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SPECIAL SECTION: PET/MR

PET/MRI for evaluation of patients with pancreatic cancer

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Abstract
Pancreatic cancers are the third leading cause of cancer-related death in the USA and outcomes remain poor despite improvements in imaging and treatment paradigms. Currently, computed tomography (CT) and magnetic resonance imaging (MRI) are frequently utilized for staging and restaging of these malignancies, but positron emission tomography (PET)/CT can play a role in troubleshooting and improve whole-body staging. PET/MRI is a novel imaging modality that allows for simultaneous acquisition of PET and MRI images, leading to improved image quality and potential increased sensitivity. Early studies suggest that PET/MRI may play a larger role in pancreatic cancer imaging in future. This manuscript will briefly discuss current imaging approaches to pancreatic cancer and outline existing evidence and published data supporting the use of PET/MRI for pancreatic cancers.

Keywords Pancreatic cancer · PET/MRI · Neuroendocrine tumor

Introduction to pancreatic cancer

Pancreatic cancer is the 10th most common cancer in the USA, with rising incidence, and is the 3rd leading cause of cancer-related death [1]. Early diagnosis of pancreatic cancer is key to improving 5-year survival and increasing treatment options [2]. However, pancreatic cancer is often asymptomatic in early stages, and if symptoms are present, they may be nonspecific, such as weight loss, dyspepsia, and nausea [3]. Currently, there are no screening guidelines, even for groups at increased risk [4].

Imaging studies are critical in multidisciplinary discussion, offering insight into staging, tumor characterization, and potential surgical candidacy. Due to indolent symptoms and no effective screening methodologies, only 15–20% of patients are surgical candidates at time of diagnosis. Surgical resection with negative margins increases 5-year survival to 21% [3]. However, even with negative surgical margins disease recurs in up to 70% of cases [3]. Initial imaging often includes multiphasic contrast-enhanced computed tomography (CT), endoscopic ultrasound (US), and/or magnetic resonance imaging (MRI), all of which can provide complimentary information for characterization of the pancreatic tumor. Positron emission tomography/CT (PET/CT) is not commonly used for pancreatic cancer outside of troubleshooting various clinical scenarios. PET/MRI is a novel imaging modality combining the strengths of both PET and MRI with distinct advantages in abdominopelvic oncology. The focus of this article will be to review how PET/MRI may improve upon existing imaging strategies based on published evidence of PET/MRI utility in patients with pancreatic cancer.

Imaging modalities for pancreatic cancer and how PET/MR may help

Imaging plays a critical role not only in the initial detection of pancreatic ductal adenocarcinoma (PDAC), but also in the development of treatment plans and subsequent surveillance. PDAC may be discovered by various imaging modalities and in a variety of clinical scenarios, for example, as part of a targeted evaluation based upon specific signs or symptoms, as an unexpected/incidental finding, or as part of a screening examination in a high-risk patient. CT, MR, and hybrid

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imaging techniques such as PET/CT or PET/MR have all been utilized in imaging of PDAC.

Considering its widespread availability, rapid acquisition, and ability to evaluate for a variety of potential pathologies, CT is often pursued as the initial imaging evaluation when there are specific signs or symptoms of concern. In the setting of nonspecific abdominal complaints, initial imaging often consists of a CT obtained in portal venous phase or approximately 65–70 s following onset of bolus administration of intravenous contrast.

As PDAC may be poorly seen on portal venous phase only CTs, for clinical scenarios in which there is specific concern for PDAC, the consensus recommendation by the Society of Abdominal Radiology and American Pancreatic Association is that initial evaluation be performed with biphasic CT [5]. The biphasic elements of the examination include both a pancreatic parenchymal phase as well as a portal venous phase. This combination of phases not only provides high sensitivity for detection of the primary lesion but also allows for accurate assessment of vascular involvement as well as the ability to screen for metastatic disease elsewhere in the abdomen. Submillimeter slice thickness and a variety of post-processing techniques are key in staging and determination of lesion resectability [6].

While the utility of PET/CT in the evaluation and management of PDAC has been not well-established, its role continues to evolve. As PET imaging seeks to take advantage of the increased glycolytic rates of cancer cells, consideration and understanding of glucose metabolism is key. Glucose intolerance, a potential complication of PDAC, can result in higher serum glucose levels and possibly a false-negative result caused by lower tumoral uptake of the glucose analog PET radiotracer 18-fluorodeoxyglucose (FDG). Nevertheless, while some studies have found PET/CT to produce similar diagnostic accuracy as CT and MR in detection of PDAC, the specificity of PET/CT is lower given that increased tracer activity may also be seen within the pancreas in the setting of various inflammatory processes and malignancies [7, 8]. PET/CT also offers potential to detect both locoregional nodal metastases as well as distant metastases. However, inherent technical limitations of PET including decreased spatial resolution may result in decreased sensitivity for detection of small metastases. PET/CT offers a unique potential benefit with respect to evaluation of tumor response or local recurrence following surgical resection. Since anatomic response as determined by a decrease in tumor size typically lags behind pathologic response, the functional element of PET/CT offers the potential to assess treatment response more rapidly and quantitatively via measurement of standardized uptake values (SUV). Given the relatively common occurrence of scarring near the surgical bed following PDAC resection, the functional/physiologic data provided by PET/CT also provides higher accuracy in detection of local recurrence with one study demonstrating 96% accuracy for PET compared to 57% for CT alone [9].

Although not the preferred imaging modality for initial evaluation in most circumstances, MRI is an important imaging alternative, particularly in special circumstances, such as in patients with severe renal dysfunction or severe allergy to iodinated contrast. Largely related to superior spatial resolution, CT demonstrates higher accuracy in determination of surgical resectability, up to 87% for CT compared to up to 79% for MR. However, with respect to lesion detection, CT and MRI have shown similar sensitivity, approaching up to 96% in the case of CT and 96%–98% in the case of MRI when diffusion-weighted images (DWI) are obtained [10]. Furthermore, MRI may be useful when lesions are inconspicuous on CT since as many as nearly 30% of pancreatic adenocarcinomas can be isoattenuating on CT [11–13]. MRI also plays a critical role in the detection of metastatic PDAC, particularly liver metastases. When obtained with DWI, MR has higher sensitivity for detection of liver metastases than CT [6, 14]. MRI has also demonstrated a higher level of accuracy in detection of peritoneal disease compared to CT [6, 14]. Several small studies indicate that DWI and apparent diffusion coefficient (ADC) could serve as important imaging biomarkers of treatment response for patients who are undergoing neoadjuvant therapy [14].

The hybrid imaging technique of PET/MR was developed to take advantage of the strengths of both PET and MR. While contrast-enhanced CT remains the primary tool for locoregional staging, PET/MR has performed similarly to PET plus contrast-enhanced CT with respect to staging accuracy and determination of lesion resectability [9]. Importantly, PET/MR has shown promise in detection of metastatic disease, evaluation of treatment response, and in detection of recurrent disease given the ability for concurrent evaluation of imaging biomarkers including SUV and ADC [14] at the same time as anatomic imaging. When compared to PET/CT, PET/MRI offers simultaneous acquisition of PET and MR data rather than the sequential acquisitions typical of PET/CT. Consequently, PET/MRI acquisitions are less susceptible to misregistration and motion artifact that may limit sensitivity for detection of small primary or metastatic lesions on PET/CT. Additionally, with PET/MRI, there is potential to concurrently perform an MRCP, thereby more thoroughly evaluating ductal involvement [9].

While biphasic CT remains the recommended initial imaging examination in the evaluation of PDAC [15], there is a growing body of evidence that a multimodality approach may be indicated in the management of PDAC. MR and the hybrid imaging techniques of PET/CT and PET/MRI are important modalities for detection of metastatic disease as well as for detection of local recurrence and in assessment of neoadjuvant treatment response. As research continues to

expand, the role of both MR and hybrid imaging in PDAC management will become more well defined.

PET/MRI protocols for pancreatic cancer

The initial consideration for imaging patients with pancreatic neoplasms using PET/MRI is radiotracer selection, a decision dictated by the histopathologic subtype of the pancreatic lesion. Somatostatin analogs are a clear choice for imaging well-differentiated neuroendocrine neoplasms (NEN), with ^{68}Ga-labeled peptides, including DOTA-D-Phe1-Tyr3-octreotide (DOTA-TOC), DOTA-1-Nal3-octreotide (DOTA-NOC), or DOTA-D-Phe1-Tyr3-octreotate (DOTATATE), used for PET due to greater sensitivity than octreotide [16, 17] which was utilized with older SPECT imaging techniques. Another potential agent is 6-l-18F-fluoro-dihydroxyphenylalanine (^{18}F-DOPA) which exploits the catecholamine metabolic pathway [18]. It demonstrates potential utility in imaging well-differentiated neuroendocrine tumors in addition to recently reported success for imaging neuroendocrine tumors with lower expression of somatostatin receptors [19]. However, routine use of ^{18}F-DOPA is limited by its expensive synthesis and reduced availability [19]. Furthermore, it has no theranostic role, as opposed to ^{68} Ga-labeled somatostatin peptide analogs, which predict usefulness of peptide receptor radionuclide therapy using ^{177}Lu or ^{90}Y-labeled peptides [19].

The glucose analog, ^{18}F-2-fluorodeoxyglucose (^{18}F-FDG), becomes important for imaging poorly differentiated/high-grade neuroendocrine tumors which may not express somatostatin receptors reliably, as well as mixed acinar cell neuroendocrine tumors and PDAC [16, 19–21]. Higher-grade neuroendocrine tumors that are more likely to take up ^{18}F-FDG are defined by the eighth edition of the American Joint Committee on Cancer 2017 guidelines as Grade 2 and Grade 3, typically with a higher Ki-67 index (3–20% and 21–55%, respectively) [22, 23].

MR protocols for targeted pancreatic cancer evaluation include not only whole-body acquisitions but also separate focused upper abdominal acquisitions. One such imaging protocol is provided by Furtado et al. and begins with a whole-body precontrast coronal Dixon VIBE (volume-interpolated breath-hold T1 weighted) acquired from the mid thighs to the craniocervical junction [24]. Dixon sequences provide concurrently acquired in-phase, opposed phase, fat, and water-only images which are required to segment tissues into different densities and allows for proper attenuation correction of the PET data [21]. A whole-body axial nonfat-saturated T2w HASTE (half Fourier single-shot fast spin echo T2 weighted) is also obtained [24]. MR-based attenuation correction sequences are employed at each PET bed position and allow for PET attenuation correction analogous to CT-based attenuation correction methods used in PET/CT [25].

The focused upper abdominal imaging is a critical adjunct for characterization of benign and malignant hepatic lesions that may not be radiotracer avid on PET [24]. Furtado et al. initiate this portion of the dedicated protocol with axial T1 dual GE (gradient echo). An axial fat-saturated T2w FSE (fast spin echo) follows as well as coronal T2w HASTE. Finally, dynamic contrast-enhanced T1w VIBE axial sequences are performed, including pancreatic parenchymal and portal venous phases [24]. Diffusion-weighted sequences are also typically acquired, and while Furtado et al. obtain these in the first set of whole-body acquisitions (axial b-values 50, 400, and 800, specifically), others use DWI only in the focused upper abdominal portion of the exam [16, 26].

To complete the entire exam, PET images are simultaneously acquired with axial whole-body T1w VIBE postcontrast sequences per Furtado et al. [24]. On the other hand, Hope et al. state that whole-body postcontrast T1 adds little to image interpretation and may be omitted without loss of sensitivity [16]. Anatomic correlation for the whole-body PET is provided with the simultaneous acquisition of the PET with axial nonfat-saturated T2w fast spin echo sequences before contrast administration [16].

Choice of appropriate gadolinium-based contrast agent (GBCA) and the corresponding variances in MR imaging offered are the final considerations when developing a PET/MRI protocol. Furtado et al. specifically describes use of gatoterate meglumine (Dotarem®, Guerbet, Princeton, NJ, USA), an extracellular macrocyclic and ionic GBCA that is primarily eliminated by renal clearance. However, others advocate for a GBCA that provides a hepatobiliary phase for upper abdominal PET/MRI acquisitions when evaluating hepatic metastatic disease [26]. Gadoxetate disodium (Eovist®, Bayer Healthcare Pharmaceuticals, Berlin, Germany) is the only FDA-approved GBCA with the ability to provide the unique hepatobiliary phase due to partial excretion into the biliary system via hepatocyte uptake. Dynamic contrast-enhanced MRI with hepatobiliary phase is thus the reference standard for evaluation of small hepatic metastases as a result of the increased sensitivity provided by inherent contrast difference between hypointense metastases and hyperintense liver parenchyma resulting from hepatocyte contrast uptake [27].

Similar to renally excreted GBCA, gadoxetate disodium allows for dynamic postcontrast imaging in the arterial, portal venous, and transitional phases due to its initial distribution in the extracellular space, allowing for lesion

characterization. Transient tachypnea during the arterial phase is described more frequently with gadoxetate disodium, creating undesirable motion artifact; however, its self-limiting nature (10–20 s) ensures the hepatocyte specific phase will be relatively free of motion [27, 28]. As this delayed phase arguably is of greatest interest in fused PET/MRI interpretation in patients with PDAC, the arterial phase motion artifact is not a particularly relevant disadvantage for targeted PET applications. Furthermore, to reduce the chance of missing the arterial timing due to dyspnea, two arterial phase timings in rapid succession may be implemented [16, 27]. A single-bed position PET acquisition may also be captured concurrently during the hepatobiliary phase for optimal coregistration during the focused examination of the liver [16].

The hepatobiliary phase becomes especially critical in the setting of PET imaging with ^{68} Ga-DOTA-peptides, as robust hepatic uptake is part of the expected radiotracer biodistribution and heterogeneous parenchymal background activity can be confused for focal lesional uptake. Conversely, small lesions with mild radiotracer uptake can be misinterpreted for normal hepatic background activity, especially when PET is combined with noncontrast CT for anatomic correlation. This is in contradistinction to hepatobiliary phase MRI which provides increased sensitivity, with the difference in performance particularly disparate for lesions sized 0–5 mm [16]. Furthermore, hepatobiliary phase outperforms DWI for small lesion detection, necessitating its inclusion in PET/MRI protocols [16].

PET/MRI for early detection and initial staging

Due to the persistently high rates of surgical unresectability and mortality, there are considerable efforts in improving early detection and initial staging of PDAC [14]. Although certain high-risk individuals qualify for screening (due to familial history and/or genetic mutations), it has not been proven cost-effective to screen for pancreatic cancer on a population-based level [29, 30]. Conventional imaging modalities, including CT, MRI, and PET/CT, all suffer from limitations in the detection of small, early-stage cancers for which surgical resection would likely be curative. Due to lack of symptoms at initial onset, these early-stage cancers will remain clinically undetected and may become locally advanced, unresectable, and/or metastatic when they present with symptoms. PET/MRI offers a unique benefit of simultaneously capturing PET and MRI data, which results in better image fusion and minimizes motion induced artifact [31].

Even when combining the strengths of PET/MRI, it remains challenging to detect early pancreatic cancers utilizing FDG. However, early preclinical work has explored the use of ^{68} Ga-FAPI-04 which targets fibroblast-activating protein and demonstrates better tumor specificity and potential utility in the early detection of PDAC [32]. It is then logical that the improved sensitivity of MRI for detection of small PDAC could be combined with additional improved sensitivity of FAPI-PET to lead to increased early PDAC detection rates and potentially improved patient mortality and outcomes.

Initial staging of both PDAC and pancreatic NENs stands to benefit the most from PET/MRI. Although the high spatial resolution of multiphasic CT remains a mainstay of local staging and assessment of resectability, MRI can serve as an alternative if performed well [14]. Additionally, while CT may be preferred for the evaluation of local resectability, MRI outperforms CT in the detection of distant metastatic disease, particularly when performed as an FDG-PET/MRI with hepatobiliary contrast agents [14]. In a retrospective cohort study of 25 patients, 49% of PDAC patients who underwent PET/MRI had a change in management due to increased information provided by PET/MRI in comparison to standard of care imaging [24]. In two prospective studies, evaluation of preoperative resectability with PET/MR was not significantly different than PET/CT combined with multidetector CT [33, 34]. However, PET/MRI detects more liver metastasis than other imaging modalities—which could play a significant role in treatment paradigms [33, 35]. Further, PET/MRI may play a role in better N stage characterization in comparison to alternate imaging modalities; however, current studies have lacked statistical power to show significance [33]. Despite this, PET/MR allows for comprehensive staging within the same imaging study—allowing a streamlined, one-stop imaging modality to expedite and streamline treatment planning [34]. Although not the focus of the manuscript, SSTR-PET/MRI offers substantial benefit for comprehensive staging of pancreatic NENs and allows for thorough evaluation and identification of hepatic metastases which may be treated with intraoperative resection or ablation [36].

PET/MRI for response to neoadjuvant therapy and prognostication

In many institutions, it is standard practice to provide neoadjuvant chemotherapy (and potential radiation therapy) to all patients with PDAC even if staging imaging demonstrates upfront resectability. As PDAC responds to therapy, it can be challenging to differentiate viable tumor, posttreatment fibrosis, and inflammation on follow-up conventional imaging. Thus, the combination of anatomic and physiologic information gained via PET/MRI and its superior image coregistration offer significant potential in accurate characterization (Figs. 1 and 2). Additionally, both PET and MRI

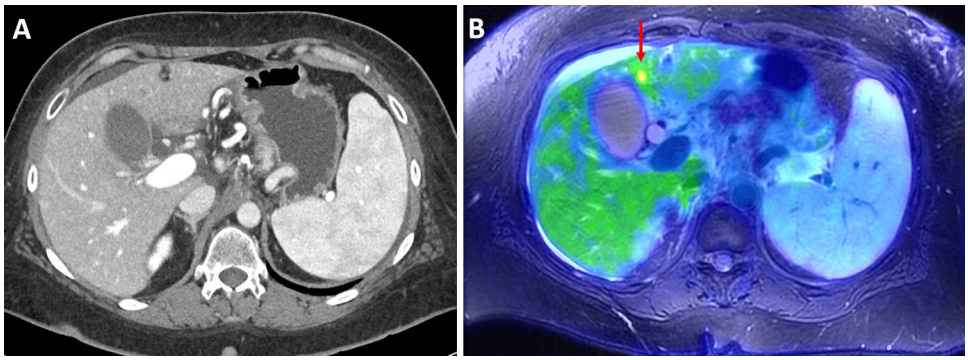

Fig. 1 A 42-Year-old female with pancreatic uncinate process adenocarcinoma status post-neoadjuvant chemotherapy and radiation. Axial contrast-enhanced CT (**a**) and fused axial FDG-PET/MRI (**b**) images of the upper abdomen demonstrate a subcentimeter metastasis (subsequently biopsy proven) in the left hepatic lobe (arrow) which was not detected prospectively on CT

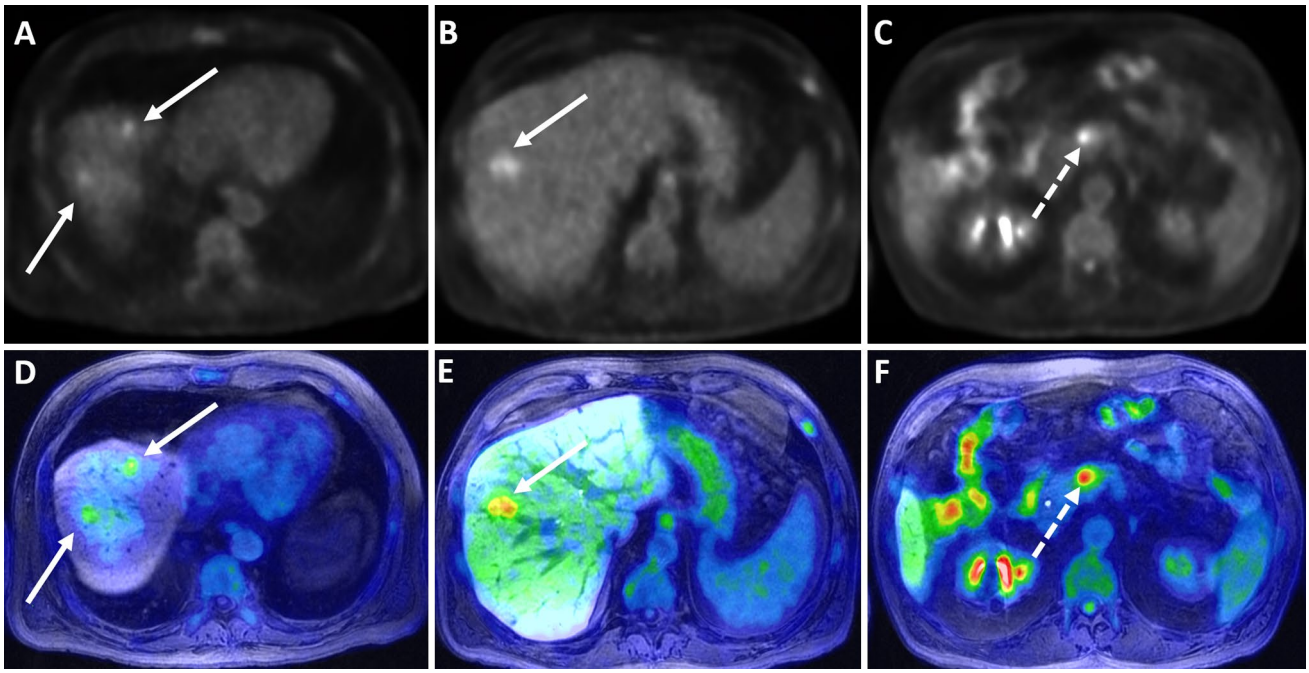

Fig. 2 A 59-Year-old male with pancreatic adenocarcinoma undergoing chemotherapy and suspected progression. Axial diffusion-weighted images (**a**–**c**) and fused FDG-PET/MRI (**d**–**f**) images of the upper abdomen demonstrate multiple hepatic metastases (solid arrow) and pancreatic neck mass (dotted arrow) with near-perfect coregistration of PET and MRI images

have been investigated to better prognosticate outcomes for patients with PDAC compared to conventional imaging modalities alone.

In pancreatic tumors that are borderline resectable, CT underestimates the effectiveness of neoadjuvant therapy due to inability to differentiate viable tissue from tumor or fibrosis, potentially limiting surgical resection following therapy (Fig. 3) [31]. PET/MRI offers the ability to differentiate these entities more confidently, potentially improving restaging evaluations. A systematic review of patients with borderline resectable and resectable PDAC who underwent FDG-PET/CT or PET/MRI after neoadjuvant chemotherapy found that the patients whose SUVs were higher at baseline prior to neoadjuvant therapy were associated with better response to therapy and better overall survival, but patients with SUVs remaining high after neoadjuvant therapy were correlated with poor prognosis [37]. An additional study evaluating the use of pretreatment PET and MRI found that both apparent diffusion coefficient and SUV values were correlated, that metabolic tumor volume was an independent predictive factor for overall and disease-specific survival, and that combining PET and MRI may assist in prediction of tumor grade and patient survival [38]. When PET and MRI were combined

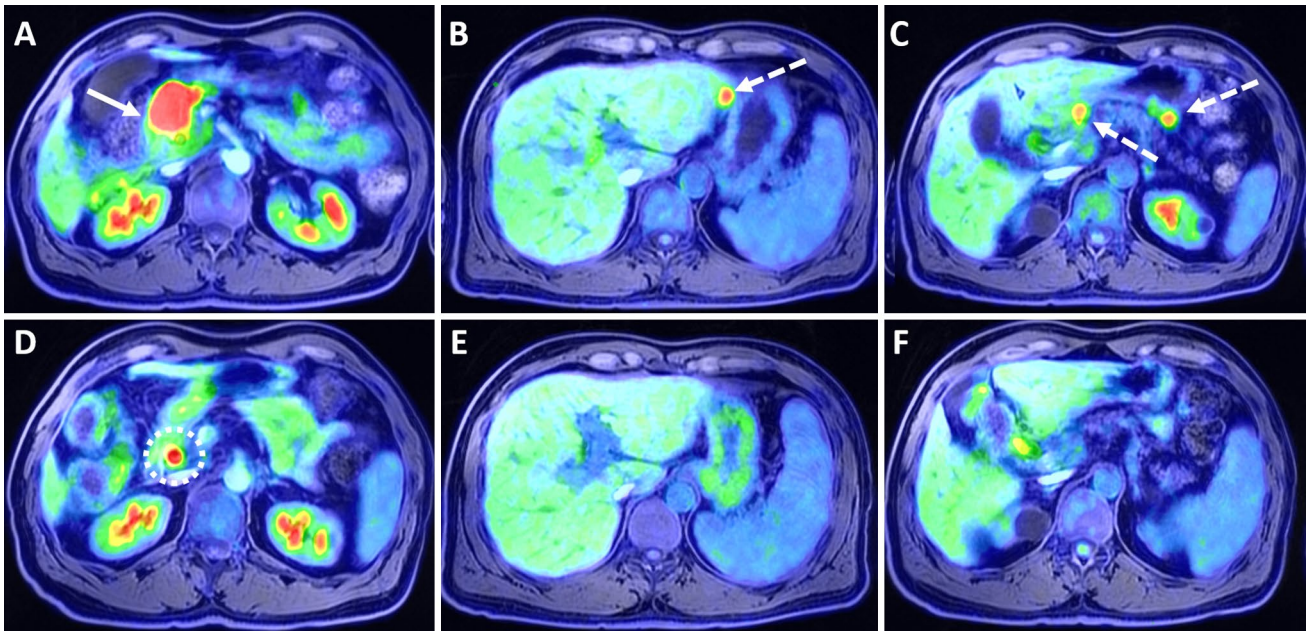

Fig. 3 A 50-Year-old male with locally advanced pancreatic head adenocarcinoma. Initial pretreatment axial fused FDG-PET/MRI images (**a**–**c**) demonstrate a large hypermetabolic pancreatic head mass (solid arrow) and multiple peritoneal/omental metastases (dotted arrow). Following chemoradiation, a repeat FDG-PET/MRI was performed (**d**–**f**) which demonstrates resolution of all abnormal activity. The focal activity in the pancreatic head (dotted circle) corresponds to inflammation along the indwelling metallic biliary stent, a common false-positive finding in these patients

in a separate study and performed as a PET/MRI with multiparametric analysis, the total lesion glycolysis/peak ratio was able to better predict overall survival compared to other imaging biomarkers and is reflective of the flow-metabolism mismatch in PDAC [39]. Additional studies evaluating multiparametric parameters on PET/MRI in PDAC before and after neoadjuvant chemotherapy found that various imaging biomarkers were able to better predict early response and outcomes compared to RECIST 1.1 and CA 19–9 [40–42].

PET/MRI for recurrence

Pancreatic cancers often recur despite adequate surgical excision and R0 resection margins. Common locations for recurrence include resection margin, liver, and peritoneum [31]. Current monitoring for recurrence typically includes CT or MRI, with PET utilized as an adjunct imaging study. Advantages to utilizing PET include differentiating residual tumor from posttreatment-related inflammatory changes; further, PET offers a larger z-direction field of view in comparison to standard CT surveillance and has the potential to image the whole body [31]. The utilization of PET/CT has shown higher sensitivities for detecting recurrence than CT or MRI alone. Conceivably, PET/MRI could show similar data as PET/CT, although little prospective research has directly compared the two. PET/MRI has the added benefit of possessing superior image coregistration, which when combined with high sensitivity and soft tissue characterization of MRI, would be advantageous for detection of early metastatic disease and local recurrence compared to PET/CT or MRI alone [31]. For pancreatic NENs with suspicion for recurrence either on conventional anatomic imaging or patient symptoms, SSTR-PET/MRI offers to accurately localize and plan further therapeutic options, including surgical resection, locoregional therapy, systemic therapy, and/or peptide receptor radionuclide therapy (Fig. 4).

Conclusion

Pancreatic cancer detection and initial management determinations, including staging and surgical candidacy, are largely dependent on imaging. However, pancreatic cancer can be difficult to assess given the nature of the disease, anatomic location of the pancreas, and challenges

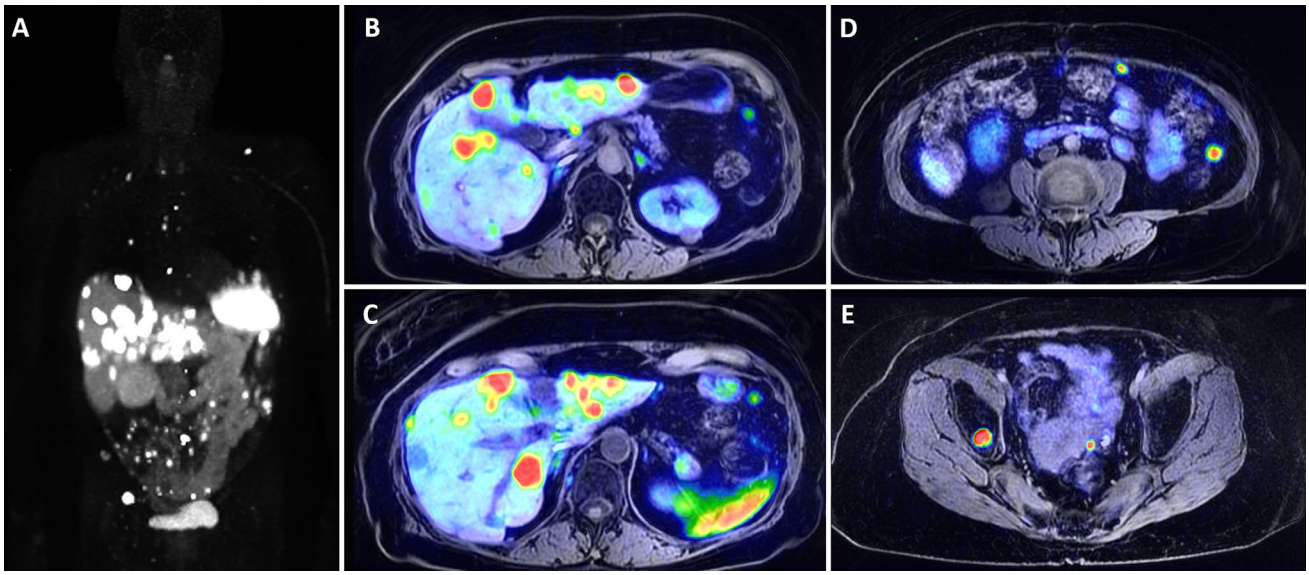

Fig. 4 A 60-Year-old female with metastatic pancreatic tail neuroendocrine tumor. Whole-body maximum intensity projection (**a**) and fused DOTATATE-PET/MRI (**b**–**e**) images demonstrate widespread metastatic disease involving the liver, peritoneum, and bony pelvis. Use of PET/MRI is advantageous to ensure that metastatic disease (typically more poorly differentiated and not DOTATATE-avid) is not present

in detection of small lesions. Innovative use of newer imaging modalities such as PET/MRI have not been fully studied in the management of pancreatic cancer, but initial, small studies display the potential benefit of PET/MRI utilization in this population. The ability to capture simultaneous PET and MRI studies becomes a one-time imaging stop for patients—potentially offering a high value imaging approach for oncologic patients.

Declarations

Conflict of interest The authors have no relevant conflicts of interest related to the content of the manuscript.

References

1. Siegel RL, Miller KD, Fuchs HE, Jemal A. Cancer statistics, 2022. CA Cancer J Clin. 2022;72(1):7-33. https://doi.org/10.3322/caac.21708.
2. Lee ES, Lee JM. Imaging diagnosis of pancreatic cancer: a state-of-the-art review. World J Gastroenterol. 2014;20(24):7864-77. https://doi.org/10.3748/wjg.v20.i24.7864.
3. Zhang L, Sanagapalli S, Stoita A. Challenges in diagnosis of pancreatic cancer. World J Gastroenterol. 2018;24(19):2047-60. https://doi.org/10.3748/wjg.v24.i19.2047.
4. Kobi M, Veillette G, Narurkar R, Sadowsky D, Paroder V, Shilagani C, et al. Imaging and Management of Pancreatic Cancer. Semin Ultrasound CT MR. 2020;41(2):139-51. https://doi.org/10.1053/j.sult.2019.12.003.
5. Al-Hawary MM, Francis IR, Chari ST, Fishman EK, Hough DM, Lu DS, et al. Pancreatic ductal adenocarcinoma radiology reporting template: consensus statement of the Society of Abdominal Radiology and the American Pancreatic Association. Radiology. 2014;270(1):248-60. https://doi.org/10.1148/radiol.13131184.
6. Chu LC, Goggins MG, Fishman EK. Diagnosis and Detection of Pancreatic Cancer. Cancer J. 2017;23(6):333-42. https://doi.org/10.1097/ppo.0000000000000290.
7. Ergul N, Gundogan C, Tozlu M, Toprak H, Kadıoglu H, Aydin M, et al. Role of (18)F-fluorodeoxyglucose positron emission tomography/computed tomography in diagnosis and management of pancreatic cancer; comparison with multidetector row computed tomography, magnetic resonance imaging and endoscopic ultrasonography. Rev Esp Med Nucl Imagen Mol. 2014;33(3):159-64. https://doi.org/10.1016/j.remn.2013.08.005.
8. Kauhanen SP, Komar G, Seppänen MP, Dean KI, Minn HR, Kajander SA, et al. A prospective diagnostic accuracy study of 18F-fluorodeoxyglucose positron emission tomography/computed tomography, multidetector row computed tomography, and magnetic resonance imaging in primary diagnosis and staging of pancreatic cancer. Ann Surg. 2009;250(6):957-63. https://doi.org/10.1097/SLA.0b013e3181b2fafa.
9. Yeh R, Dercle L, Garg I, Wang ZJ, Hough DM, Goenka AH. The Role of 18F-FDG PET/CT and PET/MRI in Pancreatic Ductal Adenocarcinoma. Abdom Radiol (NY). 2018;43(2):415-34. https://doi.org/10.1007/s00261-017-1374-2.
10. Chen FM, Ni JM, Zhang ZY, Zhang L, Li B, Jiang CJ. Presurgical Evaluation of Pancreatic Cancer: A Comprehensive Imaging Comparison of CT Versus MRI. AJR Am J Roentgenol. 2016;206(3):526-35. https://doi.org/10.2214/ajr.15.15236.
11. Yoon SH, Lee JM, Cho JY, Lee KB, Kim JE, Moon SK, et al. Small (≤ 20 mm) pancreatic adenocarcinomas: analysis of enhancement patterns and secondary signs with multiphasic multidetector CT. Radiology. 2011;259(2):442-52. https://doi.org/10.1148/radiol.11101133.
12. Kim JH, Park SH, Yu ES, Kim MH, Kim J, Byun JH, et al. Visually isoattenuating pancreatic adenocarcinoma at dynamic-enhanced CT: frequency, clinical and pathologic characteristics, and diagnosis at imaging examinations. Radiology. 2010;257(1):87-96. https://doi.org/10.1148/radiol.10100015.

13. Prokesch RW, Chow LC, Beaulieu CF, Bammer R, Jeffrey RB, Jr. Isoattenuating pancreatic adenocarcinoma at multi-detector row CT: secondary signs. Radiology. 2002;224(3):764-8. https://doi.org/10.1148/radiol.2243011284.
14. Kulkarni NM, Mannelli L, Zins M, Bhosale PR, Arif-Tiwari H, Brook OR, et al. White paper on pancreatic ductal adenocarcinoma from society of abdominal radiology's disease-focused panel for pancreatic ductal adenocarcinoma: Part II, update on imaging techniques and screening of pancreatic cancer in high-risk individuals. Abdom Radiol (NY). 2020;45(3):729-42. https://doi.org/10.1007/s00261-019-02290-y.
15. National Comprehensive Cancer Network: Pancreatic Adenocarcinoma (Version 1.2022). https://www.nccn.org/professionals/physician_gls/pdf/pancreatic.pdf Accessed September 8, 2022.
16. Hope TA, Pampaloni MH, Nakakura E, VanBrocklin H, Slater J, Jivan S, et al. Simultaneous (68)Ga-DOTA-TOC PET/MRI with gadoxetate disodium in patients with neuroendocrine tumor. Abdom Imaging. 2015;40(6):1432-40. https://doi.org/10.1007/s00261-015-0409-9.
17. Mapelli P, Bezzi C, Palumbo D, Canevari C, Ghezzo S, Samanes Gajate AM, et al. (68)Ga-DOTATOC PET/MR imaging and radiomic parameters in predicting histopathological prognostic factors in patients with pancreatic neuroendocrine well-differentiated tumours. Eur J Nucl Med Mol Imaging. 2022;49(7):2352-63. https://doi.org/10.1007/s00259-022-05677-0.
18. Papadakis GZ, Karantanas AH, Marias K, Millo C. Current status and future prospects of PET-imaging applications in patients with gastro-entero-pancreatic neuroendocrine tumors (GEP-NETs). Eur J Radiol. 2021;143:109932. https://doi.org/10.1016/j.ejrad.2021.109932.
19. Bozkurt MF, Virgolini I, Balogova S, Beheshti M, Rubello D, Decristoforo C, et al. Guideline for PET/CT imaging of neuroendocrine neoplasms with (68)Ga-DOTA-conjugated somatostatin receptor targeting peptides and (18)F-DOPA. Eur J Nucl Med Mol Imaging. 2017;44(9):1588-601. https://doi.org/10.1007/s00259-017-3728-y.
20. Mallak N, Hope TA, Guimaraes AR. PET/MR Imaging of the Pancreas. Magn Reson Imaging Clin N Am. 2018;26(3):345-62. https://doi.org/10.1016/j.mric.2018.03.003.
21. Panda A, Goenka AH, Hope TA, Veit-Haibach P. PET/Magnetic Resonance Imaging Applications in Abdomen and Pelvis. Magn Reson Imaging Clin N Am. 2020;28(3):369-80. https://doi.org/10.1016/j.mric.2020.03.010.
22. National Comprehensive Cancer Network:: Neuroendocrine and Adrenal Tumors (Version 1.2022). https://www.nccn.org/professionals/physician_gls/pdf/neuroendocrine.pdf Accessed September 8, 2022.
23. Edge SB. AJCC cancer staging manual 8th ed. 8th ed. Cancer staging manual. New York: Springer; 2017.
24. Furtado FS, Ferrone CR, Lee SI, Vangel M, Rosman DA, Weekes C, et al. Impact of PET/MRI in the Treatment of Pancreatic Adenocarcinoma: a Retrospective Cohort Study. Mol Imaging Biol. 2021. https://doi.org/10.1007/s11307-020-01569-7.
25. Galgano S, Viets Z, Fowler K, Gore L, Thomas JV, McNamara M, et al. Practical Considerations for Clinical PET/MR Imaging. PET Clin. 2018;13(1):97-112. https://doi.org/10.1016/j.cpet.2017.09.002.
26. Hope TA, Kassam Z, Loening A, McNamara MM, Paspulati R. The use of PET/MRI for imaging rectal cancer. Abdom Radiol (NY). 2019;44(11):3559-68. https://doi.org/10.1007/s00261-019-02089-x.
27. Jeong WK, Kim YK, Song KD, Choi D, Lim HK. The MR imaging diagnosis of liver diseases using gadoxetic acid: emphasis on hepatobiliary phase. Clin Mol Hepatol. 2013;19(4):360-6. https://doi.org/10.3350/cmh.2013.19.4.360.
28. ACR Manual on Contrast Media 2022. https://www.acr.org/-/media/ACR/Files/Clinical-Resources/Contrast_Media.pdf Accessed September 8, 2022.
29. Calderwood AH, Sawhney MS, Thosani NC, Rebbeck TR, Wani S, Canto MI, et al. American Society for Gastrointestinal Endoscopy guideline on screening for pancreatic cancer in individuals with genetic susceptibility: methodology and review of evidence. Gastrointest Endosc. 2022;95(5):827-54.e3. https://doi.org/10.1016/j.gie.2021.12.002.
30. Huang C, Simeone DM, Luk L, Hecht EM, Khatri G, Kambadakone A, et al. Standardization of MRI Screening and Reporting in Individuals With Elevated Risk of Pancreatic Ductal Adenocarcinoma: Consensus Statement of the PRECEDE Consortium. AJR Am J Roentgenol. 2022;219(6):903-14. https://doi.org/10.2214/ajr.22.27859.
31. Yeh R, Dercle L, Garg I, Wang ZJ, Hough DM, Goenka AH. The Role of 18F-FDG PET/CT and PET/MRI in Pancreatic Ductal Adenocarcinoma. Abdominal Radiology. 2018;43(2):415-34. https://doi.org/10.1007/s00261-017-1374-2.
32. Zhang H, An J, Wu P, Zhang C, Zhao Y, Tan D, et al. The Application of [(68)Ga]-Labeled FAPI-04 PET/CT for Targeting and Early Detection of Pancreatic Carcinoma in Patient-Derived Orthotopic Xenograft Models. Contrast Media Mol Imaging. 2022;2022:6596702. https://doi.org/10.1155/2022/6596702.
33. Zhang Z, Zhou N, Guo X, Li N, Zhu H, Yang Z. Pretherapeutic Assessment of Pancreatic Cancer: Comparison of FDG PET/CT Plus Delayed PET/MR and Contrast-Enhanced CT/MR. Front Oncol 2021;11:790462. https://doi.org/10.3389/fonc.2021.790462.
34. Joo I, Lee JM, Lee DH, Lee ES, Paeng JC, Lee SJ, et al. Preoperative Assessment of Pancreatic Cancer with FDG PET/MR Imaging versus FDG PET/CT Plus Contrast-enhanced Multidetector CT: A Prospective Preliminary Study. Radiology. 2017;282(1):149-59. https://doi.org/10.1148/radiol.2016152798.
35. Cohen D, Kesler M, Muchnik Kurash M, Even-Sapir E, Levine C. A lesson in humility: the added values of PET-MRI over PET-CT in detecting malignant hepatic lesions. Eur J Nucl Med Mol Imaging. 2023. https://doi.org/10.1007/s00259-022-06099-8.
36. Virarkar MK, Montanarella M, Itani M, Calimano-Ramirez L, Gopireddy D, Bhosale P. PET/MRI imaging in neuroendocrine neoplasm. Abdom Radiol (NY). 2022. https://doi.org/10.1007/s00261-022-03757-1.
37. Evangelista L, Zucchetta P, Moletta L, Serafini S, Cassarino G, Pegoraro N, et al. The role of FDG PET/CT or PET/MRI in assessing response to neoadjuvant therapy for patients with borderline or resectable pancreatic cancer: a systematic literature review. Ann Nucl Med. 2021;35(7):767-76. https://doi.org/10.1007/s12149-021-01629-0.
38. Dunet V, Halkic N, Sempoux C, Demartines N, Montemurro M, Prior JO, et al. Prediction of tumour grade and survival outcome using pre-treatment PET- and MRI-derived imaging features in patients with resectable pancreatic ductal adenocarcinoma. Eur Radiol. 2021;31(2):992-1001. https://doi.org/10.1007/s00330-020-07191-z.
39. Chen BB, Tien YW, Chang MC, Cheng MF, Chang YT, Yang SH, et al. Multiparametric PET/MR imaging biomarkers are associated with overall survival in patients with pancreatic cancer. Eur J Nucl Med Mol Imaging. 2018;45(7):1205-17. https://doi.org/10.1007/s00259-018-3960-0.
40. Panda A, Garg I, Truty MJ, Kline TL, Johnson MP, Ehman EC, et al. Borderline Resectable and Locally Advanced Pancreas Cancer: FDG PET/MRI and CT Tumor Metrics for Assessment of Neoadjuvant Therapy Pathologic Response and Prediction of Survival. AJR Am J Roentgenol. 2020. https://doi.org/10.2214/ajr.20.24567.

41. Wang ZJ, Behr S, Consunji MV, Yeh BM, Ohliger MA, Gao K, et al. Early Response Assessment in Pancreatic Ductal Adenocarcinoma Through Integrated PET/MRI. AJR Am J Roentgenol. 2018;211(5):1010-9. https://doi.org/10.2214/ajr.18.19602.
42. Harder FN, Jungmann F, Kaissis GA, Lohöfer FK, Ziegelmayer S, Havel D, et al. [(18)F]FDG PET/MRI enables early chemotherapy response prediction in pancreatic ductal adenocarcinoma. EJNMMI Res. 2021;11(1):70. https://doi.org/10.1186/s13550-021-00808-4.