Journal of Nuclear Medicine, published on December 3, 2015 as doi:10.2967/jnumed.115.164384

c-Met PET Imaging Detects Early Stage Loco-Regional Recurrence of Basal-Like Breast Cancer

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Short running title:

cMet imaging of loco-regional recurrence

ABSTRACT

Loco-regional recurrence of breast cancer poses significant clinical problems due to frequent inoperability once the chest wall is involved. Early detection of recurrence by molecular imaging agents against therapeutically targetable receptors, such as c-Met, would be of potential benefit. The aim of this study was to assess [^{18}F]AH113804,a peptide-based molecular imaging agent with high affinity for human c-Met, for the detection of early-stage loco-regional recurrence in a human basal-like breast cancer model, HCC1954. **Methods:** HCC1954 tumor-bearing xenograft models were established, and [^{18}F]AH113804 was administered. Distribution of radioactivity was determined via positron emission tomography (PET) at 60 min post radiotracer injection. PET and CT (computerized tomography) images were acquired 10 days after tumor inoculation, to establish baseline distribution and uptake, and then on selected days after surgical tumor resection. CT images and caliper were used to determine the tumor volume. Radiotracer uptake was assessed by [^{18}F]AH113804 PET imaging. c-Met expression was assessed by immunofluorescence imaging of tumor samples and correlated with [^{18}F]AH113804 PET imaging results. **Results:** Baseline uptake of [^{18}F]AH113804, determined in tumor-bearing animals after 10 days, was approximately 2-fold higher in the tumor as compared to muscle tissue or the contralateral mammary fat pad. The tumor growth rate, determined from CT images, was comparable between the animals with recurrent tumors, with detection of tumors of low volume (<10 mm^3) only possible by Day 20 post tumor resection. [^{18}F]AH113804 PET detected local tumor recurrence as early as six days after surgery in the recurrent tumor-bearing animals, and exhibited significantly higher [^{18}F]AH113804 uptake (in comparison to mammary fatty tissue) with a target to background (muscle) ratio of approximately 3:1 (p<0.01). The c-Met expression of individual resected tumor samples, determined by immunofluorescence, correlated with the respective [^{18}F]AH113804 imaging signals (r=0.82; p<0.05). **Conclusion:** [^{18}F]AH113804 PET provides a new diagnostic tool for the detection of c-Met-expressing primary tumor and has potential utility for the detection of loco-regional recurrence from an early stage.

Keywords

PET/CT imaging, basal-like breast cancer, HCC1954, c-Met, AH113804, cancer, loco-regional recurrence

INTRODUCTION

The proto-oncogene c-Met is a receptor tyrosine kinase activated by the ligand hepatocyte growth factor (HGF). The HGF/c-Met signaling axis has been described as a promoter of cancer cell growth, angiogenesis, invasion and metastasis (*1*). Overexpression of c-Met is associated with poor prognosis and a more malignant tumor phenotype (*2,3*). Several c-Met inhibitors are currently under evaluation in clinical trials, either as stand-alone therapies or in concomitant treatment (*4*). c-Met is overexpressed in various solid tumors (*5*), including breast cancer (BC), with higher expression in Basal-like Breast Cancer (BLBC) than in other intrinsic cancer subtypes (*6*) . BLBC, which accounts for up to 15% of all BCs, exhibits a high rate of loco-regional recurrence after initial therapy (*7-10*).

Although treatment of localized disease has improved over the past decades, up to 45% of BC patients suffer a local, regional or systemic relapse within 8 years after initial therapy (*8*). While systemic relapse in the form of distant metastasis is still regarded as incurable according to current treatment guidelines, loco-regional recurrence of BC should be treated with curative intention (*11*). Treatment success crucially depends on the earliest possible diagnosis, before chest wall involvement or further organ invasion prevents any form of aggressive treatment (*12*). Established guidelines for post-therapy monitoring in BLBC feature mammography and clinical examination which frequently fail to identify local tumor relapse at a sufficiently early stage (*13*).

Magnetic resonance imaging (MRI) and FDG-PET/CT offer a comparably higher sensitivity and specificity for detection and characterization of BC relapse (*14*). However, differentiation of recurrent BC from inflammatory or infectious processes, and the identification of small lesions (tumor size <20 mm) still impose challenges for FDG-PET (*15,16*). c-Met targeted imaging could provide such a tool to further improve the performance of post-treatment surveillance, and could aid patient stratification for targeted therapy.

For this study we chose the novel, peptide-based molecular imaging agent [^{18}F]AH113804 (Fig 1A) which binds to human c-Met with high affinity (*K*d≈2 nM), has a favorable kinetic profile, exhibits specific uptake in c-Met positive tumor tissue and rapid systemic clearance (*17*). This enables for diagnostic PET imaging as early as one hour after administration (*17*). The safety, pharmacokinetics and imaging characteristics have all been assessed using GE-137, the fluorescent-labelled analogue of

AH113804, in healthy volunteers and in patients at high risk of colorectal neoplasia (*17*).These initial studies in humans suggested that GE-137 was safe, and that it may improve visualization of colonic polyps, which display a high level for c-Met (*17*).

In this study, we assessed [^{18}F]AH113804-driven PET for the early detection of loco-regional tumor recurrence in a preclinical model of BLBC.

MATERIALS AND METHODS

Cell culture

Human basal-like subtype breast cancer cells HCC1954 (CRL-2338) were obtained from the American Type Culture Collection and cultured in RPMI 1640 (Invitrogen) with 10% fetal calf serum (Bodinco BV) and 2 mM L-glutamine (Invitrogen) at 37 °C in a fully humidified atmosphere containing 5% CO_2.

Western blotting

Immunoblotting was performed as described in ref (*18*). Detection of bound antibody was with horseradish peroxidase-conjugated secondary antibodies and enhanced chemiluminescence (ThermoScientifc Fisher) with G-Box, Syngene.

Tumor xenograft model

All animal studies were performed in compliance with the UK Home Office Animals (Scientific Procedures) Act 1986. Female SCID (Severely Immunodeficient) mice (17 to 19 g at time of first procedure, Charles River UK) were subcutaneously injected with 4×10^6 cells in 0.1 mL of a 1:1 mixture of medium and Matrigel (BD Biosciences) in the second right mammary fat pad. Tumor size was measured twice per week by caliper. The volume for the tumor was estimated as length*width^2/2. Further details on the tumor xenograft model are given in the Supplementary Methods.

Radiosynthesis of [^{18}F]AH113804

Synthesis of the peptide is described in the supplementary section of ref (*17*). Details of the radiosynthesis of [^{18}F]AH113804 are given in the Supplementary Methods.

CT and PET imaging

Small-animal PET/CT imaging was performed using microPET P4 (Concorde) and microCAT II (ImTek Inc.) systems as described earlier (*19*). Each animal was injected intravenously (iv) with approximately 7 MBq (0.1 mL) [^{18}F]AH113804. Further details of the imaging procedure are given in the Supplementary Methods.

Tumor and contralateral mammary fat pad uptake are presented as target-to-muscle retention ratio (TMRR). Further details are given in the Supplementary Methods.

Ex vivo tissue analyses

Details of all ex vivo tissue analyses are given in the Supplementary Methods. These include histology of formalin-fixed, paraffin-embedded tumor and quadriceps muscle, and [^{18}F]AH113804 autoradiography and immunofluorescence staining of snap-frozen tumor tissue.

Statistical analysis

Unless otherwise stated, group averaged data are presented as mean ± standard error of the mean (SEM). The observed skewed distribution of TMRR measures was lessened by logarithmic transformation, see Supplementary Methods. All statistical analyses were performed in R version 3.1.2 (R Project for Statistical Computing, Vienna, Austria).

RESULTS

Synthesis of [^{18}F]AH113804

Total synthesis time on the automated platform was 49 min. For all synthesis runs, the decay corrected end-of-synthesis yield was between 38 and 41%, with a radioactive concentration (RAC) between 600 and 800 MBq/mL. The radiochemical purity was always >90%, the chemical content between 15 and 20 µg/mL, and specific activity approximately 100 GBq/µmol for each test item.

c-Met expression level in HCC1954

Human c-Met protein expression level was assessed in HCC1954, compared to HT-29 (high c-Met expressing) and U87 (moderate c-Met expressing) cell line lysates. The data shows upregulation of c-Met in the HCC1954 cell line (Suppl Fig 1). Burggraff *et al*. assessed the specificity of GE-137, performing a competition study in HT-29 tumor bearing mice which showed a reduction in tumor uptake of GE-137 when co-administrated with an excess of unlabeled peptide (*17*).

Tumor targeting of [^{18}F]AH113804

Baseline uptake of [^{18}F]AH113804 (Fig 1A) was assessed in 8 tumor-bearing animals using PET imaging at 10 days post tumor inoculation (Fig. 1B). Levels of radioactivity at 60 minutes pi were 4.9±0.6% ID/mL in kidney, 2.9±0.3% ID/mL in liver, and 2.0±0.2% ID/mL in blood. PET imaging (Fig 1C) revealed a significant difference between the uptake of [^{18}F]AH113804 at the tumor site (1.5±0.2% ID/mL, white arrowhead) compared to both contralateral mammary fat pad (0.8±0.1% ID/mL, blue arrowhead) and muscle (0.8±0.1% ID/mL) at 60 minutes p.i. *Ex vivo* biodistribution studies, following PET imaging on Day 50 post tumor resection, confirmed [^{18}F]AH113804 accumulation in tumor was significantly higher compared to muscle (2.5±0.6% ID/g *vs*. 0.9±0.2%ID/g at 70 min pi, n=3. p<0.05. Suppl Fig 2).

Early-stage recurrent tumor growth is first detected with [^{18}F]AH113804, later by CT, and last by palpation

Following tumor resection 14 to 16 days after inoculation, 5 animals were found to exhibit recurrent tumor growth, confirmed by necropsy after final imaging. The remaining 3 animals did not exhibit any tumor re-growth (by caliper measurements). However, there was lack of correlation between tumor size by caliper and uptake of the tracer at the tumor site (Suppl Fig. 3). Tissue from the site of injection for one of the non-recurrent mice was stained. Negativity for tumor cells and human c-Met expression by IHC was confirmed (Suppl Fig. 4). In this case, the %ID/g in the ROI was 0.6 (c.f. the %ID/g at the contralateral site was 0.5).

Analysis of [^{18}F]AH113804 PET images provided evidence for the presence of loco-regional recurrence from Day 6 post-resection in these 5 animals (Figure 2A). There was some degree of variation in the uptake of radioactivity at the tumor site in individual animals on each study day (Suppl Table 1). However, overall uptake on each day was comparable to that observed in the tumors pre-resection. The TMRR was significantly higher at the tumor resection site in comparison to the contralateral mammary fat pad on Day 6 (2.7±0.3 *vs*. 1.0±0.3, $p<0.001$; n=5; Fig 2B). Uptake of [^{18}F]AH113804 at the site of resection remained clearly visible in the PET images on subsequent days, with the TMRR significantly smaller in the contralateral mammary fat pad on Day 13 (1.6±0.2 vs 0.9±0.2, $p<0.01$), Day 20 (1.6±0.1 vs 0.9±0.2, $p<0.001$) and Day 36 (1.5±0.8 vs 0.9±0.2, $p<0.01$). At Day 50 post tumor resection, the TMRR was also higher for the tumor site (1.7±0.7) than for the contralateral mammary fat pad (1.0±0.0), although this difference was not statistically significant. No specific [^{18}F]AH113804 retention was detected in the contralateral mammary fat pad with levels of radioactivity in this region comparable to muscle tissue for all time points (Suppl Fig 5).

By Day 20 post tumor resection, the mean tumor volume determined by CT measurement was approximately 7.0±12.5 mm^3 (Fig 3A&B). Palpable tumor recurrence was detected from Day 29 post tumor resection (Fig 3A).

[^{18}F]AH113804 retention in tumor tissue versus systemic clearance

Systemic clearance of [^{18}F]AH113804 was studied in selected tumor-bearing mice over the first 60 min pi by dynamic PET imaging. Figure 4A shows the distribution of [^{18}F]AH113804 at 15 min (13-18 min) and 60 min (55-65 min) p.i. A decrease in [^{18}F]AH113804 signal is observed in the major perfused organs, and retention of [^{18}F]AH113804 at the tumor site (Fig 4B).

Figure 4C displays the change in TMRR from 5 min to 60 min pi in relation to TMRR at 5 min p.i. While the tumor TMRR continuously increased, TMRRs for lungs, liver, heart and others decreased.

Autoradiography and immunohistochemical analysis confirm [^{18}F]AH113804 accumulation in c-Met positive tumor tissues

A heterogeneous pattern of [^{18}F]AH113804 distribution was observed within the tumor, with viable tissue in the tumor periphery exhibiting a positive signal while the central tumor regions exhibited only low activity (Figure 5A). H&E staining and immunohistochemistry of consecutive tumor slides revealed a large number of c-Met positive tumor cells (Figure 5B, left and right panels respectively). Both recurrent and primary tumors showed necrotic areas in H&E devoid also of c-Met (IHC) and displaying low [^{18}F]AH113804 uptake (Suppl. Fig 6&7).

***Ex vivo* histology correlates with the PET images**

Following immunofluorescent staining (Figure 6A), c-Met expression levels were quantified across whole tumor slides (Figure 6B).A significant correlation was found between c-Met expression and *in vivo* PET (r =0.82, p=0.023. n=7), suggesting [^{18}F]AH113804 signal in tumor at 60 min pi to be representative of c-Met expression. A similar correlation was observed between c-Met expression determined by IHC and [^{18}F]AH113804 signal *in vivo* (r=0.83, p=0.0015) (Suppl Fig 8).

In addition, it was found that the variation in the c-Met expression levels observed across the tumor samples (displayed in Fig 6B) was due to the tumor size. Indeed, a correlation (r = 0.83; p = 0.0005) was identified between the total c-Met intensity level and the surface area of the tumor sample (Suppl. Fig 9).

DISCUSSION

Early detection and identification of tumor relapse enables improved loco-regional recurrence control resulting in an increased quality of life and better overall survival for BC patients (*20*). Current surveillance guidelines have been shown to be less effective in the detection of loco-regional recurrence than the more expensive, yet more sensitive, approaches such as MRI or radionuclide imaging (Single-photon emission computed tomography, PET) (*13,14*). It is believed that either individually, or as a companion test for established diagnostic approaches, targeted molecular imaging of specific tumor markers bears the potential to positively change BC follow-up; especially in patients presenting with a high risk of relapse such as BLBC patients (*20,21*).

[^{18}F]AH113804 is known to have a high affinity for human c-Met, as demonstrated in studies by Evans *et al*., where the *in vivo* affinity of [^{18}F]AH113804 was determined via receptor blocking in HT-29 xenograft tumour mouse models (*22*) . [^{18}F]AH113804 clears fast from plasma and non-target tissues (such as liver, lungs and heart), allowing for high contrast imaging after injection, and improving the sensitivity for tumor detection, as confirmed by PET imaging in this study.

Our study shows that [^{18}F]AH113804-driven PET imaging allowed for early detection of loco-regional tumor recurrence in HCC1954 tumor-bearing mice after surgery. [^{18}F]AH113804 uptake and retention in the lungs and heart, reflecting the non-specific blood pool distribution of [^{18}F]AH113804 decreased constantly over the observation period. In contrast, a constant signal was observed within the region of tumor regrowth, indicative of specific accumulation of [^{18}F]AH113804 due to target binding. [^{18}F]AH113804 allows for excellent tissue penetration, and the *in vivo* PET imaging revealed satisfactory tumor to non-target (muscle) tissue ratio from one hour p.i.

We were able to detect statistically significant differences in tumor uptake compared to contralateral mammary fat pad at Days 6, 13, 20 and 36 after tumor resection. The lack of statistical significance at the latter timepoints is most likely due to the lower, inhomogenous distribution of radioactivity in the tumors. PET images from some of those recurrent tumor bearing animals (images not shown) showed evidence of peripheral uptake only, indicative of necrosis in the tumor core.

Currently [^{18}F]FDG is used in PET diagnostics for detection and staging in cancer. Numerous studies have revealed that other, more target-specific tracers would be beneficial for the detection of loco-regional recurrence (*23*). In a study of patients with breast cancer, it was shown that tumour size was an important factor when correctly diagnosing patients (*24*). A review of 111 patients showed that a tumor size of less than 10 mm was a significant predictor of a false negative [^{18}F]FDG PET result (*16*). In our study, a specific signal from [^{18}F]AH113804 could be detected, even when the recurrent tumor was not yet observable via CT. A previous study by Cullinane *et al.* found [^{18}F]FLT to be superior over [^{18}F]FDG in assessing the effect of the c-Met inhibitor crizotinib in human glioblastoma and human gastric cancer pre-

clinical models (*25*). When tumor size decreased within 1 week of treatment, [^{18}F]FDG uptake remained unchanged while [^{18}F]FLT PET showed a marked decrease in uptake. [^{18}F]FLT is reflective of cell proliferation, and as such was indicative of tumor therapy response. Still the use of [^{18}F]FLT as a marker for proliferation has been heavily debated, with reports suggesting that results should be viewed with caution (*26*). Such studies denote the importance of targeting radiotracers such as [^{18}F]AH113804 for accurate tumor detection and patient monitoring.

Our study demonstrates correlation between c-Met from the tumor samples and the maximum uptake (% ID/mL) from [^{18}F]AH113804 at those sites in the corresponding PET images. A recent study using an optical analogue of AH113804 (GE-137) also showed a good concordance between the expression of c-Met and the optical signal detected (*17,27*).

Other groups have investigated the use of both monoclonal antibodies and anticalins as probes for c-Met imaging. ^{89}Zr-db-/^{76}Br-ornartuzumab and ^{89}Zr-PRS-110 were developed and assessed for visualization of c-Met positive tumors in preclinical models (*28,29*). Optimal imaging time points were identified to be between 2 and 5 days after tracer administration, thus hampering potential routine clinical use as diagnostic agents. In contrast, the biodistribution of [^{18}F]AH113804 permitted early imaging after tracer administration. Similarly, Li *et al*. explored the use of c-Met targeting scFv-cys dimers in Non-Small Cell Lung Cancer xenografts. Despite showing very high affinity for c-Met, good contrast immunoPET imaging was achieved only at 20 hours after injection (*30*).

The ubiquity of c-Met dysregulation in malignant disease and its known influence on tumor progression make c-Met an attractive target for diagnostic targeting and therapeutic intervention in multiple cancer types. Phase II and III clinical studies, evaluating c-Met inhibition in gastroesophageal cancer, lung cancer and hepatocellular carcinoma have shown encouraging results with clear benefit for the individual patient (*4,31,32*).

It is hypothesized for BC, as well as for those cancer types that react more favourably to c-Met inhibition, that stratification of patients according to aberration in the c-Met axis resulting in target overexpression would strongly increase the efficiency of targeted treatment.

[^{18}F]AH113804 mediated PET signals proved to reflect the c-Met expression in individual tumors in our BC model, suggesting that this tracer could also serve as such a companion diagnostic for patient selection and for therapeutic purposes. Future studies to evaluate this utility are required.

CONCLUSION

This study demonstrates that [^{18}F]AH113804 PET provides a new diagnostic tool for the detection of c-Met-expressing primary tumor and has potential utility for the detection of loco-regional recurrence from an early stage. Further preclinical work is warranted to determine whether [^{18}F]AH113804 uptake in the regrowth provides a useful predictive tool for anti-c-Met therapeutic intervention.

ACKNOWLEDGMENTS

We thank GE Healthcare for the provision of [^{18}F]AH113804, and for providing access to their laboratory facilities and staff. In particular, we thank Joanne Nesbitt, Rochelle Lear, David Gendle and Chris Beazley (all GE Healthcare at the time of study) for excellent technical support. We also like to thank Sven Macholl and Mark Battle (both GE at the time of study) for both excellent technical and intellectual support. We thank Anthony Cheung and Fabian Flores-Borja (both KCL) for preparatory experiments.

This work was supported by a MRC UK/GE Healthcare CASE studentship to Appitha Arulappu, MR/L001640/1 to Michael Eisenblaetter, FP7-HEALTH-2010 grant 'Imagint' (number 259881) to Gregory Weitsman, CR-UK/EPSRC funding for the KCL-UCL CCIC (C1519/A10331, C1519/A16463; Myria Galazi,

Michael Eisenblaetter), an endowment fund from Dimbleby Cancer Care to KCL (Tony Ng, James Monypenny), and a Breakthrough Breast Cancer fund to Patrycja Gazinska.

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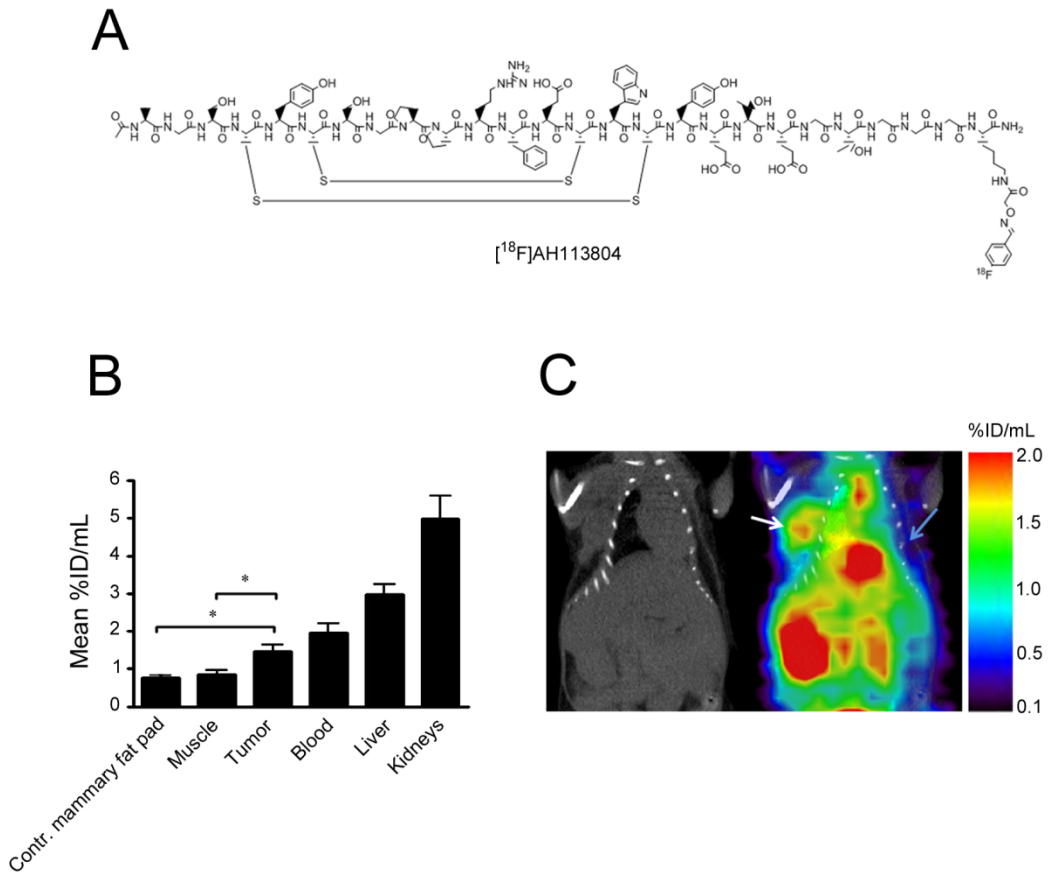

Figure 1. Biodistribution of [^{18}F]AH113804 and HCC1954 tumor. (A) Molecular structure of [^{18}F]AH113804. **(B)** Distribution of [^{18}F]AH113804 in selected organs and tissues in HCC1954 tumor xenografts 10 days p.i. Statistically significant differences were observed in the uptake of [^{18}F]AH113804 in tumor versus muscle and contralateral side (Students *t*-test, mean±SEM, n=8, *: p<0.05). **(C)** CT and PET/CT images of a representative tumor-bearing mouse 10 days p.i. demonstrates [^{18}F]AH113804 signal at the tumor site (white arrow), but not at the contralateral site (blue arrow).

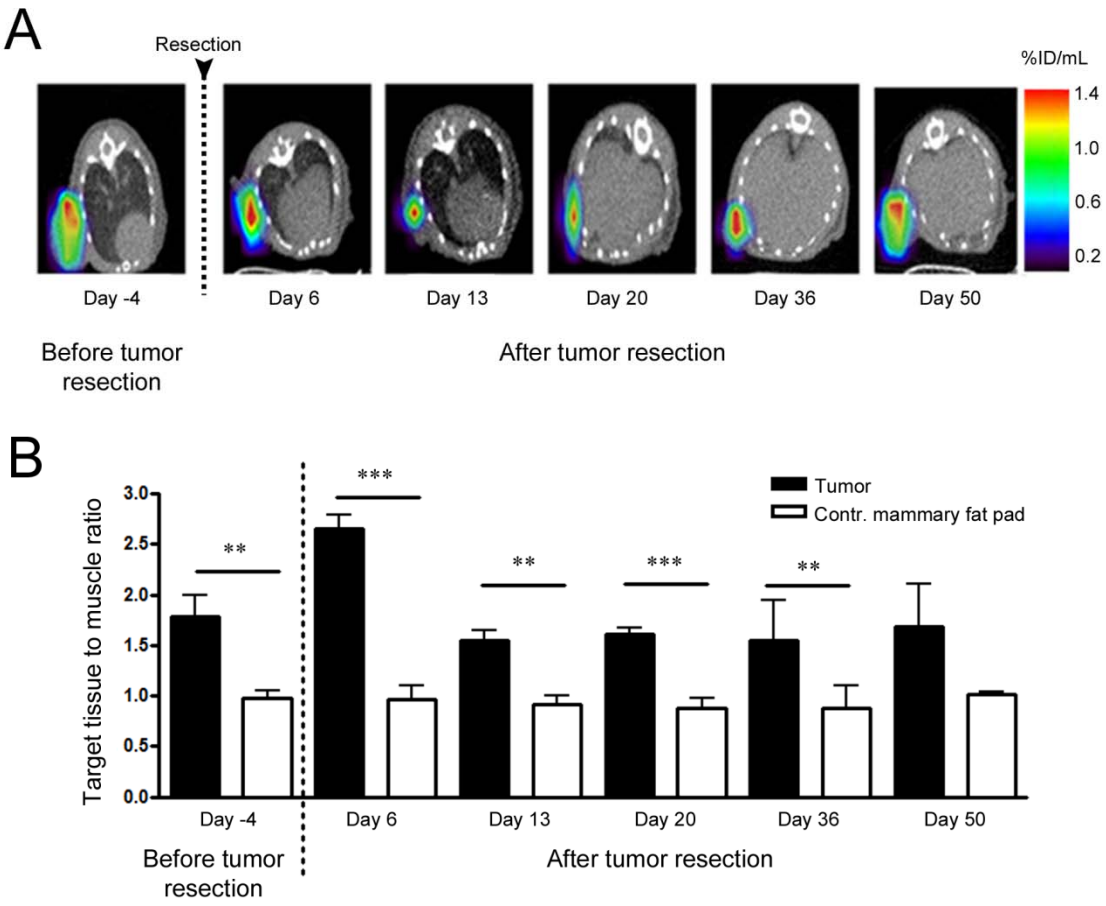

Figure 2. Early detection of tumor regrowth using [^{18}F]AH113804 for PET imaging. (A) PET/CT images of a transverse section of a representative tumor-bearing mouse, 4 days before tumor resection and at selected days after resection, show [^{18}F]AH113804 signal at the tumor site at 60 min p.i. For clarity, the PET signal only in the ROI is shown. **(B)** Target-to- muscle ratio in the tumor and contralateral sites. Statistically significant differences between both sites observed at Days 6, 13, 20 and 36 (Students *t*-test, mean±SEM, Day 4 pre-resection: n=8, Days 6 and 13 post resection: n=5, Days 20 and 36: n=4, Day 50: n=3. ** $p<0.01$, *** $p<0.001$).

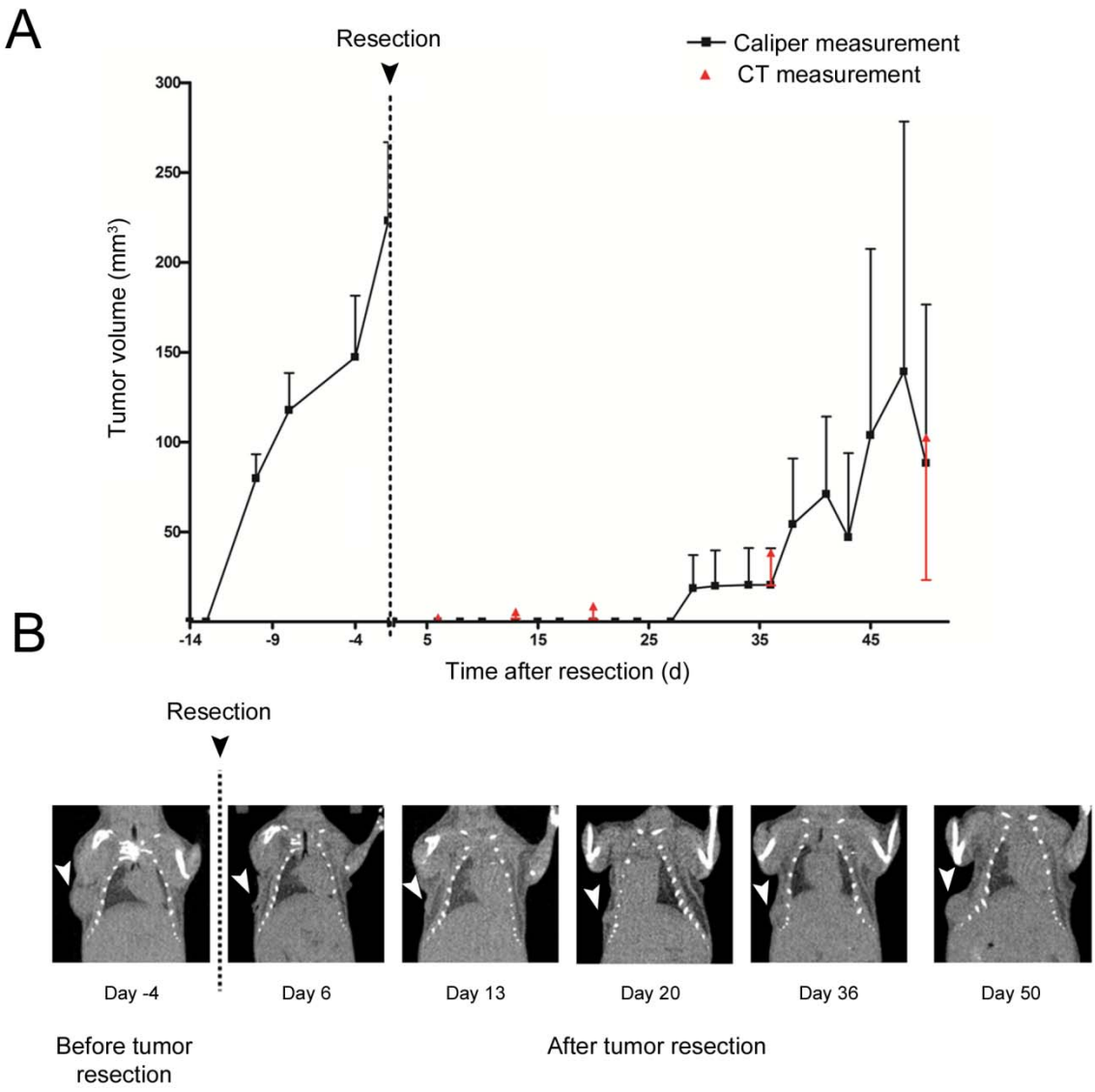

Figure 3. Detection of loco-regional tumor recurrence via CT and caliper measurements. (A) Growth curve of mean tumor volume obtained from caliper and CT measurements of the same group of animals, before and after primary tumor resection (mean±SEM, n=5 per study day, except days 20 and 36: n=4, day 50: n=3). **(B)** Coronal CT slices of a representative tumor-bearing mouse before and after resection show the presence (white arrow) and regrowth of the tumor after resection. Tumor growth was observed by CT from day 20 onwards.

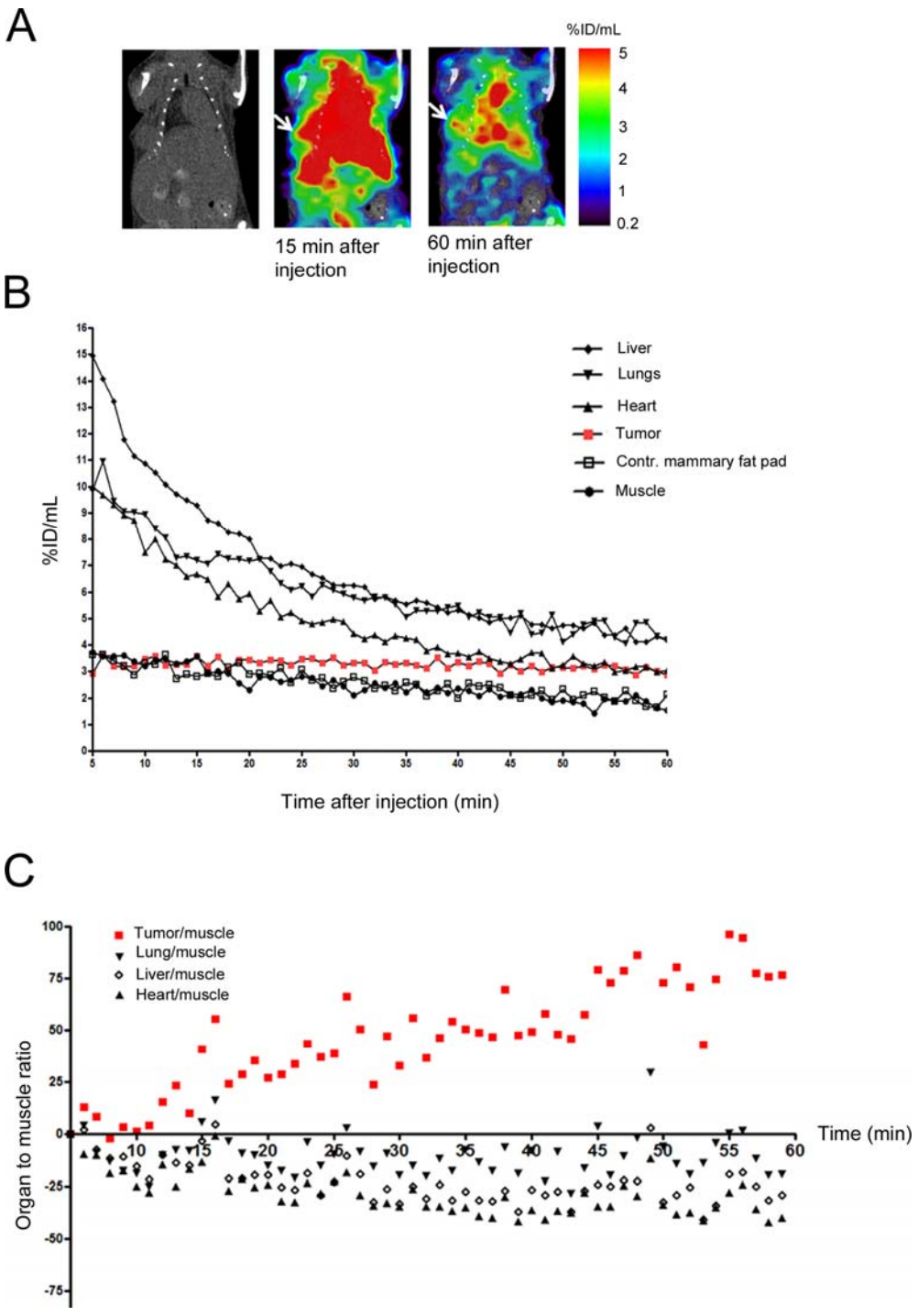

Figure 4. Biodistribution of [^{18}F]AH113804 in a recurrent HCC1954 tumor-bearing mouse. (A-left) Representative CT image of a HCC1954 xenograft mouse, acquired at Day 36 post resection. Recurrent tumor observed (White arrowhead). **(A- middle and right)** PET/CT at 15 min and 60 min p.i. of [^{18}F]AH113804, with retained radioactivity in the tumor visible by 60 min p.i.. **(B)** Dynamic ROI analysis of PET/CT shows a constant concentration at the tumor site but steady decline in all other organs (n=1). **(C)** Data of panel B normalized to the first time point show the relative change with a clear increase for tumor (n=1).

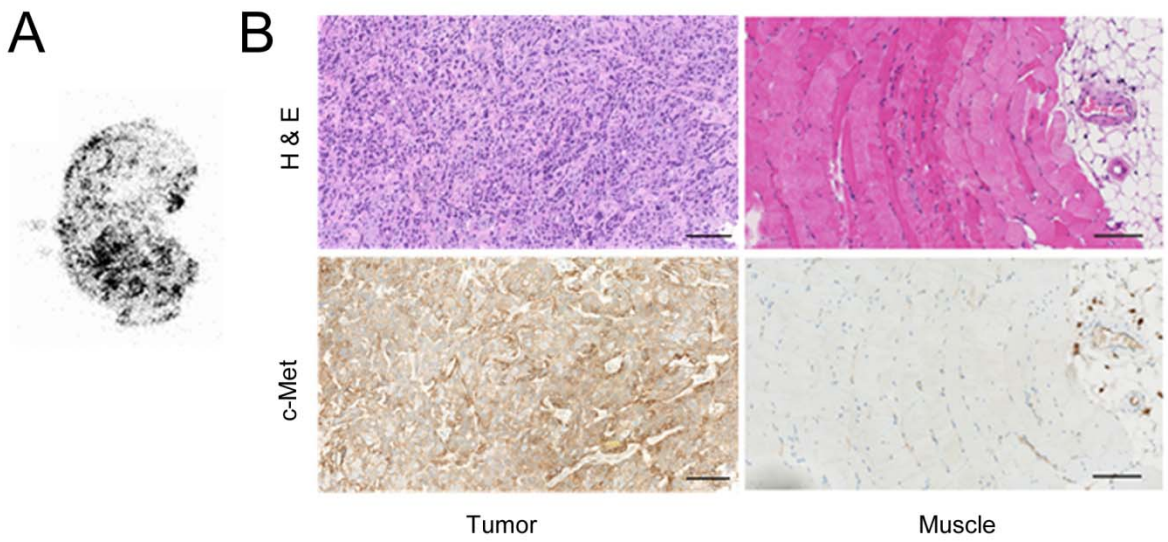

Figure 5. Autoradiography and immunohistochemistry demonstrate [^{18}F]AH113804 retention in c-Met positive HCC1954 tumor tissue.
(A) Autoradiography performed *ex vivo* on a resected tumor confirms retention of the [^{18}F]AH113804 radiotracer in tumor tissues. A heterogeneous distribution of tracer within the tumor section could be observed, not visible at the limited spatial resolution of PET imaging. **(B)** H&E staining (upper) and c-Met immunostaining (lower) of paraffin-embedded tumor and control skeletal muscle tissue (left and right columns respectively). H&E staining reveals the large, mitotic and disorganized phenotype characteristic of tumor cells, while immunohistochemistry reveals membranous c-Met staining in these cells. Scale bars=100 μm.

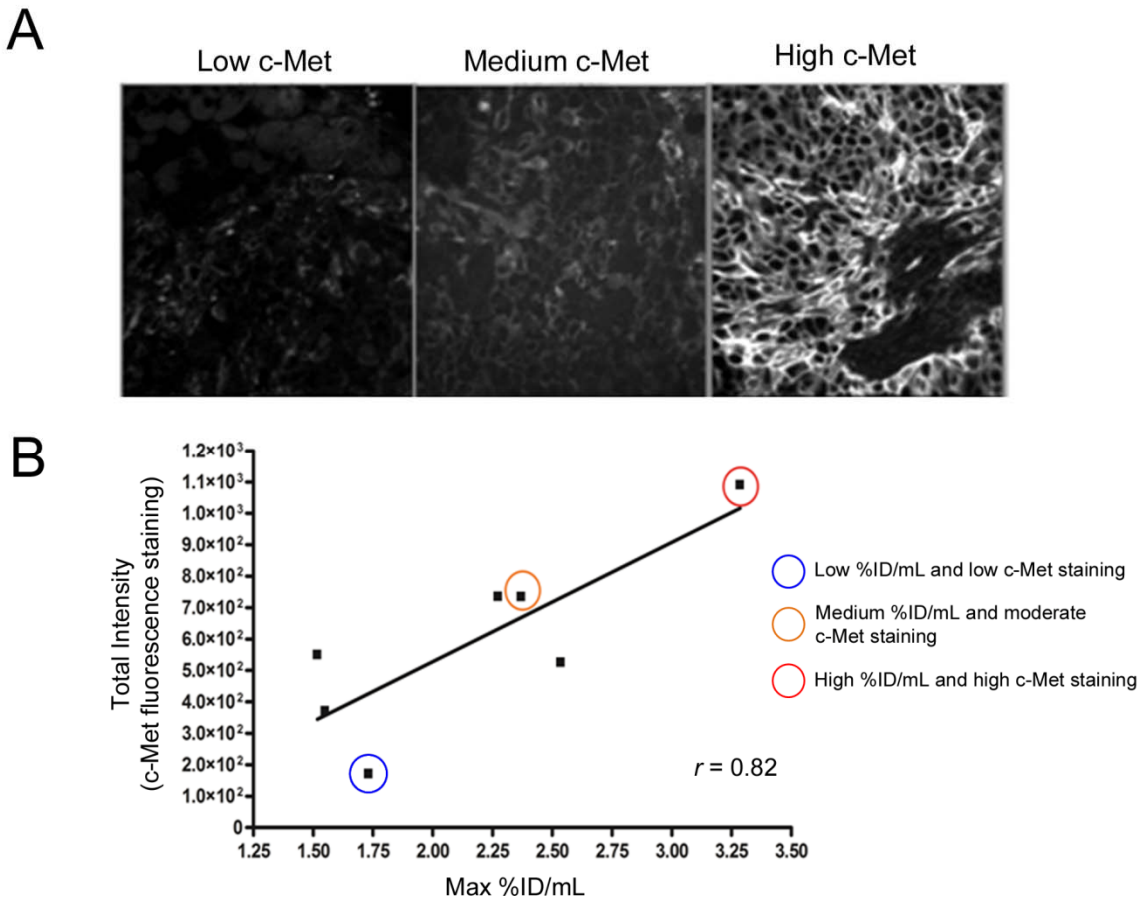

Figure 6. Uptake of [^{18}F]AH113804 correlate with the c-Met expression level in the corresponding resected tumor samples. (A) Immunofluorescent staining for c-Met in resected tumor samples (Day 14, n=7). Low, medium and high c-Met staining examples highlighted panel B. **(B)** A positive correlation is found between (a) the Max %ID/mL of tumor ROIs from *in vivo* PET images, and (b) the c-Met protein expression level from immunofluorescent staining in the same tumors after resection. Pearson's correlation coefficient=0.82 (P<0.05, n=7).