Comprehensive Review of Multimodal Imaging: PET-CT, PET-MRI, CT-DSA, MRI-Ultrasound

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Abstract- Advances in medical imaging have revolutionized disease detection, treatment planning, and patient management. This survey paper presents a comprehensive review and comparative analysis of five key imaging modalities: Positron Emission Tomography–Computed Tomography (PET-CT), Positron Emission Tomography–Magnetic Resonance Imaging (PET-MRI), Computed Tomography Digital Subtraction Angiography (CT-DSA), Magnetic Resonance Imaging (MRI), and Ultrasound. Each modality is examined in terms of its principles, clinical applications, advantages, and limitations, supported by current literature. The review highlights their role across various clinical scenarios, including oncology, neurology, vascular, and soft tissue imaging. Emerging innovations such as artificial intelligence-assisted image reconstruction, ultra-low dose protocols, integration with robotic platforms, and advanced theragnostic applications are also discussed, highlighting their potential to enhance diagnostic accuracy and personalized care. By consolidating technical advancements, clinical utility, and future trends, this work aims to provide clinicians, researchers, and biomedical engineers with an informed perspective to guide modality selection and foster further innovation in medical imaging.

Keywords- *PET-CT, PET-MRI, CT-DSA, Magnetic Resonance Imaging, Ultrasound Imaging, Multimodal Imaging, Diagnostic Radiology, Medical Imaging Trends, Theragnostic, Non-invasive Diagnostics*

1. Introduction

Dual-modality imaging leverages the complementary strengths of two distinct imaging techniques—combining functional and anatomical information—to enhance diagnostic precision and clinical decision-making. Modern clinical practice increasingly adopts hybrid systems like PET-CT, PET-MRI, CT-DSA, and MRI-Ultrasound, which offer integrated insights that are often unattainable with single modalities alone (Fass, 2008; Rong & Liu, 2024; Hicks et al., 2007). Traditional imaging modalities each possess unique advantages and limitations. CT delivers excellent spatial resolution and multiplanar anatomical detail, but it involves ionizing radiation. MRI provides superior soft tissue contrast without radiation exposure. PET reveals metabolic or molecular activity. Ultrasound enables real-time, non-radiative imaging at relatively low cost (Rong & Liu, 2024). By combining modalities, dual-modality systems can reduce ambiguity in interpretation, improve lesion localization, and decrease the need for additional diagnostic procedures (Fass, 2008; Hicks et al., 2007) In complex diagnostic scenarios such as neuro-oncology, vascular abnormalities, and interventional guidance, integrating complementary modalities improves both sensitivity and specificity. For example, PET-CT has become standard in oncology staging by merging metabolic information with precise anatomic localization (Rong & Liu, 2024) (Lee, 2014), while PET-MRI offers enhanced soft-tissue characterization alongside functional imaging (Gross et al., 2023), (Hicks et al., 2007). Similarly, CT-DSA integrates structural and vascular data beneficial in stroke and aneurysm evaluation, and MRI-ultrasound fusion aids in real-time guidance during biopsy or ablation procedures (Bazot et al., 2022a), (la Fougere et al., 2011), (Thomason et al., 2008a).

This review aims to systematically compare the four dual-modality pairings—**PET-CT, PET-MRI, CT-DSA, and MRI-Ultrasound**—focusing on their physical principles, clinical applications, advantages, and limitations. By critically analysing existing literature and clinical case uses, this survey paper will elucidate how each modality combination contributes to improved diagnostic confidence, treatment planning, and patient outcomes.

2. Modality Principles Overview

2.1. PET-CT

2.1.1. Principle of PET

Positron Emission Tomography (PET) is a functional imaging method that utilizes radiopharmaceuticals, or radiotracers, to track physiological activities such as metabolic changes, blood flow, and tissue absorption within the body. Once injected, these tracers emit positrons that rapidly encounter electrons, resulting in annihilation events that produce two gamma photons emitted in opposite directions (approximately 180° apart). Detector rings, often composed of bismuth germanate crystals, capture these coincident photon pairs within a narrow time frame (10–20 nanoseconds) to reconstruct images of tracer distribution (la Fougere et al., 2011)). Advanced PET systems employ Time-of-Flight (TOF) technology to measure slight timing differences between photon arrivals, improving image resolution and signal-to-noise ratio. Additionally, attenuation correction techniques, often using a rotating 68Ge source, further enhance image accuracy (Thomason et al., 2008a).

2.1.2. Principle of CT

Computed Tomography (CT) is a structural imaging technique that acquires multiple X-ray projections while the source rotates around the patient. As the patient moves through the CT gantry, these projections are processed to generate cross-sectional images. Traditionally, image reconstruction has relied on filtered back-projection algorithms, which are fast but prone to artifacts. Modern CT scanners increasingly use iterative reconstruction approaches, such as Maximum Likelihood Expectation Maximization (MLEM), to model scanner physics more accurately, resulting in clearer images with reduced noise (Robb et al., 2025).

2.1.3. Principle of PET-CT

PET-CT integrates the functional imaging capabilities of PET with the anatomical detail provided by CT, both acquired sequentially in a single session within the same gantry (Hicks et al., 2007). PET detects gamma photons generated by positron-electron annihilation, highlighting areas of altered metabolic activity, while CT provides precise anatomical localization of these regions. Co-registration of the two datasets produces a fused image that combines metabolic and structural information, enhancing diagnostic interpretation. The CT component may use contrast agents for improved visualization of anatomical features, aiding in the detection and staging of various diseases (la Fougere et al., 2011)

Figure 1. PET-CT machine (PET/CT | GE Healthcare (India), n.d.)

2.1.4. Clinical Applications

PET-CT is widely recognized for its utility in oncology, neurology, and infectious disease imaging. In pancreatic cancer, 18F-FDG PET/CT improves early diagnosis and staging by mapping glucose metabolism, often outperforming CT alone (Pu et al., 2021). In non–small cell lung cancer (NSCLC), SUV90-based PET/CT planning enhances radiotherapy precision and reduces the risk of radiation-induced complications (Mulita et al., 2025). PET/CT facilitates early detection of metastases in breast cancer, improving therapeutic decision-making. Whole-body PET/CT is valuable in diagnosing device-related infections, particularly in patients with left-ventricular assist devices (LVADs), by mapping infection spread (Hussain et al., 2024). Neurologically, PET/CT identifies early metabolic alterations in Alzheimer's disease before structural changes become evident. It is also

used in ophthalmic oncology for orbital tumor detection, in pediatric oncology for cancer staging, and in complex cases like renal cell carcinoma with multi-site metastases (Hussain et al., 2024; Sireesha et al., 2023). Additionally, PET/CT helps differentiate between infectious and inflammatory processes in rare conditions such as necrotizing fasciitis, enabling timely surgical intervention.

2.2. PET-MRI

2.2.1. Principle of MRI

Magnetic Resonance Imaging (MRI) uses a strong static magnetic field to align hydrogen nuclei in the body, followed by radiofrequency (RF) pulses to excite these nuclei. When the RF pulse is turned off, the nuclei relax back to their equilibrium state, emitting signals that are detected by receiver coils. Position information is obtained by applying gradient magnetic fields along the X, Y, and Z axes, allowing spatial encoding of the signal. Rapid switching of these gradient coils during excitation and signal acquisition produces the characteristic knocking sounds of MRI scans. Contrast in MRI images is primarily determined by two independent relaxation processes: **T1 (spin-lattice relaxation)** and **T2 (spin-spin relaxation)**. Adjusting repetition time (TR) and echo time (TE) allows the acquisition of T1-weighted and T2-weighted images, respectively, aiding in differentiation of tissue characteristics and pathological changes (De León-Rodríguez et al., 2015). Exogenous contrast agents may be administered to enhance image clarity and improve diagnostic visualization.

2.2.2. Principle of PET-MRI

PET-MRI is a hybrid imaging modality that combines the metabolic imaging capability of PET with the superior soft tissue contrast and multi-parametric imaging features of MRI (Antoch & Bockisch, 2009). The PET component utilizes injected radiotracers that emit positrons, which annihilate with electrons to produce gamma photons detected by specialized sensors. These data provide functional information about cellular metabolism and molecular activity. MRI, on the other hand, offers high-resolution anatomical mapping without ionizing radiation. In a combined PET-MRI system, these modalities are either arranged sequentially (tandem configuration) or integrated into a single gantry, enabling co-registered imaging in the same session (Luna et al., 2014) (Vandenberghe & Marsden, 2015). Simultaneous PET-MRI acquisition provides better alignment of images, minimizes patient movement artifacts, and facilitates comprehensive analysis of structural and functional information. Compared to PET-CT, PET-MRI is being explored as a lower-radiation alternative, particularly beneficial for paediatric and neurological imaging (Jung et al., 2016a).

Figure 2. PET-MRI machine (PET-MRI, n.d.)

2.2.3. Clinical Applications

PET-MRI is gaining prominence in multiple specialties due to its combined ability to visualize metabolic activity and provide high-quality anatomical detail.

Oncology: Enhances tumor detection, characterization, staging, and therapy monitoring by combining PET's tracer sensitivity with MRI's superior soft tissue contrast (Buchbender et al., 2012a), (Buchbender et al., 2012b), (Martinez-Möller et al., 2012)

Cardiology: Used in the evaluation of myocardial viability, cardiac inflammation, and ischemic lesions (Rischpler et al., 2013).

Neurology and Neuroscience: Assists in the assessment of neurological diseases, functional brain mapping, dementia studies, and neurodegenerative disorder tracking (Dimou et al., 2009) (Bremner et al., 2003) (Cho et al., 2013)

Translational Research: Supports understanding of pharmacokinetics, receptor binding, and disease mechanisms at the molecular level in both human and preclinical studies (Jung et al., 2016a).

This hybrid modality enables precise localization of functional abnormalities within complex anatomical structures, offering a comprehensive approach for early diagnosis, personalized medicine, therapy planning, and response monitoring. However, challenges such as high installation and operating costs (Zaidi & Del Guerra, 2011) the need for PET detectors compatible with strong magnetic fields (Jung et al., 2016a), and complex attenuation correction procedures limit its widespread adoption. Additionally, a shortage of personnel trained in both PET and MRI imaging further constrains its clinical implementation (Pichler et al., 2010).

2.3. CT-DSA

2.3.1. Principle of DSA

Digital Subtraction Angiography (DSA) is an advanced imaging method designed to improve the visibility of blood vessels by removing background anatomical structures from the image. It works by capturing an initial, non-contrast image (referred to as the "mask"), which is digitally stored. As contrast material is introduced into the bloodstream, subsequent images are captured and mathematically subtracted from the mask. This subtraction process highlights the contrast-filled vasculature while suppressing surrounding tissues. The resulting images are displayed in real time on a monitor and digitally archived. DSA allows clinicians to dynamically assess blood flow and vascular abnormalities with far greater clarity than traditional angiographic techniques (Okamoto et al., 2000).

2.3.2. Principle of CT-DSA

CT-DSA (Computed Tomography–Digital Subtraction Angiography) is a hybrid imaging technique that combines high-resolution structural imaging from CT with the vascular detail achieved through digital subtraction. It begins with the acquisition of a non-contrast CT scan, which serves as the baseline or "mask" image. Following this, contrast-enhanced CT images are acquired during various vascular phases typically including early arterial, late arterial, and venous phases after the administration of iodinated contrast material.

The digital subtraction process involves subtracting the pre-contrast mask from the contrast-enhanced images to isolate vascular structures. This enhances the visibility of blood vessels by effectively eliminating background tissues and bones from the image. To ensure optimal vessel contrast and spatial resolution, dual-energy CT (DECT) systems with fast-kV switching and fine collimation are often employed. The technique may also incorporate monochromatic image reconstruction to increase contrast conspicuity and rigid-body registration to correct for patient movement between phases before subtraction.

The result is a set of high-clarity vascular images that resemble catheter angiography but are acquired non-invasively. CT-DSA provides both functional (contrast flow dynamics) and anatomical (vessel morphology) information, making it particularly useful for evaluating vascular lesions, arteriovenous malformations, aneurysms, and tumor vascularity. Compared to conventional DSA, CT-DSA offers rapid image acquisition, 3D visualization, and less invasiveness, though it does involve radiation exposure and contrast use (Huang et al., 2019).

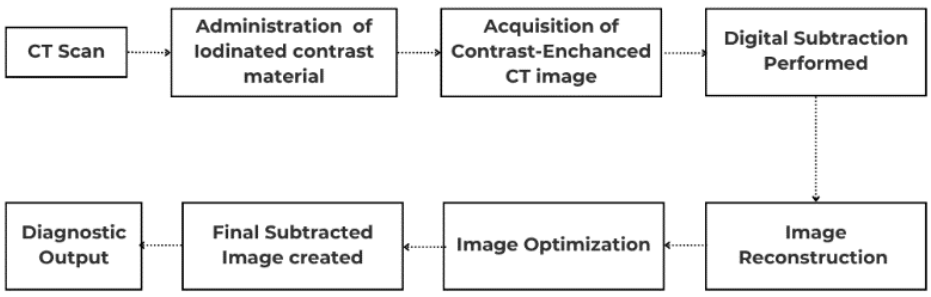

Figure 3. Diagnostic Flowchart of CT-DSA

2.3.3. Clinical Application

CT-DSA is primarily employed in vascular imaging for the detection and evaluation of various vascular abnormalities, including arteriovenous malformations (AVMs), aneurysms, vascular stenosis, and acute ischemic stroke (Glick et al., Wang & Zhang, 2012). Its ability to provide high-resolution visualization of blood vessels, while clearly distinguishing them from adjacent bone and soft tissues, makes it especially beneficial in imaging both intracranial and extracranial arteries.

This technique also plays a significant role in pre-surgical planning and guiding endovascular interventions, as it enables precise assessment of vascular anatomy and pathology. Furthermore, when compared to traditional catheter-based angiography, CT-DSA offers advantages such as reduced invasiveness, faster acquisition time, and integration into routine clinical workflows where detailed vascular mapping is required .

2.4. MRI-Ultrasound

2.4.1. Principle of Ultrasound

Ultrasound imaging operates on the principle of the piezoelectric effect, where piezoelectric crystals in the probe convert electrical energy into sound waves and vice versa. These sound waves are transmitted into the body, and when they encounter tissues with varying acoustic impedance, a portion is reflected back to the transducer to generate an image. The degree of reflection depends on the impedance mismatch between adjacent tissues—greater differences yield stronger echoes, resulting in brighter image areas. Ultrasound waves attenuate as they pass through tissues due to refraction, scattering, and absorption, which can impact image quality (Poggi & Palavecino, 2024; Cootney, 2001).

In preclinical imaging, higher frequencies (20–55 MHz) are typically used to achieve greater spatial resolution, though at the cost of reduced penetration depth, making them suitable for small animals like mice and rats Resolution both axial (parallel to the beam) and lateral (perpendicular to the beam) improves with frequency, which is critical in imaging small anatomical structures such as the mouse heart.(Cootney, 2001), (Moran & Thomson, 2020).

To optimize imaging in small models, the transducer is mounted for precise orientation, and coupling gel is used to eliminate air gaps and improve sound transmission.

2.4.2. Integration of MRI-Ultrasound

The fusion of Magnetic Resonance Imaging (MRI) with Ultrasound (US) offers a powerful hybrid approach that combines the high soft tissue contrast of MRI with the real-time imaging and convenience of ultrasound. This integration is especially beneficial in applications such as gynaecological diagnostics, hepatic interventions, and image-guided biopsies.

M. Bazot et al. outlined that, due to the limited number of clinical studies, no consensus currently exists on standardized requirements for ultrasound-MRI fusion in gynaecological imaging. However, they emphasized that the ideal protocol involves acquiring MRI and ultrasound images on the same day to maintain synchronization of pelvic organ positioning. In this workflow, MRI should be conducted first to allow for image transfer to the ultrasound system via PACS or CD-ROM. They highlighted the importance of high-quality MRI, recommending the use of 3D T2-weighted and 3D T1-weighted Dixon sequences for optimal multiplanar correlation with ultrasound. These sequences enable the reconstruction of isotropic image volumes, which can be precisely aligned with ultrasound planes during fusion imaging (Bazot et al., 2022b).

In interventional procedures, Jaesung Hong et al. developed a system using a needle insertion adapter attached to an ultrasound probe. This allowed for simultaneous display of real-time ultrasound images and corresponding cross-sectional MR images. The adapter is calibrated with a position sensor that tracks needle movement, enabling surgeons to accurately plan and guide insertions by visualizing 3D anatomical models overlaid with US and MRI data (Hong et al., n.d.).

Further advancing the field, Min Woo Lee et al. explored various tracking methods to facilitate fusion imaging, including optical, image-based, and electromagnetic (EM) tracking. EM tracking is particularly effective for US-guided hepatic interventions and involves components such as a magnetic field generator, position sensors, and a sensor unit within the US machine. These components allow precise spatial tracking of the ultrasound probe, enabling the fusion of real-time US with previously acquired MR or CT images. Registration can be accomplished using external fiducial markers visible on MRI and CT or internal anatomical landmarks such as hepatic vein bifurcations or lesions. Accurate plane and point registration techniques are employed to align the images, thereby enhancing the accuracy and speed of procedures (Lee, 2014b).

In a significant innovation, the Fraunhofer Institute for Biomedical Engineering (IBMT), in collaboration with the Fraunhofer Institute for Digital Medicine MEVIS and Saarland University Medical Center, introduced an MRI-compatible ultrasound system as part of the KoMBUS project. This system captures MRI and live ultrasound images concurrently to aid in needle path planning and guidance for biopsies. It maps breathing phases during MRI to live ultrasound, allowing physicians to plan and execute biopsies without repeated MRI scans. This reduces patient discomfort, saves valuable scanner time, and maintains diagnostic precision. The system includes an MR-compatible display, dual ultrasound probes (for motion tracking and real-time guidance), and planning software that aligns the ultrasound image with the correct MRI breathing phase. This is especially helpful for less experienced operators and marks a significant step toward cost-effective and patient-friendly MRI-guided interventions.

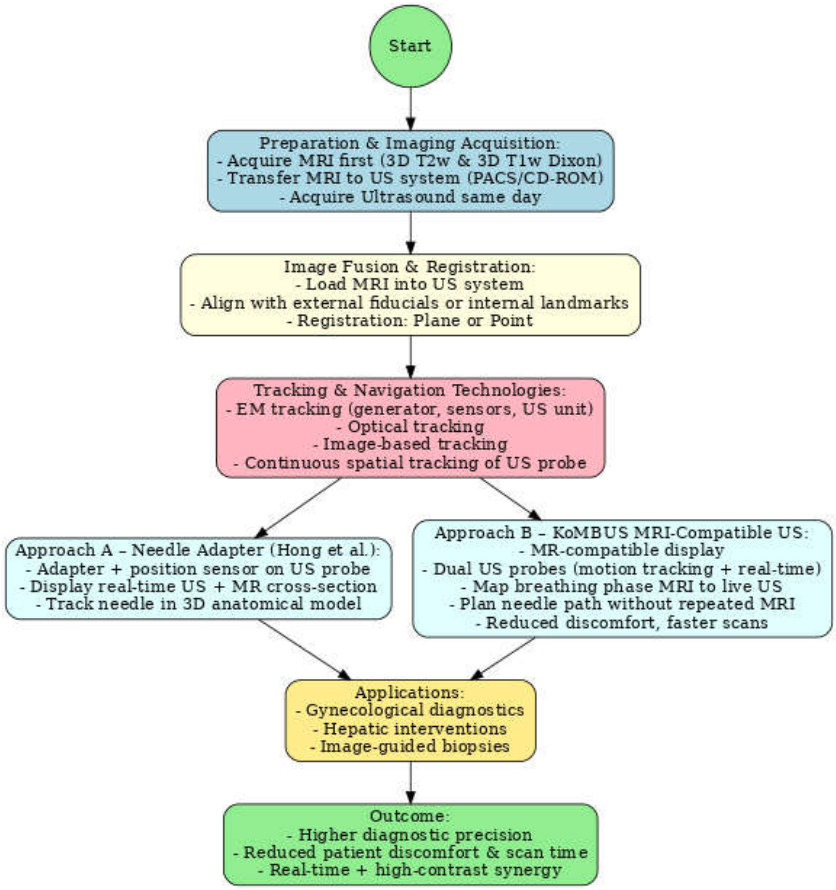

Figure 4. MRI-Ultrasound Fusion Imaging Process Flow

2.4.3. Clinical Applications

Although fusion imaging currently lacks established indications in gynaecology, it shows promising potential in certain applications. One such area is pelvic endometriosis, where combining MRI with ultrasound has been found useful for detecting superficial peritoneal implants and differentiating between endometriotic and haemorrhagic luteal ovarian lesions. Furthermore, it can enhance the visualization of deep endometriotic sites, especially at commonly involved areas like the uterosacral ligaments. A recent Cochrane review indicated that while both MRI and ultrasound have comparable accuracy for diagnosing rectosigmoid deep endometriosis, their performance varies significantly across other pelvic regions, suggesting that fusion imaging may improve overall diagnostic efficiency.

Fusion techniques have also shown early promise in identifying adenomyosis, although the lack of a definitive histological standard currently limits its widespread application. Since leiomyomas and adenomyosis are common uterine conditions that often coexist, integrating fusion imaging with power Doppler may aid in distinguishing between these two entities.

Recent research also supports the utility of MRI–ultrasound fusion in gynaecological oncology. It has been used in patients with advanced cervical and ovarian cancers, showing improved diagnostic accuracy over either imaging modality alone. Additionally, one study demonstrated the ability to use fused 3D SPECT/CT images and

real-time ultrasound to guide lymph node biopsies or radiotracer injections during radio-guided lesion localization (Bazot et al., 2022b) , (Hong et al., n.d.).

In abdominal interventions, fusion imaging addresses challenges posed by motion and organ deformation. By combining the superior spatial resolution of MRI with the real-time capabilities of ultrasound, procedures like radiofrequency ablation (RFA) or percutaneous ethanol injection therapy (PEIT) for liver tumours can be performed more effectively. Specific advancements include optical sensor-based registration techniques that minimize errors from patient movement or tissue shift (Hong et al., n.d.).

Fusion imaging has also significantly improved hepatic interventional procedures, especially in targeting small or hard-to-visualize liver lesions. It facilitates accurate localization for biopsies and enhances the detectability and treatment success for hepatocellular carcinomas (HCCs) that are difficult to identify with conventional B-mode ultrasound (Bazot et al., 2022b). The approach minimizes sampling errors, reduces unnecessary ablation of pseudo lesions, and helps guide precise overlapping ablations based on MRI or CT reference images. Notably, it has shown higher sensitivity in detecting HCCs smaller than 2 cm, where conventional ultrasound may fall short.

3. Comparative Analysis

Parameter	***CT***	***MRI***	***DSA***	***PET***	***Ultrasound***
Radiation Exposure	Uses ionizing radiation; moderate dose	No ionizing radiation	Uses ionizing radiation via fluoroscopy and contrast	Uses ionizing tracers; higher dose (e.g., ~14 mSv FDG, ~23–26 mSv PET–CT)	No ionizing radiation
Spatial Resolution	High spatial resolution; excellent detail	High spatial resolution; excellent detail	High spatial resolution; excellent detail	High spatial resolution; excellent detail	High spatial resolution; excellent detail
Contrast Resolution	Moderate; enhanced by contrast agents	Excellent soft-tissue contrast	Focus is on vessels; background suppressed by subtraction	Functional/metabolic contrast; not structural	Moderate; good for fluid interfaces—limitations with bone/gas
Functional Imaging	Limited (perfusion CT exists)	Functional MRI sequences (e.g., DWI, fMRI)	No direct function; used for vascular anatomy and flow	Yes—metabolic, molecular imaging	Limited; Doppler adds blood flow info
Real-Time Imaging	Poor (static slices)	Poor	Yes, in interventional settings	No	Excellent; real-time dynamic Imaging
Cost & Availability	Widely available; moderate cost	Expensive; less widely available	High cost; requires specialized setup	Very high; tracer production and equipment cost	Widely available; low cost
Common Use Cases	Trauma, bone fractures, vascular CTA, fast imaging	Soft tissue/pathology (brain, ligament, tumor),	Cerebral angiography, evaluation of AVMs, aneurysm	Oncology staging (PET/CT), metabolic disorders	Obstetrics, abdomen, vascular bedside scans

		functional scans			
Limitations	Radiation exposure; less soft-tissue contrast	Cost, time, contraindicated with metal implants	Invasive; radiation and contrast risks	High radiation; low anatomical detail; expensive	Operator-dependent; limited depth and bone/gas obstruction

Table 1. Comparative Analysis of Imaging Modalities

4. Challenges

PET-CT is affected by several limitations that may reduce its diagnostic reliability. Motion artifacts caused by respiratory or cardiac activity can blur images and create misalignment between PET and CT data, with thoracic and abdominal imaging being particularly vulnerable (Tsai & Liu, 2021; Thomason et al., 2008b). Metallic implants or dental restorations can generate beam-hardening and scatter artifacts in CT scans, which may transfer to PET during attenuation correction, potentially resulting in inaccurate tracer uptake measurements (Tsai & Liu, 2021; Thomason et al., 2008b).

Discrepancies in patient position or movement between the PET and CT acquisitions can further cause attenuation correction errors, leading to incorrect assessments of metabolic activity and possible false-positive or false-negative findings (Tsai & Liu, 2021), (Sarikaya & Sarikaya, 2021). Additionally, physiological FDG uptake in normal tissues such as skeletal muscle, bowel, thymus, or brown adipose tissue may appear similar to pathological lesions, especially in younger individuals, often requiring further correlation with other imaging or clinical evaluation (Thomason et al., 2008b), (Mbakaza & Vangu, 2022). The inherent spatial resolution of PET, about 4–5 mm, restricts the detection of micro-metastases or very small lesions, which can result in under-staging. Certain tumor types with low metabolic activity, including some neuroendocrine, mucinous, or prostate cancers, may not exhibit sufficient FDG uptake, increasing the risk of missed diagnoses. Moreover, FDG accumulation in inflammatory or infectious processes can mimic malignant activity, raising the possibility of misdiagnosis or unnecessary interventions (Tsai & Liu, 2021), (Sarikaya & Sarikaya, 2021), (Mbakaza & Vangu, 2022).

The integration of PET with MRI presents distinct technical challenges, as the two modalities are fundamentally different MRI uses strong magnetic fields and radiofrequency pulses, while PET relies on nuclear imaging with photodetectors. Standard PET detectors are adversely affected by MRI's magnetic environment, necessitating specialized components such as silicon photomultipliers (SiPMs) that are resistant to magnetic interference (Jung et al., 2016b). Accurate attenuation correction, a critical step for PET quantification, remains more complex in PET-MRI than in PET-CT, especially in regions like the brain and lungs where MRI sequences alone struggle to accurately map bone and air. Beyond the technical hurdles, PET-MRI systems require a significantly higher financial investment for purchase, maintenance, and operation compared to PET-CT, limiting accessibility, particularly in resource-constrained settings. Additionally, there is a shortage of personnel trained in both MRI and PET technologies, and interpreting the fused datasets demands substantial expertise. CT-based digital subtraction angiography also faces several challenges. Precise spatial and temporal registration between pre-contrast (mask) and post-contrast images is critical; however, patient movement or vascular pulsation can cause misregistration artifacts that degrade image clarity (Turski et al., 1983). The technology demands advanced angiography systems, subtraction-capable CT scanners, and well-trained operators, making it costly and maintenance-intensive (Posa et al., 2022). Motion during image acquisition, such as swallowing, breathing, or vascular wall movement, can further lead to loss of vessel detail in subtraction images (Turski et al., 1983). Its high cost and technical requirements limit its availability in rural and low-resource healthcare facilities (Posa et al., 2022). Additionally, CT-DSA involves substantial radiation exposure and the use of iodinated contrast media, which carry risks of allergic reactions and nephrotoxicity. The invasive nature of DSA also introduces procedural risks such as vascular injury, stroke, or infection at the puncture site (Posa et al., 2022), (Nam et al., 2022).

5. Future Scope

The integration of artificial intelligence into PET-CT imaging is creating new opportunities for both diagnostics and therapeutic applications. One promising direction is the generation of synthetic CT images from non-attenuation-corrected TOF-PET data. This technique has achieved encouraging performance, with a low mean absolute error (~74 HU) and high PSNR (~28 dB), while reducing patient radiation exposure and paving the way for PET-only systems .

In the domain of theranostics, advancements in ultra-sensitive PET scanners are expected to revive radiotracers that were previously underutilized due to low yield or complex pharmacokinetics. This could significantly broaden the spectrum of personalized treatment approaches for rare cancers and metabolic diseases .

Paediatric imaging is also set to benefit from ultra-low activity PET protocols. By enabling doses as low as 0.3 MBq/kg without compromising standardized uptake value (SUV) accuracy or lesion detectability, these protocols address long-standing safety concerns for children who require multiple scans over the course of chronic or recurrent illnesses (Smith et al., 2025). For CT-DSA, the future lies in its expanding role in preoperative vascular mapping, aiding surgical teams in devising precise strategies for complex spinal, neurovascular, and oncologic procedures. The modality's ability to accurately evaluate vessel involvement supports customized surgical planning and minimizes intraoperative risks (Tsuang et al., 2024), (Paushter et al., 1983)

Additionally, CT-DSA enables highly personalized treatment by allowing the modification of imaging protocols such as contrast volume and scan parameters according to each patient's unique anatomy and clinical profile, optimizing diagnostic yield while reducing potential adverse effects (Ho et al., 2020). The fusion of CT-DSA with robotic platforms is another promising development, particularly in the field of image-guided and minimally invasive interventions. Robotic assistance can improve navigation through complex vascular networks, enhance procedural precision, and reduce occupational radiation exposure for clinicians (Duan et al., 2023).

6. Conclusion

The continuous evolution of dual and multimodal imaging has transformed the landscape of medical diagnostics and interventions. Techniques such as PET-CT, PET-MRI, CT-DSA, and MRI-ultrasound have demonstrated the ability to combine complementary strengths—merging anatomical detail, functional assessment, and real-time visualization—thereby enhancing diagnostic accuracy and guiding complex clinical decision-making. PET-CT and PET-MRI enable precise correlation between metabolic activity and structural features, improving cancer detection, staging, and therapy monitoring. CT-DSA provides exceptional vascular mapping capabilities, supporting intricate surgical planning and interventional procedures, while MRI-ultrasound fusion offers radiation-free, real-time guidance for targeted therapies, especially in sensitive patient groups.

Despite their benefits, each modality faces challenges including motion artifacts, attenuation correction errors, limited spatial resolution, cost constraints, and the need for specialized expertise. However, the integration of artificial intelligence, development of ultra-low-dose imaging protocols, and the rise of high-sensitivity scanners are steadily mitigating these limitations. Furthermore, their expanding applications in theranostics, robotic-assisted interventions, and paediatric imaging highlight their potential in advancing personalized medicine.

As these imaging technologies mature, collaborative innovation between clinicians, engineers, and researchers will be vital to ensure widespread accessibility, optimize cost-effectiveness, and sustain clinical relevance. With continued progress, these modalities are poised to play an even more decisive role in early detection, minimally invasive treatments, and improved patient outcomes across diverse medical specialties.

References

[1] Antoch, G., & Bockisch, A. (2009). Combined PET/MRI: a new dimension in whole-body oncology imaging? *European Journal of Nuclear Medicine and Molecular Imaging*, *36*(S1), 113–120. https://doi.org/10.1007/s00259-008-0951-6

[2] Bazot, M., Spagnoli, F., & Guerriero, S. (2022a). Magnetic resonance imaging and ultrasound fusion technique in gynecology. *Ultrasound in Obstetrics & Gynecology*, *59*(2), 141–145. https://doi.org/10.1002/uog.24754

[3] Bazot, M., Spagnoli, F., & Guerriero, S. (2022b). Magnetic resonance imaging and ultrasound fusion technique in gynecology. Ultrasound in Obstetrics & Gynecology : The Official Journal of the International Society of Ultrasound in Obstetrics and Gynecology, 59(2), 141–145. https://doi.org/10.1002/uog.24754

[4] Bremner, J. D., Vythilingam, M., Vermetten, E., Southwick, S. M., McGlashan, T., Nazeer, A., Khan, S., Vaccarino, L. V., Soufer, R., Garg, P. K., Ng, C. K., Staib, L. H., Duncan, J. S., & Charney, D. S. (2003). MRI and PET Study of Deficits in Hippocampal Structure and Function in Women With Childhood Sexual Abuse and Posttraumatic Stress Disorder. *American Journal of Psychiatry*, *160*(5), 924–932. https://doi.org/10.1176/appi.ajp.160.5.924

[5] Buchbender, C., Heusner, T. A., Lauenstein, T. C., Bockisch, A., & Antoch, G. (2012a). Oncologic PET/MRI, Part 1: Tumors of the Brain, Head and Neck, Chest, Abdomen, and Pelvis. *Journal of Nuclear Medicine*, *53*(6), 928–938. https://doi.org/10.2967/jnumed.112.105338

[6] Buchbender, C., Heusner, T. A., Lauenstein, T. C., Bockisch, A., & Antoch, G. (2012b). Oncologic PET/MRI, Part 2: Bone Tumors, Soft-Tissue Tumors, Melanoma, and Lymphoma. *Journal of Nuclear Medicine*, *53*(8), 1244–1252. https://doi.org/10.2967/jnumed.112.109306

[7] Cho, Z. H., Son, Y. D., Choi, E. J., Kim, H. K., Kim, J. H., Lee, S. Y., Ogawa, S., & Kim, Y. B. (2013). In-vivo human brain molecular imaging with a brain-dedicated PET/MRI system. *Magnetic Resonance Materials in Physics, Biology and Medicine*, *26*(1), 71–79. https://doi.org/10.1007/s10334-012-0329-4

[8] Cootney, R. W. (2001). Ultrasound Imaging: Principles and Applications in Rodent Research. *ILAR Journal*, *42*(3), 233–247. https://doi.org/10.1093/ilar.42.3.233

[9] De León-Rodríguez, L. M., Martins, A. F., Pinho, M. C., Rofsky, N. M., & Sherry, A. D. (2015). Basic MR relaxation mechanisms and contrast agent design. *Journal of Magnetic Resonance Imaging*, *42*(3), 545–565. https://doi.org/10.1002/jmri.24787

[10] Dimou, E., Booij, J., Rodrigues, M., Prosch, H., Attems, J., Knoll, P., Zajicek, B., Dudczak, R., Mostbeck, G., Kuntner, C., Langer, O., Bruecke, T., & Mirzaei, S. (2009). Amyloid PET and MRI in Alzheimers Disease and Mild Cognitive Impairment. *Current Alzheimer Research*, *6*(3), 312–319. https://doi.org/10.2174/156720509788486563

[11] Duan, W., Akinyemi, T., Du, W., Ma, J., Chen, X., Wang, F., Omisore, O., Luo, J., Wang, H., & Wang, L. (2023). Technical and Clinical Progress on Robot-Assisted Endovascular Interventions: A Review. *Micromachines*, *14*(1). https://doi.org/10.3390/mi14010197

[12] Fass, L. (2008). Imaging and cancer: a review. *Molecular Oncology*, *2*(2), 115–152. https://doi.org/10.1016/j.molonc.2008.04.001

[13] Glick, Y., Balasubramanian, S., & Zheng, A. (2018). Digital subtraction angiography. In *Radiopaedia.org*. Radiopaedia.org. https://doi.org/10.53347/rID-62028

[14] Gross, J. S., Yaeger, A., Tchelepi, H., & Matcuk, G. R. (2023). Ultrasound Fusion: Applications in Musculoskeletal Imaging. *Life*, *13*(6), 1278. https://doi.org/10.3390/life13061278

[15] Hicks, R., Lau, E., & Binns, D. (2007). Hybrid imaging is the future of molecular imaging. *Biomedical Imaging and Intervention Journal*, *3*(3), e49. https://doi.org/10.2349/biij.3.3.e49

[16] Ho, D., Quake, S. R., McCabe, E. R. B., Chng, W. J., Chow, E. K., Ding, X., Gelb, B. D., Ginsburg, G. S., Hassenstab, J., Ho, C.-M., Mobley, W. C., Nolan, G. P., Rosen, S. T., Tan, P., Yen, Y., & Zarrinpar, A. (2020). Enabling Technologies for Personalized and Precision Medicine. *Trends in Biotechnology*, *38*(5), 497–518. https://doi.org/10.1016/j.tibtech.2019.12.021

[17] Hong, J., Konishi, K., Nakashima, H., Ieiri, S., Tanoue, K., Nakamuta, M., & Hashizume, M. (n.d.). Integration of MRI and ultrasound in surgical navigation for robotic surgery. In *World Congress on Medical Physics and Biomedical Engineering 2006* (pp. 3052–3055). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-36841-0_773

[18] Huang, Y.-C., Tsuang, F.-Y., Lee, C.-W., Wu, C.-Y., & Lin, Y.-H. (2019). Assessing Vascularity of Osseous Spinal Metastases with Dual-Energy CT-DSA: A Pilot Study Compared with Catheter Angiography. *American Journal of Neuroradiology*, *40*(5), 920–925. https://doi.org/10.3174/ajnr.A6023

[19] Hussain, D., Abbas, N., & Khan, J. (2024). Recent Breakthroughs in PET-CT Multimodality Imaging: Innovations and Clinical Impact. *Bioengineering (Basel, Switzerland)*, *11*(12). https://doi.org/10.3390/bioengineering11121213

[20] Jung, J. H., Choi, Y., & Im, K. C. (2016a). PET/MRI: Technical Challenges and Recent Advances. *Nuclear Medicine and Molecular Imaging*, *50*(1), 3–12. https://doi.org/10.1007/s13139-016-0393-1

[21] *PET MRI*. (n.d.). Retrieved October 7, 2025, from https://www.massgeneral.org/imaging/programs-and-services/nuclear-medicine/pet-mri

[22] la Fougere, C., Suchorska, B., Bartenstein, P., Kreth, F.-W., & Tonn, J.-C. (2011). Molecular imaging of gliomas with PET: Opportunities and limitations. *Neuro-Oncology*, *13*(8), 806–819. https://doi.org/10.1093/neuonc/nor054

[23] *PET/CT | GE HealthCare (India)*. (n.d.). Retrieved October 7, 2025, from https://www.gehealthcare.in/products/molecular-imaging/pet-ct

[24] Lee, M. W. (2014a). Fusion imaging of real-time ultrasonography with CT or MRI for hepatic intervention. *Ultrasonography (Seoul, Korea)*, *33*(4), 227–239. https://doi.org/10.14366/usg.14021

[25] Luna, A. ., Vilanova, J. C. ., Cruz, L. C. Hygino., & Rossi, S. E. . (2014). *Functional imaging in oncology*. Springer.

[26] Martinez-Möller, A., Eiber, M., Nekolla, S. G., Souvatzoglou, M., Drzezga, A., Ziegler, S., Rummeny, E. J., Schwaiger, M., & Beer, A. J. (2012). Workflow and Scan Protocol Considerations for Integrated Whole-Body PET/MRI in Oncology. *Journal of Nuclear Medicine*, *53*(9), 1415–1426. https://doi.org/10.2967/jnumed.112.109348

[27] Mbakaza, O., & Vangu, M.-D.-T. W. (2022). 18F-FDG PET/CT Imaging: Normal Variants, Pitfalls, and Artifacts Musculoskeletal, Infection, and Inflammation. *Frontiers in Nuclear Medicine*, *2*. https://doi.org/10.3389/fnume.2022.847810

[28] Moran, C. M., & Thomson, A. J. W. (2020). Preclinical Ultrasound Imaging—A Review of Techniques and Imaging Applications. *Frontiers in Physics*, *8*. https://doi.org/10.3389/fphy.2020.00124

[29] Mulita, A., Valsamaki, P., Bekou, E., Anevlavis, S., Nanos, C., Zisimopoulos, A., Giatromanolaki, A., & Koukourakis, M. I. (2025). Benefits from 18F-FDG PET-CT-Based Radiotherapy Planning in Stage III Non-Small-Cell Lung Cancer: A Prospective Single-Center Study. *Cancers*, *17*(12), 1969. https://doi.org/10.3390/cancers17121969

[30] Nam, H. H., Jang, D. K., & Cho, B. R. (2022). Complications and risk factors after digital subtraction angiography: 1-year single-center study. *Journal of Cerebrovascular and Endovascular Neurosurgery*, *24*(4), 335–340. https://doi.org/10.7461/jcen.2022.E2022.05.001

[31] Okamoto, K., Ito, J., Sakai, K., & Yoshimura, S. (2000). The principle of digital subtraction angiography and radiological protection. *Interventional Neuroradiology : Journal of Peritherapeutic Neuroradiology, Surgical Procedures and Related Neurosciences*, *6 Suppl 1*(Suppl 1), 25–31. https://doi.org/10.1177/15910199000060S102

[32] Paushter, D., Borkowski, G., Buonocore, E., Belhobek, G., & Marks, K. (1983). Digital subtraction angiography for preoperative evaluation of extremity tumors. *American Journal of Roentgenology*, *141*(1), 129–133. https://doi.org/10.2214/ajr.141.1.129

[33] Pettinato, C., Nanni, C., Farsad, M., Castellucci, P., Sarnelli, A., Civollani, S., Franchi, R., Fanti, S., Marengo, M., & Bergamini, C. (2006). Artefacts of PET/CT images. *Biomedical Imaging and Intervention Journal*, *2*(4), e60. https://doi.org/10.2349/biij.2.4.e60

[34] Pichler, B. J., Kolb, A., Nägele, T., & Schlemmer, H.-P. (2010). PET/MRI: Paving the Way for the Next Generation of Clinical Multimodality Imaging Applications. *Journal of Nuclear Medicine*, *51*(3), 333–336. https://doi.org/10.2967/jnumed.109.061853

[35] Poggi, C., & Palavecino, M. (2024). Ultrasound principles and instrumentation. *Surgery Open Science*, *18*, 123–128. https://doi.org/10.1016/j.sopen.2024.02.005

[36] Posa, A., Tanzilli, A., Barbieri, P., Steri, L., Arbia, F., Mazza, G., Longo, V., & Iezzi, R. (2022). Digital Subtraction Angiography (DSA) Technical and Diagnostic Aspects in the Study of Lower Limb Arteries. *Radiation*, *2*(4), 376–386. https://doi.org/10.3390/radiation2040028

[37] Pu, Y., Wang, C., Zhao, S., Xie, R., Zhao, L., Li, K., Yang, C., Zhang, R., Tian, Y., Tan, L., Li, J., Li, S., Chen, L., & Sun, H. (2021). The clinical application of 18F-FDG PET/CT in pancreatic cancer: a narrative review. *Translational Cancer Research*, *10*(7), 3560–3575. https://doi.org/10.21037/tcr-21-169

[38] Rischpler, C., Nekolla, S. G., Dregely, I., & Schwaiger, M. (2013). Hybrid PET/MR Imaging of the Heart: Potential, Initial Experiences, and Future Prospects. *Journal of Nuclear Medicine*, *54*(3), 402–415. https://doi.org/10.2967/jnumed.112.105353

[39] Robb, E. L., Regina, A. C., & Baker, M. B. (2025). *Organophosphate Toxicity*.

[40] Rong, J., & Liu, Y. (2024). Advances in medical imaging techniques. *BMC Methods*, *1*(1), 10. https://doi.org/10.1186/s44330-024-00010-7

[41] Sarikaya, I., & Sarikaya, A. (2021). PET/CT Image Artifacts Caused by the Arms. *Journal of Nuclear Medicine Technology*, *49*(1), 19–22. https://doi.org/10.2967/jnmt.120.248641

[42] Sireesha, P., Kalawat, T. C., Ajit, N., Hemalatha, D. S., & Priya, R. R. (2023). 18Fluorodeoxyglucose positron emission tomography-computed tomography findings in bilateral adrenal metastases in renal cell carcinoma. *Journal of Clinical and Scientific Research*, *12*(Suppl 2), S119–S122. https://doi.org/10.4103/jcsr.jcsr_136_22

[43] Smith, C. L. C., Zwezerijnen, G. J. C., den Hollander, M. E., Zijlstra, J. M., Menke-van der Houven van Oordt, C. W., Bahce, I., Yaqub, M., & Boellaard, R. (2025). Feasibility of Ultra-Low-Activity ^{18} F-FDG PET/CT Imaging Using a Long–Axial-Field-of-View PET/CT System. *Journal of Nuclear Medicine*, *66*(6), 961–966. https://doi.org/10.2967/jnumed.124.269272

[44] Thomason, M. E., Chang, C. E., Glover, G. H., Gabrieli, J. D. E., Greicius, M. D., & Gotlib, I. H. (2008a). Default-mode function and task-induced deactivation have overlapping brain substrates in children. *NeuroImage*, *41*(4), 1493–1503. https://doi.org/10.1016/j.neuroimage.2008.03.029

[45] Tsai, Y.-J., & Liu, C. (2021). Pitfalls on PET/CT Due to Artifacts and Instrumentation. *Seminars in Nuclear Medicine*, *51*(6), 646–656. https://doi.org/10.1053/j.semnuclmed.2021.06.015

[46] Tsuang, F.-Y., Huang, Y.-C., Liao, T.-W., Lin, Y.-H., & Lee, C.-W. (2024). Association of CT-DSA vascular assessment and perioperative outcomes in metastatic spinal surgery. *European Journal of Radiology*, *178*, 111639. https://doi.org/10.1016/j.ejrad.2024.111639

[47] Turski, P. A., Zwiebel, W. J., Strother, C. M., Crummy, A. B., Celesia, G. G., & Sackett, J. F. (1983). Limitations of intravenous digital subtraction angiography. *AJNR. American Journal of Neuroradiology*, *4*(3), 271–273.

[48] Vandenberghe, S., & Marsden, P. K. (2015). PET-MRI: a review of challenges and solutions in the development of integrated multimodality imaging. *Physics in Medicine and Biology*, *60*(4), R115–R154. https://doi.org/10.1088/0031-9155/60/4/R115

[49] Wang, L.-H., & Zhang, G.-Q. (2012). Use of digital subtraction angiography for assessment of digital replantation. *Journal of Zhejiang University. Science. B*, *13*(3), 209–212. https://doi.org/10.1631/jzus.B1100223

[50] Zaidi, H., & Del Guerra, A. (2011). An outlook on future design of hybrid PET/MRI systems. *Medical Physics*, *38*(10), 5667–5689. https://doi.org/10.1118/1.3633909