PET/MR system [30]. The results show that the augmentation of solid angle coverage leads to an expected overall boost in sensitivity. However, there is also a substantial increase in scattered and random coincidences, both due to the higher sensitivity and to the presence of MR hardware in the field-of-view. Indeed, assuming an inverse quadratic dependency of the scatter count rate on the detector ring diameter and an inverse proportional dependency of the true count rates on the detector ring diameter, the scatter fraction of a PET with a 66-cm detector ring diameter is about 1.3 times that of a PET with an 85-cm diameter ring. Our simulations show further that the main contributions to scatter come from the bed and central part of the body coil inside the active field-of-view. Figure 4 shows the contribution of these components to the PET scatter fraction for different low energy thresholds.

The subsequent increase in scattered and random coincidences leads to a degradation of the noise-equivalent count rate (NECR) curves. This problem, which is shared by insert architectures, is mainly due to the limited timing resolution of APD detectors and the difficulty in providing proper shielding.

A possible solution to the temporal resolution issue can be found in the promising reports on the performance of silicon photomultiplier detectors (SiPM) [31, 32]. These semiconductor devices are basically a tightly packed array of APDs (up to 1,000 per square millimetre) on a common silicon substrate. Each cell operates in Geiger mode, that is they provide a binary response to excitation. The SiPM output is the combination of all the individual cell responses, achieving a dynamic range proportional to the number of cells. They are compact, offer quantum efficiency and gain similar to traditional PMT, temporal resolution in the order of a nanosecond, and can operate within the magnetic field. SiPM-based PET detectors are a core element of the "Hyper Image" project development of an integrated PET/MRI system.

In the absence of shielding, PET random count rates increase significantly due to out-of-field activity, and can even lead to significant triple coincidence count rates and dead time problems in the case of high activities. At the time of writing it is not clear how to include effective gamma shielding of the PET detector ring inside the MR scanner [33]. Gamma shields are generally constituted of metals with high atomic number in order to provide

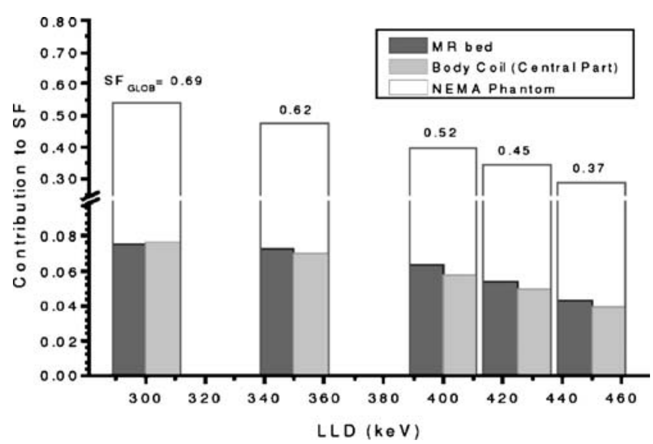


**Fig. 4** Influence of MR system components on the PET scatter fraction for different settings of the lower level energy discriminator (LLD). SF, scatter fraction

sufficient stopping power within a reasonable thickness. Obviously, the use of these shields would lead to two problems in PET/MRI: first, the magnetic susceptibility of these shields would lead to distortions of the permanent magnetic field, and, second, the changing magnetic fields would induce Eddy currents in the shield. Both effects would lead to significant distortions of the MR image.

Finally, little is still known about the cost of combined PET/MR system. Recent polls on a mixed sample of medical and technical specialists have shown that the expected average cost of a combined PET/MRI system is 2.5 million Euros.

## Discussion

None of the described designs is in clinical use yet. The technological challenges of combined whole-body PET/MRI are manifold. Nonetheless, there appear to be a number of research and clinical applications that justify the continued investment in this field.

While sequential PET/MR scanning in a tandem design (Fig. 1a) resembles current PET/CT practice, it results in potentially long overall imaging times. Furthermore, renouncing a feature such as simultaneous acquisition should be given careful consideration. The possibilities of using MR data to perform motion correction of the PET data scan and of monitoring dynamic processes are likely to lead to valuable new applications once combined PET/MR systems became widely available. The study of tumours with dual labelled contrast agents [34] and simultaneous PET and fMRI monitoring of brain activity are just two examples of what might come. However, for simultaneous acquisition to pay off, numerous technical challenges have to be overcome to ensure that the image quality is not degraded by cross-talk effects.

To conclude, we can expect technical advances in the near future to trigger the development of correction algorithms both on the PET side—for attenuation as well as scatter and random coincidences—and on the MRI side—such as shimming and Eddy current compensation. New detector technology may facilitate very advanced systems. Light sensors, which require less-sophisticated and less-sensitive electronics, in combination with matching scintillation crystals may offer new opportunities. Ultimately, only the use in preclinical and clinical settings will prove which PET/MR design will be advantageous for which application.

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**Conflict of interest** None.

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