Targeted In vivo Imaging of Integrin αvβ6 with an Improved Radiotracer and Its Relevance in a Pancreatic Tumor Model

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Abstract

The cell surface receptor αvβ6 is epithelial specific, and its expression is tightly regulated; it is low or undetectable in adult tissues but has been shown to be increased in many different cancers, including pancreatic, cervical, lung, and colon cancers. Studies have shown αvβ6 as a prognostic biomarker linked to poor survival. We have recently shown the feasibility of imaging αvβ6 in vivo by positron emission tomography (PET) using the peptide [18F]FBA-A20FMDV2. Here, we describe improved αvβ6 imaging agents and test their efficacy in a mouse model with endogenous αvβ6 expression. The modified compounds maintained high affinity for αvβ6 and >1,000-fold selectivity over related integrins (by ELISA) and showed significantly improved αvβ6-dependent binding in cell-based assays (>60% binding versus <10% for [18F]FBA-A20FMDV2). In vivo studies using either a melanoma cell line (transduced αvβ6 expression) or the BxPC-3 human pancreatic carcinoma cell line (endogenous αvβ6 expression) revealed that the modified compounds showed significantly improved tumor retention. This, along with good clearance of nonspecifically bound activity, particularly for the new radiotracer [18F]FBA-PEG28-A20FMDV2, resulted in improved PET imaging. Tumor/pancreas and tumor/blood biodistribution ratios of >23:1 and >47:1, respectively, were achieved at 4 hours. Significantly, [18F]FBA-PEG28-A20FMDV2 was superior to 2-[18F]fluoro-2-deoxy-D-glucose (2-[18F]FDG) in imaging the BxPC-3 tumors. Pancreatic ductal adenocarcinoma is highly metastatic and current preoperative evaluation of resectability using noninvasive imaging has limited success, with most patients having metastases at time of surgery. The fact that these tumors express αvβ6 suggests that this probe has significant potential for the in vivo detection of this malignancy, thus having important implications for patient care and therapy.

Introduction

In recent years, positron emission tomography (PET) imaging, using 2-[18F]fluoro-2-deoxy-D-glucose (2-[18F]FDG), has become routine for detection of tumors and monitoring of treatment response (1–3). [18F]FDG, a radiolabeled analogue of glucose, is taken up and trapped primarily in cells with high metabolism. As glucose hypermetabolism is commonly found in inflammation, as well as in many malignancies, distinguishing cancer from other hypermetabolic states remains a challenge (1, 4, 5). Although PET has been combined with other imaging modalities, most notably computed tomography (CT), which relies on subtle differences in soft tissue density to distinguish between normal and malignant tissues (5–7), [18F]FDG-PET/CT still leaves considerable room for improvement in diagnosis and clinical management of many cancers (8). The availability of more disease-specific imaging agents (7) could help to mitigate the limited specificity of [18F]FDG for malignant tissue. Rather than relying on slight changes in tissue density or metabolic rate alone, targeting disease-specific tissue markers could considerably aid in tumor detection and localization. The feasibility of this approach has been shown with [18F]galacto-RGD, a small radiolabeled peptide used for PET imaging of the cancer-related integrin αvβ3 (9). In contrast to αvβ6, other members of the integrin family have received relatively little attention. However, newly emerging evidence indicates that αvβ6 may also be an important target for diagnosis and treatment of cancer (10–14). The integrin αvβ6 was first identified in a human pancreatic carcinoma cell line (15). Subsequent studies established that although αvβ6 is epithelial specific, its expression is low or undetectable in healthy adult tissues. Up-regulation has been recognized during tissue remodeling, including inflammation and wound healing (16–18). Significantly, expression has also been shown to be increased in many different cancers (13, 19). Among gastroenteropancreatic adenocarcinomas, αvβ6 expression was found to be strongest in pancreatic ductal adenocarcinomas (PDAC; ref. 20). Moreover, αvβ6 has recently been described as a prognostic indicator, with high levels of expression correlating with poor prognosis for cancer of the colon, cervix, lung, and stomach (10–12, 21). Antibody-blockade of αvβ6 was shown to inhibit tumor progression in vivo in animal models (13). Thus, mounting evidence implicates αvβ6 as an important and biologically relevant target for molecular imaging of cancer.

Recently, we showed the ability to selectively image αvβ6-expressing tumors in vivo with microPET using the αvβ6-specific [18F]fluorobenzoyl-labeled peptide [18F]FBA-A20FMDV2 (22). Whereas targeted imaging was achieved, low uptake and poor retention in the target tissue limited its general utility. For this current study, we conjugated small, monodisperse polyelectrolyte glycol (PEG) polymers to A20FMDV2 to improve pharmacokinetics, generating the two new radiotracers [18F]FBA-PEG28-A20FMDV2 and [18F]FBA-(PEG28)2-A20FMDV2. We report that both PEGylated A20FMDV2 variants showed significantly improved retention in two different αvβ6-expressing human tumor xenograft models: DX3; and 6, a human melanoma cell line transduced to express αvβ6, and BxPC-3, a human pancreatic carcinoma cell line that endogenously expresses αvβ6. In the BxPC-3 model, retention of [18F]FBA-PEG28-A20FMDV2 in tumors was 12-fold greater than
retention of the non-PEGylated [18F]FBA-A20FMDV2. Tumor/pancreas and tumor/blood ratios of >23:1 and >47:1, respectively, were achieved with [18F]FBA-PEG28-A20FMDV2 at 4 hours. The ability to noninvasively detect regional tumor invasion or occult metastatic disease using αvβ6 PET imaging would have a large effect on patient management, reducing the number of unnecessary surgeries of unresectable disease (23).

Materials and Methods

Reagents and cell lines. Reagents, materials, and DX3puro/DX3puro/6 cell lines have been described previously (22). Pancreatic cancer cell lines were obtained from American Type Culture Collection. Transforming growth factor β1 human latency-associated peptide (TGFβ1-LAP) was purchased from Sigma. A Leica CM1850 cryostat (Leica Microsystems) was used for tissue sectioning.

Competitive binding ELISA. The in vitro efficacies of the peptides toward integrins αvβ6, α5β1, α5β3, αvβ3, and αvβ5 were analyzed by competitive binding ELISA as described previously (22).

Flow cytometry. Integrin expression on the cell lines was determined as previously described (24).

Cell binding and internalization. A cell suspension (3.75 × 10^6 cells) was incubated with the radiotracer (0.2 μCi) in serum-free medium (pH 7.2, 100 μL). For each radiotracer, the cell lines were assayed concurrently (n = 4 samples per cell line per time point). The fraction of bound radioactivity was determined with a γ-counter (cell pellet versus supernatant). To determine the fraction of internalized radioactivity, the cells were then treated with acidic wash buffer [0.2 mol/L sodium acetate, 0.5 mol/L sodium chloride (pH 2.5), 4°C] to release surface-bound activity (25). The internalized fraction was determined with a γ-counter (cell pellet versus radioactivity released into supernatant).

Xenograft cells and animal model. All animal studies were carried out using male athymic nude mice (nu/nu; Charles River Laboratories) following approved protocols. DX3puro/6 (αvβ6 positive) and DX3puro (control) cells were injected s.c. (n = 20 mice; 3 × 10^5 cells/cell line in 100 μL serum-free DMEM; Invitrogen) in opposite flanks in the shoulder region, as previously described (22). BxPC-3 cells were injected s.c. (n = 30 mice; 5 × 10^5 cells in 100 μL 1:1 serum-free DMEM/Matrigel HC; BD Biosciences) in the left shoulder region. Studies commenced once tumors had reached a diameter of 0.5 cm.

Biodistribution studies. Radiotracers (~15–30 μCi) in saline/PBS (150–200 μL) were injected, and data were analyzed as previously described (n = 3 per time point; ref. 22).

MicroPET imaging studies. The [18F]FBA peptides or [18F]FDG (~120–230 μCi) in saline/PBS (100–200 μL) were injected as previously described (n = 3 per time point; ref. 22). Two animals were imaged side-by-side in a feet-first prone position. For blocking studies, the [18F]FBA peptide (30 mg/kg as 10 mg/mL solution in saline) was injected 10 min before the radiotracer. Imaging data were collected and analyzed as previously described (22, 26).

Standard uptake values (SUV) were computed by dividing the activity concentration in each voxel by the injected dose and then multiplying by the weight of the animal (26). Maximum intensity projection (MIP) images were created by collapsing across one dimension with the maximum value in each column of voxels.

 Autoradiography studies. Frozen tissue slices (tumor and surrounding tissue, 50 μm) in freezing medium (Tissue-Tek, Sakura Finetek) were exposed to a storage phosphor screen (GE Healthcare) overnight. The screen was read at a 30-μm resolution using a Storm 860 phosphorimager (GE Healthcare).

Statistical analysis. The data are reported as mean ± SD. Two-tailed Student’s t tests were performed to evaluate statistical significance. P < 0.05 was considered significant. In plots, the SD is smaller than the size of the symbol for some data points.

Results

PEGylated peptide ligands for αvβ6. PEGylated A20FMDV2 variants were compared by ELISA to the established αvβ6 peptide ligand FBA-A20FMDV2 (Fig. 1). They exhibited IC50 of 3 to 6 nmol/L, similar to FBA-A20FMDV2. Inhibition of binding by the natural ligands to integrins αvβ6, αvβ3, and αvβ5, required at least 1,000-fold higher concentrations of peptide (IC50 > 10 μmol/L), indicating that introduction of the PEG moieties did not have a deleterious effect on αvβ6 affinity and selectivity of A20FMDV2.

Integrin αvβ6 expression in human pancreatic cancer cell lines. Seven cell lines were screened by flow cytometry for αvβ6 expression (Fig. 2). With the melanoma cell line DX3puro/6, stably transduced to express αvβ6, and its paired control line DX3puro, lacking expression of αvβ6, were analyzed as positive and negative controls, respectively; both of these cell lines express similar levels of other integrins, including αvβ3, α5β1, and α5β3 (22). BxPC-3 and Capan-2 showed high αvβ6 expression levels comparable with that of the positive control DX3puro/6. Capan-1 and L3.3 showed intermediate expression of αvβ6, whereas MIA-PaCa2, Panc-1, and BCL-2c9 showed expression levels equivalent to that of the negative control DX3puro.

Cell binding and internalization. The binding of the radiotracers [18F]FBA-[PEG28]2-A20FMDV2 (n = 0, 1, 2) showed significant increase in binding levels at 1 hour (Fig. 3A), 5.3 ± 0.8% and 9.7 ± 1.2% of [18F]FBA-A20FMDV2 bound to the αvβ6-expressing DX3puro/6 and BxPC-3 cell lines, respectively. For [18F]FBA-PEG28-A20FMDV2, the binding levels increased significantly to 73.5 ± 1.3% and 68.9 ± 0.2%, respectively. Similarly, [18F]FBA-[PEG28]2-A20FMDV2 showed markedly elevated binding levels of 38.5 ± 1.7% and 25.8 ± 0.6%, respectively. Approximately two-thirds of the bound radioactivity was internalized in the αvβ6-expressing cell lines in the case of the two PEGylated radiotracers, whereas less than half of the bound [18F]FBA-A20FMDV2 was internalized. Incubation in the presence of excess nonradioactive [18F]FBA-PEG28-A20FMDV2 (≥1 μmol/L) completely abrogated binding of the radiotracer to DX3puro/6 cells (Supplementary Fig. S3).

Figure 3B illustrates the rapid cell binding of radiotracer. Within 1 minute, approximately one quarter of [18F]FBA-PEG28-A20FMDV2 bound to DX3puro/6 and BxPC-3 (30.5 ± 2.7% and 24.5 ± 1.2%, respectively). Binding levels approached their maximum within 15 to 30 minutes and then remained steady. When the two cell lines were incubated with [18F]FBA-PEG28-A20FMDV2 for 1 hour in the presence of LAP, the radiotracer was able to efficiently compete for binding: binding levels in presence of 5 nmol/L LAP remained at ≥75% of those observed under LAP-free conditions (Supplementary Fig. S4).

[18F]FBA-[PEG28]2-A20FMDV2 (n = 0, 1, 2) biodistribution in the DX3puro/DX3puro/6 model. Initial in vivo evaluation of [18F]FBA-PEG28-A20FMDV2 and [18F]FBA-[PEG28]2-A20FMDV2 was performed using our previously described mouse model bearing the paired human xenografts of DX3puro/6 (αvβ6 positive) and DX3puro (αvβ6 negative; Supplementary Table S1). Whereas uptake of both PEGylated radiotracers in the target tissue at 1 hour postinjection was slightly below the level previously seen for the non-PEGylated [18F]FBA-A20FMDV2 (22), the introduction of the PE unit(s) resulted in excellent retention of radioactivity in the αvβ6-positive tumor ([18F]FBA-PEG28-A20FMDV2, 1 hour: 0.49 ± 0.12% ID/g, 4 hours: 0.49 ± 0.04% ID/g; [18F]FBA-[PEG28]2-A20FMDV2, 1 hour: 0.52 ± 0.09% ID/g, 4 hours: 0.54 ± 0.08% ID/g; compared with [18F]FBA-A20FMDV2, 1 hour: 0.66 ± 0.09% ID/g,

A comparison of the uptake in the two xenografts consistently showed preferential uptake in the \( \alpha_v\beta_6 \)-positive xenograft over the \( \alpha_v\beta_6 \)-negative xenograft, particularly for the PEGylated radiotracers. Whereas \([^{18}F]FBA-A20FMDV \) resulted in a 4.3:1 maximal \( \alpha_v\beta_6 \)-positive/\( \alpha_v\beta_6 \)-negative ratio, ratios of 8.0:1 and 9.2:1 were seen for \([^{18}F]FBA-PEG28-A20FMDV \) and \([^{18}F]FBA-(PEG28)_2-A20FMDV \), respectively (for \( P \) values, see Supplementary Table S1).

\([^{18}F]FBA-(PEG28)_n-A20FMDV \) \( (n = 0, 1, 2) \) biodistribution in the \( \alpha_v\beta_6 \)-endogenous BxPC-3 model. The feasibility of \( \alpha_v\beta_6 \)-targeted pancreatic tumor detection in vivo was evaluated in the BxPC-3 mouse model (Fig. 4; Supplementary Table S1). For \([^{18}F]FBA-A20FMDV \) initial uptake in and washout from the BxPC-3 xenograft (1 hour: 0.69 \( \pm \) 0.19% ID/g, 4 hours: 0.12 \( \pm \) 0.03% ID/g) were similar to those seen in the DX3puro/\( \alpha_v\beta_6 \) xenograft (1 hour: 0.66 \( \pm \) 0.09% ID/g, 4 hours: 0.06 \( \pm \) 0.00% ID/g). By contrast, for both of the PEGylated radiotracers uptake in the BxPC-3 xenograft 1 hour after injection was three to four times higher than in the DX3puro/\( \alpha_v\beta_6 \) xenograft, combined with excellent retention (\([^{18}F]FBA-PEG28-A20FMDV \) 1 hour: 1.85 \( \pm \) 0.44% ID/g, 4 hours: 1.48 \( \pm \) 0.04% ID/g; \([^{18}F]FBA-(PEG28)_2-A20FMDV \) 1 hour: 1.57 \( \pm \) 0.25% ID/g, 4 hours: 2.08 \( \pm \) 0.37% ID/g). Autoradiography images obtained for the PEGylated radiotracers of BxPC-3 xenografts 1 hour after injection also showed preferential, tumor-specific uptake (Fig. 5).

Renal clearance was the major route of elimination for all three radiotracers (Fig. 4 and data not shown). High-performance liquid chromatography (HPLC) analyses of urine samples showed three metabolites for \([^{18}F]FBA-A20FMDV \) and one major metabolite for each of the PEGylated radiotracers. Distribution of the radiotracers in healthy tissues generally depended on the number of PEG units present (Fig. 4; Supplementary Table S1). Non-PEGylated \([^{18}F]FBA-A20FMDV \) was washed out efficiently from all tissues examined, with gall bladder and kidneys containing the highest levels of radioactivity. By contrast, the di-PEGylated \([^{18}F]FBA-(PEG28)_2-A20FMDV \) was generally retained throughout, most notably in the kidneys (~42% ID/g); only blood showed clearing of radioactivity. Pharmacokinetics of the mono-PEGylated \([^{18}F]FBA-(PEG28)_2-A20FMDV \) in healthy tissues compared favorably to the di-PEGylated radiotracer, resulting in a desirable clearing behavior resembling that observed for the non-PEGylated compound in healthy tissues; highest levels of radioactivity were detected in the kidneys and the gall bladder.

The BxPC-3/blood ratio remained relatively low for \([^{18}F]FBA-A20FMDV \) (1 hour: 3.3:1, 4 hours: 7.0:1) and the BxPC-3/muscle ratio only reached statistically significant levels at the 4-hour time point (1 hour: 1.3:1, \( P = 0.38 \); 4 hours: 2.5:1, \( P = 0.02 \)) because of more rapid washout from healthy tissues than from the tumor (Fig. 4, Supplementary Table S1). By comparison, improved BxPC-3/muscle ratios were seen for \([^{18}F]FBA-(PEG28)_2-A20FMDV \) (1 hour: 2.5:1, 4 hours: 3.6:1) and \([^{18}F]FBA-(PEG28)_3-A20FMDV \) (1 hour: 4.1:1, 4 hours: 4.4:1), along with significantly higher BxPC-3/blood ratios (\([^{18}F]FBA-(PEG28)_3-A20FMDV \) 1 hour: 11.8:1, 4 hours: 47.9:1; \([^{18}F]FBA-(PEG28)_2-A20FMDV \) 1 hour: 9.0:1, 4 hours: 150:1).

**Figure 1.** Use of ELISA to measure the effect of introducing PEG groups with and without [\(^{19}F\)]FBA on the ability of A20FMDV to inhibit binding of biotinylated natural ligands to immobilized integrins. Peptides and biotinylated ligands were mixed and allowed to compete during 1 h for binding to integrin \( \alpha_v\beta_6 \) (A) and \( \alpha_v\beta_5, \alpha_v\beta_1, \alpha_v\beta_3, \alpha_v\beta_{10}, \alpha_v\beta_{11}, \) or \( \alpha_v\beta_4 \) (B). Ligands used were biotinylated fibronectin (\( \alpha_v\beta_1, \alpha_v\beta_3 \), biotinylated vitronectin (\( \alpha_v\beta_5, \alpha_v\beta_6 \)), or biotinylated fibrinogen (\( \alpha_v\beta_6 \)). Points represent triplicate experiments at each concentration. Points, percentage of inhibition; bars, SD. IC\(_{50}\) values were derived from A.
reflecting the improved retention of these radiotracers in the BxPC-3 tumor.

Importantly, levels of radioactivity in the BxPC-3 tumor were at least 4-fold higher than those for the pancreas itself for all radiotracers at all time points measured (Supplementary Table S1). For \([^{18}F]FBA-A20FMDV2\), the BxPC-3/pancreas ratio rose to 9.5:1 at 4 hours postinjection due to the more efficient washout from the pancreas than from the tumor. On the other hand, because of retention of \([^{18}F]FBA-(PEG28)_2-A20FMDV2\) in healthy pancreas, the BxPC-3/pancreas ratio for this radiotracer remained nearly unchanged throughout (1 hour: 5.6:1, 4 hours: 4.4:1). \([^{18}F]FBA-(PEG28)_2-A20FMDV2\) exhibited good retention in the tumor together with efficient washout from the pancreas (and other healthy tissues), resulting in a steadily increasing BxPC-3/pancreas ratio (1 hour: 4.2:1, 4 hours: 23.6:1). In summary, the mono-PEGylated \([^{18}F]FBA-(PEG28)_2-A20FMDV2\) had the most favorable pharmacokinetic characteristics.

MicroPET imaging of the \(\alpha_v\beta_6\)-endogenous BxPC-3 pancreatic cancer model. Figure 5A depicts representative coronal and transaxial MIPs obtained with the three \([^{18}F]FBA\) peptide tracers and with \([^{18}F]FDG\) (1 hour postinjection). Tumor uptake was compared based on maximum SUVs (SUV\(_{max}\); \(n=3\) animals).

The observations made for the peptide radiotracers during microPET imaging paralleled the results seen in the biodistribution study with preferential uptake noted in the tumor along with major uptake in kidneys, bladder (urine), and, for \([^{18}F]FBA-A20FMDV2\), gall bladder. \([^{18}F]FBA-A20FMDV2\) showed moderate initial tumor uptake and significant washout over time (SUV\(_{max}\) 15 minutes: 0.50 ± 0.22, 1 hour: 0.22 ± 0.11; 4 hours: < 0.05). \([^{18}F]FBA-(PEG28)_2-A20FMDV2\) showed improved uptake and retention in the tumor (SUV\(_{max}\) 15 minutes: 0.99 ± 0.18, 1 hour: 0.79 ± 0.24, 4 hours: 0.59 ± 0.20), along with significant renal retention. \([^{18}F]FBA-(PEG28)_2-A20FMDV2\) combined favorable tumor uptake characteristics (SUV\(_{max}\) 15 minutes: 1.07 ± 0.29, 1 hour: 0.91 ± 0.25, 4 hours: 0.63 ± 0.12) with good renal clearance.

Administration of nonradioactive \([^{19}F]FBA-(PEG28)_2-A20FMDV2\) (30 mg/kg) 10 minutes before the corresponding \([^{18}F]FBA\) peptide greatly reduced BxPC-3 tumor uptake [Δ(SUV\(_{max}\)) = −77%; Fig. 5B]. Similar results were obtained for \([^{19}F]FBA-(PEG28)_2-A20FMDV2\) (30 mg/kg)/\([^{18}F]FBA\)-peptide [Δ(SUV\(_{max}\)) = −60%; Fig. 5C]. Interestingly, \([^{18}F]FBA-(PEG28)_2-A20FMDV2\) and \([^{19}F]FBA-(PEG28)_2-A20FMDV2\) were retained in the mouse oral cavity in scans without prior administration of nonradioactive FBA-peptide, suggesting that there may be limited expression of \(\alpha_v\beta_6\) (27).

MicroPET scans obtained with \([^{18}F]FDG\) revealed an SUV\(_{max}\) of 0.62 ± 0.13 in the BxPC-3 tumor (1 hour postinjection, \(n=3\); Fig. 5A). This level of tumor uptake is relatively low for \([^{18}F]FDG\), and it was within the range observed for the surrounding tissue (0.4–0.8). Thus, whereas the \([^{18}F]FBA\) peptide tracers clearly revealed the BxPC-3 tumor in vivo, \([^{18}F]FDG\) did not.

Figure 2. Expression of integrin \(\alpha_v\beta_6\) by cell lines used in this study. Flow cytometry histogram plots for an \(\alpha_v\beta_6\)-positive (DX3puro/6) and an \(\alpha_v\beta_6\)-negative (DX3puro) cell line (A) and seven pancreatic cancer cell lines (B) were obtained. Levels of \(\alpha_v\beta_6\) (gray histograms) were determined using the integrin \(\alpha_v\beta_6\)-specific antibody 10D5. Mouse IgG (MOPC 21; white histograms) was used as antibody control.
in vivo (pharmacokinetic) properties. Additionally, owing to the monodisperse nature of the polymer, the final product is obtained as a single compound, allowing for precise characterization and batch-to-batch reproducibility, in contrast to mixtures containing polymer chains of different lengths encountered with the larger PEG products available.

As presented here, initial in vitro evaluation by ELISA indicated unchanged, high αvβ6-specificity for the PEGylated compounds (Fig. 1). Further binding experiments with the DX3puro/6 and DX3puro cell lines showed strong, αvβ6-specific and PEG-dependent binding to the receptor expressed on cells in the presence of other related integrins (including αvβ5, αvβ6, and αvβ7; Fig. 3). In vivo studies also showed improved, αvβ6-targeted PEG-dependent tumor retention in the DX3puro/6/DX3puro model (Supplementary Table S1). Taken together, these data confirmed our initial expectations for the two new PEGylated radiotracers, [18F]FBA-PEG28-A20FMDV2 and [18F]FBA-(PEG28)2-A20FMDV2.

The DX3puro/6/DX3puro melanoma cancer model was generated by viral transduction of human β6 into human melanoma cells. To examine a model more closely resembling the actual human disease, we sought a cancer wherein the expression of αvβ6 was relevant to the disease and for which cell lines that had endogenous expression of αvβ6 existed; we chose to investigate pancreatic cancer. Sipos and colleagues (20) reported, as part of a study of gastroenteropancreatic adenocarcinomas, that αvβ6 expression was strongest in PDACs. Thus, of the 34 human PDAC samples analyzed, 32 (94%) received the maximum score (the mean score was 2.8/3.0, with none of the other carcinomas receiving a score over 1.5). These observations make αvβ6 a very appealing target for selective in vivo detection of pancreatic cancer. The possibility of detecting primary tumors and metastases earlier by imaging αvβ6 and, thus, directing therapy sooner may improve upon the very poor prognosis of this disease. In addition, recent studies associate strong expression of αvβ6 with poor prognosis (for colon, lung, cervical, and stomach cancers; refs. 10–12, 21), so the relevance of our data is not restricted only to pancreatic cancer.

As shown here by flow cytometry (Fig. 2), many common pancreatic carcinoma cell lines exhibit an αvβ6 profile that reflects expression seen for PDAC in the clinic (20). In vitro cell-binding assays showed that [18F]FBA-PEG28-A20FMDV2 performed equally well with the endogenously αvβ6-expressing pancreatic BxPC-3 cell line and the transduced αvβ6-expressing DX3puro/6 cell line, showing rapid and high binding together with significant internalization (Fig. 3). Contrary to conditions in the in vivo environment, these assays were performed in the absence of natural ligands competing for binding to αvβ6. We, therefore, sought to further show their relevance as predictors for in vivo performance by carrying out a binding assay in the presence of a biologically relevant αvβ6 ligand. LAP was chosen as it binds to αvβ6 with high affinity and has significance in the context of tumor biology (13, 18, 30). In association with TGFβ1, particularly TGFβ1, LAP binds to αvβ6 thereby affecting signaling pathways understood to play significant roles in tumor development (18, 30). We found that, even in the presence of 5 mmol/L LAP, the radiotracer, present at subpicomolar levels, was still able to efficiently bind to the cells (at ≥5% of binding observed under LAP-free conditions; Supplementary Fig. S4). The feasibility of evaluating αvβ6-specific in vivo imaging radiotracers for pancreatic carcinoma was shown in a mouse model bearing...
BxPC-3 xenografts. In microPET images, the BxPC-3 tumors were clearly identifiable throughout. These data confirm that selective in vivo imaging of αvβ6-expressing cancers is possible with cancers that endogenously express αvβ6 and not only those engineered to express it. Importantly for pancreatic imaging, the best pharmacokinetic behavior was observed for [18F]FBA-PEG28-A20FMDV2, resulting in the highest tumor/pancreas ratio (>23:1; 4 hours), making this radiotracer a promising lead compound for in vivo detection.

Close examination of the biodistribution data revealed that introduction of the second PEG unit was not beneficial. Simply modifying from [18F]FBA-PEG28-A20FMDV2 to [18F]FBA-(PEG28)2-A20FMDV2 resulted only in a slight increase in tumor uptake, whereas, concurrently, washout of radioactivity from healthy tissue (except blood) was suppressed over the time span examined; particularly notable are the high and constant levels of radioactivity in the kidneys (Fig. 4). PET images also showed that [18F]FBA-PEG28-A20FMDV2 outperformed [18F]FBA-(PEG28)2-A20FMDV2; it showed slightly higher uptake (SUVmax) together with better BxPC-3/background ratios, largely due to preferential clearing of nonspecifically bound activity (Fig. 5). Thus, in this study, [18F]FBA-PEG28-A20FMDV2 seemed to have the best balance of αvβ6-dependent tumor uptake and a suitable rate of clearance from healthy tissues, including the pancreas. The high retention of [18F]FBA-(PEG28)2-A20FMDV2 in healthy tissues, caused by introduction of the second PEG unit, had not been predicted. These observations seem to stand in contrast to the common belief that renal clearance remains highly efficient for compounds bearing small PEG units (under ~30 kDa; refs. 28, 29). Despite the comparatively small PEG units used in this study, the PEGylation of A20FMDV2 seemed to result in an "enhanced permeation and retention" effect toward the BxPC-3 tumors along with some improved radiotracer stability (29). Positive effects of PEGylation on the in vivo stability of pharmaceuticals are generally recognized (28). Likewise, in our study, only one major radioactive metabolite was found in HPLC samples of pharmaceuticals collected 1 hour after injection of [18F]FBA-PEG28-A20FMDV2 or [18F]FBA-(PEG28)2-A20FMDV2, whereas the non-PEGylated analogue had yielded three equally large metabolite signals (22). However, because the cell-based assays showed very rapid binding (~25% of [18F]FBA-PEG28-A20FMDV2 bound to BxPC-3 within 1 minute; Fig. 3B) and significant, PEG-dependent internalization (approximately two thirds of bound activity were internalized at 1 hour; Fig. 3A), delivery efficiency to the target likely was of principal importance for these radiotracers, provided that radioactive metabolites were rapidly cleared from the body, as observed particularly for [18F]FBA-PEG28-A20FMDV2. Taken together, these data suggest that rapid binding and internalization of the PEGylated radiotracers in cells are key to increased uptake and retention in the tumors. That being said, a detailed characterization of metabolites and further modification of the radiotracers remain of interest. They include selective deletion of redundant amino acids and replacement with unnatural amino acids in conjunction with multimeric radiotracers and incorporation of branched PEG. These approaches have already been successful in improving the pharmacokinetics of tracers for integrin αvβ3 (28, 31, 32).
Paralleling the in vitro blocking studies with the $\alpha_v \beta_6$-expressing cell lines, in vivo blocking experiments using the nonradioactive analogues showed a significant reduction of uptake in the BxPC-3 tumors. Before the blocking experiments, the animals were also evaluated by $^{18}$F-FDG-PET, the standard radiotracer for PET imaging. Significantly, $^{18}$F-FDG failed in all animals to detect the BxPC-3 tumors. In the clinical setting, $^{18}$F-FDG is by far the most widely used PET radiotracer for the detection of many cancers, including pancreatic cancer, despite the risk of false positive (e.g., pancreatitis) or false negative (e.g., low GLUT-1 glucose transporter expression in tumor; hyperglycemic patient) diagnosis. Thus, our observation parallels findings from the clinical setting wherein $^{18}$F-FDG is estimated to miss over one third of all pancreatic malignancies (and about half of the lesions smaller than 1 cm; refs. 6, 8, 33).

Better understanding of the biology of pancreatic cancer (34) and improved early, more accurate diagnosis are sorely needed. By combining detailed anatomical information with functional metabolic information, $^{18}$F-FDG-PET/CT has shown some promise (5, 6, 8, 33). However, the use of $^{18}$F-FDG as radiotracer does not take advantage of the molecular biological differences of tumors beyond their increased (glucose) metabolism. The integrin $\alpha_v \beta_6$ is expressed strongly by most human pancreatic cancers (20) and is likely to be a prognostic indicator for this cancer. Therefore, it is clear that targeted in vivo imaging of $\alpha_v \beta_6$ will be a major improvement for preoperative staging and monitoring response to treatment for this lethal malignancy in humans. Using a metabolic probe ($^{18}$F-FDG) in conjunction with receptor-specific radiotracers in PET/CT could provide crucial additional information, particularly for occult disease. In a step

![Figure 5](image-url).
toward making this a clinical reality, we have shown that \(^{[18F]}\)FBA-PEG\(_{28}\)-A20FMDV2 holds promise for \(\alpha_3\beta_6\)-specific tumor imaging.

**Disclosure of Potential Conflicts of Interest**

No potential conflicts of interest were disclosed.

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**References**

Targeted In vivo Imaging of Integrin $\alpha$<SUP>VI</SUP>$\beta$<SUP>6</SUP> with an Improved Radiotracer and Its Relevance in a Pancreatic Tumor Model


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