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REVIEW

Abdominal and pelvic ^{18}F-FDG PET/MR: a review of current and emerging oncologic applications

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Abstract

Positron emission tomography (PET) using fluorodeoxyglucose (^{18}F-FDG) combined with magnetic resonance imaging (MR) is an emerging hybrid modality that has shown utility in evaluating abdominal and pelvic disease entities. Together, the high soft tissue contrast and metabolic/functional imaging capabilities make this modality ideal for oncologic imaging in many organ systems. Its clinical utility continues to evolve and future research will help solidify its role in oncologic imaging. In this manuscript, we aim to (1) provide an overview of the various PET/MR systems, describing the strengths and weaknesses of each system, and (2) review the oncologic applications for ^{18}F-FDG PET/MR in the abdomen and pelvis.

Keywords PET/MRI · PET/MR · Oncology · Staging · Cancer

Introduction and technical aspects of PET/MR

Introduction

Positron emission tomography (PET) using fluorodeoxyglucose (^{18}F-FDG) combined with magnetic resonance imaging (MR) is an emerging hybrid modality largely built on the success of conventional PET/CT which achieved rapid clinical adoption in the early 2000s [1, 2]. Though only recently available in clinical practice, PET/MR harnesses the molecular imaging capabilities of PET and is combined with the high soft tissue and contrast resolution of conventional MR. In addition, multiparametric MR including diffusion, spectroscopy, and perfusion imaging add functional imaging capabilities which can be used to assess tissue cellularity, metabolite concentrations, and vascular permeability. A growing body of research suggests that this combination of anatomic and functional imaging is at least equivalent to and likely superior to CT, PET/CT, and conventional MR for

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many anatomic regions including the liver, bones, breasts, musculoskeletal system, head and neck, and the pelvis [3]. In this manuscript, we describe the current and emerging clinical body imaging applications of ^{18}F-FDG PET/MR in oncologic imaging including cancer detection, staging, restaging, and monitoring tumor response [4].

PET/MR systems

There were many engineering challenges to be overcome in designing integrated PET/MR systems, including magnetic field inhomogeneity caused by ferromagnetic materials in the PET systems and radiofrequency signals created by PET detector electronics which compromised the MR acquisitions [5]. Similarly, the high magnetic field caused a curved trajectory of the photons within the photomultiplier tubes which caused temporal and spatial distortion [5, 6] and the gradients and RF pulses interfered with PET signal analysis, which compromised the PET acquisition. Complex engineering innovations have made possible the construction of integrated PET/MR systems available today.

There are different PET/MR system configurations available; the most simple and first put into clinical use in 2010 was a sequential system in which the PET and MR components are acquired individually in a series [5, 7, 8]. While often in the same room in a linear setup (Philips Ingenuity TF PET/MR, Philips, Best, The Netherlands), such systems can also utilize nearby but separate PET and MR scanners, with the patient shuttled from one room to another (GE PET/CT+MR, GE, Milwaukee, USA). The advantage of these systems is that less extensive modifications are needed to the underlying equipment to overcome the deleterious effects of the magnetic field. On the other hand, the major disadvantage of these systems is that the data are acquired sequentially as opposed to in parallel, which can potentially cause misregistration artifacts. Additionally, these systems also have a larger footprint and longer acquisition times, as both the PET and MR components must be independently acquired.

Simultaneous or integrated [9, 10] systems (GE Signa TOF PET/MR, GE, Milwaukee, USA, and Siemens Biograph mMR, Siemens Healthineers, Erlangen, Germany, and uPMR 790 HD TOF, Shanghai United Imaging Healthcare, Shanghai, People's Republic of China) have many advantages over sequential systems and were later to enter the market as they required more technological hurdles to be overcome during development. Combined systems allow for improved spatial coregistration due to the simultaneous acquisition. These systems also permit shorter exam times, often in the range of 30–70 min versus 40–90 min for sequential systems [3] depending on the imaging protocol performed.

PET/MR protocols

Similar to PET/CT, patient instructions are provided prior to the exam for reduced background soft tissue uptake and increased target anatomical uptake, with the patient in fasting status and minimizing muscle activity prior to imaging. The specific set of sequences utilized depends on the underlying disease process being evaluated and the radiotracer being utilized and its half-life. An example imaging protocol for colon cancer staging is included in Table 1, with total imaging time of approximately an hour.

Essentially all the same radiotracers available for use for PET/CT are also available for PET/MR, with ^{18}F-FDG being the most commonly utilized for general oncologic imaging. While there are exceptions such as mucinous tumors, clear cell renal cancers, and well-differentiated hepatocellular carcinomas, which show decreased uptake compared with other

Table 1 Example PET/MR protocol for colon cancer staging

Sequence	Body area	Anatomic plane
T1-weighted Dixon VIBE	WB	Coronal
T2-weighted HASTE	WB	Axial
Diffusion-weighted images (50–400–800 *b*-values)	WB	Axial
T1-weighted dual GRE	Abdomen	Axial
T2-weighted FSE	Abdomen	Axial
T2-weighted HASTE	Abdomen	Coronal
T1-weighted VIBE (pre- and post-contrast)	Abdomen	Axial
T2-weighted FSE	Pelvis	Sagittal
T2-weighted FSE	Pelvis	Axial
T2-weighted FSE	Pelvis	Coronal
T1-weighted VIBE (post-contrast)	WB	Axial
PET	WB, 5–6 bed positions	

VIBE volume interpolated breath-hold examination, *HASTE* half-fourier acquisition single-shot turbo spin echo, *GRE* gradient recall echo, *FSE* fast spin echo, *PET* positron emission tomography

histologic types [11], the majority of tumors demonstrate increased uptake of the ^{18}F-FDG glucose analog compared to normal tissues. For other neoplasms such as neuroendocrine tumors and prostate cancer, there is increasing use of novel radiotracers such as ^{68}Ga-DOTATATE and ^{18}F-Fluciclovine/Prostate Specific Membrane Antigen (PSMA), respectively.

Advantages of PET/MR

Compared with PET/CT, MR offers better signal-to-noise and contrast-to-noise ratios than CT, which improves soft tissue resolution and can facilitate disease detection. Additionally, multiparametric imaging including anatomic T2-weighted imaging and dynamic T1-weighted fat suppressed contrast-enhanced images paired with functional imaging techniques such as diffusion-weighted images, spectroscopy, and perfusion can help identify and characterize lesions which would not otherwise be seen on conventional imaging.

One of the major limitations of PET/CT is that the images are sequentially acquired, i.e., initially a low-dose attenuation correction CT is performed which is followed with the PET portion and the two data sets are fused. Integrated PET/MR, on the other hand, can acquire the PET and MR images concurrently which allows for precise correlation of PET avid lesions with anatomy. Additionally, since integrated PET/MR is acquired for a longer period of time than PET/CT, more PET data can be collected which reduces noise and increases sensitivity for subtle lesions compared with PET/CT [12].

PET/MR also has a significantly reduced radiation dose with the exclusion of the CT component of the exam. Assuming an average dose of 14 mSv for a combined ^{18}F-FDG PET/CT, average radiation dose could drop to 7–10 mSv [3]. Since patients who are candidates for PET/CT often receive numerous scans over their lifetime, the aggregate dose reduction may be substantial.

Limitations of PET/MR

Since the diagnostic accuracy of PET/CT for many types of cancer is already high, it is difficult to show a clear advantage in individual cancers. Initial data suggest an advantage of PET/MR for certain types of malignancies while in others, it confers no advantage [13, 14]. In general, for disease processes where conventional MR is superior to CT, it may be advantageous to use PET/MR. Also, depending on the disease process, PET/MR may offer increased sensitivity for when the tumor burden is low, and the lesions are small and multifocal.

The use of MR requires longer examination times which decreases patient comfort and allows for more accumulation of radiotracer in the bladder, so care must be taken to select an abbreviated protocol that is sufficient to accurately diagnose and stage the disease process, ideally in the 20–30 min range [15]. Unlike with CT whereby multiplanar reformats can be obtained, since the resolution of MR is maximized in-plane, if additional imaging planes are needed, they should be acquired independently which increases total exam time [16]. Recently described so-called "ultra-fast" PET/MR protocols have been developed and have shown reduced acquisition times, comparable to those of PET/CT, without sacrificing diagnostic accuracy [17, 18].

Every imaging modality, including both PET and MR, is susceptible to patient motion such as through respiration. This limitation can be especially problematic in the detection of lung lesions. However, the synchronous acquisition of MR and PET data allows for motion correction of both PET and MR data using different approaches, including self-navigated methodologies that do not necessitate any external monitoring devices and are not available for PET/CT [19–21]. Additional novel techniques such as zero-TE lung imaging have shown great promise in improving diagnostic performance for small lung lesions [22].

Finally, although PET/MR is FDA approved, insurers may offer no or selective reimbursement for certain indications, which may place undue financial burden on patients. The aggregate cost to the patient and healthcare system is typically greater than the cost of MRI or PET/CT alone.

Oncologic ^{18}F-FDG PET/MR applications in the abdomen and pelvis

Pancreatic adenocarcinoma

Despite advancements in diagnosis and treatment, pancreatic ductal adenocarcinoma (PDAC) remains a major cause of morbidity and mortality in the US, owing in part to the lack of specific biomarkers, symptoms, and the heterogeneity of appearances on imaging. Once detected, fewer than 20% of patients have resectable disease at diagnosis. As such, imaging plays a key role not only in initial diagnosis but also in monitoring treatment response. Contrast-enhanced CT has historically been the preferred modality for initial diagnosis and staging of PDAC at many institutions, largely due to the high spatial resolution of CT to identify anatomic landmarks and vascular involvement critical to the staging [23]. While current guidelines do not recommend the use of PET imaging in pancreatic cancer except in high risk patients in the evaluation of metastases, when used, PET/CT and PET/MR are similar in terms of assessing tumor resectability and staging [24–27].

Nevertheless, there may be an evolving role for PET/MR in diagnosis and staging, as the combined functional

and anatomic imaging has shown promise. For example, one meta-analysis reported a higher sensitivity of PET in the diagnosis of PDAC (92%), compared with CT (87%) or MR (69%) alone [28], though it had lower specificity than either. The low specificity is due to pancreatitis and other inflammatory non-neoplastic processes that also demonstrate increased ^{18}F-FDG uptake, though malignant pancreatic lesions generally have higher SUV than inflammation [29]. Another study showed that combined PET/MR has increased accuracy in pancreatic cancer detection compared with PET/CT (96.6% vs 86.6%)[30]. In this study, the addition of T2-weighted imaging also permitted identification of pancreatic cystic lesions that were not identified on CT. Other authors have also shown improved confidence scores with PET/MR for characterizing pancreatic tumors compared with PET/CT [31].

Pancreatic cancer often metastasizes to the liver, lungs, and peritoneum [23] and many individuals with PDAC and indeterminate liver lesions end up needing liver MR, PET/CT, and/or biopsy in addition to the initial staging CT. Additionally, physiologic uptake of ^{18}F-FDG within the liver may obscure some lesions on PET/CT which may lead to additional diagnostic imaging or biopsy. In light of these limitations, PET/MR may be useful in some cases to detect and characterize indeterminate lesions (especially lesions < 1 cm) in a single session which reduces overall cost and time to diagnosis (Fig. 1).

An additional emerging area for clinical use of PET/MR is in the context of monitoring treatment response, as RECIST measurements are not a good predictor of resectability in the context of neoadjuvant chemotherapy [32]. It has been shown that DWI and SUV values provide useful insight regarding treatment response [33, 34]. Other research has demonstrated that DWI and ADC obtained from MRI and metabolic tumor volume and total lesion glycolysis measurements obtained from PET may reveal early response to therapy [35]. Similarly, the functional abilities of PET may help delineate post-treatment changes from residual or recurrent malignancy.

Gastrointestinal tract malignancies

Colorectal cancer (CRC) is the third most common cancer in the USA [36, 37]. Although the incidence and mortality rates are decreasing among adults greater than 50 years old, they have been increasing among adults younger than 50 years old [38]. Recurrence rates for locally advanced rectal tumors have also declined, largely attributed to new surgical techniques and chemotherapy regimens. However, despite advances in treatment, recurrence rates are as high as 30–45% for more advanced stages and up to one-third of patients with locally advanced rectal cancer will die within 5 years of completion of treatment [39–41]. Diagnostic imaging plays a pivotal role in initial staging of untreated CRC and in the surveillance of treated CRC [42, 43].

The National Comprehensive Cancer Network (NCCN) guidelines recommend chest, abdominal and pelvic CT for initial colon cancer staging with ^{18}F-FDG PET/CT indicated in the staging of patients with presumably resectable oligometastatic disease to rule out other occult metastases. Similarly, the role of ^{18}F-FDG PET/MRI in colon cancer staging is limited to evaluation of metastatic disease. In surveillance, PET/CT is recommended in the same situation or with serial CEA elevation despite negative physical examination, colonoscopy, and chest and abdominopelvic contrast-enhanced CTs.

In rectal cancer, on the other hand, MR is the modality of choice for initial evaluation, owing to its ability to provide detailed anatomic information as well as information about the extent of involvement of key structures such as the peritoneal reflection, mesorectal fascia, and lymph nodes [44] (Fig. 2). Initial experiences have shown high diagnostic

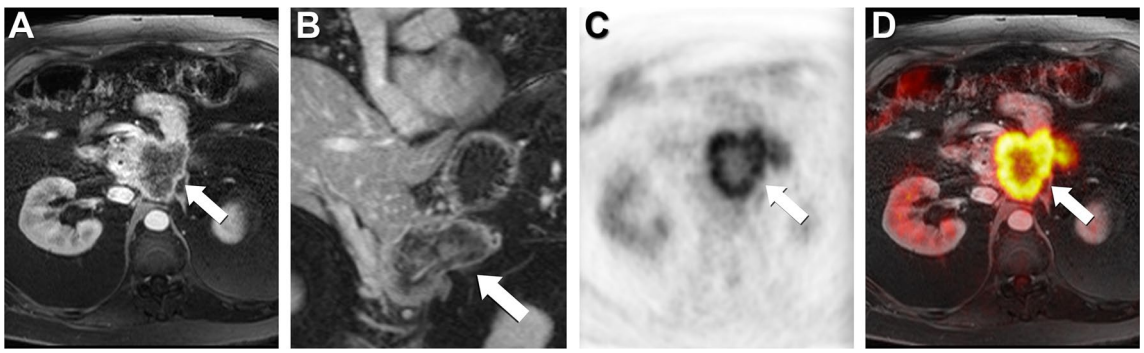

Fig. 1 63-year-old man with pancreatic adenocarcinoma. Axial (**a**) and coronal (**b**) contrast-enhanced MR demonstrates a peripherally enhancing, centrally necrotic mass (white arrow) within the pancreatic uncinate process that extends posteriorly in the retroperitoneum. There is corresponding ^{18}F-FDG uptake on the unfused (**c**) and fused (**d**) axial images. The addition of PET in this case shows clear delineation of tumor margins and facilitates accurate staging. An additional benefit of PET/MR is evaluation for local and distant spread in a single study

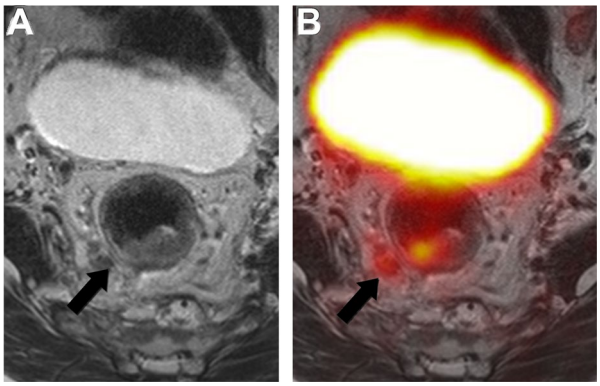

Fig. 2 PET/MR in a 60 year old patient demonstrates a mid rectal polypoid mass confined to the muscularis. Axial high resolution T2w image (**a**) and fused PET/MR image (**b**). There is a subcentimeter ovoid T2 hypointense lymph node in the right lateral mesorectal fat (**a**, black arrow) which is equivocal for nodal involvement. However, the presence of ^{18}F-FDG uptake on fused image (**b**) confirms the mesorectal nodal involvement with malignancy

accuracy of PET/MR in rectal cancer T staging and comparable N and M staging and restaging when compared with PET/CT [45]. Anatomic localization of areas of ^{18}F-FDG uptake can be challenging with PET/CT scans, due to the low soft tissue signal-to-noise and contrast-to-noise ratios of CT scans, as well as the asynchronous acquisition of the PET data and CT images. These factors decrease the performance of PET/CT scans, particularly in the assessment of T and N factors in rectal cancer, in liver lesions measuring less than 1 cm, subcapsular liver lesions, peritoneal metastases, and in the case of nonspecific intestinal ^{18}F-FDG uptake [46]. Moreover, PET/MR allows for whole body staging with very low radiation exposure in the same study to assess both locoregional and distant disease extension in a single study.

Most published studies include small mixed populations of initial staging and recurrence. However, available studies show that ^{18}F-FDG PET/MR outperforms contrast-enhanced CT and PET/CT in clinical practice by detecting occult metastases and by recharacterizing lesions falsely described as metastases by other imaging modalities [47, 48]. In the context of treated colorectal metastases, PET/MR has been shown to change oncologic management in up to 36% of patients [49]. There are large clinical implications of missing a metastasis or erroneously characterizing a lesion. In healthy non-steatotic/cirrhotic patients a substantial amount of liver parenchyma can be resected as long as two adjacent liver segments or at least 20% of total estimated liver volume remain [50]. Moreover, extrahepatic metastases, including those to the peritoneum, are no longer an absolute contraindication for liver metastases resection which increases the need for an accurate pre-operative assessment of the extent of disease [51]. Overall, PET/MR has been shown to have an accuracy of 94% in detection of pelvic recurrence in rectal cancer patients [52] and 74% accuracy in detection of liver lesions in colorectal cancer patients [53].

Primary hepatic masses

Imaging of primary liver malignancies such as hepatocellular carcinoma (HCC) and intrahepatic cholangiocarcinoma (ICC) plays a critical role in the management of these tumors. HCC is the most common primary malignancy of the liver and a common cancer in the USA overall [54]. Prompt and accurate diagnosis of HCC is critical as surgical resection or liver transplantation can provide a cure for certain patients. For HCC, imaging alone through Organ Procurement and Transplantation Network (OPTN) or Liver Reporting and Data System (LIRADS) criteria with contrast-enhanced CT or MR is sufficient to diagnose these tumors in certain patient cohorts without the need for biopsy. ^{18}F-FDG uptake has been shown to correlate with the degree of HCC differentiation, with higher grade HCC demonstrating increased uptake and SUV compared with lower grade HCC [55]. As a result, the increased variability of ^{18}F-FDG uptake with HCC decreases overall sensitivity, with overall ranges quoted in the literature of approximately 50–60% [56]. Therefore, PET alone is insufficient for the management of HCC. PET/CT has been studied for its utility with extrahepatic metastases, which typically occur with higher grade tumors [57]. Currently, very little has been established on the use of PET/MR in HCC. Preliminary studies have investigated the correlation with ^{18}F-FDG uptake and multiparametric MR on HCC characterization [58].

The workup for ICC often includes imaging such as CT or MR based on NCCN guidelines. Both imaging modalities have demonstrated suboptimal sensitivity in the detection of intrahepatic metastases, lymphadenopathy, and peritoneal disease [59, 60]. Metabolic imaging with PET and PET/CT can help improve sensitivity of detection of lesions, although literature regarding its utility is scarce and heterogeneous. PET/CT appears to suffer from inherent limitations of fine anatomic detail essential in the imaging of these tumors, especially for small lesions (< 10 mm), bile ductal involvement, and vascular involvement. PET/MR has theoretical benefits by maximizing the combined benefits of both modalities, in utilizing the high sensitivity of PET and the anatomic precision of MR (Fig. 3). Recently, PET/MR has been suggested to improve pre-surgical guidance, changing the clinical management in up to 30% of patients with intrahepatic cholangiocarcinoma [61].

Hepatic metastases

Appropriate liver imaging is crucial in the staging and management of many types of malignancies. For example, the liver is the most common site of distant metastases from

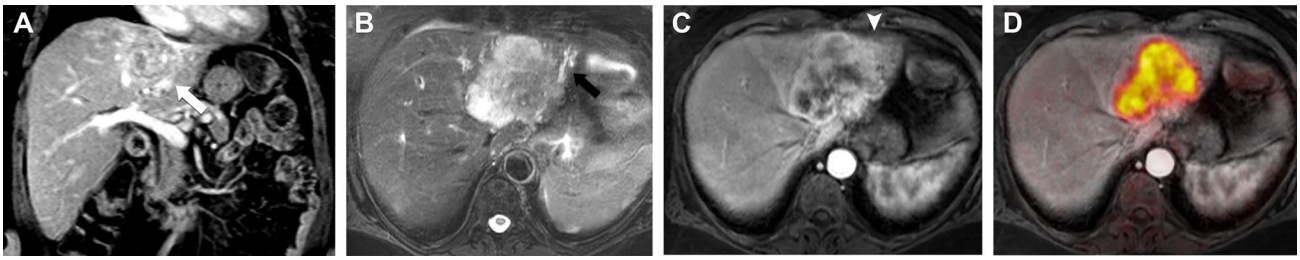

Fig. 3 57-year-old man with intrahepatic cholangiocarcinoma. Coronal contrast-enhanced T1-weighted image (**a**) demonstrates a subcapsular heterogeneously enhancing mass in segments 2/3 (white arrow) with associated areas of segmental intrahepatic biliary ductal dilation (black arrow, **b**) and capsular retraction (arrow head, **c**). Simultaneously acquired PET/MR (**d**, fused image) shows marked ^{18}F-FDG uptake within the mass. While the findings are nonspecific, they suggest an aggressive pattern of disease including hepatocellular carcinoma, cholangiocarcinoma, or metastasis. The diagnosis of cholangiocarcinoma was subsequently confirmed on biopsy

colorectal cancer, with over 50% of patients having hepatic metastases [62]. Unlike many other malignancies, colorectal metastases to the liver are potentially curable with surgical resection in approximately one-third of patients. An additional subset of patients with previously unresectable lesions can be treated with curative intent following neoadjuvant chemotherapy [63, 64]. Many other primary malignancies commonly metastasize to the liver and, as such, imaging plays a key role in detection and characterization and in monitoring response to therapy.

Traditionally, contrast-enhanced CT has been the primary imaging modality for the detection and localization of liver lesions with either PET or MR used to further evaluate indeterminate liver lesions. In staging, ^{18}F-FDG PET has been shown to have improved sensitivity for the detection of liver metastases and has high predictive value in monitoring therapy response [65, 66]. In the neoadjuvant setting, liver MR is superior to other modalities with a pooled sensitivity of 86% in the detection of colorectal liver metastasis [67] (Fig. 4). As such, combined PET/MR allows for improved liver lesion detection as well as assessment of treatment response [68–71]. Initial studies investigating the value of whole body PET/MR in the management of hepatic metastases have shown improved diagnostic performance, particularly with small metastases [48, 71]. Others have shown that PET/MR has a higher sensitivity than PET/CT (98.3% versus 84.2%, respectively) and is particularly suitable for detecting lesions less than one centimeter [72]. The use of hepatobiliary specific contrast agents such as gadobenate dimeglumine (Gd-BOPTA, Multihance) has been shown to further increase diagnostic confidence and accuracy for correct assessment of benign and malignant liver lesions in PET/MRI [73].

Lymphoma

Lymphomas are collectively a heterogeneous group of neoplasms arising from lymphocytes, with dozens of recognized

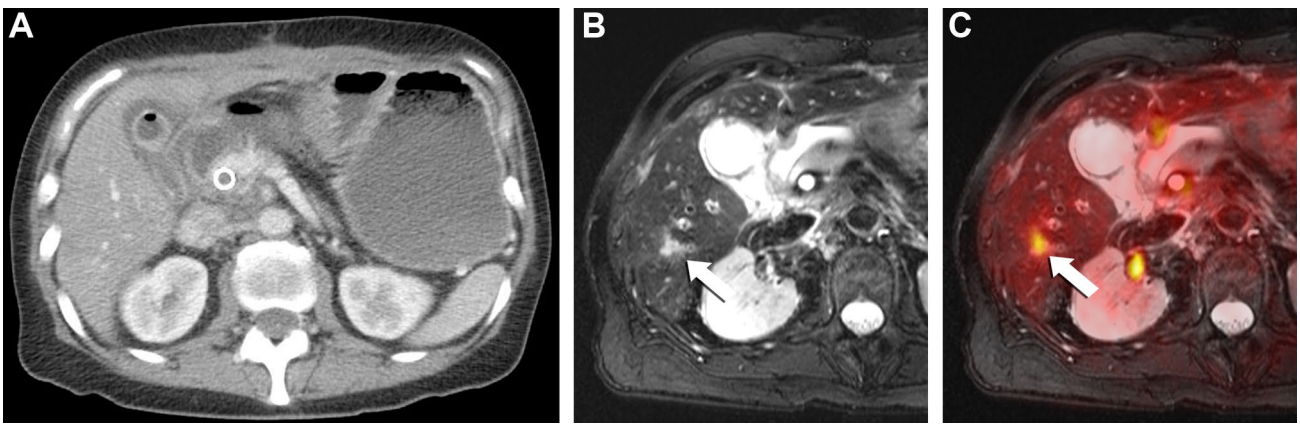

Fig. 4 66-year-old woman with pancreatic adenocarcinoma metastases. Initially performed contrast-enhanced CT (**a**) for surveillance of pancreatic adenocarcinoma demonstrates no focal liver lesions. Subsequently performed PET/MR demonstrates a segment 6 hepatic lesion (white arrow) that is mildly T2 hyperintense (**b**) and hypermetabolic (**c**, fused image) consistent with metastasis. PET/MR can facilitate detection of small metastases that are occult on CT

subtypes differentiated by histology, immunophenotype, and cytogenetics. The most common subtypes include diffuse large B-cell lymphoma, follicular lymphoma, Hodgkin's lymphoma, marginal zone lymphoma, chronic lymphocytic leukemia, and mantle cell lymphoma. These can be further differentiated at the cellular level by their ^{18}F-FDG avidity, which has become an important measure of tumor metabolic activity for staging, monitoring treatment response, and surveillance [74].

The role of ^{18}F-FDG PET for staging and monitoring treatment response has been well established in both Hodgkin's and non-Hodgkin's lymphoma (NHL) [75–77]. ^{18}F-FDG PET/CT is the current modality of choice for initial staging of FDG-avid lymphomas, although ^{18}F-FDG PET/MR is a promising alternative which has been shown to have comparable diagnostic accuracy [78–80] (Fig. 5). Since in most cases, 50–80% of the ionizing radiation dose from PET/CT is attributable to the whole body CT examination, a clear advantage of ^{18}F-FDG PET/MR compared to PET/CT is substantially lower radiation doses [81]. Lower radiation doses are particularly attractive in this context, where a significant portion of the expected patient population falls in the pediatric age range and serial follow-up examinations may be indicated. Additionally, PET/MR has superior soft tissue resolution compared to PET/CT, as well as the ability to acquire simultaneous multiparametric MR data, both of which may improve diagnostic accuracy, particularly in the case of initial staging or assessing treatment response in poorly FDG-avid disease. Differentiating viable lymphomatous masses from post-treatment changes can be difficult in this context, and multiparametric MR may offer valuable functional information about tumor activity at restaging. Although whole body diffusion-weighted imaging (DWI) alone is inferior to PET/CT, Kirchner et al. demonstrated that multiparametric PET/MR with additional simultaneously acquired contrast-enhanced and DWI can achieve improved diagnostic accuracy on a per lesion basis compared to PET/CT [17, 80]. In the current guidelines, PET/CT remains the standard of care for initial staging, restaging, and surveillance, although there is a growing role for multiparametric PET/MR for which further investigation is needed [82].

Urinary tract malignancies

^{18}F-FDG PET imaging alone has limited utility in evaluating for urinary tract malignancies, as there is physiologic uptake of ^{18}F-FDG within the kidneys and excretion into the bladder, resulting in intense uptake in these anatomic regions. As such, its utility is primarily in the detection of extra-renal lesions. For example, ^{18}F-FDG PET/CT has been shown to have a sensitivity of 84% and specificity of 91% in the detection of extra-renal cell carcinoma [83]. Additional studies and clinical trials are currently under way to evaluate the utility of PET with respect to tumor grade. Similarly, ^{18}F-FDG PET has limited utility in prostate cancer imaging, as these tumors are slow growing and usually demonstrate non-glucose metabolic pathways, which limits the uptake of the radiotracer [84, 85]. Consequently, the addition of ^{18}F-FDG PET imaging has not been consistently shown to improve diagnostic performance when compared with the use of MRI alone.

Gynecologic malignancies

PET/MR is an ideal modality to evaluate gynecologic malignancies, which include endometrial, cervical, and ovarian cancers. MR provides superior soft tissue resolution which

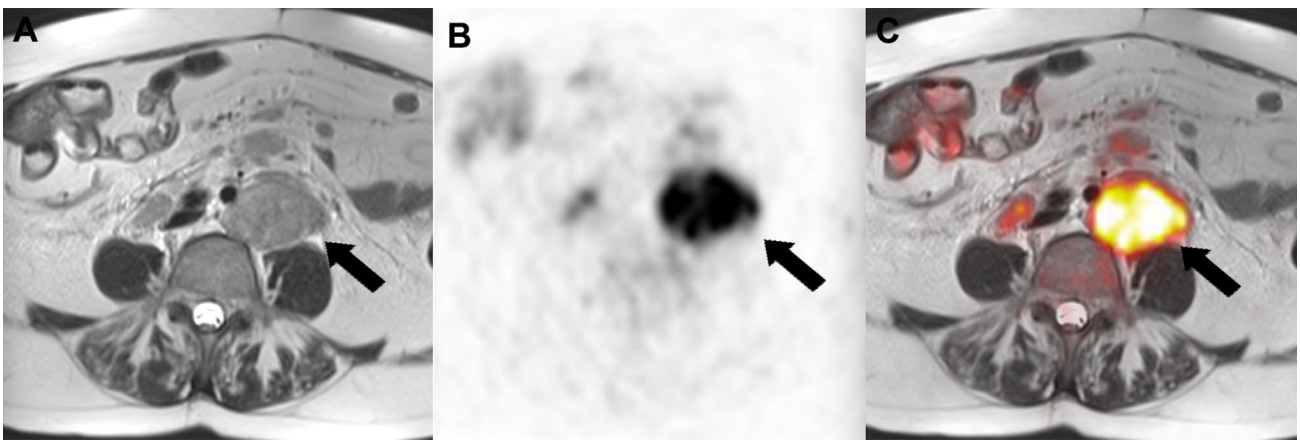

Fig. 5 58-year-old man undergoing treatment for Hodgkin's lymphoma. Axial T2-weighted image (**a**) demonstrates an enlarged left distal para-aortic/common iliac lymph node (black arrow). Simultaneously acquired PET image (**b**) and fused image (**c**) demonstrate corresponding increased ^{18}F-FDG uptake indicating metabolic activity and incomplete treatment response

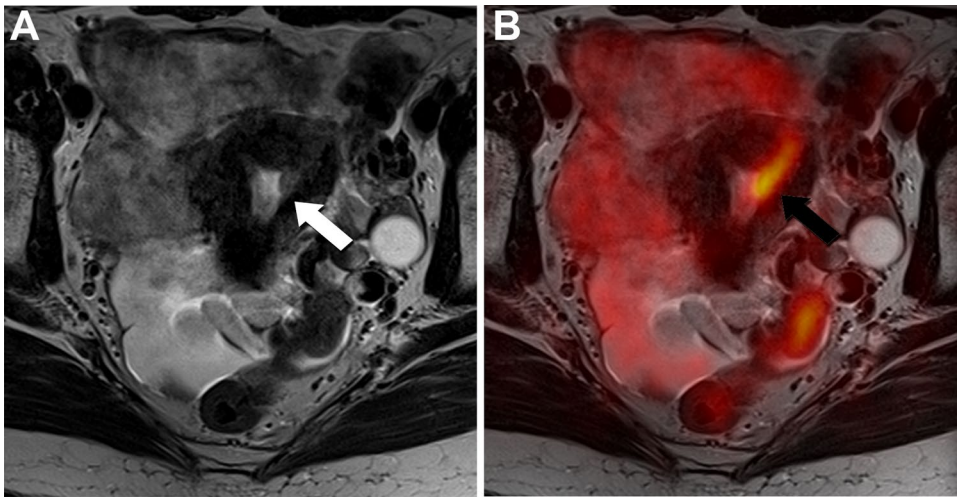

Fig. 6 48-year-old woman with endometrial cancer. Axial T2-weighted image (**a**) demonstrates a hypointense mass along the left fundal endometrium (white arrow) which appears to be confined to the endometrium. Simultaneously acquired PET image demonstrates increased ^{18}F-FDG uptake within the uterine fundus, which, when fused and coregistered with T2WI (**b**) shows myometrial invasion > 50% (black arrow) which upstaged the patient's endometrial cancer to IB from IA

can help delineate the fine details of local extent of disease, identify the ovaries and adjacent lymph nodes, and differentiate physiologic uptake (for example, in a corpus luteum cyst) from abnormal ovarian uptake compared with PET/CT.

Much of the extant literature evaluating PET/MR in the context of gynecologic malignancies reports studies with small sample sizes and with combined analysis of uterine, endometrial, and cervical malignancies. Pooled sensitivity and specificity of PET/MR for diagnosing gynecologic malignancies is 89–95% and 87–89%, respectively, depending on whether the analysis was performed on a per-patient or per lesion basis [86].

For endometrial cancer, PET/MR outperforms PET/CT in terms of tumor delineation and assessment of local infiltration [87] (Fig. 6). PET/MR is also sensitive and specific in detecting vaginal, parametrial, or myometrial invasion, with sensitivities of 86–92% and specificities of 78–98%, and also demonstrates 100% sensitivity and specificity in detecting pelvic sidewall invasion [86]. In one study, PET/MR was able to detect soft tissue invasion in 7 cases of cervical or endometrial cancer whereas PET/CT detected no cases [88]. In this same study, PET/MR correctly upstaged 5 patients and changed management in 2 patients. PET/MR including T2-weighted imaging has also been shown to have improved detection of uterine and ovarian lesions compared with PET/CT [89].

As with endometrial cancer, PET/MR in cervical cancer has been shown to be superior to PET/CT in terms of tumor delineation and assessment of local infiltration [87] (Fig 7). Quantitative analyses of SUV and ADC in patients with cervical cancer have shown correlation with tumor grade and size [90–92].

PET/MR also outperforms PET/CT in assessing lymphadenopathy, with varying results depending on station and the type of primary malignancy [93–96]. Using the larger field of view images, PET/MR can also detect peritoneal carcinomatosis (Fig. 8).

Conclusion

While still in its infancy, a growing body of ^{18}F-FDG PET/MR research has demonstrated its utility in oncologic applications within the abdomen and pelvis. The major advantages of PET/MR over conventional PET/CT include simultaneous acquisition of PET and MR for more accurate spatial coregistration, high soft tissue resolution for improved delineation of soft tissue, lower radiation dose, and additional information provided by diffusion in interrogating tissue cellularity.

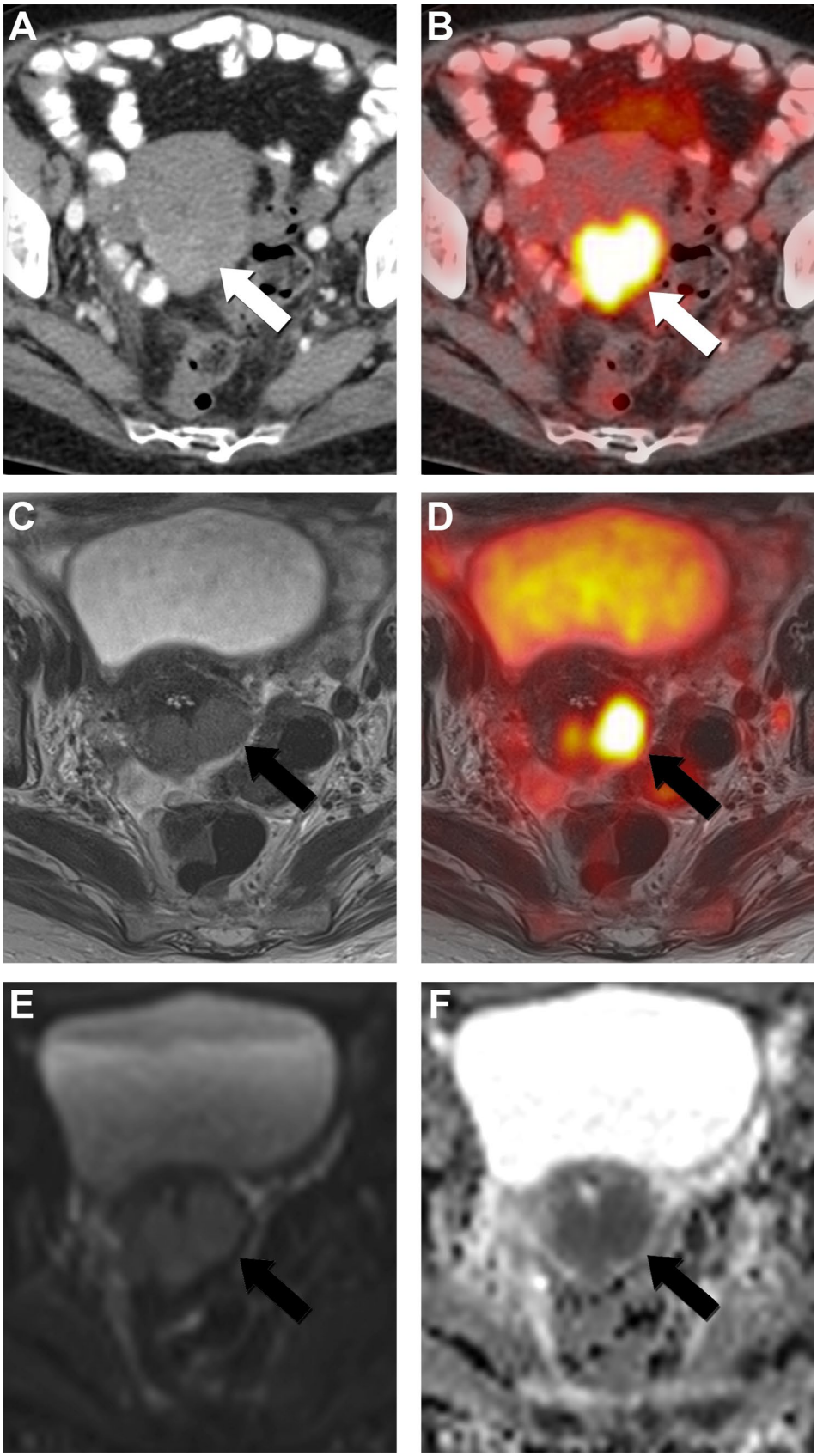

Fig. 7 45-year-old woman with cervical cancer. Contrast-enhanced CT (**a**) demonstrates fullness in the lower uterine segment with equivocal enhancing soft tissue (white arrow). PET/CT with fused images (**b**) confirms a corresponding hypermetabolic mass in the lower uterine segment/cervical region. Subsequently performed PET/MR shows a T2 hyperintense (**c**), ^{18}F-FDG avid (**d**) bilobed mass with restricted diffusion (**e**, DWI; **f**, ADC) in the cervix (black arrow) extending into the parametrial soft tissues. The high soft tissue contrast of MR combined with PET permits accurate staging as IIB, not readily apparent on conventional PET/CT

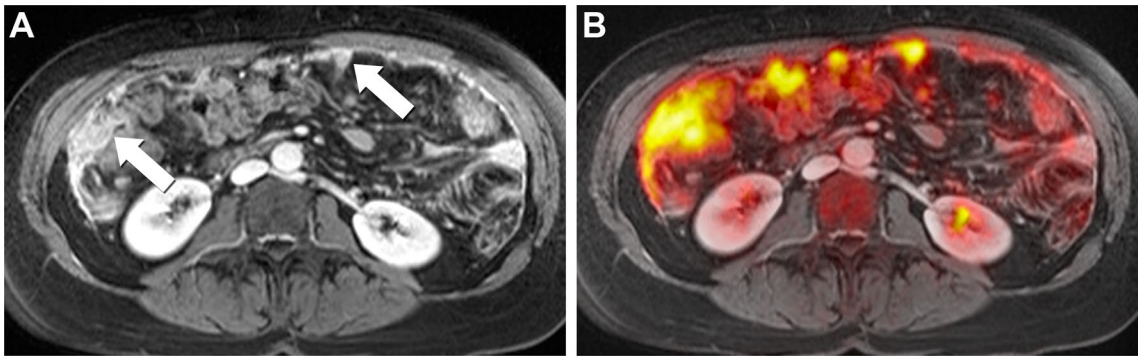

Fig. 8 53-year-old woman with peritoneal carcinomatosis. Post-contrast T1-weighted MR (**a**) demonstrates multifocal areas of nodular enhancing soft tissue within the lower abdomen (white arrows). There is corresponding ^{18}F-FDG uptake (**b**, fused image) in keeping with peritoneal carcinomatosis

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