

In Vivo Tomographic Imaging of Deep-Seated Cancer Using Fluorescence Lifetime Contrast

William L. Rice¹, Daria M. Shcherbakova², Vladislav V. Verkhusha^{2,3}, and Anand T.N. Kumar¹

Abstract

Preclinical cancer research would benefit from noninvasive imaging methods that allow tracking and visualization of early-stage metastasis *in vivo*. Although fluorescent proteins revolutionized intravital microscopy, two major challenges that still remain are tissue autofluorescence and hemoglobin absorption, which act to limit intravital optical techniques to large or subcutaneous tumors. Here, we use time-domain (TD) technology for the effective separation of tissue autofluorescence from extrinsic fluorophores, based on their distinct fluorescence lifetimes. In addition, we use cancer cells labeled with near infrared fluorescent proteins (iRFP) to allow deep-tissue imaging. Our results dem-

onstrate that TD imaging allows the detection of metastasis in deep-seated organs of living mice with a more than 20-fold increase in sensitivity compared with conventional continuous wave techniques. Furthermore, the distinct fluorescence lifetimes of iRFPs enable lifetime multiplexing of three different tumors, each expressing unique iRFP labels in the same animal. Fluorescence tomographic reconstructions reveal three-dimensional distributions of iRFP720-expressing cancer cells in lungs and brain of live mice, allowing ready longitudinal monitoring of cancer cell fate with greater sensitivity than otherwise currently possible. *Cancer Res*; 75(7); 1236–43. ©2015 AACR.

Introduction

Fluorescent proteins (FP) have revolutionized microscopic biologic imaging as highly specific cell and gene-expression markers (1). However, whole-body small animal imaging of FPs has still not been realized to its full potential. This is primarily due to high tissue absorption and autofluorescence in the visible wavelength regions where most current FPs of the GFP-like family absorb and emit light. Thus, deep tissue whole-body imaging using GFP-like FPs has required extremely large tumors and extended acquisition times (2–4). The near infrared (NIR) optical transparency window (~650–900 nm), in which mammalian tissue absorption is minimized, is ideal for deep tissue whole-body imaging. Indeed, much effort in the past two decades has been focused on developing disease targeted NIR synthetic fluorophores for *in vivo* imaging (5, 6). However, the task of identifying disease-specific markers has proven to be challenging. As a result, much of the available targeted organic dyes exhibit significant nonspecific uptake, reducing detection sensitivity (6–8). Recently, several types of genetically encoded NIR FPs, such as permanently fluorescent infrared fluorescent proteins (iRFP; ref. 9), photoacti-

vatable PAiRFPs (10) and iSplit reporter (11), that are excited and emit light in the NIR window have been developed and have shown great promise for whole-body optical imaging. A major challenge for the application of iRFPs to whole-body imaging of small and deep-seated disease is their relatively low molecular brightness, which implies that tissue autofluorescence can still remain a significant contributor to the fluorescent signal. Although whole-animal imaging of iRFP-labeled tumors has been demonstrated (9, 12, 13), the tumors in these studies were either subcutaneous or consisted of several million cells in deep tissue. The ability to detect smaller metastases in deep organs of whole animals is of far more significance for preclinical oncology studies (14), because it will allow optimization of drug treatments to control the disease in its earliest stages. This motivates the development of techniques that can enhance the specificity for *in vivo* detection of iRFPs in the presence of background autofluorescence. More generally, the ability to image NIR FPs in deep tissue with high sensitivity will enable a wide range of applications ranging from detecting early-stage disease to tracking gene expression (15).

Fluorescence lifetime contrast (16) using time-domain (TD) detection (17–19) is a powerful mechanism for separating intrinsic tissue autofluorescence from extrinsic fluorescence. The lifetime characteristics of tissue autofluorescence are distinct from that of several FPs and NIR fluorophores. Furthermore, several fluorophores and FPs exhibit distinct *in vivo* lifetimes (20, 18). Exploiting fluorescence lifetime contrast can, thus, allow two key advantages: (i) the rejection of tissue autofluorescence, thereby significantly enhancing imaging sensitivity, and (ii) the simultaneous detection of multiple targets in whole animals by labeling with fluorophores of distinct lifetimes (termed lifetime multiplexing). We have recently demonstrated the tomographic lifetime multiplexing of anatomically targeted fluorophores in living mice (20). We have also shown that fluorescence lifetime contrast allows for a greater than 25-fold increase in sensitivity over traditional continuous wave (CW) techniques for detecting

¹Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, and Harvard Medical School, Charlestown, Boston, Massachusetts. ²Department of Anatomy and Structural Biology, Albert Einstein College of Medicine, Bronx, New York, New York. ³Department of Biochemistry and Developmental Biology, Faculty of Medicine, University of Helsinki, Helsinki, Finland.

Note: Supplementary data for this article are available at Cancer Research Online (<http://cancerres.aacrjournals.org/>).

Corresponding Author: Anand T.N. Kumar, Massachusetts General Hospital, Room 2301, Martinos center, Mass General Hospital, Charlestown, MA 02474. Phone: 617-726-6542; Fax: 617-726-7422; E-mail: ankumar@nmr.mgh.harvard.edu

doi: 10.1158/0008-5472.CAN-14-3001

©2015 American Association for Cancer Research.

subcutaneous tumors expressing GFP (21). On the basis of the NIR spectral properties of iRFPs and the dramatic increase in sensitivity afforded by fluorescence lifetime contrast, we investigated whether the pairing of these two technologies provides a viable option for deep tissue imaging in intact mice. Here, we present the first demonstration of tomographic imaging of iRFPs in deep-seated organs, such as the lungs and brain, using fluorescence lifetime contrast.

Materials and Methods

Bacterial and mammalian cell culture

Bacterial LMG194 cells were transfected with pBAD-His/B plasmids (Life Technologies) encoding one of five iRFP proteins. Rat adenocarcinoma MTLn3 cells were obtained from Dr. John Condeelis (Albert Einstein College of Medicine, Bronx, NY). Cell line authentication and validation was performed using immunofluorescence. MTLn3 cells stably expressing either iRFP670, iRFP702, or iRFP720 were obtained as previously described (9). Cells were maintained in α -MEM culture medium supplemented with 5% FBS, 1% penicillin—streptomycin, and 700 μ g/mL G418 (all reagents from Life Technologies.)

Animal models

All procedures were performed in accordance with the Massachusetts General Hospital animal welfare guidelines. Female Nu/Nu mice were obtained from the Cox-7 defined-flora animal facility in MGH. Before experimentation, mice were either anesthetized or euthanized by inhaled isoflurane (2% or 5%, respectively).

To prepare cells for injection into animals, MTLn3-iRFP670, MTLn3-iRFP702, and MTLn3-iRFP720 cells were detached from

culture dishes (TrypLE; Life Technologies), washed twice, and resuspended in calcium- and magnesium-free PBS (Life Technologies). For orthotopic injections, cells suspended in a 1:1 (v/v) PBS/Matrigel (BD Biosciences) solution were injected in the mammary fat pad via 30-gauge needle. Tail vein injection of 2.5×10^4 to 2×10^6 cells in PBS were performed in a total volume of 150 μ L. Intracranial injections were performed stereotactically in freshly sacrificed mice and consisted of 1×10^6 MTLn3-iRFP720 cells in 3 μ L PBS at a rate of 300 nL/min. Cryopreservation was achieved by immersing sacrificed mice in liquid nitrogen followed by storage at -80°C . Slices of frozen mice were obtained using a cryotome blade and kept on dry ice until fluorescence imaging.

Imaging system

Time resolved images were acquired with a custom-built imaging system described in detail previously (17). Briefly, fluorescence was excited by either the direct output of a titanium sapphire laser (Mai Tai; Spectra Physics; 80 MHz repetition rate) tuned to 710 nm, or the pulsed broadband (500–850 nm) output of a Mai Tai-driven photonic crystal fiber (Thorlabs NL-PM-750) filtered through a 650/40 nm filter. The resulting fluorescence emission was detected with either a 700-nm long pass filter, or a 750-nm longpass filter coupled to an intensified CCD camera (PicostarHR; LAVision; 12-bit cooled CCD, 300–500 ps gate width, 600 V gain, 150 ps steps, 4×4 hardware binning). The use of a CCD camera allowed a full-field acquisition compared with fiber-based detection. Excitation powers did not exceed ANSI standards for skin exposure to pulsed lasers. Camera integration times ranged from 0.3 to 3 seconds. Reflectance images (Figs. 1, 2H–J, 3D and F and 4F) were acquired by exposing the sample to the output of an optical fiber expanded with a diffusing filter

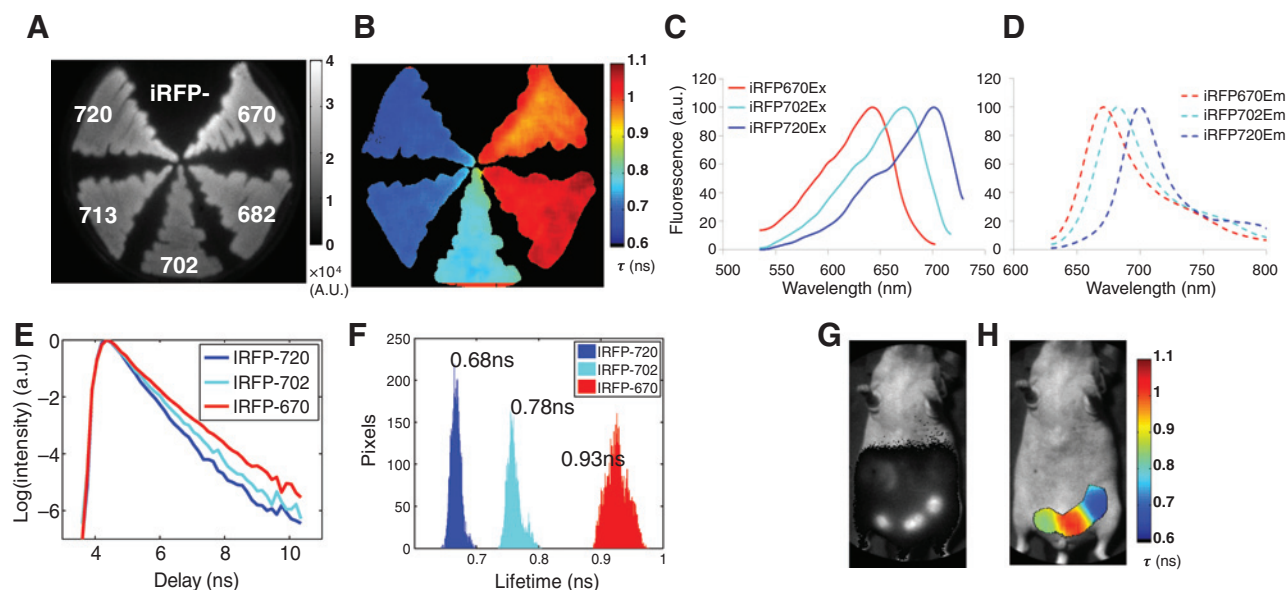


Figure 1.

In vitro and *in vivo* lifetime multiplexing of iRFPs. All fluorescence data were acquired with single excitation/emission filter pair: Ex, 650/40 nm; Em, 700-nm long pass. A and B, CW (A) and fluorescence lifetime (B) images of bacteria expressing five iRFP variants (iRFP670, 682, 702, 713, and 720). C and D, normalized excitation (C) and emission spectra (D) of iRFP670, 702, and 720. E, TD fluorescence signal of iRFP670, 702, and 720 in bacteria. F, histogram of lifetime distribution derived from fluorescence lifetime image in B. G and H, CW (G) and fluorescence lifetime (H) image of three MTLn3 tumors expressing iRFP670, 702, and 720 in the mammary fat pad of a female nude mouse.

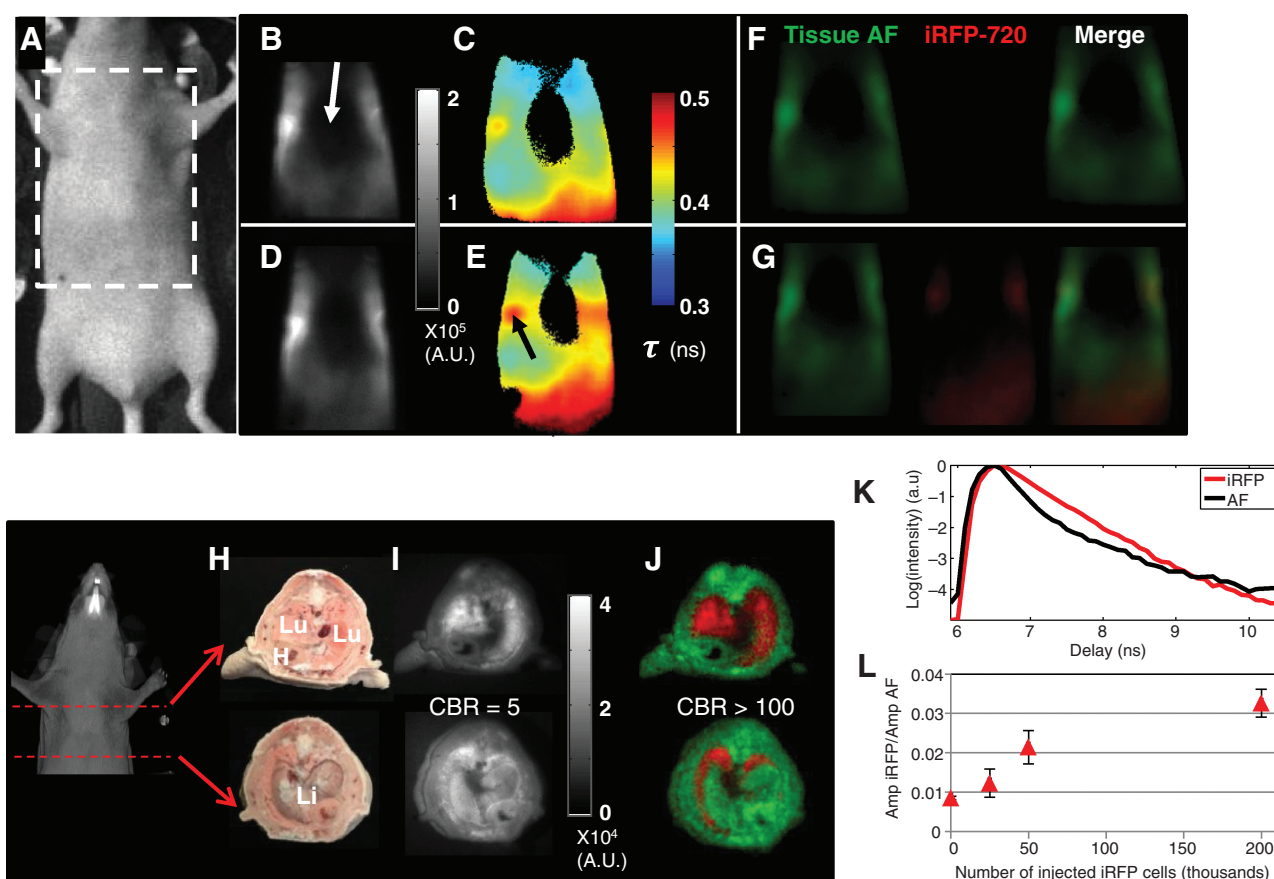


Figure 2.

In vivo and *ex vivo* planar lifetime imaging of iRFP720-labeled cells in the lungs. A, snapshot and imaging region of interest. Transmission fluorescence images before (B, C, and F) and after (D, E, and G) i.v. injection of 2.0×10^6 MTLn3-iRFP720 cells. B and D, CW fluorescence. C–G, fluorescence lifetime images obtained from single exponential fits at each pixel (C and E) and fluorescence decay amplitudes of tissue autofluorescence (green) and iRFP720 (red) obtained from a dual-basis function analysis (Eq. 1) of transmission TD fluorescence measurements, shown separately and as a merged RGB image (F and G). H, white light (Lu, lungs; Li, liver; H, heart). I and J, CW fluorescence (I), and dual fluorescence decay amplitude (J) images of cryosections from the thorax of a mouse following i.v. injection of 2.0×10^6 MTLn3-iRFP720 cells, showing autofluorescence (green) and iRFP720 (red) decay amplitudes as a single composite RGB image. K, representative TD fluorescence profiles of mouse tissue autofluorescence (black line) and iRFP720 (red line) from the cryosection measurements. L, The ratio of iRFP720 to tissue autofluorescence fluorescence decay amplitude obtained from a dual-basis function analysis of planar TD transmission fluorescence images of mice that received serial dilutions of MTLn3-iRFP720 cells via the tail vein.

(Thorlabs ED1-S50-MD). In the transmission measurements (Figs. 2B–G, 3 and 4B and C), the output of the optical fiber was focused to a 1-mm diameter spot translated to multiple source locations below the mouse. The output power at each source was dynamically adjusted to ensure optimum usage of camera dynamic range (4,096 counts). Full tomographic scans of the thorax (37 time gates, 28 sources) took 55 minutes whereas a 17 source scan of the mouse head was completed in less than 10 minutes. X-ray CT was obtained on a triple modality microPET-SPECT-CT imaging device (Triumph; GE Healthcare).

Image processing and tomographic reconstructions

Fluorescence image processing, X-ray CT segmentation, and fluorescence yield reconstruction algorithms were implemented in MATLAB (Mathworks; Natick). The full-field TD data were processed in two different ways. First, fluorescence lifetime images were obtained by fitting the decay portion of TD fluorescence measurements across the image with a single exponential func-

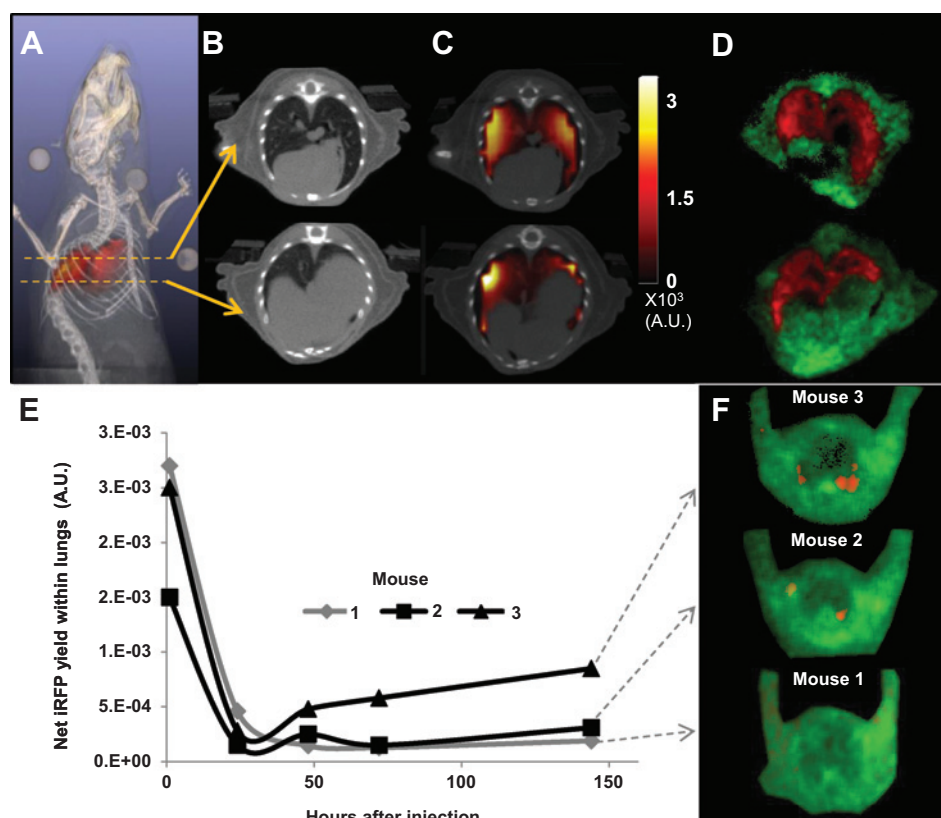
tion, $e^{-t/\tau(r)}$, where r denotes pixel location. The images of $\tau(r)$ constitute the lifetime maps shown in Figs. 1B and H and 2C and E. Second, decay amplitude images were obtained by fitting the decay portion of the TD fluorescence measurements to the following dual-basis function:

$$U(t) = a_{AF}B(t) + a_{FP}e^{-t/\tau_{FP}}, \quad (1)$$

where $B(t)$ is an empirically determined basis function representing tissue autofluorescence (obtained from naive animals and usually consisting of a biexponential decay), and a_{FP} , τ_{FP} , are the decay amplitude and lifetime of iRFP720 fluorescence. For both lifetime and decay amplitude analysis, pixels with intensities below 20% of the maximum intensity were rejected from the analysis. The recovered decay amplitudes of the autofluorescence (a_{AF}) and FP (a_{FP}) are assigned to the green and red components of a single RGB image matrix in Figs. 2F, G and J, 3D and F, and 4C.

Figure 3.

Tomography and longitudinal imaging of iRFP720 cancer cells from the lungs. A, reconstructed *in vivo* fluorescence yield distribution (red) immediately following the injection of 2×10^6 MTLn3-iRFP720 cells in the tail vein of a nude mouse, coregistered with X-ray CT (grayscale; see also Supplementary Video S1). B and C, coronal slice of the CT (B) and the ATD (C) reconstruction of iRFP720 yield coregistered with CT. D, decay amplitude images obtained from dual-basis function analysis (Eq. 1) of reflectance TD images of lung cryosections of the same mouse shown in A–C. Autofluorescence (green) and iRFP720 (red) amplitudes are shown as a single RGB image. E, longitudinal study to monitor MTLn3 fate in three live nude mice following tail vein injection of 1×10^6 MTLn3-iRFP720 cells. Tomographic measurements were made from the injection time point up to 144 hours after injection. Net iRFP720 fluorescence yield within the lungs of the three mice, reconstructed using the ATD approach. F, decay amplitude images of lung cryoslices from the three mice in E following sacrifice at 144 hours after injection, showing autofluorescence (green) and iRFP720 (red).



Tomographic reconstruction of the three-dimensional (3D) distributions of iRFP fluorescence was performed using the asymptotic time-domain (ATD) approach (22), which has been shown to be the optimal approach for tomographic lifetime multiplexing using the decay portion of the TD data (23). Briefly, the ATD approach directly relates the decay amplitude, a_{FP} , for the iRFP fluorescence (Eq. 1) to the *in vivo* yield distribution, $\eta_{FP}(r)$, of iRFP fluorescence as the following linear forward problem:

$$a_{FP}(r_s, r_d) = \int d^3r W(r_s, r_d, r) \eta_{FP}(r), \quad (2)$$

where r_s and r_d are source and detector locations on the surface of the mouse, respectively, W is a reduced absorption CW sensitivity matrix for light propagation through tissue at the excitation and emission wavelengths (22), and r is the location of a voxel within the mouse. The weight function for the forward model, W , is a product of Greens functions at the excitation and emission wavelengths (24) and was computed using a GPU-accelerated Monte Carlo algorithm (Monte Carlo Extreme; ref. 25). Light propagation was simulated in a segmented mouse volume, derived from the X-ray CT images. The medium voxels corresponding to each CT-defined anatomical region were assigned tissue-specific optical properties (Supplementary Table S1).

The fluorescence yield distribution can be obtained by inverting Eq. (2), which is equivalent to the standard CW fluorescence tomography inversion (24). To improve the conditioning of the problem, the inversion was performed in two steps (26). First,

each CT-defined anatomical segment or region, such as lung, liver, bone, kidneys, and heart, was assumed to have a constant value of iRFP fluorescence yield, η^j , where j denotes the index of the segment. This allowed a few parameter estimation of the fluorescence yield from the decay amplitudes using a reduced dimensional inversion problem, which was solved using a fast fluorescence Monte Carlo algorithm based on stored photon path histories (27). The η^j 's recovered from the parameterized fit were next used to define a regularization matrix L of dimension $(M \times M)$; where M is the number of medium voxels, whose diagonal elements are:

$$L = 1/\sqrt{\eta^j}. \quad (3)$$

The matrix L was used in a Tikhonov-type inversion to recover the full fluorescence yield distribution $\eta(r)$ as follows (17):

$$\eta(r) = L^{-1} V S [S^2 + \lambda I]^{-1} U^T a_{FP}, \quad (4)$$

where U , S , and V are obtained from a singular value decomposition of the weight matrix:

$$W L^{-1} = U S V^T, \quad (5)$$

I is the identity matrix and λ is the regularization parameter. The singular value analysis of the weight matrix (Eq. 5) was implemented in MATLAB. The final reconstructed fluorescence yields were coregistered with X-ray CT in MATLAB and visualized in VolView 3.4 (Kitware Inc.), as shown in Figs. 3A and C and 4D and E.

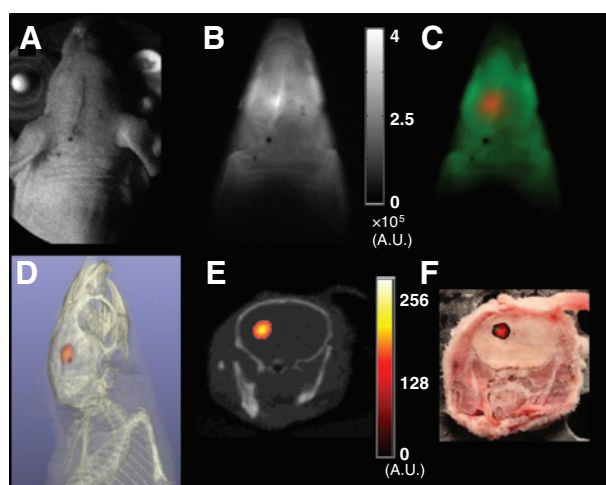


Figure 4. Tomography of iRFP720 tumors in the mouse brain. A, white light image. B, planar transmission CW fluorescence (integrated TD signal). C, fluorescence decay amplitude images for excitation source locations spanning the head of a sacrificed nude mouse following stereotactic injection of the left cerebral hemisphere with 1×10^6 MTLn3-iRFP720 cells in $3 \mu\text{L}$. C, shows the autofluorescence (green) and iRFP720 (red) decay amplitudes computed from the full TD data using a dual-basis function approach (see Materials and Methods). D and E, volumetric (D) and coronal slice (E) from tomographic reconstruction of iRFP720 fluorescence yield distribution (red) in the mouse head coregistered with X-ray CT (grayscale). F, snapshot of cryosection slice corresponding to the anatomical location depicted in E with coregistered overlay (red) of iRFP720 fluorescence decay amplitude showing the location of the tumor.

Results and Discussion

In vitro lifetime imaging of iRFPs

First, we performed an initial screen of expression bacteria carrying five iRFP variants (9): iRFP670, 682, 702, 713, and 720 to determine their *in vitro* fluorescence lifetimes. Despite a 50 nm difference in the absorption maxima of iRFP670 and iRFP720, all variants display significant overlap in both their absorption and emission spectra (Fig. 1C and D). The spectral overlap allowed capture of TD reflectance fluorescence images from all five iRFPs simultaneously with a single excitation and emission filter set (650/40- and 700-nm long pass). As expected, the total CW fluorescence image, calculated as the AUC of the TD fluorescence signal (Fig. 1E), provides no contrast among the iRFPs (Fig. 1A). On the other hand, a single exponential fit of the TD fluorescence decay at each image pixel reveals the characteristic fluorescence lifetime of each iRFP (Fig. 1B). From this group of five iRFPs, there are three fully distinct and sharp fluorescence lifetime distributions (Fig. 1E and F) with mean (SD) values of $\tau = 0.93$ ns ($\sigma = 0.02$ ns), $\tau = 0.78$ ns ($\sigma = 0.01$ ns), and $\tau = 0.68$ ns ($\sigma = 0.008$ ns). iRFP670 and iRFP682 share a similar fluorescence lifetime distribution (Fig. 1B; $\tau = 0.93$ ns), as do iRFP713 and iRFP720 (Fig. 1B; $\tau = 0.68$ ns).

In vivo planar lifetime multiplexing of three iRFPs in living mice

Next, to verify that the iRFP fluorescence lifetimes as measured in bacteria were maintained in mammalian cells, three iRFP variants were expressed in rat adenocarcinoma MTLn3 cells and grown in the mammary fat pad of mice. As for the *in vitro* case,

tumors carrying iRFP670, iRFP702, or iRFP720 were indistinguishable in the CW reflectance fluorescence image (Fig. 1G) using a single excitation emission filter set, whereas fluorescence lifetime (Fig. 1H) offered clear contrast between the iRFP-expressing tumors. In these measurements, gut autofluorescence was minimized by feeding animals with alfalfa-free diet. Gut autofluorescence can also be separated by taking advantage of its relatively long fluorescence lifetime (1.5 ns) compared with the iRFPs (Supplementary Fig. S1).

In vivo planar lifetime imaging of iRFP720-labeled cells in the live mouse lung

We next ascertained whether iRFPs can enable the detection of labeled cancer cells in the lungs of live mice. We introduced by tail vein injection, between 2.5×10^4 and 2.0×10^6 lung colonizing (28) MTLn3-iRFP720 cells into female nude mice, followed by transmission TD fluorescence measurements of the thorax. To ensure complete imaging coverage of the chest, multiple transmission TD fluorescence measurements were made with the excitation laser focused at different locations (source positions) under the mouse. These measurements were then combined into a single transmission TD fluorescence image. As seen in Fig. 2B and D, even in the NIR wavelengths (ex: 710 nm, em: 750 nm long pass), tissue autofluorescence was significant and dominated the CW fluorescence signal. Indeed, injection of 2.0×10^6 MTLn3-iRFP720 cells (Fig. 2D) resulted in only a 7% increase in CW fluorescence intensity. However, fluorescence lifetime images (Fig. 2C and E), generated by performing a single exponential fit to the decay portion of the TD fluorescence signal at each pixel on the mouse surface, reveal a significant increase in lifetime above the lungs (Fig. 2E, arrow), after injection of iRFP720 cells. Here, the measured lifetimes on the mouse surface above the lungs ($\tau \cong 0.5$ ns) do not match the iRFP720 lifetime (0.68 ns) observed from cells *in vitro*, because these values represent a mixture of the iRFP720 fluorescence and tissue autofluorescence. Furthermore, it is seen that minimal signal is detected in the central thoracic region (Fig. 2B, arrow) due to the strong absorption by the heart.

To confirm the localization of the MTLn3-iRFP720 cells *in vivo*, and to determine the true *in vivo* lifetime of iRFP720 fluorescence upon biodistribution, we performed *ex vivo* reflectance TD fluorescence images on cryosections of sacrificed mice following tail vein injection. In cryosections through the thorax (Fig. 2H–J) it is clear that MTLn3-iRFP720 cells are confined to the lungs, and maintain a sharp fluorescence lifetime distribution with a mean lifetime of 0.68 ns *in vivo*, similar to the *in vitro* lifetimes. No significant fluorescence was detected in the other organs.

Knowledge of the *in vivo* lifetime of iRFP720 cells in the lungs, which equals the *in vitro* lifetime (as seen from Fig. 2J), allows the use of a dual-basis function approach (18, 21) to eliminate autofluorescence from the transmission TD fluorescence images. In this approach, the decay portion of the TD fluorescence was fit with a dual-basis function (Eq. 1) consisting of a biexponential decay representing the tissue autofluorescence, determined experimentally before injecting cells, and a single exponential decay at the known *in vitro* fluorescence lifetime of iRFP720 ($\tau = 0.68$ ns). As a result, the contributions of iRFP720 fluorescence and tissue autofluorescence were separated into two independent

fluorescence decay amplitude datasets, shown as red and green, respectively, in Fig. 2F, G, and J. The dual-basis function approach allows a dramatic increase in the contrast with background ratio (defined as the ratio of either the CW intensity or decay amplitude inside the lungs to that of the surrounding tissue; 21) of more than 20-fold by separating the iRFP720 fluorescence and tissue autofluorescence. Unlike the CW images (Fig. 2B and D) the dual-basis function approach clearly delineates the injected (Fig. 2G) from noninjected (Fig. 2F) mice, in which no iRFP720 fluorescence decay amplitude is recovered. Applying this technique, we were able to detect iRFP720 fluorescence down to approximately 5.0×10^4 MTLn3-iRFP720 cells dispersed in nude mouse lungs (Fig. 2L), surpassing the sensitivity of previous reports using CW fluorescence imaging in the lungs or other deep tissue organs (2, 3, 29, 30). Separately, we also estimated the detection threshold for s.c. placed iRFP720 cells in live mice. As shown in Supplementary Fig. S2, lifetime multiplexing enables the detection of approximately 1,400 subcutaneous MTLn3-iRFP720 cells. This should be compared with the previously reported detection threshold of 5×10^4 subcutaneous iRFP720 cells using CW fluorescence imaging (13).

Tomographic lifetime imaging of iRFP-labeled cells in the live mouse lung

The fluorescence decay amplitudes corresponding to the iRFP720 lifetime, recovered from the basis function approach, as in Fig. 2G, can be directly used to recover the *in vivo* 3D distribution of MTLn3-iRFP720 cells using a previously established asymptotic TD (ATD) fluorescence lifetime tomography approach (22, 27). X-ray CT scans, acquired after fluorescence imaging sessions, allowed for the segmentation of the mouse volume by tissue type, the assignment of tissue optical properties, and the use of anatomical priors in the fluorescence reconstruction algorithm (31). As seen in Fig. 3A and C, and Supplementary Video S1, the fluorescence yield reconstructions in mice that received cells i.v. indicate that the iRFP720-expressing cells are confined to the lung, and no nonspecific fluorescence is reconstructed. The confinement of the fluorescence to the lungs is confirmed in cryosections of the thorax (Fig. 3D and Supplementary Fig. S3A–S3C), which closely match the tomographic fluorescence reconstructions overlaid on X-ray CT (Fig. 3C).

Longitudinal monitoring of MTLn3-iRFP720 fate in the mouse lung

To further demonstrate the advantage of the improved detection sensitivity of the ATD approach for monitoring cancer progression, we performed a longitudinal study of experimental metastasis production with 1×10^6 MTLn3-iRFP720 cells injected i.v. in nude mice (Fig. 3E and F). As observed in Fig. 3A–D, the MTLn3 cells are rapidly dispersed throughout the lung following injection. The longitudinal progression of these emboli was followed by TD imaging and tomographic reconstructions using the ATD approach. Following injection, the ATD-reconstructed iRFP720 fluorescence yield (Fig. 3E) showed a 10-fold increase in the injected mice compared with that observed from naive animals. Twenty-four hours after injection, the fluorescence yield rapidly drops as the MTLn3-iRFP720 emboli are cleared by the mouse's innate immune system (32). Continued imaging illustrates the progress of experimental MTLn3-iRFP720 metastasis formation as those cells that were

able to extravasate into the lungs continue to survive and grow. At 144 hours after injection, mouse 3 exhibits the greatest recovered iRFP720 fluorescence yield in the tomography results, followed by mouse 2 and mouse 1. The relative iRFP720 fluorescence yields of mouse 2 and mouse 1 relative to mouse 3 were 0.36:1 and 0.22:1. These differences between the metastatic burden in the mice are confirmed in fluorescence amplitude images of cryosections from the corresponding mice (Fig. 3F) in which the ratio of the total iRFP720 amplitude within four (2–3-mm thick) cryoslices were 0.37:1 (mouse 2) and 0.10:1 (mouse 1) relative to mouse 3. Visually, bright, focal iRFP720 fluorescence was observed in the cryoslices of mouse 3, whereas fewer foci were visible in mouse 2, and no bright iRFP720 foci were observed in mouse 1 (Supplementary Fig. S4). The cryosections in Fig. 3F showcase the significant autofluorescence (green) present in all the mice compared with the iRFP720 fluorescence (red), thus highlighting the sensitivity challenge posed to whole-body imaging with CW imaging techniques alone. These results illustrate that the tomographic reconstructions using the ATD approach reflect the ground truth observed in the cryosections, establishing the great utility of TD imaging technology for longitudinal studies in which an understanding of the total tumor/metastasis burden is necessary for both accurate tumor size matching of treatment groups and for real-time, animal-specific, assessment of treatment outcomes (33).

Tomographic lifetime imaging of iRFP-labeled cells in the mouse brain

Finally, we performed tomographic TD fluorescence imaging of the brain of sacrificed mice (Fig. 4). Point-like fluorescent inclusions, approximately 1-mm diameter and approximately 2.5-mm deep in the cerebrum were induced by stereotactic injection of 1×10^6 MTLn3-iRFP720 cells. As with imaging in the thorax (Fig. 3), tissue autofluorescence is a significant contributor to the transmission CW images (Fig. 4B), with a 46% increase in CW fluorescence intensity observed following injection of MTLn3-iRFP720 cells. A dual-basis function analysis of the TD fluorescence data (Fig. 4C) clearly delineates the iRFP720 fluorescence (red) from tissue autofluorescence (green). The ATD reconstruction of iRFP720 yield using the decay amplitudes of the 0.68 ns component indicates that the injected cells were limited to the left cerebral hemisphere (Fig. 4D and E; Supplementary Video S2). This localization is confirmed in cryosections of the mouse head (Fig. 4F). The 3D localization error across multiple mice was 1.9 mm (0.6 mm SD; $n = 5$). This error is computed by comparing the location of the fluorescence yield reconstruction with an estimate of the true location of the injected cells derived from fluorescence images of mouse cryoslices (~3-mm thickness). This is necessary because the injections offer no X-ray contrast. These results demonstrate the advantage of the combination of iRFP720 cell labeling with fluorescence lifetime contrast for whole-body imaging of deep-seated metastasis. It is noteworthy that studies in Figs. 3 and 4 are the first instance, to our knowledge, in which fluorescence optical tomography has been shown to detect cancer cell densities well below those visible in X-ray CT.

In summary, we have demonstrated the advantage of fluorescence lifetime contrast for whole-body imaging in the combination with the use of genetically encoded NIR FPs for highly specific labeling of cancer cells. Fluorescence lifetime contrast complements the favorable spectral properties of iRFPs for deep tissue imaging by allowing the rejection of tissue autofluorescence,

which has thus far remained a major impediment for whole-body fluorescence imaging. We have shown that lifetime contrast, using TD technology, enables *in vivo* imaging of iRFP720-expressing cancer cells in live mice, at levels well-below current detection limits in deep tissues using CW fluorescence methods. We have also demonstrated the ability to obtain 3D distributions of iRFP720 cancer cells in deep-seated organs such as the lungs and the brain. The technique presented here should, therefore, allow precise localization of early-stage metastasis across various organ systems and the efficient screening of cancer therapies (34). Moreover, we have shown that at least three of the iRFP variants exhibit distinct fluorescence lifetimes and can be separated in live mice. To our knowledge, this is the first report of the lifetimes of iRFPs *in vitro* and in living mice. The ability to distinguish multiple iRFPs simultaneously in a single animal using lifetime multiplexing holds great promise for visualizing multiple genetically encoded tags *in vivo*. More generally, the ability to detect NIR FPs in deep tissue with high sensitivity holds a promising future for translating existing applications of FPs from cell microscopy to whole-body imaging.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

References

- Chudakov DM, Matz MV, Lukyanov S, Lukyanov KA. Fluorescent proteins and their applications in imaging living cells and tissues. *Physiol Rev* 2010;90:1103–63.
- Hoffman RM, Yang M. Whole-body imaging with fluorescent proteins. *Nat Protoc* 2006;1:1429–38.
- Zacharakis G, Kambara H, Shih H, Ripoll J, Grimm J, Saeki Y, et al. Volumetric tomography of fluorescent proteins through small animals *in vivo*. *Proc Natl Acad Sci U S A* 2005;102:18252–7.
- Yang M, Baranov E, Li XM, Wang JW, Jiang P, Li L, et al. Whole-body and intravital optical imaging of angiogenesis in orthotopically implanted tumors. *Proc Natl Acad Sci U S A* 2001;98:2616–21.
- Bloch S, Lesage F, McIntosh L, Gandjbakhche A, Liang KX, Achilefu S. Whole-body fluorescence lifetime imaging of a tumor-targeted near-infrared molecular probe in mice. *J Biomed Opt* 2005;10:054003.
- Weissleder R, Tung CH, Mahmood U, Bogdanov A. *In vivo* imaging of tumors with protease-activated near-infrared fluorescent probes. *Nat Biotechnol* 1999;17:375–8.
- Sosnovik DE, Nahrendorf M, Deliolanis N, Novikov M, Aikawa E, Josephson L, et al. Fluorescence tomography and magnetic resonance imaging of myocardial macrophage infiltration in infarcted myocardium *in vivo*. *Circulation* 2007;115:1384–91.
- Goergen CJ, Chen HH, Bogdanov A, Sosnovik DE, Kumar ATN. *In vivo* fluorescence lifetime detection of an activatable probe in infarcted myocardium. *J Biomed Opt* 2012;17:056001.
- Shcherbakova DM, Verkhusha VV. Near-infrared fluorescent proteins for multicolor *in vivo* imaging. *Nat Methods* 2013;10:751–4.
- Piatkevich KD, Subach FV, Verkhusha VV. Far-red light photoactivatable near-infrared fluorescent proteins engineered from a bacterial phytochrome. *Nat Commun* 2013;4:2153.
- Filonov GS, Verkhusha VV. A near-infrared BiFC reporter for *in vivo* imaging of protein–protein interactions. *Chem Biol* 2013;20:1078–86.
- Deliolanis NC, Ale A, Morscher S, Burton NC, Schaefer K, Radrich K, et al. Deep-tissue reporter-gene imaging with fluorescence and optoacoustic tomography: a performance overview. *Mol Imaging Biol* 2014;16:652–60.
- Jiguet-Jiglaire C, Cayol M, Mathieu S, Jeanneau C, Bouvier-Labit C, Ouafik L, et al. Noninvasive near-infrared fluorescent protein-based imaging of tumor progression and metastases in deep organs and intraosseous tissues. *J Biomed Opt* 2014;19:16019.
- Talmadge JE, Singh RK, Fidler IJ, Raz A. Murine models to evaluate novel and conventional therapeutic strategies for cancer. *Am J Pathol* 2007;170:793–804.
- Marx V. Probes: seeing in the near infrared. *Nat Methods* 2014;11:717–20.
- Lakowicz JR, Masters BR. Principles of fluorescence spectroscopy, Third Edition. *J Biomed Opt* 2008;13:029901.
- Kumar ATN, Raymond SB, Dunn AK, Bacskaï BJ, Boas D. A time domain fluorescence tomography system for small animal imaging. *IEEE Trans Med Imaging* 2008;27:1152–63.
- Kumar ATN, Chung E, Raymond SB, van de Water J, Shah K, Fukumura D, et al. Feasibility of *in vivo* imaging of fluorescent proteins using lifetime contrast. *Opt Lett* 2009;34:2066–8.
- Venugopal V, Chen J, Lesage F, Intes X. Full-field time-resolved fluorescence tomography of small animals. *Opt Lett* 2010;35:3189–91.
- Raymond SB, Boas DA, Bacskaï BJ, Kumar ATN. Lifetime-based tomographic multiplexing. *J Biomed Opt* 2010;15:046011.
- Rice WL, Kumar ATN. Preclinical whole body time domain fluorescence lifetime multiplexing of fluorescent proteins. *J Biomed Opt* 2014;19:046005.
- Kumar AT, Raymond SB, Boverman G, Boas DA, Bacskaï BJ. Time resolved fluorescence tomography of turbid media based on lifetime contrast. *Opt Express* 2006;14:12255–70.
- Hou SS, Rice WL, Bacskaï BJ, Kumar ATN. Tomographic lifetime imaging using combined early- and late-arriving photons. *Opt Lett* 2014;39:3–7.
- Arridge SR, Schotland JC. Optical tomography: forward and inverse problems. *Inverse Probl* 2009;25:123010.
- Fang Q, Boas DA. Monte Carlo simulation of photon migration in 3D turbid media accelerated by graphics processing units. *Opt Express* 2009;17:20178–90.
- Hyde D, Miller EL, Brooks DH, Ntzichristos V. Data specific spatially varying regularization for multimodal fluorescence molecular tomography. *IEEE Trans Med Imaging* 2010;29:365–74.
- Kumar ATN. Direct Monte Carlo computation of time-resolved fluorescence in heterogeneous turbid media. *Opt Lett* 2012;37:4783–5.
- Oku N, Sugawara M, Tsukada H, Irimura T, Okada S. Positron emission tomography analysis of metastatic tumor cell trafficking. *Cancer Res* 1994;54:2573–6.

Authors' Contributions

Conception and design: W.L. Rice, V.V. Verkhusha, A.T.N. Kumar
Development of methodology: W.L. Rice, V.V. Verkhusha, A.T.N. Kumar
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): W.L. Rice, D.M. Shcherbakova, A.T.N. Kumar
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): W.L. Rice, D.M. Shcherbakova, A.T.N. Kumar
Writing, review, and/or revision of the manuscript: W.L. Rice, D.M. Shcherbakova, V.V. Verkhusha, A.T.N. Kumar
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): W.L. Rice
Study supervision: V.V. Verkhusha, A.T.N. Kumar

Acknowledgments

The authors would like to thank Dr. Brian Bacskaï's laboratory at MGH for a demonstration of the stereo-tactic cerebral injection technique.

Grant support

This work was supported by grants R01-EB105325, CA164468, GM073913, and GM108579 from the U.S. National Institutes of Health.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received October 9, 2014; revised January 6, 2015; accepted January 25, 2015; published OnlineFirst February 10, 2015.

29. Winnard PT, Kluth JB, Raman V. Noninvasive optical tracking of red fluorescent protein-expressing cancer cells in a model of metastatic breast cancer. *Neoplasia* 2006;8:796–806.
30. Deliolanis NC, Kasmieh R, Wurdinger T, Tannous BA, Shah K, Ntziachristos V. Performance of the red-shifted fluorescent proteins in deep-tissue molecular imaging applications. *J Biomed Opt* 2008;13:044008.
31. Radrich K, Ale A, Ermolayev V, Ntziachristos V. Improving limited-projection-angle fluorescence molecular tomography using a co-registered x-ray computed tomography scan. *J Biomed Opt* 2012;17:126011.
32. Le Dévédec SE, van Roosmalen W, Maria N, Grimbergen M, Pont C, Lalai R, et al. An improved model to study tumor cell autonomous metastasis programs using MTLn3 cells and the Rag2(–/–) gammac (–/–) mouse. *Clin Exp Metastasis* 2009;26:673–84.
33. Kodack DP, Chung E, Yamashita H, Incio J, Duyverman A, Song Y, et al. Combined targeting of HER2 and VEGFR2 for effective treatment of HER2-amplified breast cancer brain metastases. *Proc Natl Acad Sci U S A* 2012;109:E3119–27.
34. Begley CG, Ellis LM. Drug development: raise standards for preclinical cancer research. *Nature* 2012;483:531–3.

Supplementary Information

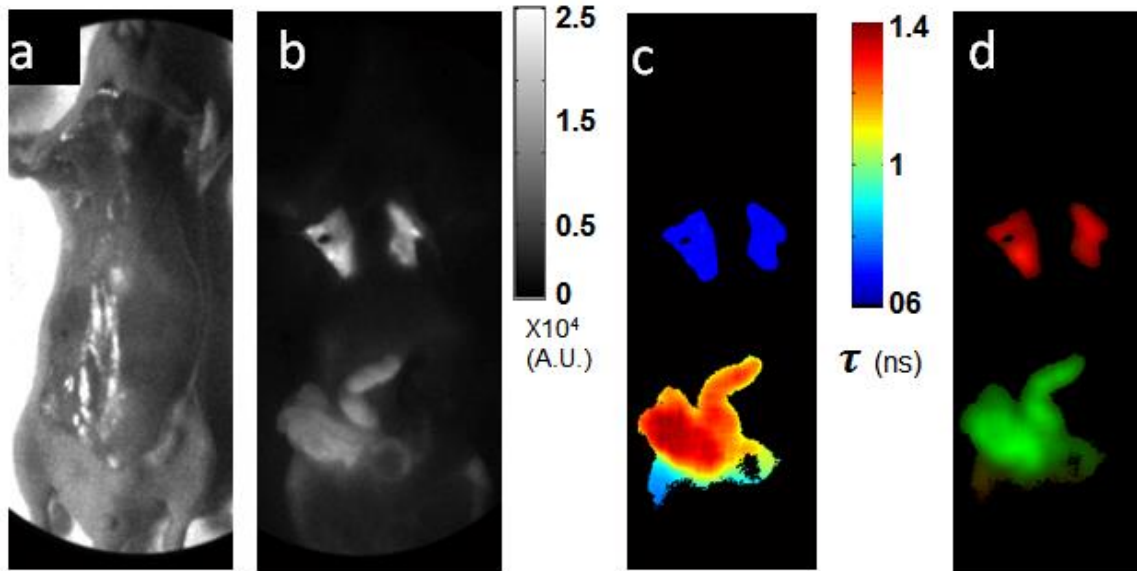
Supplementary Table 1: Tissue Optical properties

Segment:	Muscle	Fat	Lung	Heart	Liver
μ_a (mm ⁻¹)	.013	.001	.02	.1	.03
μ_s (mm ⁻¹)	15	35	35	25	25

Food autofluorescence:

Due to the presence of alfalfa and other sources of natural fluorophores, mice fed on standard diet will exhibit significant fluorescence in the gut. As an alternative to specially formulated autofluorescence-free diet (TestDiet AIN-93), time domain imaging makes it possible to take advantage of the fluorescence lifetime contrast between the food autofluorescence ($\tau \cong 1.4$ ns) and many NIR fluorophores (typically $\tau < 1$ ns). In Figure S1b, it is evident that the CW intensity of the gut autofluorescence is of similar magnitude to the 2×10^6 MTLn3-iRFP-720 cells in the lungs. To distinguish between the two sources of fluorescence, a single exponential fit of the time domain fluorescence data can be performed resulting in the fluorescence lifetime image in Figure S1c. The iRFP720 and gut autofluorescence can be further separated into distinct datasets by fitting the decay portion of the time domain fluorescence data with two single exponential decay basis functions, representing iRFP720 ($\tau = 0.68$ ns) and the food autofluorescence ($\tau = 1.4$ ns).

ns)



Supplementary Figure 1: Fluorescence lifetime contrast separates food autofluorescence

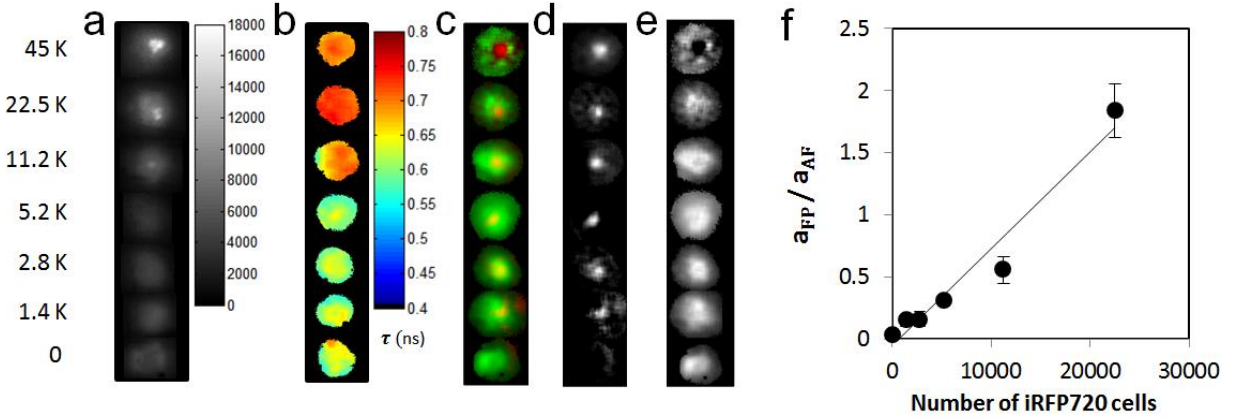
from iRFP fluorescence. *In situ* reflectance time domain fluorescence images were acquired from a

sacrificed female nude mouse following tail vein injection of 2×10^6 MTLn3-iRFP720 cells. (a) Snapshot of mouse without skin. (b) CW fluorescence intensity image, *in situ* with muscle and ribs removed. (c)

Fluorescence lifetime image, generated from a single exponential decay fit of the time domain

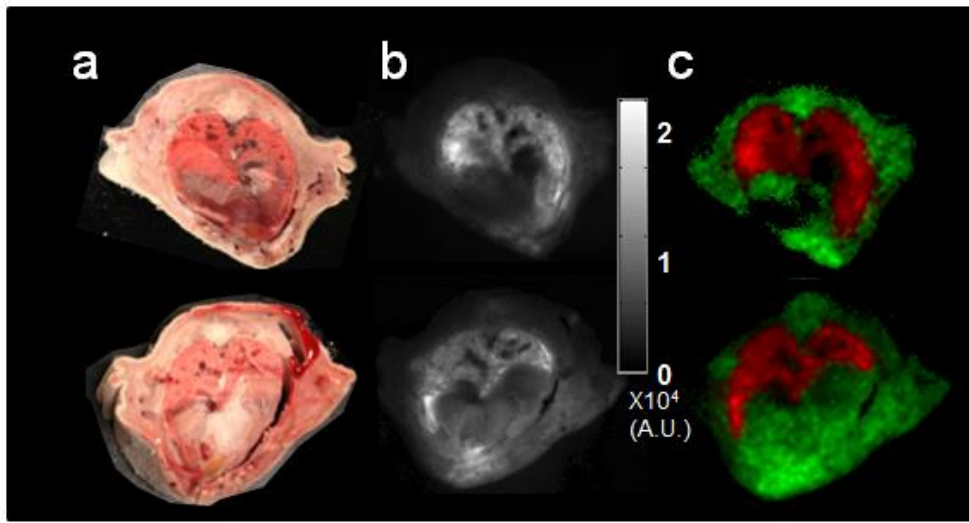
fluorescence data. (d) Fluorescence decay amplitude image, red corresponds to $\tau = 0.68$ ns and green to

$\tau = 1.4$ ns. Images acquired by exciting at 710 nm, and collecting fluorescence through a 750 nm longpass filter.



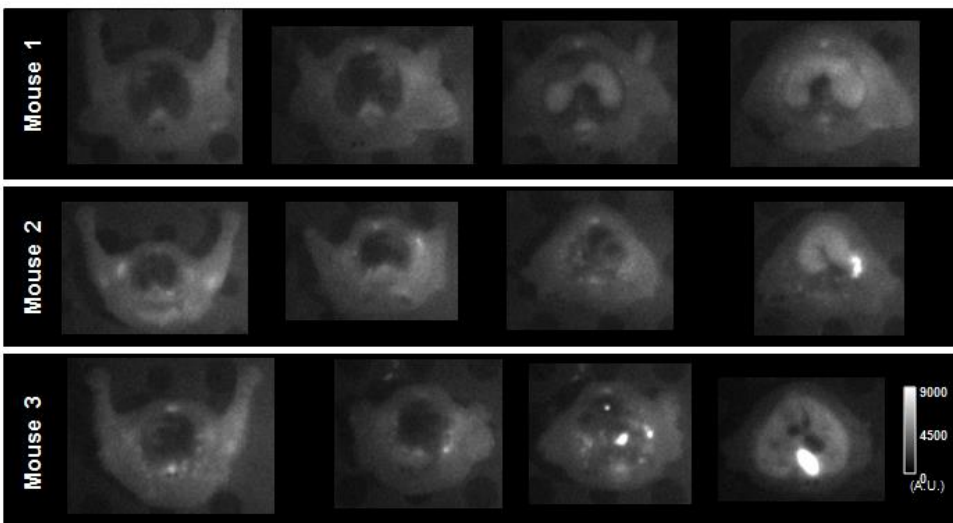
Supplemental Figure 2

(a) CW fluorescence images of a series of MTLn3-iRFP720 cells injected subcutaneously in nude mice. (b) Corresponding fluorescence lifetime images obtained from a single exponential fit of the TD fluorescence decays. (c-e) Fluorescence decay amplitudes from a dual basis function analysis of the TD data. (c) Merged RGB image with red component assigned to the amplitude a_{FP} for a single exponential decay corresponding to iRFP720 lifetime ($\tau=0.68$ ns) and the green component assigned to the amplitude a_{AF} , for a biexponential basis function representing tissue autofluorescence. Both the amplitudes are normalized to the maximum computed value for each cell dilution. The amplitudes a_{FP} and a_{AF} are shown separately in (d) and (e), respectively. The contrast to background ratio (CBR) for decay amplitude images ranges from 17.3 for 4.5×10^4 iRFP720 cells to 5.7 for 1,400 subcutaneous cells. In comparison, in the CW images there is no contrast (CBR =1) between the surrounding skin and injection site for injections below 1.2×10^4 iRFP720 cells (CBR =1.6), with a maximum CBR of 2.95 observed from 4.5×10^4 iRFP720 cells. (f) A ratio of the iRFP720 and mouse autofluorescence lifetime amplitudes (a_{FP}/a_{AF}) eliminates variations in excitation power and camera integration times and demonstrates both the linearity and sensitivity of this fluorescence lifetime based detection method.



Supplemental Figure 3

(a) White light, (b) CW fluorescence, and (c) fluorescence decay amplitude images from cryosections corresponding to the mouse in Figure 3a. In (c), the tissue AF is shown in green and iRFP-720 in red.



Supplemental Figure 4

CW fluorescence images (excitation: 710nm, emission: 750nm Long pass) of cryosections corresponding to the three mice in Figure 3e-f at 144 hours post tail vein injection of 1×10^6 MTLn3-iRFP720. Each mouse displays a significant level of tissue autofluorescence. Bright foci are observed in cryosections from Mouse 2 and Mouse 3. These bright foci exhibit the characteristic fluorescence lifetime of iRFP720 (0.68 ns).