PET/MRI in practice

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EDITORIAL

PET/MRI in practice: a clinical centre survey endorsed by the European Association of Nuclear Medicine (EANM) and the EANM Forschungs GmbH (EARL)

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Since its inception in the 1970s, positron emission tomography (PET) has been a powerful tool for imaging metabolic and functional processes in vivo [1]. Meanwhile, magnetic resonance imaging (MRI) has been widely used for anatomical and functional imaging since its development in the 1980s [2]. The combination of PET and MRI, known as PET/MRI, was first proposed in the mid-1990s to simultaneously obtain anatomical images and molecular information on disease activity [3].

Early attempts to integrate PET and MRI for human use were hampered by technical challenges, such as the compatibility of the magnetic field with the PET detectors and the need for specialized attenuation correction methods [4]. Advancements in technology and imaging acquisition

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protocols in the early 2000s allowed for the development of the first fully integrated whole-body hybrid PET/MRI system, which was introduced for research purposes in 2010 and approved for clinical applications shortly after [5].

Besides the ability to simultaneously acquire functional and anatomical images, the MRI component of PET/MRI provides improved soft tissue contrast and spatial resolution compared to the CT component of PET/CT, without the need for ionizing radiation exposure [6]. Considering new-generation PET/CT systems, the cost difference between PET/MRI and PET/CT is not as significant. Compared to a combined PET/CT and separate MRI setup, the cost-effectiveness of PET/MRI varies. However, PET/MRI systems still present operational complexity and typically lower patient throughput due to longer scan times. Furthermore, while there is still limited evidence regarding the clinical benefits of PET/MRI compared to PET/CT and standalone MRI, ongoing research is exploring its potential applications in oncology [7], cardiology [8], and in infection and inflammation [9].

To further improve the integration of PET/MRI into clinical practice, several guidelines have been developed. The European Association of Nuclear Medicine (EANM) has published a set of guidelines for the use of PET/MRI in oncology [10], neurology [11], and cardiology [12]. The guidelines provide recommendations for patient preparation, image acquisition and reconstruction, data analysis and interpretation, and quality control.

The Society of Nuclear Medicine and Molecular Imaging (SNMMI), in collaboration with other expert bodies, has published recommendations and guidelines for PET/MRI usage, including diagnosis of large vessel vasculitis and polymyalgia rheumatica [13], cardiovascular applications [14], dopaminergic imaging in Parkinsonian syndromes [15], and gliomas [16], with recommendations for image acquisition and reconstruction, data analysis, and interpretation, and reporting [17].

PET/MRI workshops to chart future directions were organized, concluding that much work needs to be done on clinical implementation, data integration, and the development of a common language for all stakeholders [18, 19].

The most recently introduced PET/MRI systems, like those which include silicon photomultiplier (SiPM) detectors and time of flight (TOF) capabilities, have higher sensitivity levels compared to conventional PET/CT devices, but comparable to the latest generation PET/CT systems. Furthermore, advancements in MRI technology such as synthetic MRI and fingerprinting techniques [20], augmented by artificial intelligence reconstruction methods [21], show great promise in research settings. These developments may potentially accelerate MRI acquisition time, while maintaining the ability to provide both functional and anatomical imaging capabilities.

However, it is important to note that the landscape is set for change with the upcoming launch of a new generation of PET/MRI systems. These new systems are expected to incorporate several advancements, including larger axial coverage and thus higher PET sensitivity, an upgraded MRI system utilizing a new magnet and a larger diameter bore. Furthermore, these new systems will be equipped with dedicated AI software designed to enhance clinical throughput via state-of-the-art imaging sequences. This will result in shorter acquisition times (25–30 min) and improved MRI sensitivity.

Considering these anticipated advancements, the European Association of Nuclear Medicine (EANM) Forschungs GmbH has endorsed a survey. The aim of the survey is to collect information and experiences regarding the most common practices for integrating this technology into clinical workflows and to ascertain the level of interest in the next generation of PET/MRI systems. This survey is expected to provide important information to guide the future integration of PET/MRI into clinical practice and related research.

Methods

The survey was distributed electronically to the list of EARL accredited PET/CT and PET/MRI centres (> 400) between March 1 and April 15, 2023 (see Supplement 1). A reminder was sent to potential participants who met the inclusion criterion of having PET/MRI equipment. The participants were requested to complete 22 questions. These questions covered various aspects such as the location and type of PET/MRI system(s) in use, the clinical and research utilization of the system, and the distribution of system deployment for different disease areas. Participants were also requested to provide information on the number of employees operating (scan acquisition) the PET/MRI. Additionally, the survey collected information regarding which department primarily operates the PET/MRI and its location of installation. The percentage of MRI-only scans performed using the PET/MRI camera system, and the clinical indications for PET/MRI were gathered. All responses were collected and analysed anonymously to identify trends in PET/MRI usage, provide insights into best practices for integrating PET/MRI into clinical workflows and research applications, and evaluate the multiple-choice and open-ended responses. Descriptive statistics were generated using the IBM SPSS software (Armonk, NY, USA, V.29).

Results

Out of the 47 institutes from 18 countries world-wide that responded, 4 were excluded for not meeting the inclusion criterion of having a PET/MRI. Single participants from each of the remaining 43 institutes made up a diverse group

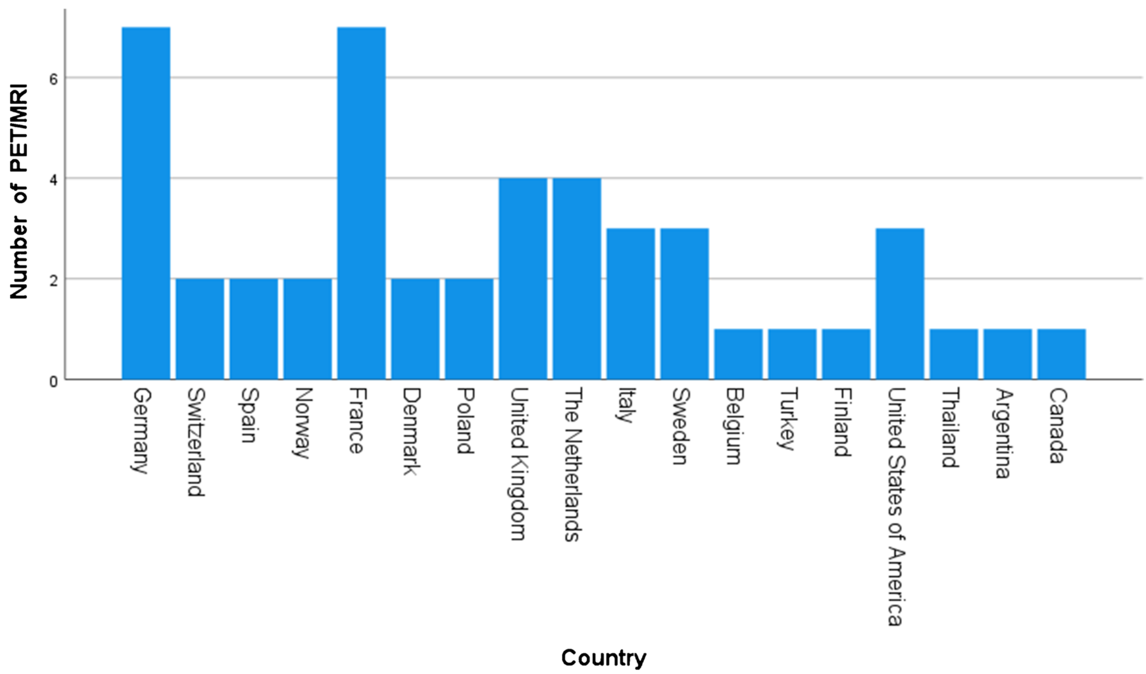


Fig. 1 Distribution of 47 PET/MRI scanners in 18 countries following this survey

of professionals, including physicists, physicians, technologists, and other health professionals (Figs. 1 and 2). Across countries, the availability of PET/MRI systems varied widely. Of the responding centres, the most used system was the Siemens Biograph mMR, which was installed in 25 institutes, followed by the General Electric (GE) Signa, which was used in 17 institutes. Only one institute used a Philips Ingenuity TF system. The PET/MRI systems were installed between 2008 and 2023, with an average starting year of 2016 ± 3.3. Employees operating the PET/MRI systems were primarily physicians (5.6 ± 5.4), followed by technologists (3.5 ± 2.4), physicists (2.2 ± 2.9), and other professionals (3.1 ± 4.3), including PhDs and fellow researchers. The distribution of employees by role is shown in Fig. 3, while the departments, where the PET/MRI systems were installed, are illustrated in Fig. 4.

On average, 55.5% ± 32% of PET/MRI usage was for clinical purposes, while 44.3% ± 31.6% was for research purposes. PET/MRI was commonly used clinically for oncology (33 institutes), neurology (31 institutes), cardiovascular (17 institutes), and infection and inflammation (16 institutes) indications, as well as other clinical indications (5

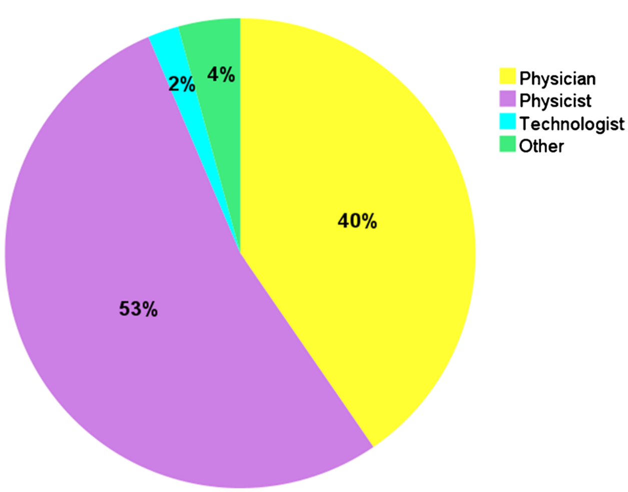


Fig. 2 Survey completed by 43 responders

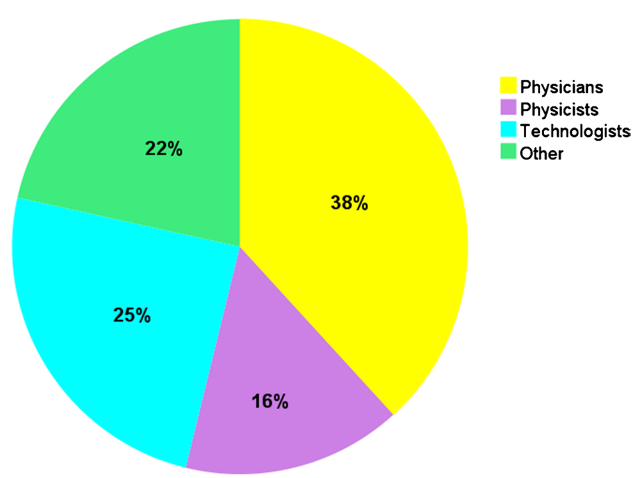


Fig. 3 Percentage of employees working on PET/MRI

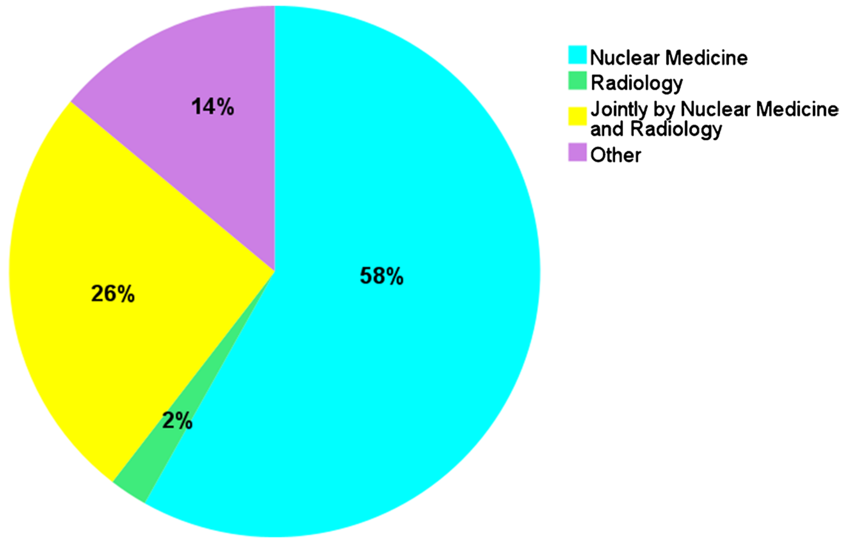


Fig. 4 Department where PET/MRI is installed. Other departments included radiotherapy (1), private (1), and research facility (4)

institutes), as shown in Fig. 5. Additionally, 42 institutes performed clinical MRI-only scans on PET/MRI. For research purposes, PET/MRI was frequently utilized in neurology (38 institutes), oncology (31 institutes), cardiovascular (26 institutes), infection and inflammation (19 institutes), and other research indications (7 institutes), as illustrated in Fig. 6.

Based on the responses of the survey participants, the use of attenuation correction algorithms in PET/MRI systems varies depending on both the application and the system manufacturer. It was noted that a segmentation-based algorithm operating on a two-point Dixon MR sequence is most frequently employed for whole-body and single organ imaging, barring the brain. When it comes to brain imaging, survey respondents reported that GE predominantly utilizes a zero-echo time (ZTE) sequence, while Siemens leans towards an ultrashort echo time (UTE) sequence, for improved bone representation. Participants also indicated the use of several in-house developed, atlas-based approaches for precise imaging of specific regions such as the head, lungs, and pelvis.

Participants highlighted the emergence of deep learning for pseudo-CT synthesis as a significant advancement in the field, notably for pelvis PET/MRI attenuation correction [22].

Furthermore, the survey respondents underscored the enhanced image quality and quantification in the head region that can be achieved through the application of specific PET attenuation correction algorithms.

It was mentioned it is crucial to differentiate between motion correction and attenuation correction due to the distinct in-house and manufacturer-provided solutions available for each.

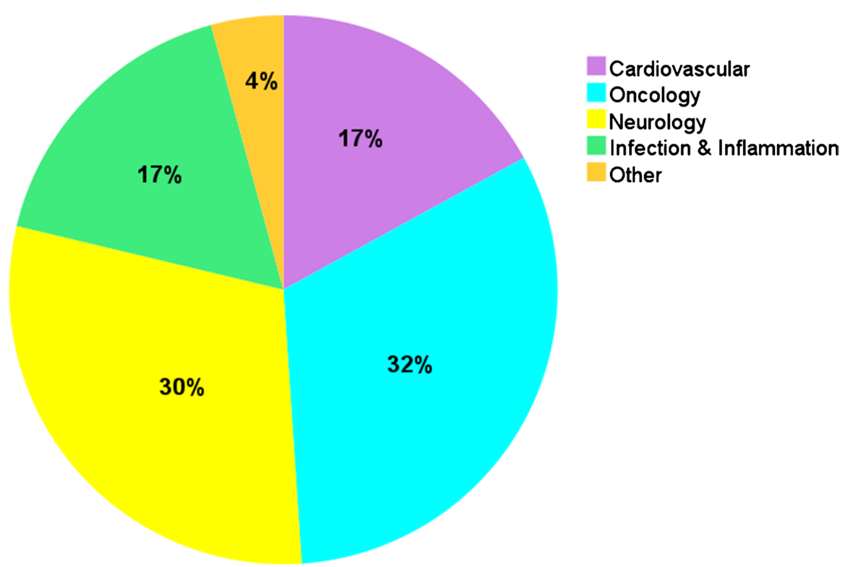
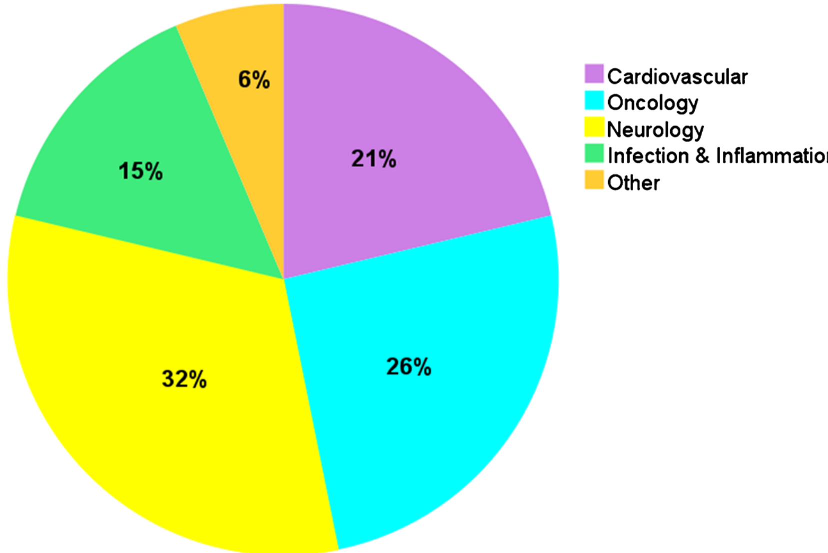


Fig. 5 In which clinical indications is the PET/MRI system used?

Fig. 6 In which research field is the PET/MRI system used?



The respondents also identified the simultaneous acquisition feature of head and whole-body PET/MRI imaging as beneficial, as it improves image registration and motion correction [23]. Within lung PET/MR imaging, participants shared that respiratory motion correction minimizes blurring and artifacts caused by lung motion. Moreover, they reported that MRI-based lung segmentation algorithms accurately outline lung regions, which aids in precise quantification and comprehensive analysis of lung PET data. However, some respondents pointed out that for smaller lesion sizes, these techniques may be less effective [24].

The level of satisfaction with the available attenuation correction algorithms in PET/MRI studies is presented in Fig. 7.

In total, 41 institutes employed a dedicated MRI acquisition protocol on the PET/MRI scanner, which was specifically designed to accommodate custom coils and address unique acquisition requirements.

The experienced level of support from the clinical departments for using the PET/MRI system is depicted in Fig. 8.

The general impression of the added value of a PET/MRI system for the various institutes is mixed. It is highly valued in specific indications, such as neurology, psychiatry, paediatrics, and selected oncology cases. It is considered excellent, very good, or valuable for research purposes, as it permits more versatile research questions to be answered and complements existing imaging capabilities (e.g., simultaneous functional and anatomical

Fig. 7 Is the available attenuation correction algorithm in PET/MRI studies satisfactory?

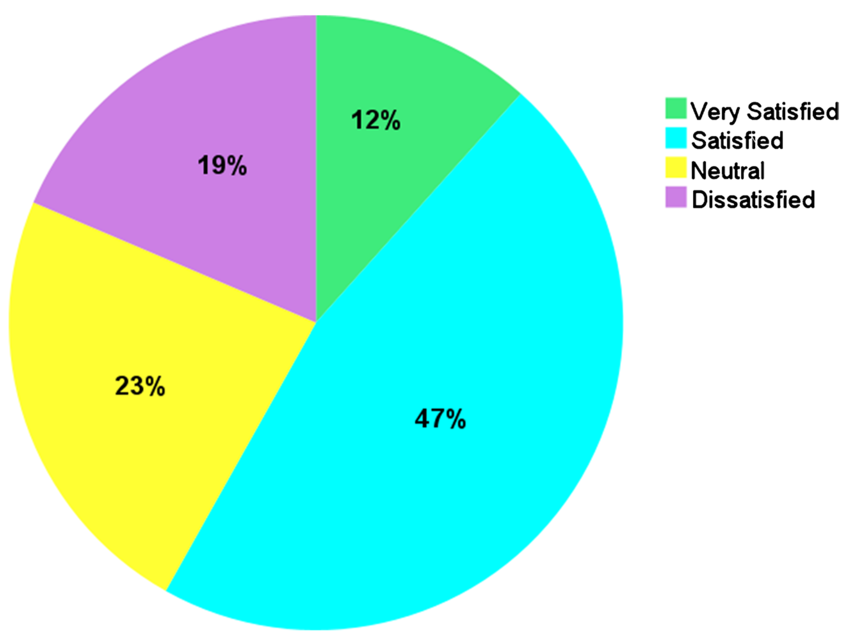
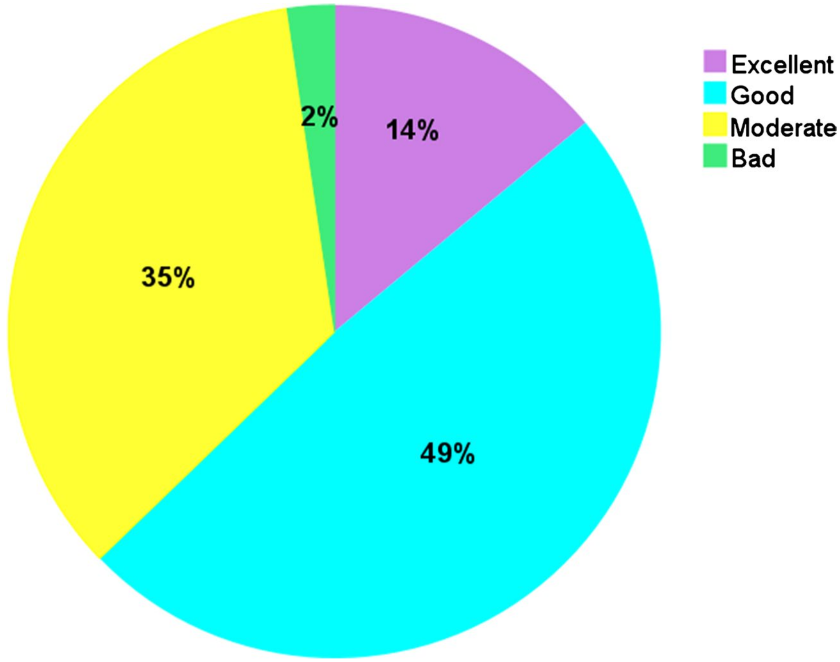


Fig. 8 How is the support of the clinical departments for using the PET/MRI system?



imaging, improved soft tissue contrast, effective motion correction, reduced radiation exposure, multimodal image fusion and integration, development of novel imaging biomarkers).

Some survey participants, such as those using the PET/MRI for body oncology, gave some more critical feedback. They think its clinical role and benefit are still uncertain, and it may have limited or no added value on a diagnostic level (diagnostic accuracy, clinical decision-making, cost-effectiveness), depending on the disease. Additionally, the survey participants commented that the high maintenance and operating costs, coupled with the lack of secured separate reimbursement by health insurance companies, make it challenging to achieve a break-even business case. The perspective of survey participants on the advantages and challenges of PET/MRI is presented in Table 1.

When centres are interested in purchasing and installing a PET/MRI system, institutions should keep in mind several important considerations, which are mentioned by the participants in Table 2. Of the 43 included centres, 34 reported that they would either purchase a new PET/MRI or upgrade their existing system.

Table 1 Survey participants' perspective: advantages and challenges of PET/MRI

Advantages	Challenges
Lower radiation exposure*	Attenuation correction issues, especially in paediatric and whole-body imaging
Enhanced soft tissue contrast*	Long acquisition times and potential patient dropouts
Improved accuracy for diagnosis in complex cases	Non-integrated systems and limitations in combining PET and MRI exams
High accuracy for local staging for certain tumours	Lack of reimbursement for certain applications
Optimal registration between PET and MRI compared to separate imaging	User interface issues and poor design
One-stop-shop imaging capability	Resource requirements and coordination challenges compared to separately acquired PET and MRI
Extraction of valuable complementary information	Cooling and detector failures, MRI image quality issues, and ICT data processing capacity problems, due to large data sets
Simultaneous acquisition of PET and MRI	High maintenance and operating costs
Possibility of performing functional MRI and dynamic PET simultaneously	Staffing issues and shortage of qualified (hybrid) personnel

*Compared to PET/CT

Discussion

This PET/MRI survey provides valuable insights into the perspectives and experiences of participants regarding the utilization of PET/MRI systems in clinical practice and research. The findings highlighted both the advantages and challenges associated with PET/MRI. Participants recognized the simultaneous acquisition of PET and MRI as a significant advantage of PET/MRI. The combined use of PET/MRI, either simultaneous or sequential as exemplified by the Philips system, offers several advantages. These include reduced radiation exposure compared to PET/CT, superior soft tissue contrast, and improved spatial registration, which may be further supplemented by stand-alone MRI. Moreover, the value of simultaneous image acquisition lies in its time efficiency, leading to a shorter imaging session and consequently increased patient comfort. It also provides the possibility for MR-based PET motion correction and monitoring real-time physiological changes, such as those occurring post-drug intervention. These benefits collectively improve accuracy in complex cases and ensure optimal registration between PET and MRI. PET/MRI was also acknowledged for its ability to address versatile research questions and complement existing imaging capabilities.

However, the adoption of PET/MRI faces several challenges that influence decision-making; these include uncertainty regarding the clinical role and added value of PET/MRI, increased maintenance and operating costs, reimbursement issues, and limited interest from clinical groups and researchers. One major challenge is advancing quantification in PET/MRI, particularly through better exploitation of the quantitative capabilities of multiparametric MRI. The emerging synthetic MRI methods, which allow for multiple contrast-weighted sequences to be extrapolated from a single acquisition, hold great promise for this. While they require further refinement, these methods could potentially accelerate acquisition protocols in the future, alongside improved functional imaging capabilities, especially in the context of hybrid PET/MRI. Additionally, the inherent machine instability and the requirement for longer acquisition times—due to the MR imaging component which significantly exceeds the PET part in duration—pose further difficulties.

Important considerations for centres interested in acquiring PET/MRI systems include evaluating clinical demand, research objectives, financial viability, technical requirements, and available resources. Collaboration among multidisciplinary teams is deemed crucial for successful implementation. To ensure the best outcomes for patients and researchers, it is crucial that the decision to purchase and install a PET/MRI system is made after careful consideration of these factors (Table 2).

The upcoming PET/MRI generation is set to feature several hardware and software advancements that will benefit image quality and speed-up PET/MRI procedures, particularly addressing the traditionally time-consuming MRI component. A key point will likely be the shift towards more quantitative imaging. Currently, the MRI component often serves primarily to replace the CT part of the scan with superior soft tissue contrast. Yet, as demonstrated by a

Table 2 Survey participants' opinion: important PET/MRI system considerations

Consideration areas	Key factors
Clinical demand and research applications	Understanding specific clinical needs and research objectives
Need for simultaneous PET and MRI	Integration of PET and MRI multimodal functionalities
Financial aspects	Cost analysis and potential for return on investment
Technical and regulatory aspects	Compliance with technical standards and regulatory requirements
Infrastructure and building requirements	Adequate space, power supply, and shielding provisions
Workflow and project management	Efficient processes and effective project management
Multidisciplinary collaboration and expertise	Collaborative approach and expertise in relevant disciplines, involvement of other clinicians
Human resources	Adequate qualified staff and appropriate staffing levels
Availability of radiotracers	Access to appropriate radiotracers for imaging studies
Imaging protocols	Optimized protocols for desired applications
MRI coils	Compatibility and suitability for different anatomical regions
PET sensitivity	High sensitivity for accurate detection
Attenuation correction options	Reliable methods for accurate attenuation correction
Time-of-flight PET	Enhanced image quality and lesion detection
Scan duration and dedicated time slots	Optimal scanning time and efficient scheduling
Awareness of PET and MRI techniques	Familiarity and knowledge of both PET and MRI methodologies
Programmatic needs	Meeting specific program requirements and goals
Regular updates and maintenance of the system	Support for system updates and regular maintenance

decade's worth of literature, this approach has not consistently provided significant added value against CT in routine PET practice. Utilizing MRI's inherent quantitative abilities, especially with new synthetic MRI techniques, could notably elevate its role within PET/MRI systems.

In conclusion, the survey underlines the complexity of implementing PET/MRI in clinical practice and research. Despite its unique advantages, addressing challenges related to cost, clinical demand, reimbursement, and technical considerations is crucial. Centres should assess their specific needs when considering PET/MRI adoption. Future advancements and collaborations are essential for optimizing the clinical utility and research potential of this imaging technique.

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Declarations

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent to anonymously collect and publish personal and opinion data of this survey was obtained in the presentation page of the web questionnaire.

Conflict of interest The authors declare no competing interests.

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