Hepatocellular carcinoma (HCC) is a highly aggressive and lethal cancer. It is typically asymptomatic at the early stage, with only 10%–20% of HCC patients being diagnosed early enough for appropriate surgical treatment. The delayed diagnosis of HCC is associated with limited treatment options and much lower survival rates. Therefore, the early and accurate detection of HCC is crucial to improve its currently dismal prognosis. The epidermal growth factor receptor (EGFR) has been reported to be involved in HCC tumorigenesis and to represent an attractive target for HCC imaging and therapy. In this study, an affibody molecule, Ac-Cys-Z\textsubscript{EGFR}1907, targeting the extracellular domain of EGFR, was used for the first time to assess its potential to detect HCC xenografts. By evaluating radio- or fluorescent-labeled Ac-Cys-Z\textsubscript{EGFR}1907 as a probe for positron emission tomography (PET) or optical imaging of HCC, subcutaneous EGFR-positive HCC xenografts were found to be successfully imaged by the PET probe. Thus, affibody-based PET imaging of EGFR provides a promising approach for detecting HCC in vivo.

1. Introduction

Primary liver cancer, also known as hepatocellular carcinoma (HCC), is the fifth most common neoplasm and the third leading cause of cancer-related deaths worldwide [1–3]. Symptoms of HCC at early stage are usually atypical, and thus, HCC patients often present with symptoms at an advanced stage. Only 10%–20% of HCC are diagnosed early enough for appropriate surgical treatment [4–6]. The poor prognosis of this disease is largely due to the lack of effective and accurate early diagnostic methods, causing most patients to be diagnosed at the late stages, which seriously limits treatment options. Therefore, highly sensitive and accurate molecular imaging techniques that allow early HCC detection are urgently needed. Currently, the most commonly used positron emission tomography (PET) probe for tumor imaging is \textsuperscript{18}F-fluorodeoxyglucose (\textsuperscript{18}F-FDG). However, the use of \textsuperscript{18}F-FDG-PET in the detection of HCC is rather limited, and it was reported that \textsuperscript{18}F-FDG could even miss 30%–50% of HCC lesions in the liver [7]. Another PET probe commonly used for detection of HCC is \textsuperscript{11}C-labeled acetate, which was reported to show higher sensitivity than \textsuperscript{18}F-FDG [8, 9]. It plays a complementary role to \textsuperscript{18}F-FDG in both HCC cell lines and human HCC detection, being able to detect HCC tumors with low \textsuperscript{18}F-FDG uptake only. But similar as \textsuperscript{18}F-FDG, \textsuperscript{11}C-labeled acetate is a largely nonspecific probe for HCC imaging, as it typically enters the tricarboxylic acid cycle as a substrate for \(\beta\)-oxidation in fatty acid synthesis [10].
Development of molecular probes suitable for imaging other HCC-associated biomarkers is thus considered as a promising strategy whereas a largely unexplored field.

The contextual complexity of understanding HCC is defined by the functional involvement of several signaling cascades (epidermal growth factor, insulin-like growth factor, RAS, WNT-β-catenin, etc.) as well as multiple risk factors (such as hepatitis B and C viral infection and alcohol abuse) [1, 11, 12]. Among them, epidermal growth factor (EGF) signaling is one of the most thoroughly evaluated signaling cascades in human HCC development. EGF is demonstrated to control proliferation, differentiation, and cell survival and is overexpressed in a wide range of solid tumors including HCC [13, 14]. The growth factor receptor (EGFR) is a receptor tyrosine kinase that regulates a number of key processes, including cell proliferation and differentiation, tissue homeostasis, and tumorigenesis [15, 16]. Dysregulation of EGFR expression is associated with several key features of cancer, such as autonomous cell growth, apoptosis inhibition, invasion, and metastasis [17, 18]. Overexpression of EGFR has been frequently detected in a wide range of human tumors, including non-small-cell lung cancer, gastric cancer, breast cancer, as well as liver cancer [19]. In HCC, there is increasing evidence demonstrating a correlation between EGFR overexpression and tumor aggressiveness, metastasis formation, therapy resistance, and poor prognosis of this disease [15, 20–22]. Functional involvement of EGFR in HCC development was best demonstrated by the observation that EGFR inhibitor, Gefitinib, can significantly reduce HCC incidence in a genotoxic animal model of HCC [23]. Taken together, EGFR represents an attractive target for small molecules or antibodies in applications such as tumor-targeted imaging and therapy.

Several anti-EGFR affibody molecules (ZEGFR) with high affinities (in nanomolar range) have been reported recently. Among them, the affibody molecule, ZEGFR1907, has been shown to specifically bind EGFR with no cross-binding to other growth factor receptors [24], as well as fast tumor targeting and excellent tumor-to-normal tissue contrast on EGFR-expressing xenografted epithelial cancer models [25–29]. Affibody molecules are small (approximately 7 kDa), engineered proteins with 58-amino acid residues and a three-helix bundle scaffold structure [24, 30]. Its small molecular weight, high stability, high binding specificity, and affinity make it an excellent probe for tumor-targeted imaging in vivo [31, 32]. In this study, we hypothesized that EGFR targeted affibody probes can be promising molecular probes for HCC detection. Two types of affibody-based probes, 64Cu-DOTA-ZEGFR1907 for PET, and Alexa680-ZEGFR1907 for near-infrared fluorescent (NIRF) imaging (Figure 1), were evaluated and compared for molecular imaging of three type of HCC xenograft models. It is expected that the EGFR targeted NIRF probe can not only image HCCs noninvasively but also provides a tool for image-guided therapy, whereas the PET probe can find more broad applications for clinical cancer imaging.

2. Materials and Methods

2.1. Preparation of Affibody-Based Molecular Probes.

The affibody molecule Ac-Cys-ZEGFR1907 (Ac-CVDNKFNKEMWAAWEIRPLNLN GWQMTAFIA SLVDDPSQSANLAEAKKLNDQAAPK-NH₂) was synthesized and analyzed as previously described [25]. 1,4,7,10-Tetraazacyclododecane-1,4,7,10-tetraacetic acid mono-N hydroxysuccinimidide ester (DOTA-NHS ester) was obtained from Macrocyclics Inc. (Dallas, TX). Near-infrared fluorescent dye Alexa Fluor 680 C2 maleimide was purchased from Invitrogen LifeTechnologies (Carlsbad, CA).

The general procedure for the conjugation of maleimido-derivative DOTA and Alexa Fluor 680 C2 maleimide with Ac-Cys-ZEGFR1907 was performed as previously reported [25]. The purity and molecular mass of the resulting affibody derivatives, DOTA-ZEGFR1907 and Alexa680-ZEGFR1907,
were determined by analytical scale reverse phase high-performance liquid chromatography (RP-HPLC) and matrix-assisted laser desorption/ionization-time of flight mass spectrometry (MALDI-TOF-MS). $^{64}$CuCl$_2$ was purchased from the Department of Medical Physics, University of Wisconsin at Madison. $^{64}$Cu radiolabeling of DOTA-Z$_{EGFR,1907}$ was performed as reported previously [12].

2.2. Cell Culture and Animal Models. The human HCC cell lines HepG2, PLC/PRF/5, and Hep3B were purchased from American Type Culture Collection (ATCC) (Manassas, VA). PLC/PRF/5 and Hep3B cells were cultured in Dulbecco’s Modified Eagle’s Medium (DMEM), and HepG2 cells were cultured in ATCC-formulated Eagle’s Minimum Essential Medium (MEM), supplemented with 10% fetal bovine serum (FBS), and 1% penicillin-streptomycin (Invitrogen Life Technologies, Carlsbad, CA). All cell lines were maintained in a humidified atmosphere of 5% CO$_2$ at 37°C.

All animal studies were carried out in compliance with Federal and local institutional rules for the conduct of animal experiments. The animal protocol was approved by the Stanford University Administrative Panels on Laboratory Animal Care. In brief, male athymic nude (nu/nu) mice were obtained from Charles River Laboratories, Inc. (Cambridge, MA) at 4 weeks of age. To generate animal tumor models, approximately, $10^5$ HepG2 cells were injected subcutaneously into the upper left shoulder. On separate mice, approximately $5 \times 10^5$ of Hep3B or PLC/PRF/5 cells were injected into the upper right shoulder. Tumors were allowed to grow to a size of approximately 1.0 cm in largest diameter (3-4 weeks after inoculation), and tumor-bearing mice were subjected to in vivo imaging and biodistribution studies ($n = 3$ for each tumor models).

2.3. Quantitative Real-Time PCR. Total RNA was extracted from human HCC cell lines using the RNeasy mini kit (Qiagen, Valencia, CA). First-strand cDNA was generated using Taqman Reverse Transcription Reagent with random primers. Quantitative real-time PCR assays were performed using Taqman EGFR gene expression assay and Universal PCR Master Reagent in a Stratagene MX3000P Q-PCR system (Stratagene, La Jolla, CA). The EGFR expression level was assessed in terms of threshold cycle value using Stratagene MxPro software and normalized to the internal level was assessed in terms of threshold cycle value using system (Stratagene, La Jolla, CA). The EGFR expression was performed using a microPET R4 rodent-model scanner (Siemens Medical Solutions USA, Knoxville, TN). Imaging studies were conducted at 1, 2, 4, and 24 h after tail vein injection of $\sim 3.7$ MBq ($\sim 100 \mu$Ci) $^{64}$Cu-DOTA-Z$_{EGFR,1907}$ with or without coinjection of 300 $\mu$g of nonradioactive (blocking) Ac-Cys-Z$_{EGFR,1907}$. At different time points after injection, the mice were anesthetized with 2% isoflurane and placed in the prone position near the center of the field of view of

2.5. Fluorescence Microscopy. Hep3B, PLC/PRF/5, and HepG2 cells were seeded onto cover slips approximately 24 h prior to the experiment. Staining using EGFR polyclonal antibody was performed at 1:500 dilution and AlexaFlour 660 goat anti-rabbit IgG (H + L) (Invitrogen Life Technologies, Carlsbad, CA). For staining using Alexa680-Z$_{EGFR,1907}$-labelled conjugates, cover slips were washed with PBS and then incubated with Alexa680-Z$_{EGFR,1907}$ (100 nM) at 37°C for 1 h in the dark. The EGFR-binding specificity of Alexa680-Z$_{EGFR,1907}$ in cells was verified by coinubcation with or without large excess of blocking dose of nonfluorescent-labeled Ac-Cys-Z$_{EGFR,1907}$ peptide (10 $\mu$M). Stained slides were imaged using the Talamasca 2P confocal microscope (Zeiss LSM510, Thornwood, NY) on the same day using 40x oil immersion lens.

For immunohistochemistry (IHC) on subcutaneous xenograft tumors, tissue treatment and fixation were performed by the Department of Surgical Pathology, Stanford University. IHC staining of EGFR was performed using polyclonal EGFR antibodies (Ab2430, Abcam, Cambridge, MA) at 1:500 dilution and DAKO Envision Plus Kit (Dako, Carpinteria, CA). For immunofluorescence on human tissue microarrays, 100 nM of Alexa680-Z$_{EGFR,1907}$ was incubated with the slides for 1 h in the dark. Stained slides were imaged using Talamasca 2P confocal microscope on the same day.

2.6. Optical Imaging and Image Analysis. In vivo optical imaging was performed with an IVIS 200 small animal imaging system (Caliper, Alameda, California). A filter set (excitation 615 to 655 nm; emission 695 to 770 nm) was used for acquiring Alexa680-Z$_{EGFR,1907}$ fluorescence in vivo. Identical illumination settings were used to acquire all images, and fluorescence emission was normalized to photons per second per centimeter squared per steradian (p/sec/cm$^2$/sr). Images were analyzed using Living Image 3.0 software (Caliper, Alameda, CA). A prescan image before injection was acquired to eliminate autofluorescence. Mice ($n = 3$) were injected with 500 pmol of Alexa680-Z$_{EGFR,1907}$ via tail vein and subjected to optical imaging at 0.5, 1, 2, 4, and 24 h post injection (p.i.). For blocking experiments, mice ($n = 3$) were injected with a mixture of 300 $\mu$g nonfluorescent Ac-Cys-Z$_{EGFR,1907}$ and 500 pmol of Alexa680-Z$_{EGFR,1907}$. IVIS-200 NIR fluorescent images were acquired using a 1 s exposure time. After the final scan at 24 h p.i., animals were euthanized and imaged ex vivo. Tumor and other major tissues were dissected out and fluorescence images acquired to obtain the mean fluorescence value (p/sec/cm$^2$/sr) for each sample.

2.7. Small Animal PET, Biodistribution, and Image Analysis. Small animal PET of tumor-bearing mice ($n = 3$ each group) was performed using a microPET R4 rodent-model scanner (Siemens Medical Solutions USA, Knoxville, TN). Imaging studies were conducted at 1, 2, 4, and 24 h after tail vein injection of $\sim 3.7$ MBq ($\sim 100 \mu$Ci) $^{64}$Cu-DOTA-Z$_{EGFR,1907}$ with or without coinjection of 300 $\mu$g of nonradioactive (blocking) Ac-Cys-Z$_{EGFR,1907}$. At different time points after injection, the mice were anesthetized with 2% isoflurane and placed in the prone position near the center of the field of view of
3. Results

3.1. Characterization of Human HCC Cell Lines. To assess the endogenous EGFR expression in human HCC cell lines, we first detected EGFR protein level by Western blotting in a panel of three human HCC cell lines (Hep3B, PLC/PRF/5, and HepG2). Among these cell lines, Hep3B cells have the highest level of EGFR expression, PLC/PRF/5 cells have moderate level of EGFR expression, whereas HepG2 cells have undetectable EGFR expression (Figure 2(a)). The varying levels of EGFR expression in these cell lines were confirmed by quantitative real-time PCR (Figure 2(b)). Immunohistochemistry using polyclonal anti-EGFR antibody also showed highest level of EGFR staining in Hep3B cells, moderate level of EGFR staining in PLC/PRF/5 cells, and absence of EGFR staining in HepG2 cells (Figure 2(c)).

To demonstrate the EGFR binding specificity and subcellular localization of the fluorescently labeled affibody, Alexa680-Z\textsubscript{EGFR,1907}, in HCC cells, immunofluorescence staining was done in Hep3B, PLC/PRF/5, and HepG2 cells. Fluorescence signal was observed mainly on the cell surface of Hep3B cells (Figure 2(d)), consistent with the fact that this probe was designed to primarily target the extracellular domain of EGFR [24]. Furthermore, the fluorescence signal from the Hep3B cells could be significantly reduced by incubation with large excess (10 \(\mu\)M) of the unlabeled Ac-Cys-Z\textsubscript{EGFR,1907}, indicating binding specificity of the probe. In PLC/PRF/5 cells, reduced fluorescence signals were detected, consistent with the lower level of EGFR expression in these cells. Coincubation of PLC/PRF/5 cells with large excess (10 \(\mu\)M) of unlabeled Ac-Cys-Z\textsubscript{EGFR,1907} resulted in loss of positive signals, again demonstrating binding specificity.
3. EGFR Expression in HCC Xenografts. Based on the previous results, HCC mice xenografts with Hep3B, PLC/PRF/5, and HepG2 cells were generated to represent HCC tumors with high-, moderate-, and no-EGFR expression, respectively, for subsequent imaging studies. The subcutaneous xenografts (n = 3 for each tumor model) were harvested for assessment of EGFR protein expression. Immunofluorescence using Alexa680-ZEGFR<sub>1907</sub> showed that Hep3B and PLC/PRF/5 xenografts express high levels of EGFR expression, whereas HepG2 xenografts showed no detectable EGFR expression (Figure 3(a)). Immunohistochemistry of paraffin-embedded tissue sections from Hep3B, PLC/PRF/5, and HepG2 xenografts showed that Hep3B xenografts have extensive staining of EGFR, whereas PLC/PRF/5 xenografts showed regional positive staining, and HepG2 tumor did not show any positive regions (Figure 3(b)). Visual inspection of tumor xenografts revealed that Hep3B and HepG2 are highly vascularized, and both tumor samples showed much darker color than that of PLC/PRF/5 tumors (Figure 3(c)).

3.3. In Vivo and Ex Vivo Tumor Targeting by Optical Imaging. After demonstrating the specific binding of Alexa680-ZEGFR<sub>1907</sub> toward EGFR in both in vitro cell culture and in vivo xenografts of human HCC cell lines, this fluorescent affinity probe was used for optical imaging of nude mice bearing subcutaneous Hep3B, PLC/PRF/5, or HepG2 xenografts. The PLC/PRF/5 xenografts could be clearly distinguished from the surrounding background tissue from prescan, 1 h to 4 h p.i. (Figure 4(a)). Based on quantification analysis of region-of-interest (ROI), PLC/PRF/5 tumor accumulations are significant higher than those of normal tissues at 0.5, 1, 2, and 4 h (P < 0.001, resp.) (Figure 4(b) left), with tumor-to-normal tissue ratio reaching a peak around 1.60 at 1 h p.i. (Figure 4(b) right). Minimum fluorescent signals were detected in the HepG2 xenografts which are EGFR negative. Even though Hep3B xenografts express reasonably high levels of EGFR (Figure 3), only very weak fluorescent signals could be detected. All xenografts from imaged mice (n = 3 for each groups) were harvested for assessment of EGFR expression by Western blotting, which showed high levels of EGF expression in Hep3B and PLC/PRF/5 tumors but undetectable EGFR expression in HepG2 tumors (Figure 4(c)).

Receptor specificity of the Alexa680-ZEGFR<sub>1907</sub> probe was further verified by blocking experiments in mice bearing PLC/PRF/5 xenografts. After coinjection of a large excess of nonfluorescent Ac-Cys-ZEGFR<sub>1907</sub>, tumor as well as overall uptake was significantly reduced at 2h and 4h p.i. (Figure 4(d)). Tumor-to-background contrasts as quantified by ROI analysis of images at 2 h and 4 h p.i. are shown in Figure 4(e). Significant differences (P < 0.05) between the ratios for blocking and nonblock group at both time points were observed.

After the final scan at 24 h p.i., animals were euthanized and ex vivo fluorescence imaging on tumor and major organs were performed (Figure 4(f)). Quantitative analysis showed that PLC/PRF/5 tumors have much stronger fluorescence signals than HepG2 tumor, and that a significant level of signal remained in the liver and kidney. The stomach and intestine also showed some level of probe accumulation.

3.4. Small Animal PET of HCC. Ac-Cys-ZEGFR<sub>1907</sub> was also conjugated with DOTA and radiolabeled with 64Cu for PET of HCC small animal models. Decay-corrected coronal PET images of mice bearing Hep3B and PLC/PRF/5 tumors at 1, 2, 4, and 24 h after tail vein injection of 64Cu-DOTA-ZEGFR<sub>1907</sub> are shown (Figure 5(a)). Hep3B xenografts, which express high levels of EGFR, were clearly visualized starting at 1 h p.i., with the excellent tumor imaging quality at later time points (4 and 24 h p.i.). PLC/PRF/5 xenografts, which express low levels of EGFR, also showed distinct tumor accumulation, with clear tumor imaging and high tumor-to-background ratios at 4 and 24 h p.i. (Figures 5(a) and 5(b)). Quantification analysis showed that the PET probe uptake into both Hep3B and PLC/PRF/5 xenografts increased with time (Figure 5(c)), with the highest tumor uptakes for Hep3B and PLC/PRF/5 xenografts occurring at 24 h p.i. (8.52 ± 1.10% and 6.46 ± 0.59%, resp.). In addition to the tumor, high radioactivity accumulations were also observed in the liver of mice bearing...
Figure 4: Continued.
either xenografts. The level of liver accumulation, however, decreased with time (from 26.19 ± 2.89% at 1 h p.i. to 16.04 ± 1.19% at 24 h p.i. in mice bearing Hep3B xenografts, and from 16.79 ± 1.64% at 1 h p.i. to 12.89 ± 0.69% at 24 h p.i. in mice bearing PLC/PRF/5 xenografts) (Figure 5(c)).

Figure 4: Optical Imaging and quantification. (a) In vivo fluorescence imaging of subcutaneous PLC/PRF/5 (labeled as PLC5 in the figure), Hep3B, and HepG2 tumor-bearing nude mice at prescan, 1 h, 2 h, 4 h, and 24 h p.i. Approximately 500 pmol Alex680-ZEGFR$_{1907}$ was injected. Arrows indicate the location of tumors. (b) ROI analysis of tumor and normal tissue (muscle) fluorescence flux and tumor-to-muscle ratio after tail vein injection of Alex680-ZEGFR$_{1907}$ in mice bearing PLC/PRF/5 tumor ($n = 3$). (c) Protein extractions from subcutaneous tumor tissues were harvested and assessed for EGFR expression. Bands for EGFR and β-actin are indicated by arrowheads. Protein ladders are indicated in kDa. (d) Contrast of in vivo fluorescence imaging of subcutaneous PLC/PRF/5 tumor-bearing nude mice at 2 h and 4 h. Alex680-ZEGFR$_{1907}$ with (right) or without (left) coinjection of unlabeled Ac-Cys-ZEGFR$_{1907}$ (300 μg). (e) Fluorescence intensity ratio of tumor to muscle in blocking and unblocking PLC/PRF/5 tumor-bearing nude mice at 2 h and 4 h p.i. (f) Ex vivo imaging of tumor and normal tissues of PLC/PRF/5 tumor-bearing animals injected with Alex680-ZEGFR$_{1907}$ and sacrificed at 24 h p.i.. Tm: tumor; H: heart; L: lung; Lv: liver; Sp: spleen; Kn: kidney; St: stomach; Ins: intestine; Br: brain; Bo: bone; Ms: muscle.

When a large excess of nonlabeled affibody was coinjected with $^{64}$Cu-DOTA-ZEGFR$_{1907}$ in mice bearing PLC/PRF/5 xenografts, the overall uptake of $^{64}$Cu-DOTA-ZEGFR$_{1907}$ was significantly decreased, and the xenografts were barely visible by PET at all time points (Figure 5(a)).
Figure 5: Small-animal PET and quantification analysis. (a) Small animal PET imaging of tumor-bearing mice at 1h, 2h, 4h, and 24h after tail vein injection of 110 μCi of $^{64}$Cu-DOTA-ZEGFR. Representative decay-corrected coronal PET images were shown on different tumor-bearing animals, including Hep3B, PLC/PRF/5, and PLC/PRF/5 with blocking dose of unlabeled Ac-Cys-ZEGFR. Arrows indicate the location of tumors. (b) Quantification analysis of tumor-to-normal organ ratio in Hep3B and PLC/PRF/5 tumor-bearing mice, respectively, at 1h, 2h, 4h and 24h after tail vein injection. (c) Quantification analysis of tumor or liver uptake of $^{64}$Cu-DOTA-ZEGFR in PLC/PRF/5 tumor models (represented as PLC5 in Figure) and Hep3B tumor models at different time points after injection of the PET probe. (d) Quantification analysis of the probe accumulation in PLC/PRF/5 tumor with (represent as time point B) or without coinjection of unlabeled Ac-Cys-ZEGFR at 1h, 2h, 4h, and 24h p.i.

Quantification analysis of PET images showed much lower tumor as well as liver uptake at all time points ($P < 0.05$, Figure 5(d)), suggesting successful blocking by the nonlabeled affibody and implying the high specificity of $^{64}$Cu-DOTA-ZEGFR for EGFR.

To further validate the PET tumor imaging study, biodistribution analysis was done after the final PET scan at 24 h p.i. Biodistribution patterns of $^{64}$Cu-DOTA-ZEGFR in the tumor, liver, and kidney of mice bearing Hep3B and PLC/PRF/5 xenografts were similar (Figure 6(a)). High kidney and liver uptakes and moderate tumor uptakes were observed. The tumor-to-normal tissue ratios, including tumor/blood and tumor/muscle ratios, were not significantly different between the two tumor models (Figure 6(b)). Blocking experiment using coinjection of a large excess of Ac-Cys-ZEGFR caused a significant decrease in overall uptake of $^{64}$Cu-DOTA-ZEGFR (Figure 6(c)). The probe uptake in the PLC/PRF/5 xenograft dropped significantly from 7.84 ± 0.43% to 3.39 ± 1.25% ($P < 0.05$), whereas the radioactivity uptake in the liver dropped significantly from 18.20 ± 2.73% to
7.9 ± 2.11% (P < 0.05). Radioactivity uptakes in the kidneys were unaffected by blocking.

**4. Discussion**

Our study reports the first use of an engineered, EGFR-targeted affibody molecule, Ac-Cys-ZEGFR:1907, as a probe for the detection of human HCC lesions. Affibody molecules are small scaffold proteins that have recently emerged as a promising platform for molecular imaging and therapy in oncology. Several anti-EGFR affibodies with high binding affinity and specificity have been reported [24, 31]. Among them, Ac-Cys-ZEGFR:1907 showed high specific binding to EGFR without cross-binding to other EGFR isoforms [24]. Earlier studies have reported the high tumor-specific uptake and good tumor-to-background ratio of the ZEGFR:1907 affibody in EGFR-expressing A431 tumor xenografts using optical and PET imaging modalities [25]. High EGFR expression in a subset of HCC suggests that Ac-Cys-ZEGFR:1907 may also be useful for the detection of HCC.

Indeed, fluorescently labeled Ac-Cys-ZEGFR:1907 was able to specifically bind to and identify endogenous EGFR protein expressed in human HCC cell lines in vitro. Additionally, the expression of EGFR in subcutaneous xenografts generated from these cell lines corresponded with their expression in vitro, suggesting that Alexa680-ZEGFR:1907 could be used...
for detecting HCC xenografts derived from these cell lines. Surprisingly, when Alexa680-ZEGFR based PET imaging of HCC xenografts, only PLC/PRF/5 tumors could be clearly visualized. Xenografts from Hep3B cells, which express even higher EGFR levels than that of PLC/PRF/5 tumors, could not be delineated. This observation reveals a limitation of optical imaging, in that fluorescence signals may be blocked and/or absorbed by tumor tissues enriched with blood vessels, such as Hep3B xenografts (Figure 3(c)). However, when Ac-Cys-ZEGFR based PET probe, Cu-DOTA-ZEGFR, was used, both Hep3B and PLC/PRF/5 xenografts could be clearly imaged. The targeting specificity of the both optical and PET probes was further confirmed by coinjection of nonlabeled Ac-Cys-ZEGFR into mice bearing EGFR-positive tumors. Furthermore, Cu-DOTA-ZEGFR was found to have good PET imaging quality and very similar biodistribution patterns in animals bearing Hep3B and PLC/PRF/5 xenografts. Therefore, PET imaging using Cu-DOTA-ZEGFR to target EGFR may be more useful than optical imaging using Alexa680-ZEGFR in detecting the heterogeneous subtypes of HCC tumors.

During the course of our study, Sogawa et al. reported the use of a novel human monoclonal antibody against EGFR for HCC imaging [34], confirming the value of EGFR-based diagnostic imaging of HCC and highlighting the challenge of detecting HCC tumors in vivo. Since the liver is the major organ for drug/reagent clearance and metabolism, it can take up and even retain large amounts of imaging agents, giving rise to high background signals. Even though the enhanced permeability and retention (EPR) effect of the tumor (due to the leaky vasculature and lack of lymphatic drainage in the tumor) or receptor-mediated targeted uptake of imaging agents may facilitate probe accumulation in the tumor over other tissues [35], the liver background for nonspecific probe accumulation can still be high. Reducing the nonspecific liver accumulation continues to be a major obstacle in HCC imaging. Our previous studies and reports by other groups have found that affibodies were mainly cleared through the kidneys which showed high renal accumulation, with relatively lower liver uptake [24, 33, 36, 37]. Thus, it is advantageous to use affibody-based probes to image biomarkers expressed in HCC because of the preferred renal clearance. Our current data confirmed the higher renal uptakes of both affibody probes, although liver accumulations could also be detected (likely caused by the expression of basal levels of EGFR in normal liver tissue [38]). In PET quantitative analysis of Cu-DOTA-ZEGFR in both Hep3B and PLC/PRF/5 xenografts, probe uptake in the xenografts increased over time, while the uptake in normal liver decreased over time. Thus, it is reasonable to propose that introduction of a longer half-life radionuclide, which will allow imaging at later time points, may enhance the tumor-to-liver ratios, making it more clinically useful [39].

5. Conclusion

We have successfully demonstrated that EGFR-expressing HCC lesions can be specifically detected by using the EGFR-targeted affibody Ac-Cys-ZEGFR. In particular, in vivo PET imaging based on a modified version of this affibody appears to have greater diagnostic value than optical imaging based on the same affibody. The early and sensitive detection of HCC based on molecular cancer markers, such as EGFR, is a critical step in improving the currently dismal prognosis of HCC patients.

Conflict of Interests

The authors declare no conflict financial of interests.

Authors’ Contribution

Ping Zhao and Xiaoyang Yang contributed equally to this work.

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