The Role of PET Imaging Before, During, and After Percutaneous Hepatic and Pulmonary Tumor Ablation

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Abstract

Keywords

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The combination of anatomic and metabolic information provided by positron emission tomography (PET)/computed tomography makes it an important imaging modality to be obtained in conjunction with percutaneous ablation of primary and secondary malignancies of the lungs and liver. Advantages include more accurate preprocedural staging to determine appropriate treatment options, intraprocedural guidance to target difficult-to-see lesions, and postprocedural detection of residual or recurrent disease. Future applications of PET include strategies for intraprocedural guidance with real-time determination of incompletely ablated tumor, and combined PET/magnetic resonance imaging before, during, and after ablation for greater sensitivity to detect disease.

Objectives: Upon completion of this article, the reader will be able to describe the use of PET/CT in the evaluation of patients before, during, and after percutaneous ablation of malignancies.

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Percutaneous thermal ablation is a potentially curative treatment option for patients with one to several small primary malignancies or metastatic lesions in the lungs or liver. Advantages over surgical resection include decreased morbidity, lower complication rates, and decreased hospital expenses associated with predominately same-day proce-

dures. Positron emission tomography/computed tomography (PET/CT) provides both metabolic and anatomic information and is useful initially for disease staging to determine if percutaneous ablation should be performed, periprocedurally for lesion targeting, and postprocedurally to evaluate for residual disease and/or recurrence. In this article, the authors review the use of PET/CT imaging before, during, and after percutaneous ablation of hepatic and pulmonary primary and secondary malignancies. In addition, several new applications of PET for patients undergoing ablation that could become widely used after further research are discussed.

PET/CT before Percutaneous Tumor Ablation

Hepatic Malignancies

Percutaneous ablation of hepatic malignancies is typically indicated for patients with three or fewer lesions measuring no greater than 3 cm each, without evidence of intravascular or extrahepatic disease.¹ PET/CT has been shown to be superior to CT or magnetic resonance imaging (MRI) alone in staging patients with hepatic metastases and can often lead to a change in the treatment plan in patients being considered for percutaneous ablation.^{2,3} Kuehl et al evaluated the use of

PET/CT in 58 patients before radiofrequency ablation (RFA) of hepatic tumors, and reported an accuracy of 98% in the identification of extrahepatic disease.² Preablation PET/CT led to a change in clinical management in 26% (15/58) of patients in whom extrahepatic disease was identified and ablation was not performed. Similarly, Georgakopoulos et al found that PET/CT altered the clinical management in 25% (4/16) of potential RFA candidates with colorectal hepatic metastases in whom extrahepatic disease missed by conventional imaging, and systemic chemotherapy was offered instead of performing ablation.³

Pulmonary Malignancies

PET/CT imaging is also useful before percutaneous ablation for staging patients with primary or metastatic lung tumors. In a prospective study of patients with colorectal cancer being considered for ablation of pulmonary metastases, Kodama et al reported that PET/CT changed the treatment strategy in 20% (12/60) of patients in whom extrapulmonary metastases missed by whole body CT were identified.⁴ Ablation was canceled in 12% (7/60), and the treatment plan was modified to include additional procedures or chemotherapy following ablation in another 8% (5/60). PET/CT was especially valuable in patients with an elevated serum carcinoembryonic antigen (CEA) level (> 6 ng/mL); extrapulmonary metastases were identified in 36% (9/25) compared with 9% (3/35) in patients with serum CEA levels ≤ 6 ng/mL. Deandreis et al also found that PET/CT before percutaneous ablation of primary and metastatic pulmonary lesions often led to an alternative treatment strategy.⁵ In this study, percutaneous ablation was canceled in 12% (4/34) of patients, percutaneous ablation of additional pulmonary lesions was performed in 12% (4/34) of patients, and percutaneous ablation along with thyroid surgery was performed in 3% (1/34) of patients.

PET/CT before pulmonary ablation may also be useful for predicting patients at risk for local recurrence after ablation of pulmonary malignancies (**Fig. 1**). Two retrospective studies found an association between a higher preablation maximum standard-uptake value (SUV) and a higher risk of local recurrence.^{6,7} Harada et al found that patients with SUVs in the upper third of the study population had an odds ratio of recurrence of 4.1 compared with patients in the lower third.⁶ Singnurkar et al also determined that a higher SUV was associated with a greater risk of local recurrence.⁷ Both of these studies, however, are confounded by the association between SUV and tumor size, which is also independently associated with higher risk of recurrence after ablation.⁸

PET/CT during Percutaneous Tumor Ablation

PET/CT is more sensitive than conventional ultrasound (US), CT, or MRI in the detection of recurrent pulmonary and hepatic malignancies.^{9,10} For patients with lesions amenable to ablation and visible only with PET imaging, PET may be useful for guiding the placement of ablation probes; a variety of techniques have been described to incorporate PET imaging into intraprocedural guidance.

Figure 1 (A) Axial image from PET acquired 1 day after percutaneous radiofrequency ablation of NSCLC in the right upper lobe shows photopenic region centrally with asymmetric activity along the anterior medial border (arrow). (B) Follow-up PET acquired 6 months later shows significantly increased activity at the ablation site (arrow) consistent with recurrent disease. NSCLC, non-small-cell lung carcinoma; PET, positron emission tomography.

PET-guided procedures have been performed in dedicated PET/CT scanners.¹¹ PET images obtained at the beginning of the procedure can be fused with intermittent CT images obtained to guide needle placement. In addition, a method for directly using PET images for guidance was described by Prior et al.¹² Using this method, a small amount of ^{18}F -fluorodeoxyglucose (FDG) is placed within an introducer needle allowing visualization of the needle tip using the PET scanner. PET images are then used to guide the introducer needle to an FDG avid lesion not visible with CT or US imaging. Challenges with the above method include the availability of combined PET/CT scanners for procedural use, in addition to the longer gantries needed for PET imaging that can be physically cumbersome during attempted needle placement.

PET/CT-guided ablations may also be accomplished by fusing diagnostic PET images obtained before the procedure with intraprocedural CT images.^{13,14} The intraprocedural CT images may be directly registered to the PET images or indirectly registered to the CT images from the prior PET/CT. Fused PET/CT images can allow for more precise placement of ablation probes to ensure adequate treatment of difficult-to-see lesions with one treatment, and may potentially reduce the rate of residual/recurrent malignancy.

The use of periprocedural PET/CT imaging to determine ablation completeness has also been investigated, but single FDG dose imaging has not been found to be helpful. A prospective study by Sainani et al investigated the use of FDG PET/CT for guiding percutaneous RFA and cryoablation with an immediate postprocedural PET/CT to determine if the preprocedural dose of FDG was dissipated by the ablation procedure.¹⁵ Following ablation, both the tumor SUV_{max} and ratio of tumor SUV_{max}-to-average liver SUV were measured. No decrease in FDG activity (SUV_{max} or SUV_{max}-to-liver ratio) within the treated lesions was identified following ablation. A case report by Schoellnast et al also found that preprocedurally administered FDG within pulmonary tumors were not dissipated by ablation and could not be used to determine ablation completeness.¹⁶

PET/CT following Percutaneous Tumor Ablation

Hepatic Malignancies

Unfortunately, recurrence after percutaneous ablation of hepatic malignancy is relatively common. Following ablation of hepatocellular carcinoma, local recurrence rates of 11 to 36% have been described with more frequent recurrence after treatment of larger lesions and lesions close to large vessels.¹⁷ Compared with hepatocellular carcinoma, metastatic colorectal cancer recurs even more frequently, with rates over 50% reported.^{17,18} Therefore, high-quality follow-up imaging is needed after percutaneous ablation to identify residual or recurrent neoplasm early enough to retreat while the lesions remain small. The challenge, however, is to distinguish findings suggestive of recurrent or residual disease from those present due to normal treatment response.

Immediately following thermal ablation of the liver, the central area of postablation necrosis is surrounded by a zone of hyperemia with blood-filled sinusoids and a peripheral rim of mild reactive change.¹⁹ Early postablation imaging of the liver with contrast-enhanced MR, CT, and US demonstrates a rim of increased enhancement compared with normal liver tissue in the hyperemic zone surrounding the central non-enhancing area of necrosis (►Fig. 2). The rim of increased enhancement may mask residual viable tumor in the early postablation period. Cells destroyed by thermal ablation lose their ability to concentrate glucose within the cell, and FDG PET demonstrates a corresponding photopenic area (►Fig. 3). Glucose metabolism within the zone of hyperemia is unaltered and normal FDG uptake or a rim of uniform, low-grade FDG uptake surrounding the ablation site may be present. Within the first 48 hours following ablation, focal areas of increased FDG uptake adjacent to the photopenic area of necrosis suggest residual macroscopic tumor.²⁰ At 3 days and lasting up to 6 months following ablation, a band of regenerative tissue containing neutrophils and fibroblasts is observed that demonstrates variable degrees of both peripheral enhancement and increased FDG uptake surrounding the ablation site.¹⁹

The combined functional and anatomic information provided by PET/CT offers advantages over traditional morpho-

Figure 2 Axial postcontrast T1-weighted MR image from a study performed 3 weeks after percutaneous radiofrequency ablation of a liver lesion demonstrating rim enhancement of the ablated lesion (arrow) with central necrosis. MR, magnetic resonance.

logic imaging by US, CT, and MR in distinguishing residual or recurrent neoplasm from postablation change (►Fig. 4). A retrospective study by Wang et al of 36 patients following RFA or surgical resection of HCC found that PET/CT had a significantly higher sensitivity and accuracy (96.7 and 94.4%, respectively) compared with contrast-enhanced US (56.7 and 63.9%, respectively).²¹ Similarly, Chen et al retrospectively reviewed 33 lesions treated with RFA in 28 patients, and reported that PET/CT demonstrated superior sensitivity and accuracy (94.1 and 87.9%, respectively) compared with MRI (66.7 and 75%, respectively) and multiphase contrast-enhanced CT (66.7 and 64.3%, respectively).²²

Detecting local recurrence to allow retreatment and prolong survival is the goal of early and frequent postablation PET/CT. Although no established guidelines exist for when to perform PET/CT after ablation, intervals of 3 to 6 months for

Figure 3 Axial PET image acquired several hours following radiofrequency ablation of a liver metastasis demonstrating focal photopenia at the ablation site (arrow). PET, positron emission tomography.

Figure 4 Axial PET image acquired several months after percutaneous radiofrequency ablation of a colorectal liver metastasis demonstrates nodular increased FDG uptake adjacent to the photopenic ablation site (arrow). This finding is compatible with recurrence outside of the previously ablated region. PET, positron emission tomography.

the 1st year following ablation have been proposed due to the fact that more than 95% of local recurrences are identified within 1 year of treatment.²³ However, one retrospective study reported no effect by the frequency of surveillance following ablation or resection of colorectal liver metastases on the time to a second procedure or median survival duration.²⁴ This suggests that more research is needed to create definitive guidelines for PET/CT surveillance following ablation of hepatic malignancy.

Pulmonary Malignancies

Following percutaneous ablation of pulmonary lesions, high recurrence rates are observed for primary lung tumors (up to 45%) and metastatic pulmonary lesions (20–30%).^{7,25} Similar to hepatic disease, early detection of recurrence is important to allow for retreatment.

Within the first several days following ablation, central photopenia at the ablation site with a surrounding rim of intense FDG uptake is commonly observed.³ Peripheral FDG uptake corresponding to reactive changes in lung tissue surrounding the ablation site may be seen as early as 1 day following ablation and last for up to 6 months.^{3,26} At 6 to 12 months following ablation, contraction of the peripheral reactive lung tissue leads to a decrease in the size of the ablated lesion on CT and increasing FDG activity in the center of the lesion. These reactive changes may cause the SUV to remain equal to or greater than the preablation SUV for up to 1 year following ablation, and the pattern of FDG uptake on PET/CT may identify recurrence better than SUV alone. Singnurkar et al identified six patterns of FDG uptake following ablation and categorized them as favorable or unfavorable. Unfavorable patterns, including focal uptake and rim with a focus of uptake at the site of the original tumor, were associated with local recurrence. Favorable patterns of uptake, including diffuse, heterogenous, rim, and rim uptake with a focus at a location away from the original tumor, were

more likely to represent inflammation. Inflammatory FDG uptake can also be seen along the path of the ablation probe and in mediastinal lymph nodes for up to 3 months following ablation.⁵

PET/CT follow-up beginning at 3 months postablation of pulmonary tumors may be optimal to limit false-positive results due to inflammation.^{5,27,28} PET/CT has also been shown to be better at detecting residual or recurrent disease as compared with CT alone in the 6-month postprocedural period.^{29,30}

Future Directions

Recently, a method has been described utilizing a split dose of FDG that allows PET to be used for both intraprocedural lesion targeting and immediate postprocedural evaluation of ablation completeness.³¹ An initial 4 mCi of FDG is given intravenously for preprocedural PET imaging. These images are fused with CT images acquired to localize the lesion of interest, guide placement of the ablation probes, and confirm the position of the probe before ablation. Following ablation, an 8 mCi dose of FDG is administered and a follow-up PET/CT is performed. Because of the higher dose of the second FDG administration and the decay of the initial dose throughout the procedure, approximately 90% of the signal on the follow-up PET is from the second injection. Utilizing this “split-dose” method, no residual activity was seen in 97% (28/29) of lesions. The lesion with residual activity was immediately retreated and demonstrated no evidence of recurrence on follow-up imaging. Marginal recurrences occurred in 7% (2/28) of the lesions negative for residual activity on the postprocedural PET. Initial results using this technique are promising, warranting further investigation.

Another possibility for real-time PET imaging during ablation involves the utilization of ¹⁵O-water as a perfusion radiotracer. Because of its 2 minutes half-life, PET imaging can be performed at 20 minutes intervals, demonstrating areas of tumor that are still taking up water and are, therefore, still viable. This allows for simultaneous PET-guided lesion targeting and determination of ablation completeness.³² However, because of its short half-life, production of this isotope requires an onsite cyclotron, greatly limiting its availability; this procedure has yet to be tested on humans.

The use of electromagnetic device tracking with multimodality preprocedural imaging such as PET or MRI has been described to provide real-time guidance for the placement of ablation probes. An ablation probe containing electromagnetic sensor coils within the tip is tracked within a patient using technology similar to a global positioning system, and its location and orientation may be displayed relative to the preprocedural imaging. Real-time US can also be fused with CT and PET images, and the position of the transducer can be tracked with optical or electromagnetic sensors.^{33,34}

The development of combined PET/MRI over the past several years has multiple applications with regard to percutaneous ablation. With the addition of simultaneous PET

imaging to MRI, the increased sensitivity for detecting both intrahepatic and extrahepatic disease has the potential to improve the accuracy of cancer staging. In addition, the technology allows for possible combined PET and MRI guidance during ablation procedures for the purpose of lesion targeting, and after treatment, the combined imaging modalities could allow for earlier diagnosis and treatment of residual and recurrent disease.³⁵

Conclusion

PET/CT can be useful in determining the appropriateness of treating hepatic and pulmonary malignancies by restaging patients with previously nonvisualized disease. During percutaneous ablation, the addition of PET imaging can help target lesions that are difficult to see with conventional imaging. In the follow-up period, PET/CT has proven to be more sensitive in detecting residual or recurrent disease compared with conventional imaging for both hepatic and pulmonary malignancies. There is no consensus as to the follow-up intervals at which PET/CT should be performed for surveillance after treatment of hepatic disease, but an initial 3-month follow-up study after ablation of pulmonary disease has been recommended by multiple authors. Future uses of PET associated with percutaneous ablation include utilizing combined PET/MRI before, during, and after treatment, and utilization of split FDG dosing or alternative radiotracers for potential real-time targeting with determination of treatment completeness.

Conflict of Interest

We have no conflict of interest, financial or otherwise, to disclose.

References

- Crocetti L, de Baere T, Lencioni R. Quality improvement guidelines for radiofrequency ablation of liver tumours. *Cardiovasc Intervent Radiol* 2010;33(1):11–17
- Kuehl H, Rosenbaum-Krumme S, Veit-Haibach P, et al. Impact of whole-body imaging on treatment decision to radio-frequency ablation in patients with malignant liver tumors: comparison of [18F]fluorodeoxyglucose-PET/computed tomography, PET and computed tomography. *Nucl Med Commun* 2008;29(7):599–606
- Georgakopoulos A, Pianou N, Kelekis N, Chatziioannou S. Impact of 18F-FDG PET/CT on therapeutic decisions in patients with colorectal cancer and liver metastases. *Clin Imaging* 2013;37(3):536–541
- Kodama H, Yamakado K, Takaki H, Suzawa N, Yamada T, Takeda K. Impact of 18F-FDG-PET/CT on treatment strategy in colorectal cancer lung metastasis before lung radiofrequency ablation. *Nucl Med Commun* 2013;34(7):689–693
- Deandreis D, Leboulleux S, Dromain C, et al. Role of FDG PET/CT and chest CT in the follow-up of lung lesions treated with radiofrequency ablation. *Radiology* 2011;258(1):270–276
- Harada S, Sato S, Suzuki E, et al. The usefulness of pre-radiofrequency ablation SUV(max) in 18F-FDG PET/CT to predict the risk of a local recurrence of malignant lung tumors after lung radiofrequency ablation. *Acta Med Okayama* 2011;65(6):395–402
- Singnurkar A, Solomon SB, Gonen M, Larson SM, Schöder H. 18F-FDG PET/CT for the prediction and detection of local recurrence after radiofrequency ablation of malignant lung lesions. *J Nucl Med* 2010;51(12):1833–1840
- Yu HC, Cheng JS, Lai KH, et al. Factors for early tumor recurrence of single small hepatocellular carcinoma after percutaneous radiofrequency ablation therapy. *World J Gastroenterol* 2005;11(10):1439–1444
- Kinkel K, Lu Y, Both M, Warren RS, Thoeni RF. Detection of hepatic metastases from cancers of the gastrointestinal tract by using noninvasive imaging methods (US, CT, MR imaging, PET): a meta-analysis. *Radiology* 2002;224(3):748–756
- Israel O, Kuten A. Early detection of cancer recurrence: 18F-FDG PET/CT can make a difference in diagnosis and patient care. *J Nucl Med* 2007;48(Suppl 1):28S–35S
- Tatli S, Gerbaudo VH, Feeley CM, Shyn PB, Tuncali K, Silverman SG. PET/CT-guided percutaneous biopsy of abdominal masses: initial experience. *J Vasc Interv Radiol* 2011;22(4):507–514
- Prior JO, Kosinski M, Delaloye AB, Denys A. Initial report of PET/CT-guided radiofrequency ablation of liver metastases. *J Vasc Interv Radiol* 2007;18(6):801–803
- Lei P, Dandekar O, Widlus D, Shekhar R. Incorporation of preprocedural PET into CT-guided radiofrequency ablation of hepatic metastases: a nonrigid image registration validation study. *J Digit Imaging* 2010;23(6):780–792
- Giesel FL, Mehndiratta A, Locklin J, et al. Image fusion using CT, MRI and PET for treatment planning, navigation and follow up in percutaneous RFA. *Exp Oncol* 2009;31(2):106–114
- Sainani NI, Shyn PB, Tatli S, Morrison PR, Tuncali K, Silverman SG. PET/CT-guided radiofrequency and cryoablation: is tumor fluorine-18 fluorodeoxyglucose activity dissipated by thermal ablation? *J Vasc Interv Radiol* 2011;22(3):354–360
- Schoellnast H, Larson SM, Nehmeh SA, Carrasquillo JA, Thornton RH, Solomon SB. Radiofrequency ablation of non-small-cell carcinoma of the lung under real-time FDG PET/CT guidance. *Cardiovasc Intervent Radiol* 2011;34(Suppl 2):S182–S185
- Kuehl H, Stattaus J, Hertel S, et al. Mid-term outcome of positron emission tomography/computed tomography-assisted radiofrequency ablation in primary and secondary liver tumours—a single-centre experience. *Clin Oncol (R Coll Radiol)* 2008;20(3):234–240
- Liu ZY, Chang ZH, Lu ZM, Guo QY. Early PET/CT after radiofrequency ablation in colorectal cancer liver metastases: is it useful? *Chin Med J (Engl)* 2010;123(13):1690–1694
- Vogt FM, Antoch G, Veit P, et al. Morphologic and functional changes in nontumorous liver tissue after radiofrequency ablation in an in vivo model: comparison of 18F-FDG PET/CT, MRI, ultrasound, and CT. *J Nucl Med* 2007;48(11):1836–1844
- Purandare NC, Rangarajan V, Shah SA, et al. Therapeutic response to radiofrequency ablation of neoplastic lesions: FDG PET/CT findings. *Radiographics* 2011;31(1):201–213
- Wang XY, Chen D, Zhang XS, Chen ZF, Hu AB. Value of ¹⁸F-FDG-PET/CT in the detection of recurrent hepatocellular carcinoma after hepatectomy or radiofrequency ablation: a comparative study with contrast-enhanced ultrasound. *J Dig Dis* 2013;14(8):433–438
- Chen W, Zhuang H, Cheng G, Torigian DA, Alavi A. Comparison of FDG-PET, MRI and CT for post radiofrequency ablation evaluation of hepatic tumors. *Ann Nucl Med* 2013;27(1):58–64
- Nielsen K, van Tilborg AA, Scheffer HJ, et al. PET-CT after radiofrequency ablation of colorectal liver metastases: suggestions for timing and image interpretation. *Eur J Radiol* 2013;82(12):2169–2175
- Hyder O, Dodson RM, Mayo SC, et al. Post-treatment surveillance of patients with colorectal cancer with surgically treated liver metastases. *Surgery* 2013;154(2):256–265
- Ambrogi MC, Lucchi M, Dini P, et al. Percutaneous radiofrequency ablation of lung tumours: results in the mid-term. *Eur J Cardiothorac Surg* 2006;30(1):177–183
- Sharma A, Lanuti M, He W, Palmer EL, Shepard JA, Digumarthy SR. Increase in fluorodeoxyglucose positron emission tomography

- activity following complete radiofrequency ablation of lung tumors. *J Comput Assist Tomogr* 2013;37(1):9–14
- 27 Pou Ucha JL, Nogueiras Alonso JM, Alvarez Paez AM, et al. Diagnostic yield of baseline and follow-up PET/CT studies in ablative therapy for non-small cell lung cancer. *Rev Esp Med Nucl Imagen Mol* 2012;31(6):301–307
 - 28 Yoo DC, Dupuy DE, Hillman SL, et al. Radiofrequency ablation of medically inoperable stage IA non-small cell lung cancer: are early posttreatment PET findings predictive of treatment outcome? *AJR Am J Roentgenol* 2011;197(2):334–340
 - 29 Suzawa N, Yamakado K, Takao M, Taguchi O, Yamada T, Takeda K. Detection of local tumor progression by (18)F-FDG PET/CT following lung radiofrequency ablation: PET versus CT. *Clin Nucl Med* 2013;38(4):e166–e170
 - 30 Akeboshi M, Yamakado K, Nakatsuka A, et al. Percutaneous radiofrequency ablation of lung neoplasms: initial therapeutic response. *J Vasc Interv Radiol* 2004;15(5):463–470
 - 31 Ryan ER, Sofocleous CT, Schöder H, et al. Split-dose technique for FDG PET/CT-guided percutaneous ablation: a method to facilitate lesion targeting and to provide immediate assessment of treatment effectiveness. *Radiology* 2013;268(1):288–295
 - 32 Bao A, Goins B, Dodd GD III, et al. Real-time iterative monitoring of radiofrequency ablation tumor therapy with 15O-water PET imaging. *J Nucl Med* 2008;49(10):1723–1729
 - 33 Venkatesan AM, Kadoury S, Abi-Jaoudeh N, et al. Real-time FDG PET guidance during biopsies and radiofrequency ablation using multimodality fusion with electromagnetic navigation. *Radiology* 2011;260(3):848–856
 - 34 Wood BJ, Locklin JK, Viswanathan A, et al. Technologies for guidance of radiofrequency ablation in the multimodality interventional suite of the future. *J Vasc Interv Radiol* 2007;18(1 Pt 1):9–24
 - 35 Pichler BJ, Kolb A, Nägele T, Schlemmer HP. PET/MRI: paving the way for the next generation of clinical multimodality imaging applications. *J Nucl Med* 2010;51(3):333–336