Emerging clinical applications of PET based molecular imaging in oncology: the promising future potential for evolving personalized cancer care

Vandana K Dhingra¹,², Abhishek Mahajan², Sandip Basu³
¹Department of Nuclear Medicine, Cancer Research Institute, Himalayan Institute Hospital Trust, Dehradun, Uttarakhand, ²Department of Radiology, Tata Memorial Hospital, ³Radiation Medicine Centre, Bhabha Atomic Research Centre, Tata Memorial Hospital, Mumbai, Maharashtra, India

Correspondence: Prof. Sandip Basu, Radiation Medicine Centre, Bhabha Atomic Research Centre, Tata Memorial Hospital, Annexe Building, Jerbai Wadia Road, Parel, Mumbai - 400 012, Maharashtra, India. E-mail: drsanb@yahoo.com

Abstract

This review focuses on the potential of advanced applications of functional molecular imaging in assessing tumor biology and cellular characteristics with emphasis on positron emission tomography (PET) applications with both 18-fluorodeoxyglucose (FDG) and non-FDG tracers. The inherent heterogeneity of cancer cells with their varied cellular biology and metabolic and receptor phenotypic expression in each individual patient and also intra- and inter-lesionally in the same individual mandates for transitioning from a generalized “same-size-fits-all” approach to personalized medicine in oncology. The past two decades have witnessed improvement of oncological imaging through CT, MR imaging, PET, subsequent movement through hybrid or fusion imaging with PET/CT and single-photon emission computerized tomography (SPECT-CT), and now toward the evolving PET/MR imaging. These recent developments have proven invaluable in enhancing oncology care and have the potential to help image the tumor biology at the cellular level, followed by providing a tailored treatment. Molecular imaging, integrated diagnostics or Radiomics, biology-driven interventional radiology and theranostics, all hold immense potential to serve as a guide to give “start and stop” treatment for a patient on an individual basis. This will likely have substantial impact on both treatment costs and outcomes. In this review, we bring forth the current trends in molecular imaging with established techniques (PET/CT), with particular emphasis on newer molecules (such as amino acid metabolism and hypoxia imaging, somatostatin receptor based imaging, and hormone receptor imaging) and further potential for FDG. An introductory discussion on the novel hybrid imaging techniques such as PET/MR is also made to understand the futuristic trends.

Key words: Molecular imaging; oncology; personalized medicine; positron emission tomography/computerized tomography; positron emission tomography/magnetic resonance

Introduction

The following three can be identified as the major thrust application areas in the domain of personalized cancer care where the evolving molecular imaging will have important clinical impact:

- The right therapeutic agent/modality: As assessed by the surrogate diagnostic imaging molecules

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• The right time: Interval imaging during early course of therapy and changing to salvage schedule at the earliest opportunity in case of ineffective therapy
• The right dose (e.g. tailoring of radiation plan, chemotherapy agents and their doses, extent of surgery, radiopharmaceutical therapy and their doses): Functional imaging with various tracers exploring tumor biology from multiple aspects.

All these are possible if we could have the personalized blueprint of tumors which can be made possible with biomarkers, known as Radiomics. The importance of histopathological data and in vitro diagnostics has been greatly promising in personalized medicine in oncology and other clinical disciplines. In vivo molecular imaging, whether by using radionuclide or non-radioactive imaging technologies, addresses some of the practical shortcomings of the in vitro biomarker tests (which assess the unique variables of individual’s genetic material, proteins, and other biological molecules i.e. biomarkers). Visual mapping of intra-and inter-tumoral heterogeneity (due to differences in cellular characteristics) which may be observed during the disease course, leading to varying degrees of response among the different primary and metastatic sites or even within the same lesion in the same individual can be studied in great detail with molecular imaging.[9] These are termed as “regional proteomics” or “Radiomics,” and these make in vivo imaging modalities more feasible and practical to reliably explore the tumor. Molecular imaging involves imaging of functional aspects where cellular level dynamics of pathological processes using various in vivo markers [Table 1]. In this review, we shall focus on the current trends in radionuclide molecular imaging in the mainstream clinical setting.

Radionuclide Molecular Imaging: An Introduction to Single-photon Emission Computed Tomography and Positron Emission Tomography

Radioisotope based-molecular imaging has emerged at the forefront in the area of personalized medicine. The older methods of radionuclide imaging like planar and single-photon emission computed tomography (SPECT) are also based on molecular level techniques. With the advent of positron emission tomography combined with computerized tomography (PET/CT) with fluorodeoxyglucose (FDG) and other novel molecules, mainstream molecular imaging appears to have unlimited potential today.

Both SPECT and PET imaging involve injection of radiopharmaceuticals labeled with “short-lived” gamma and positron emitting radioisotopes, respectively. These can provide information of biological processes in vivo through quantitative tomographic images using a gamma camera or PET scanner. These techniques have the sensitivity needed to visualize most interactions between physiological targets and ligands, which can enable non-invasive detection down to the picomolar level. The target molecules are labeled with suitable radioisotopes and with suitable imaging characteristics for SPECT or PET imaging. PET imaging has greater advantages with respect to sensitivity and resolution, and also the ability of positron emitters being labeled to normal elements of the cell, hence has been gaining significantly more clinical popularity over the last decade.[2]

Over the past decade, PET/CT, especially using F18-FDG, has become an indispensable tool in oncology, mainly in the staging work-up and response to therapy including recurrent tumor. Among non-FDG PET agents [e.g. 3′-18F-fluoro-3′′-deoxythymidine and 18F-1-(2′-deoxy-2′-fluoro-β-d-arabinofuranosyl) thymine, 60/62/64Cu-labeled diacetyl-L-bis (N4-methylthiosemicarbazone) and 18F-fluoromisonidazole, L-(methyl-11C) methionine, 16β-18F-fluoro-5α-dihydrotestosterone and 16α-18F-fluoro-17β-estradiol], many are being studied for use in oncology, especially in monitoring therapy.[3] SPECT imaging is used more often worldwide and many tracers ranging from the well-established radioiodine for thyroid cancer and radiolabeled metaiodobenzyl guanidine and radiolabeled octreotide analogs for neuroendocrine tumors (NETs)[4] to the newer anti-CD20 radiolabeled antibodies 90Y-ibritumomab tiuxetan and 131I-tositumomab for lymphoma have been approved for clinical use. Other futuristic agents like radiolabeled annexin molecules used for the detection of cell apoptosis have shown great promise in clinical trials.[5]
Emerging Role of 18F-fluorodeoxyglucose in Assessing Tumor Biology

The rationale for the use of FDG in PET imaging in oncology is the fact that the vast majority of malignant cancer phenotypes exhibit an increased glycolytic rate (Warburg effect). PET imaging with 18F-FDG provides metabolic information of anatomic tumors qualitatively. FDG has also been used as a quantitative biomarker since the first reports on standardized uptake value (SUV) measurement in breast cancer. The SUV is a widely used metric for assessing tissue accumulation of tracers. SUV can be normalized to body mass, lean body mass (SUL), or body surface area. Comparison of SUV linearly with time was tried as a parameter for assessing response in tumors and quantifying it. It was proven beyond doubt that the SUV of FDG in tumors reduced with response to therapy. Data supports that 18F-FDG PET is a useful tool for response assessment in a variety of malignancies, at the end of treatment, mid treatment, and when performed soon after treatment is initiated, and has led to the advent of the PET response criteria in solid tumors PERCIST.[6] Recently, FDG-PET has taken a very important step further from anatomical-based imaging in that it allows the characterization of tumor biology; aggressive tumors tend to have higher levels of FDG uptake, while less aggressive tumors tend to have lower levels of FDG uptake and this has been shown histologically [Figures 1 and 2]. This new dimension of diagnostic information that is provided by FDG-PET can be used to improve determination of disease prognosis and treatment planning.

Degree and extent of FDG uptake of tumors was found to be an independent predictor of prognosis and tumor aggressiveness [Table 2] in most cancers.[7] In vivo imaging offers two added advantages: (i) aids to eliminate sampling error which may occur with histopathology (ii) allows mapping of the intra-and inter-tumoral heterogeneity.

Non-fluorodeoxyglucose Positron Emission Tomography Tracers in Oncology: An Enumeration

Currently, a number of non-FDG-PET tracers are in use or hold potential for future clinical use. With advances in radiochemistry and better understanding of tumor biology, we would be continuing to witness the advent of more tracers in the clinical routine [Table 3].

Overview of Salient Pathways, Positron Emission Tomography/Single-photon Emission Computerized Tomography Tracers and Their Potential Clinical Applications

Imaging of tumor hypoxia

One of the biggest challenges to efficacious treatment in oncology is tumor hypoxia. The presence of hypoxic/anoxic areas is a characteristic feature of about 50–60% of locally advanced solid tumors.[14] These cells become resistant to conventional anticancer therapies like radiotherapy (RT; intrinsic dependence of RT on oxygen to cause damage to the tumor cell) and chemotherapy (by causing cells within hypoxic regions to cycle more slowly and by providing a selection mechanism for cells with reduced susceptibility for apoptosis). Various mechanisms have been postulated; the most popular is through expression of hypoxia inducible factors (HIFs) such as HIF1α and HIF2α.[15]

The current gold standard for direct in vivo determination of tumor oxygenation is a commercially available oxygen electrode – the Eppendorf electrode – which is practically demanding. Non-invasive methods for detection of presence and extent of tumor hypoxia can have a significant impact on clinical outcome, based upon the use of nitroimidazole derivatives [Figure 3 and Table 4].[14]
Imaging of tumor proliferation

Imaging biomarkers (IB) of proliferation, cell death, and tumor heterogeneity can be thought of as possible tools in molecular imaging. One of the IBs is ([18]F)-3'-deoxy-3'-fluorothymidine with PET (FLT-PET).\(^{18}\) Increased proliferation is a hallmark of many cancers; several tracers have been tested to track the DNA synthesis pathway. Thymidine, which is incorporated into DNA but not RNA, has been used in laboratory studies to measure tumor growth. One such tracer is 18F-labeled 39-deoxy-39-fluorothymidine (18F-FLT). Several studies on breast, lung, and brain tumors [Figure 4] have demonstrated that retention of 18F-FLT correlated with tumor proliferation.\(^{17}\) Another novel potential application is measurement of simplified quantitative parameters of FLT uptake which could be of use for prognostication of therapy, for example, with tyrosine kinase inhibitors.\(^{18,19}\) This has been found to be independent of perfusion parameters.

Amino acid targeting for positron emission tomography imaging

In addition to increased glucose metabolism, which principally forms the basis of F-18 FDG-PET oncology imaging, increased amino acid transport and metabolism is also a characteristic of cancer cells. Methionine is a physiological amino acid which is transported into the cells by neutral amino acid transporter and metabolized. C-11 labeled methionine (C-11 MET) was first developed

Table 2: Recent data on the potential future role of FDG in assessing tumor biology

| Type of cancer         | Correlation of FDG uptake in relation to tumor biology                                                                 | Comment                                                                 |
|------------------------|--------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Breast cancer          | Low tumor grade independently associated with (false?) negative results                                                   | Positive correlation of FDG uptake with tumor biology (figures 2 and 3)  |
|                        | Triple-negative breast cancer associated with enhanced FDG uptake\(^{18}\)                                                 |                                                                        |
| Thyroid cancer         | Survival correlated with disease volume on FDG-PET                                                                         | A negative FDG-PET scan in a patient with thyroid cancer should not be regarded as false negative, but as true negative in terms of overall prognosis |
|                        | FDG volume greater than 125 ml had significantly reduced short-term survival\(^{12}\)                                      |                                                                        |
| Lymphomas              | Prognosis of patients with a pretreatment SUVmax \(\leq 5\) was better than that of patients with a pretreatment SUVmax \(>5\)\(^{11}\) | Degree of glycolysis (FDG uptake) of lymphoma and early interim PET allows prediction of tumor grade and prognosis |
| Prostate cancer        | Multiple factors like Gleason’s score, S. PSA levels, and FDG uptake have been included for prognostication                 | Negative FDG-PET scan in prostate cancer indicates less-aggressive tumor behavior (as demonstrated by lower PSA levels and the tendency to lower Gleason scores) than a positive FDG-PET scan |
|                        | A negative FDG-PET scan in a patient with thyroid cancer should not be regarded as false negative, but as true negative in terms of overall prognosis |
|                        | Interim PET findings emerged as a strong prognostic indicator\(^{11}\)                                                   |                                                                        |
| Hepatocellular         | Comparison of FDG and C-11 acetate uptake\(^{12}\)                                                                       | Low FDG uptake in HCC appears to be associated with better tumor differentiation and outcome than high FDG uptake |
| carcinoma              | Studies to compare uptake of FDG and SSR (dual tracer)\(^{13}\)                                                          | High FDG uptake suggests an aggressive behavior and the possibility of treatment refractoriness of the cells at the site, whereas low uptake would indicate a biologically indolent lesion |
| Neuroendocrine tumors  |                                                                                                                          |                                                                        |

FDG: Fluorodeoxyglucose, PET: Positron emission tomography, SUVmax: Maximum standardized uptake value, PSA: Prostate-specific antigen, HCC: Hepatocellular carcinoma, SSR: Somatostatin receptor
**Table 3: Enumeration of newer PET tracers for molecular imaging in oncology**

| PET tracer (molecule) | Molecular mechanism of tumor uptake | Preliminary clinical data on future applications in oncology |
|-----------------------|-------------------------------------|-------------------------------------------------------------|
| [18F] fluoroethyl-tyrosine (FET) | Amino acid transport system | Clinical management of cerebral gliomas |
| 11C-methionine (MET) | Amino acid transport system | Clinical management of cerebral gliomas |
| C11-choline | Cell membrane synthesis targeting related to upregulation of choline kinase associated with cancer | Enhanced sensitivity and accuracy for the preoperative staging of prostate cancer in pelvic lymph nodes in prostate cancer |
| 18F-FMISO (nitroimidazoles) | Nitroimidazoles are reduced to RNO2 radicals, bind covalently to intracellular macromolecules and remain within hypoxic cells | GBM, head and neck cancers. Hypoxia-specific treatment in patients with head and neck cancer |
| Ga-68-DOTATATE and others | SSTR uptake | Neuroendocrine tumor imaging and targeted therapy |
| 18F-FES | Hormone receptor A binding through protein bound to albumin or SSBP (also known as sex hormone-binding globulin) to ER | ER imaging in breast cancer for prognosis, and prediction of response to hormone therapy |
| C-11 acetate | Uptake dependant on FAS expression in tumors | Prostate cancer for detection of recurrence |
| 68Ga PSMA | Binding to PSMA | Androgen independence, metastasis in prostate cancers |
| 18F-galacto-RGD and 18FAH111 | Target the integrin molecule αvβ3 | Assessment of angiogenesis-inhibiting drugs |

**Table 4: Hypoxia imaging: Available and potential PET/SPECT tracers**

| Agent | Category | Clinical data | Comments |
|-------|----------|---------------|----------|
| [18F] FMISO | PET Nitroimidazole compounds | Yes | Thorough clinical evaluation* |
| [18F] FAZA | PET Nitroimidazole compounds | Yes | Prelim results only** |
| [18F] FETA | PET Nitroimidazole compounds | No | - |
| [18F] FETNM | PET Nitroimidazole compounds | Yes | Limited experience in head and neck tumors only |
| [18F] EF5, [18F] EF3, [18F] EF1 | PET Nitroimidazole compounds | Yes | Clinical feasibility studies only |
| [124I] IAZA and [18F] FAZA | PET Nitroimidazole compounds | No | - |
| Cu-ATSM | PET Non-nitroimidazole compound | Yes | Holds the greatest promise for the future* |
| [123I] IAZA | SPECT agent Nitroimidazole compounds | Yes | Clinical feasibility studies only |
| Tc99m BMS 181321, BRU59-21 | SPECT agent Nitroimidazole compounds | Yes | Clinical feasibility studies only |

*Various preclinical and clinical data have shown significant correlation between hypoxic area within tumors (intra-tumoral) and between various tumors (inter-tumoral), correlating with immunohistochemistry findings for the same. Studies have shown [18F]FMISO uptake to be an independent prognostic marker for predicting outcome of radiotherapy in head and neck cancers. It may predict freedom from disease as well as overall survival. In vivo experiments (preclinical and clinical) have given conflicting results when showing a correlation between the uptake of [18F]FDG and the existence of hypoxia in tumors. Cu-ATSM has one of the best selectivity for hypoxic tissue and shows a rapid delineation of tumor hypoxia and high tumor to background ratios, **Radiation treatment planning and intensity-modulated radiotherapy based on [18F]FAZA uptake measurements are feasible. PET: Positron emission tomography, SPECT: Single-photon emission computerized tomography, [18F]FMISO: [18F] fluoromisonidazole, [18F]FAZA: [18F] fluoroazomycin-arabinofuranoside, [18F]FETA: [18F] fluoroetanidazole, [18F]FETNIM: [18F] fluoroethyltrinitroimidazole, [124I]IAZA: [124I]idoazomycininarabinoside

by Comar et al. (1976). It was first evaluated for tumor imaging by Syrota et al. (1982). It was later evaluated for various cancers; the highest clinical utility has been seen in evaluation of brain tumors due to its advantage of low brain uptake in normal brain tissue. Currently, C-11 MET PET has been one of the most useful imaging techniques for evaluation of recurrence versus radiation necrosis in gliomas. Recently, 18F-fluorothyrsine (FET) and 18F-fluorodopa PET/CT have demonstrated excellent promising for assessing brain tumors, particularly the low-grade ones where FDG shows limitations [Figure 5].

Even though the most studied radiolabeled amino acid for PET imaging of brain tumors is PET, other 18F-labeled aromatic amino acid analogs have been developed recently for tumor imaging, including FET and 1,3,4-dihydroxy-6-[18F]fluorophenylalanine (FDOPA).

The main advantage of this is the relative long half-life of fluorine-18 (at 110 min) in comparison to the short half-life of [11C] (20 min) that requires an onsite cyclotron.

### Cell membrane synthesis targeting

Up-regulation of choline kinase is often associated with cancer, a strong rationale behind using 11C-choline in oncology. 11C-choline has been reported to be a new agent...
for PET of brain tumors and other cancers.[22] In particular, 11C-choline PET has been shown to provide clear images of the pelvic region, of prostate carcinoma and pelvic lymph node metastasis.[22] It has been also shown to have sensitivity and accuracy for the preoperative staging of prostate cancer in pelvic lymph nodes.

Imaging of protein receptors

**Estrogen receptor based imaging**

Hormonal therapy has a major role in cancer care, particularly for prostate and breast cancer patients. Imaging of tumor expression of estrogen receptors (ERs) by PET and of human epidermal growth factor receptor 2 (HER2) by PET and SPECT is under way in trials predominantly involving breast cancer patients and also in studies involving uterine tumors and meningioma.[23] In breast cancer, the expression of ERs by tumor cells predicts mortality and the efficacy of antiestrogen–ER treatments and (non-hormonal) chemotherapy.

Of many tracers that have been clinically tested for imaging of ERs, 16α-18F-fluoro-17β-estradiol (18F-FES) has emerged as the leading contender. It has been shown that uptake values of 18F-FES on imaging correlate with response to therapy.

**Androgen receptor imaging**

18-fluorine-dihydrotestosterone (18F-FDHT) is an analog of 5α-dihydrotestosterone, the main prostatic form of androgen. Imaging of androgen receptor expression in prostate cancer has two potential roles in evaluating the response to therapy:

- Imaging of focal ectopic expression of androgen receptors may be a more tumor-specific manifestation of prostate metastases than other commonly used imaging characteristics (e.g. osseous activity on bone scintigraphy, hyper-attenuation on CT, and combinations of MRI signal patterns) and may allow better disease staging and therapeutic response assessment
- In vivo functional imaging of androgen metabolism can help in assessing treatment response and detecting recurrence due to development of resistance.[24]

**Imaging of prostate-specific membrane antigen and therapeutic potential in prostate carcinoma**

Prostate cancer is the most commonly diagnosed cancer and the second leading cause of cancer death among men in the United States.[25] Molecular imaging of prostate cancer has addressed the challenges in a multifaceted manner from staging to studying the tumor biology:

- Variations in growth rate and challenges on use of F-18 FDG: Higher glucose utilization is characteristic of most tumors; however, prostate cancer can vary greatly in growth rate, ranging from slow growing and less

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**Figure 3(A-C):** (A-C) [18 F] EF5-PET/MR imaging of malignant brain tumor hypoxia for radiation treatment planning. Axial [18 F] EF5 PET (A), axial MR (B), and fused PET/MR images (C) show uptake of [18 F] EF5 in the anterior portion of tumor, indicating intralesional hypoxia. Note discrepant findings between [18 F] EF5 uptake in lesion and structural appearance of lesion. Hypoxic tumors are resistant to either radiation or chemotherapy. Hypoxia agents may play a major role in selection of appropriate patients for radiation therapy planning (Reproduced with permission from[21])

**Figure 4:** Comparing PET with FDG (upper panel) and FLT (lower panel) in the same patient with metastatic brain tumor. The absence of normal gray matter uptake has been a major advantage of newer PET tracers compared to FDG in brain tumor imaging

**Figure 5:** A 19-year-old male, a post-operative case of right-sided pilocytic astrocytoma. FET-PET/CT illustrating residual lesion noted in right midbrain tectal plate (Courtesy: Dr. A. Jaimini and Dr. A. Mondal, INMAS, New Delhi)
aggressive to rapidly disseminating and aggressive, thus limiting F18-FDG–based tumor evaluation. 

- **Tumor location:** Tumor location and excretion into bowel and urinary bladder in most of the tracers has made tumor localization challenging in the vicinity, especially with current conventional imaging agents like In-111 labeled monoclonal antibody capromab pendetide (ProstaScint).

Prostate-specific membrane antigen (PSMA) is a type II transmembrane protein that is over-expressed in prostate carcinoma, including androgen-independent, advanced, and metastatic disease as well as in a few subtypes of urinary bladder carcinoma, schwannoma, and in the tumor neovasculature of many solid tumors. Because PSMA levels are directly related to androgen independence, metastasis, and progression, PSMA has proven to be an important target for the development of new radiopharmaceuticals for PET [Figure 6].

The shortcoming with ProstaScint is that it recognizes an internal epitope of PSMA; hence, it is believed that cells must be dead in order for them to be imaged with this agent. To circumvent this shortcoming, preclinical data and the early clinical results for new PSMA-based radiotracers had shown promise, such as with newer 89Zr- and 64Cu-labeled anti-PSMA antibodies (directed toward external epitopes) and antibody fragments, 64Cu-labeled aptamers, 68Ga-, 64Cu-, and 86Y-labeled low molecular weight inhibitors of PSMA.

The therapeutic potential of the radiolabeled PSMA monoclonal antibody deserves special mention here. Phase III trials with β-emitting radionuclide-labeled PSMA monoclonal antibody [(177) Lu-J591] targeted therapy for progressive metastatic castration-resistant prostate cancer have shown positive results in the form of accurate tumor targeting and PSA responses. Future for these agents as specific molecular targeted therapy appears very promising.

**Molecular imaging of somatostatin receptors with an introduction to radiolabeled peptide receptor therapy**

NETs are unique tumors that originate almost everywhere in the body from neuroendocrine cells and the majority of NETs express somatostatin receptors (SSTR) which bind to somatostatin (SST) and can be successfully targeted for imaging and therapy. SSRI is one of the most glaring examples of the application of molecular imaging in clinical oncology.

SST is a cyclic and regulatory peptide consisting of 14 amino acids, which comprises five distinct subtypes (labeled SSTR1–5). The imaging of the overexpressed SST subtype 2 (SST2) NETs has been developed and has found extensive clinical applications for almost two decades [Table 5]. Various studies have shown the impact of SSRI in the management of NETs, with the sensitivity and specificity of PET or PET/CT reported to be 93% and 91%, respectively [Figures 7-9].

In NETs, the histological tumor grading is of pivotal importance in prognostic risk stratification and has been frequently utilized for treatment decision making. In this regard, the Ki-67 labeling index or the MIB-1 labeling index is the common determinant [Figures 7-9]. Recently, predicting the treatment outcome more appropriately using dual tracer (SRI and FDG PET/CT) imaging approach has been proposed for the tumors having MIB-1 (Ki-67) LI between 20 and 30%, where the current guidelines fall in gray areas. The human SSTR subtype 2 (hSSTR2), as a reporter gene, is under research for molecular imaging applications which have several features for potential translation to human studies.

**Angiogenesis imaging**

Newer techniques of cancer therapy involve clinical assays of tumor blood vessels that can be applied for individualization of vascular targeted therapies by optimizing dose selection and identifying drug resistance. So, PET imaging of angiogenesis has potential in the future with two imaging agents having entered clinical trials: 18F-galacto-RGD and 18FAH111. Both tracers target the integrin molecule αvβ3 and have various affinities for...
The integrin \( \alpha v \beta 3 \) receptor is upregulated on most tumors and several RGD-based peptide ligands, for example, 18F-galacto-RGD, have the potential for imaging a variety of tumors like breast cancer, brain tumors, lung cancers, squamous cell carcinoma of head and neck (SCCHN), differentiated thyroid carcinoma, sarcoma, and melanoma. The potential of imaging with these tracers to measure angiogenic density, which would show changes after targeted therapy even before other molecular imaging tools like F18-FDG PET or functional MRI images would reveal any changes in the tumor holds great promise.

18F-fluoride positron emission tomography/computerized tomography for skeletal imaging

18F-fluoride is a recently developed popular positron emitting bone imaging radiopharmaceutical. PET provides quantitatively accurate, high-resolution images with improved sensitivity compared to SPECT or planar scanners and is now frequently preferred over the planar whole-body 99mTc-methylene diphosphonate (MDP) radionuclide bone scintigraphy, in centers where it is available.

**Table 5: Imaging options available with somatostatin receptor analogs for neuroendocrine tumors**

| Radioisotope (radiopharmaceutical) | Indium-111 (In-111 pentetreotide), (In-111 DTPAOC), (In-111-DOTA-Tamreotide), (In-111-DOTA-NOC-ATE), (In-111-DOTA-BOC-ATE) | Technetium 99m (99mTc-labeled hydrazinonicotinyl-Tyr3-octreotide) (HYNIC-TOC) | Indium-123 (I-123-Octreotide) | Gallium-68 (Ga-68-DOTATATE), (Cu-64-DOTATOC), (Ga-68-DOTANOC) | Copper-64 | Fluorine-18 |
|----------------------------------|-------------------------------------------------|-----------------------------------|-------------------|---------------------|-----------------|-----------------|
| Half-life | 2.8 days | 6 h | 13 h | 68.3 min | 12.7 h | 109.8 min |
| Imaging type | SPECT | SPECT | SPECT | PET | PET | PET |

PET: Positron emission tomography, SPECT: Single-photon emission computerized tomography

**Figure 7**: A 65-year-old male diagnosed to have rectal neuroendocrine tumor (MIB-8–10%, i.e. Grade 2 tumor); discordance was observed between 99mTc-HYNIC-TOC (left panel, which is avidly concentrated in the hepatic metastatic lesions) and FDG-PET/CT (right panel, MIP view; demonstrating no uptake in metastatic lesions)

**Figure 8(A and B)**: (A and B) A 35-year-old male having neuroendocrine tumor of pancreas with infiltration into duodenum and superior mesenteric vein on CECT. Duodenal growth biopsy was indicative of poorly differentiated neuroendocrine carcinoma. Before the scan was taken, the patient had been treated with chemotherapy with carboplatin and etoposide and referred for consideration for radiolabeled peptide receptor therapy (PRRT). The 99mTc HYNIC-TOC (A) FDG-PET/CT (B) demonstrated total concordance consistent with poorly differentiated histopathology.

**Future Advances in Molecular Imaging: Magnetic Resonance Imaging Combined with Positron Emission Tomography Imaging**

Recent introduction of integrated whole-body PET/MR scanners (BiographmMR; Siemens Healthcare, Germany) for clinical use has lead to various technical feasibility and early clinical studies of PET/MR in oncology.

Hybrid PET/MR systems provide complementary multimodal information about perfusion, metabolism, receptor status, and function, together with excellent high-contrast soft tissue visualization without the need to expose the patient to additional radiation. Challenges remain in the field of attenuation correction in PET/MR which is important for quantitative PET imaging. MR-based methods like template, sequence, atlas and transmission-based methods are being intensively evaluated. Costs and clinical utility apart, the small bore of MRI in comparison to the PET scanner and truncation artifacts currently pose major physical limitations for this promising modality.
Prognostic value of [18F]fluorodeoxyglucose
Assessment of simplified methods to measure
Early interim 2-[18F]fluoro-2-deoxy-D-glucose

There are no conflicts of interest.

Conflicts of interest

The superior resolution of the 68Ga-DOTA-NOC/TATE PET-CT is
coronal images that demonstrate multiple bilobar hepatic metastases.
The left panel shows only PET and the right panel shows fused PET-CT

Potential Areas for Application of Positron Emission Tomography/Magnetic Resonance in Clinical Oncology and Neuro-oncology

Early experiences have shown favorable results in comparison to PET/CT for evaluation of NSCLC, mainly due to its multiparametric nature allowing for the additional integration of diffusion-weighted images (DWI), primary tumor (T) evaluation in head and neck cancers, evaluation of metastases (M) in brain and liver, NETs, and evaluation of pelvic tumors, especially prostate carcinoma. MRI is the first-line method of choice in neurological disorders and in many applications of neuro-oncological imaging. So, PET/MR has become a desirable alternative for brain imaging. Promising results have been obtained in areas of intracranial mass evaluation with addition of arterial spin labeling and MR spectroscopy. FDG-PET and MRI are superior to the unimodal approach, with an accuracy rate of 94% for the differentiation of Alzheimer’s disease and fronto-temporal lobar degeneration.

Conclusion

A close collaboration between the scientists, the physicists and the physicians has resulted in emergence of molecular medicine. Numerous novel molecules are showing promise for personalized care, newer drugs and assessment of their response on diseases; and potential for tailored treatment strategies for individual patients depending on the behavior of the disease. With Radiomics and theranostics gearing up for oncology of the future, this would be most applicable to the field of oncological imaging.

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References

1. Basu S. Personalized versus evidence-based medicine with PET-based imaging. Nat Rev Clin Oncol 2010;7:665-8.
2. Mahajan A, Goh V, Basu S, Vaish R, Weeks AJ, Thakur MH, et al. Bench to bedside molecular functional imaging in translational cancer medicine: To image or to imagine? Clin Radiol 2015;70:1060-82.
3. Dunphy MP, Lewis JS. Radiopharmaceuticals in preclinical and clinical development for monitoring of therapy with PET. J Nucl Med 2009;50 Suppl 1:1065-215.
4. Lastoria S, Maurea S, Caracò C, Vergara E, Maurelli L, Indolfi P, et al. Iodine-131 metiodobenzylguanidine scintigraphy for localization of lesions in children with neuroblastoma: Comparison with computed tomography and ultrasonography. Eur J Nucl Med 1993;20:1161-7.
5. Blankenberg FG. In vivo detection of apoptosis. J Nucl Med 2008;49 Suppl 2:815-95S.
6. Wahl RL, Jacene H, Kasamon Y, Lodge MA. From RECIST to PERCIST: Evolving considerations for PET response criteria in solid tumors. J Nucl Med 2009;50 Suppl 1:1225-505.
7. Jadvar H, Alavi A, Gambhir SS. 18F-FDG uptake in lung, breast, and colon cancers: Molecular biology correlates and disease characterization. J Nucl Med 2009;50:1820-7.
8. Basu S, Kumar R, Mavi A, Alavi A. Exploring tumor biology with fluorodeoxyglucose-positron emission imaging in breast carcinoma. PET Clin 2009;4:381-9.
9. Basu S, Chen W, Tchou J, Mavi A, Cernek T, Czerniecki B, et al. Comparison of triple-negative and estrogen receptor-positive/progesterone receptor-positive/HER2-negative breast carcinoma using quantitative fluorine-18 fluorodeoxyglucose/positron emission tomography imaging parameters: A potentially useful method for disease characterization. Cancer 2008;112:995-1000.
10. Wang W, Larson SM, Fazzari M, Tickoo SK, Kolbert K, Sgouros G, et al. Prognostic value of [18F]fluorodeoxyglucose positron emission tomographic scanning in patients with thyroid cancer. J Clin Endocrinol Metab 2000;85:1107-13.
11. Gallamini A, Hutchings M, Rigacci L, Specht L, Merli F, Hansen M, et al. Early interim 2-[18F]fluoro-2-deoxy-D-glucose positron emission tomography is prognostically superior to international prognostic score in advanced-stage Hodgkin’s lymphoma: A report from a joint Italian-Danish study. J Clin Oncol 2007;25:3746-52.
12. Park JW, Kim JH, Kim SK, Kang KW, Park KW, Choi JI, et al. A prospective evaluation of 18F-FDG and 11C-acetate PET/CT for detection of primary and metastatic hepatocellular carcinoma. J Nucl Med 2008;49:1912-21.
13. Basu S, Sirohi B, Shrikhande SV. Dual tracer imaging approach in assessing tumor biology and heterogeneity in neuroendocrine tumors: Its correlation with tumor proliferation index and possible multifaceted implications for personalized clinical management decisions, with focus on PRRT. Eur J Nucl Med Mol Imaging 2014;41:1492-6.
14. Mee G, Dierckx R, Vangestel C, Van de Wiele C. Molecular imaging of hypoxia with radiolabelled agents. Eur J Nucl Med Mol Imaging 2009;36:1674-86.
15. Calzada MJ, del Peso L. Hypoxia-inducible factors and cancer. Clin Transl Oncol 2007;9:278-89.
16. Tehrani OS, Shields AF. PET imaging of proliferation with pyrimidines. J Nucl Med 2013;54:903-12.
17. Shields AF, Grierson JR, Dohmen BM, Machulla HJ, Stayanoff JC, Lawhorn-Crews JM, et al. Imaging proliferation in vivo with [F-18]FLT and positron emission tomography. Nat Med 1998;4:1334-6.
18. Frings V, Yaqub M, Hoeyng LL, Golla SS, Windhorst AD, Schuit RC, et al. Assessment of simplified methods to measure 18F-FLT uptake changes in EGFR-mutated non-small cell lung...
28. Chang SS, Reuter VE, Heston WD, Gaudin PB. Comparison of anti-prostate-specific membrane antigen antibodies and other immunomarkers in metastatic prostate carcinoma. Urology 2001;57:1179-83.

29. Troyer JK, Beckett ML, Wright GL Jr. Location of prostate-specific membrane antigen in the LNCaP prostate carcinoma cell line. Prostate 1997;30:232-42.

30. Tagawa ST, Milowsky MI, Morris M, Vallabhajosula S, Christos P, Akhtar NH, et al. Phase II study of lutetium-177-labeled anti-prostate-specific membrane antigen monoclonal antibody [591 for metastatic castration-resistant prostate cancer. Clin Cancer Res 2013;19:5182-91.

31. Reubi JC, Maecke HR. Peptide-based probes for cancer imaging. J Nucl Med 2008;49:1735-8.

32. Krenning EP, Kwekkeboom DJ, Bakker WH, Breeman WA, Kooij PP, Oei HY, et al. Somatostatin receptor scintigraphy with [111In-DTPA-D-Phe1]- and [123I-Tyr3]-octreotide: The Rotterdam experience with more than 1000 patients. Eur J Nucl Med 1993;20:716-31.

33. Kenny LM, Coombes RC, Oulie I, Contractor KB, Miller M, Spinks TJ, et al. Phase I trial of the positron-emitting Arg-Gly-Asp (RGD) peptide radioligand 18F-AH111585 in breast cancer patients. J Nucl Med 2008;49:879-86.

34. Philipp-Abbrederis K, Herrmann K, Knop S, Schottelius M, Eiber M, Lückerath K, et al. In vivo molecular imaging of chemokine receptor CXCR4 expression in patients with advanced multiple myeloma. EMBO Mol Med 2015;7:477-87.

35. Heusch P, Buchbender C, Köhler J, Nensa F, Beiderwellen K, Kühl H, et al. Correlation of the apparent diffusion coefficient (ADC) with the standardized uptake value (SUV) in hybrid 18F-FDG PET/ MRI in non-small cell lung cancer (NSCLC) lesions: Initial results. Rofo 2013;185:1056-62.