The Promise use of Hybrid PET/MRI

Mohammed Ibrahem Alghannam[1]*, Yaseer Shaed Almutairi[2], Haneen Talal Aljoudi[3], Turki Yahya Shrahili[4], Malak Al Rajeh[5]

[1] Radiographer, Prince Sultan Military Hospital, Riyadh, KSA

Email: M7mri@hotmail.com

[2] Senior Radiographer, Prince Sultan Military Hospital, Riyadh, KSA

Email: Yasser9821@gmail.com

[3] Prince Sultan Military Hospital, Riyadh, KSA

Email: Haneentalalaljoudi@gmail.com

[4] Radiology Technician, Prince Sultan Military Hospital, Riyadh, KSA

Email: shrahiley.0.7@gmail.com

[5] Senior Radiographer, Prince Sultan Military Hospital, Riyadh, KSA

Email: Malak.rajeh.mr@gmail.com

Abstract - Hybrid PET/MRI is a cutting-edge imaging modality that integrates the molecular imaging capabilities of Positron Emission Tomography (PET) with the superior anatomical and functional imaging strengths of Magnetic Resonance Imaging (MRI). This integration offers significant promise in enhancing diagnostic accuracy, reducing radiation exposure, and providing comprehensive imaging in a single session. Clinically, hybrid PET/MRI has shown particular value in oncology, neurology, and cardiology, offering improved tumor characterization, early detection of neurodegenerative diseases, and detailed cardiac assessments. In the research domain, it provides critical insights into physiological and pathological processes, aiding drug development and the study of disease mechanisms. Despite its high cost, complexity, and limited availability, ongoing technological advancements and the integration of artificial intelligence are expected to expand its clinical applications and improve its practicality. Hybrid PET/MRI thus represents a promising advancement in medical imaging, with the potential to significantly impact personalized and precision medicine.

Keywords: Hybrid PET/MRI, Positron Emission Tomography, Magnetic Resonance Imaging, Molecular Imaging, Diagnostic Accuracy, Oncology, Neurology, Cardiology, Tumor Characterization, Neurodegenerative Diseases, Cardiac Imaging, Radiation Exposure, Clinical Applications, Research Applications, Pharmacokinetics, Technological Advancements, Artificial Intelligence, Medical Imaging, Personalized Medicine, Image Fusion

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INTRODUCTION

Positron Emission Tomography (PET) is a key technique for molecular imaging and quantitative assessment, but it lacks detailed anatomical information.

- To address this, PET is often combined with other modalities like Magnetic Resonance Imaging (MRI). MRI is widely used for both molecular and functional imaging.
- The combination of PET and MRI offers valuable opportunities for both clinical and research applications.

Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) are two of the most advanced imaging modalities in modern medical diagnostics. PET is highly sensitive and provides quantitative information about physiological processes by detecting gamma rays emitted by radiotracers. MRI, on the other hand, offers superior soft-tissue contrast and spatial resolution without using ionizing radiation. The integration of PET and MRI into a single hybrid imaging system has been proposed to leverage the strengths of both modalities while overcoming their individual limitations. This paper explores the promise of hybrid PET/MRI technology, highlighting its potential benefits in clinical and research applications, its challenges, and the future directions of this innovative imaging modality.

HYBRID PET/MRI: AN OVERVIEW

Technical Integration

Hybrid PET/MRI systems combine the metabolic and molecular imaging capabilities of PET with the anatomical and functional imaging strengths of MRI. This integration is achieved either by using sequential or simultaneous acquisition methods. In sequential systems, PET and MRI images are acquired one after the other, while in simultaneous systems, both imaging modalities operate concurrently. The latter is more advantageous as it allows for precise temporal and spatial correlation of the data from both modalities, which is particularly useful in dynamic imaging studies.

Clinical Applications

The primary clinical application of hybrid PET/MRI is in oncology, where it provides comprehensive information about tumor morphology, metabolism, and microenvironment. For instance, hybrid PET/MRI has been shown to be superior in characterizing brain tumors, where MRI offers high-resolution anatomical details and PET provides insights into metabolic activity and molecular markers such as glucose uptake.

In addition to oncology, hybrid PET/MRI is being explored in neurology, particularly in the study of neurodegenerative diseases like Alzheimer's and Parkinson's. MRI's capability to visualize structural brain changes, when combined with PET's ability to detect early molecular alterations, enables early diagnosis and monitoring of disease progression.

Another promising area is cardiovascular imaging. PET/MRI can simultaneously assess myocardial perfusion, viability, and fibrosis, along with providing detailed anatomical and functional information about the heart, making it a powerful tool for comprehensive cardiac assessment.

Research Applications

In the research domain, hybrid PET/MRI is being utilized to study various physiological and pathological processes at a molecular level. It has proven particularly valuable in studying the brain's metabolic and functional responses to different stimuli. For instance, hybrid PET/MRI is used in preclinical studies to investigate the effects of novel therapies on brain tumors, stroke, and psychiatric disorders.

The system is also used in drug development and pharmacokinetic studies, where it provides insights into the biodistribution and pharmacodynamics of new compounds. By combining the molecular imaging capabilities of PET with the detailed anatomical information from MRI, researchers can obtain a more comprehensive understanding of drug effects and mechanisms of action.

ADVANTAGES OF HYBRID PET/MRI

Improved Diagnostic Accuracy

One of the most significant advantages of hybrid PET/MRI is its potential to improve diagnostic accuracy. By combining the strengths of PET and MRI, clinicians can obtain more comprehensive and accurate information about a patient's condition. This is particularly true in oncology, where hybrid PET/MRI can provide better tumor characterization, staging, and treatment response assessment.

Reduction in Radiation Exposure

Another key advantage of hybrid PET/MRI is the reduction in radiation exposure compared to PET/CT. MRI, unlike CT, does not use ionizing radiation, making it a safer option, especially for pediatric patients and those requiring multiple follow-up scans.

Comprehensive Imaging in a Single Session

Hybrid PET/MRI allows for comprehensive imaging in a single session, reducing the need for multiple scans and appointments. This not only improves patient comfort and compliance but also enhances workflow efficiency in clinical settings.

CHALLENGES AND LIMITATIONS

High Cost and Complexity

Despite its promise, the widespread adoption of hybrid PET/MRI is hindered by its high cost and technical complexity. The integration of two advanced imaging modalities into a single system requires significant investment in both hardware and software, as well as specialized training for operators.

Limited Availability and Accessibility

Currently, hybrid PET/MRI systems are not widely available, limiting their accessibility to patients and researchers. The high cost and complexity of these systems contribute to their limited installation in clinical and research centers worldwide.

Technological and Logistical Challenges

Technological challenges such as the need for specialized PET detectors that can function within the strong magnetic fields of MRI, as well as the difficulty in optimizing the imaging protocols for both modalities, pose additional hurdles. Logistical challenges, such as longer scan times compared to standalone PET or MRI, also need to be addressed to enhance the practicality of hybrid PET/MRI.

FUTURE DIRECTIONS

Advancements in Technology

Ongoing advancements in PET and MRI technology, such as the development of more sensitive PET detectors and faster MRI sequences, are expected to enhance the performance of hybrid PET/MRI systems. These advancements will likely lead to shorter scan times, improved image quality, and lower radiation doses, making hybrid PET/MRI more practical and appealing for routine clinical use.

Expansion of Clinical Applications

As the technology continues to evolve, it is expected that the clinical applications of hybrid PET/MRI will expand beyond oncology, neurology, and cardiology. Emerging applications in areas such as infectious diseases, autoimmune disorders, and personalized medicine are being explored, potentially broadening the utility of this hybrid modality.

Integration with Artificial Intelligence

The integration of artificial intelligence (AI) with hybrid PET/MRI holds significant promise for enhancing image analysis, interpretation, and workflow efficiency. AI algorithms can assist in the automatic segmentation of tumors, quantification of PET/MRI biomarkers, and even prediction of treatment outcomes, thereby improving the clinical utility of hybrid PET/MRI.

Design Considerations

There are two types of combined PET/MRI systems:

1) Sequential: In this setup, PET and MRI modalities are separate but operate over a common bed (as shown in Figure)
2) This configuration requires some modifications to both systems, such as shielding the PET detector.

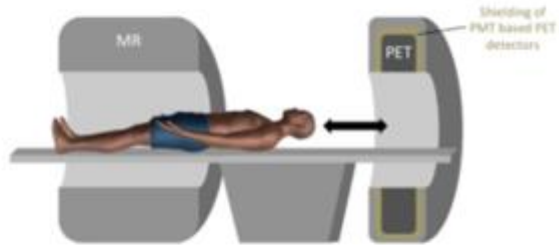

Figure 1 (Vandenberghe and Marsden, 2015)

2. **Concurrent:** This design is more complex and involves a compact PET/MRI system that allows for simultaneous data acquisition (as shown in Figure 2).

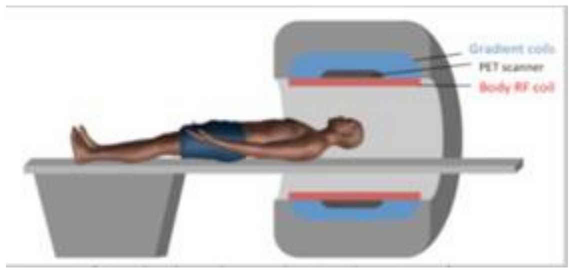

Figure 2 (Vandenberghe and Marsden, 2015)

Quantitative PET/MRI

PET/MRI is a promising technique for radiotracer uptake quantification; however, some challenges exist.

Partial Volume Effect (PVE). Attenuation correction in PET/MRI.

1- partial-Volume Effect (PVE)

Approaches to correct PVE:

1. Recovery coefficients.

2. Post-reconstruction techniques (MRI or

CT).

2- Attenuation Correction

- MRI-guided attenuation correction (MRAC) presents challenges for whole-body imaging.
- The lack of correlation between MRI signal intensity and electron density adds complexity to converting signal intensity into attenuation correction (as shown in Figure 3).

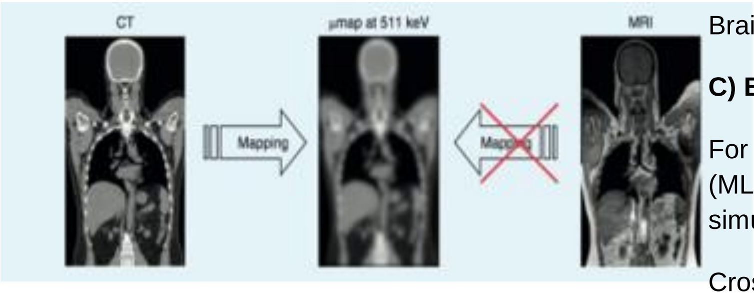

Figure 3 (Zaidi and Becker, 2016)

- Three techniques are employed for

identifying and mapping various biological tissues, each with distinct signal attenuation properties.

MRAC

A) MRI segmentation -based technique

B) Atlas- based technique

C) Emission- based algorithms

A) MRI Segmentation-based Technique

- Adv. Simple to perform and requires only a single, fast MR sequence.
- Disadv. it has limited accuracy in determining the attenuation coefficient due to the restricted number of segmented clusters (as shown in Figure 4).

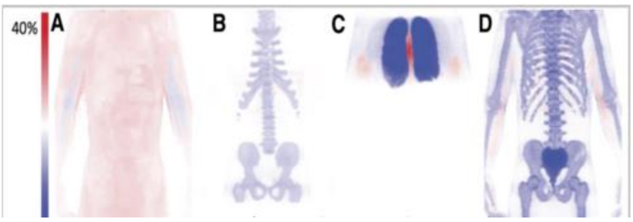

Figure 4 (Bezrukov et al., 2013)

In this approach, bone is replaced by soft tissue, and its attenuation coefficient is ignored. Additionally, cortical bone is challenging to distinguish in MRI.

B) Atlas-based Technique

An MRI atlas is registered to the patient's MRI, and prior information about the atlas's attenuation properties, obtained from a CT template, is used to create the patient's attenuation map.

Limitation

Atlas cannot predict different patient attenuation maps.

Example

Brain imaging

C) Emission-based algorithms

For attenuation map estimation, maximum- likelihood (MLAA) is used to estimate activity and attenuation simultaneously.

Cross-talk is a major limitation, but this can be overcome by using Time of Flight (TOF)

PET/MRI Artifacts

Truncated artifact caused by:

Small trans-axial FOV in MRI (45cm)

Compared to PET FOV (70 cm).

Inhomogeneous static magnetic field B0.

It can be solved by the non-attenuation corrected map of PET data or by MLAA (figure 5).

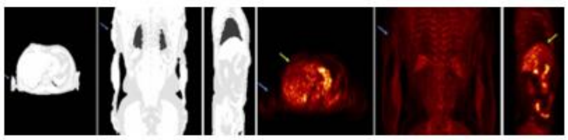

Figure 5 (Martinez-Mo Ï ler et al., 2012).

Metal artifact

Metal object will result in signal loss in MR

acquisition, which result in misleading

image segmentation process (figure 6).

Metal will be classified as air instead of

soft tissue (Martinez-Mo˙ller et al., 2012).

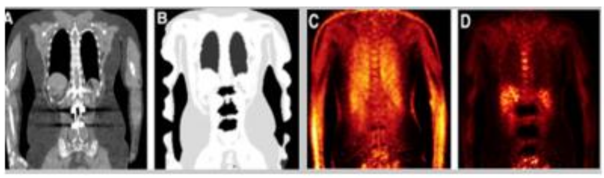

Figure6(Martinez-MoÏleretal.,2012).

CONCLUSION

Several challenges may impact the widespread adoption of PET/MRI.

Partial Volume Effects (PVE) and attenuation correction (AC) are particularly problematic in PET/MRI, and various approaches have been developed to address these issues.

Artifacts can occur, affecting the quality of the resulting PET/MRI images.

Further research is necessary for PET/MRI to become more widely used.

Hybrid PET/MRI represents a significant advancement in medical imaging, combining the molecular imaging capabilities of PET with the superior anatomical and functional imaging strengths of MRI. Despite the challenges associated with its high cost, complexity, and limited availability, hybrid PET/MRI has demonstrated great potential in improving diagnostic accuracy, reducing radiation exposure, and providing comprehensive imaging in a single session. As technology continues to evolve and more clinical applications emerge, hybrid PET/MRI is expected to play an increasingly important role in both clinical practice and research, paving the way for more personalized and precise medical care.

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Corresponding Author

Mohammed Ibrahem Alghannam*

Radiographer, Prince Sultan Military Hospital, Riyadh, KSA

Email: M7mri@hotmail.com