Real-time, Near-Infrared Fluorescence Imaging with an Optimized Dye/Light Source/Camera Combination for Surgical Guidance of Prostate Cancer

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Abstract

Purpose: The prostate-specific membrane antigen (PSMA) is a surface glycoprotein overexpressed on malignant prostate cells, as well as in the neovascularature of many tumors. Recent efforts to target PSMA for imaging prostate cancer rely on suitably functionalized low-molecular-weight agents. YC-27 is a low-molecular-weight, urea-based agent that enables near-infrared (NIR) imaging of PSMA in vivo. Experimental Design: We have developed and validated a laparoscopic imaging system (including an optimized light source, LumiNIR) that is capable of imaging small tumor burdens with minimal background fluorescence in real-time laparoscopic extirpative surgery of small prostate tumor xenografts in murine and porcine models.

Results: In a mouse model, we demonstrate the feasibility of using real-time NIR laparoscopic imaging to detect and surgically remove PSMA-positive xenografts. We then validate the use of our laparoscopic real-time NIR imaging system in a large animal model. Our novel light source, which is optimized for YC-27, is capable of detecting as little as 12.4 pg/mL of the compound (2.48-pg YC-27 in 200-μL agarose). Finally, in a mouse xenograft model, we demonstrate that the use of real-time NIR imaging can reduce positive surgical margins (PSM).

Conclusions: These data indicate that a NIR-emitting fluorophore targeted to PSMA may allow improved surgical treatment of human prostate cancer, reduce the rate of PSMs, and alleviate the need for adjuvant radiotherapy postoperatively.

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Introduction

 Radical prostatectomy is the gold standard in the surgical treatment of prostate cancer (1). Despite advances in technique, surgery for prostate cancer remains fraught with positive surgical margins (PSM) due to the inability to detect early extra capsular extension intraoperatively (2). Efforts to decrease PSM by the use of numerous technical maneuvers during the procedure have been disappointing, suggesting that new techniques are needed to prevent residual malignant tissue at the time of surgery, when it can still be removed (3). The proximity of the neurovascular bundles and rectum to the prostate precludes routine-wide excision during radical prostatectomy, and efforts to spare the neurovascular bundles (and preserve penile erectile function) results in PSM in 10% to 38% of men at high volume centers, with particularly high rates in men with the most dangerous and aggressive disease (2, 4). Men with PSM are more likely to suffer biochemical recurrence (2) and require adjuvant radiotherapy (5), with increased morbidity and expense as a consequence (6).

Every PSM causes the patient to undergo salvage radiotherapy, which adds an additional $25,000 to $35,000 to their care. In some reports, robotic prostatectomy patients have as high as a 3.7-fold higher risk of a PSM than open surgery (7). Hu and colleagues reported that an estimated 27.8% of men undergoing robotic prostatectomy underwent salvage radiation, compared with 9.1% with open surgery. Given that currently more than 233,000 men are diagnosed with prostate cancer each year and more than 54,000 men undergo robotic-assisted prostatectomy as their primary treatment, as many as 15,000 men undergo adjuvant radiotherapy primarily because of an issue with PSM. The estimated cost to our government is >$375 million for radiotherapy alone and more than $1 billion in other costs from the impact of that treatment. Therefore, novel technologies that limit PSM...
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Translational Relevance

Robot-assisted laparoscopic prostatectomy is completely dependent upon visualization to assure complete removal of malignant tissue. Here, we present a technique that enhances the capacity to provide a negative surgical margin after prostatectomy using a near-infrared (NIR) fluorescent compound recently described in conjunction with a light source specifically tuned to its detection in the NIR region of the spectrum. A negative margin avoids the morbidity experienced by patients who often undergo irradiation if a positive margin is identified.

during prostatectomy may decrease the morbidity and expense associated with surgery for prostate cancer.

Advances in the sensitivity of imaging techniques and the development of new fluorophores with high quantum yields have raised interest in real-time fluorescence-guided imaging for use in surgery. Recent work has focused on fluorophores in the near-infrared (NIR) range (wavelengths between 700 and 900 nm), due to the low absorption and autofluorescence of biologically relevant molecules in this range, particularly hemoglobin and water (8). Thus, in a surgical field in which blood and bodily fluids are present, signal from the NIR fluorophore should remain readily visible. These fluorophores permit a high signal-to-noise ratio due to the low level of autofluorescence, thus depicting target cells as bright stars in a dark background. Use of this technology relies on the development of fluorescent probes that specifically target cancer cells as well as imaging modalities that provide accurate real-time imaging.

Prostate-specific membrane antigen (PSMA) is a type II transmembrane glycoprotein that catalyzes the hydrolysis of N-acetylglutamyl phosphotidylethanolamine (NAAG) to glutamate and N-acetylglutamate (NAA) through an extracellular domain. PSMA is markedly overexpressed in virtually all malignant prostate tissue and expression increases with tumor aggressiveness (9). In addition, PSMA has been identified in the neovasculature of nearly all solid tumors, including colorectal cancer, bladder cancer, glioblastoma multiforme, breast cancer, pancreatic cancer, and testicular cancer (10–11). Accordingly, PSMA is emerging as an important target in cancer imaging and therapy (12–16). We have previously described the development and use of YC-27, a novel low-molecular-weight fluorescent agent (absorbance maximum, 774 nm; emission maximum, 792 nm) that targets PSMA and enables NIR imaging of cells expressing PSMA in murine models of prostate cancer in preclinical testing (17). Here, we report the use of a proprietary laparoscopic imaging system (LumiNIR) designed to detect NIR fluorescent agents in vivo that consists of a novel NIR laser light source using a wavelength optimized for YC-27, and a modified low light charged couple device (CCD) camera, which is operated similarly to a conventional white light laparoscopic platform. When combined with YC-27, the LumiNIR system allowed detection of very small burdens of PSMA-positive cells in vivo with minimal signal from PSMA-negative cells. In a murine model, PSMA-positive xenografts were readily detectable after intravenous (i.v.) administration of YC-27, even allowing visualization of PSMA-positive tumors through the skin in real time. In a porcine laparoscopic model that closely approximated human laparoscopic extraperitoneal surgery, a PSMA-positive xeno-graft was clearly identified and removed using the LumiNIR system. The use of the LumiNIR along with a targeted dye (YC-27) allows for refinement of current surgical techniques to decrease PSMA.

Materials and Methods

Cell culture

PSMA-expressing LNCaP cells were obtained from the ATCC (cat. no. CRL1740). Both the PSMA-expressing PC3-PIP and PSMA-negative PC3-FLU cell lines were obtained from Dr. Warren Heston (Cleveland Clinic, Cleveland, OH). LMD and LMD-PSMA cells were generated by lentiviral transduction of cells derived from lung metastasis of mice bearing orthotopic MDA-MB231 tumors that were provided by Dr. Sridhar Nimmagadda (Johns Hopkins University, Baltimore, MD; Supplementary Methods). All cells were cultured in RPMI-1640 medium (Corning Cellgro; cat. no. 10-040) with 10% FBS (Sigma-Aldrich; cat. no. F4135-500ML), 50 µg/mL of Gentamicin (Quality Biological; cat. no. 120-099-661) and 5 µg/mL of ciprofloxacin (US Biological; cat. no. C5074). Cells were passaged at confluence of 90% at a dilution of 1:10. Cell cultures were maintained in 5% CO2 at 37°C in a humidified incubator.

Authentication of cell lines

All cell lines used in the study were tested for the lack of Mycoplasma using the MycoAlert Mycoplasma Detection Kit (Lonza) every 6 months. The LNCaP cells were authenticated by short tandem repeat (STR) analysis. The PC3-PIP, PC3-FLU, LMD-PSMA, and LMD cells were characterized by their PSMA expression status and cell morphology.

Immunohistochemistry

The resected tumor was fixed using formalin, embedded in paraffin, and sectioned. Histologic analysis was performed using hematoxylin and eosin (H&E)–stained slides. Immunohistochemistry for PSMA expression was completed using a Ventana automated immunostainer and an i-View immunolabeling kit (Ventana Medical Systems). For antigen retrieval, the specimen was incubated with Standard CC1 (EDTA buffer) for 60 minutes, followed by incubation with the primary antibody [PSMA clone 3E6, 1:100 dilution (30 minutes) at 37°C; Dako Cytomation].

Animal models

All animal experiments were approved by the Animal Care and Use Committee at our institution and performed in accordance with relevant guidelines and regulations.

Resection of murine orthotopic prostate cancer

Under inhalational anesthesia with a mixture of isoflurane (Baxter Healthcare Corporation) and oxygen, a lower abdominal incision was made in an athymic Nu/Nu mouse. To establish an orthotopic prostate cancer model, 50 µL of a 1:1 suspension of 300,000 PC3-PIP cells and Matrigel (BD Biosciences; cat. no. 354248) was injected into the dorsal lobe of the prostate, and the animal was closed. Sixteen days later, 79.4 µg/kg of YC-27 was administered via tail vein injection. Twenty-four hours after injection, an exploratory surgery was performed using the Fluobeam (Fluoptics), an NIR imaging system. The abdomen and pelvis were carefully inspected for fluorescent signal. NIR imaging was performed at 5 to 15 frames per seconds (fps; the Fluobeam...
automatically adjusted the frame rate based on the signal intensity. The orthotropic tumor was identified by its fluorescent signal and resected.

**Epididymis imaging**

Athymic Nu/Nu mice were injected with 79.4 μg/kg of YC-27 and 24 hours later imaged with the Pearl. Animals were euthanized and organs were harvested, washed once with 1 × PBS and imaged on the Odyssey. Images were captured at 700 and 800 nm at a resolution of 21 mm using the same parameter settings. The 800-nm channel was displayed using a pseudocolor output and overlaid on the gray-scaled 700-nm channel in Adobe Photoshop, Version 11.0.

**RT-PCR for PSMA**

Six athymic Nu/Nu mice were sacrificed and organs were harvested. RNA was isolated from kidneys, liver, and epididymis using Trizol reagent (Invitrogen; cat. no. 15596-026). One milligram of total RNA was reverse transcribed using the QuantiTect Reverse Transcription Kit (Qiagen; cat. no. 205311) to generate cDNA. Intron/exon spanning mouse PSMA-specific primers were used to detect PSMA message in the different organs. cDNA (250 ng) was used in PCR analysis using GoTaq Green Master Mix (Promega Corporation; cat. no. M712) according to the manufacturer’s protocol.

**Proprietary laparoscopic NIR imaging system with the LumiNIR light source**

A proprietary 5.5 W 870-nm class 4 laser was designed and fabricated (Patent pending) and named LumiNIR. The complete system is depicted in Supplementary Fig. S1. The light source was coupled with a Stryker 502-457-010 10 mm 0° laparoscope (Stryker) using a Karl Storz 495NCS light cable (Karl Storz). The laparoscope was adapted to the Prosilica GX1920 camera (Allied Vision Technologies) using a c-mount Stryker 24 mm coupler (Stryker). The Prosilica GX1920 camera uses a Sony EXview HAD ICX674 sensor that has a quantum efficiency of approximately 31% at 800 nm. A long pass filter (Tarlo Technologies) using a c-mount Stryker 24 mm coupler (Stryker) was adapted to the Prosilica GX1920 camera (Allied Vision Technologies) using a Karl Storz 495NCS light cable (Karl Storz). The light source was fabricated (Patent pending) and named LumiNIR. The complete system is depicted in Supplementary Fig. S1. The light source was coupled with a Stryker 502-457-010 10 mm 0° laparoscope (Stryker) using a Karl Storz 495NCS light cable (Karl Storz). The laparoscope was adapted to the Prosilica GX1920 camera (Allied Vision Technologies) using a c-mount Stryker 24 mm coupler (Stryker). The Prosilica GX1920 camera uses a Sony EXview HAD ICX674 sensor that has a quantum efficiency of approximately 31% at 800 nm. A long pass filter, HQ800lp (Chroma Technology Corporation), which allows light of 800 nm or higher to pass through, was used in between the coupler and the sensor of the camera. The system is designed to allow the user to manually set the exposure time/frame rate, gain, and resolution during video and still image capture.

**NIR-guided laparoscopic resection of subcutaneous tumor in a murine model**

A PSMA-positive xenograft was established by injecting a 2:1 suspension of 3 × 10^6 LMD-PSMA cells and Matrigel into the right flank of athymic Nu/Nu mice. When tumors reached a volume of approximately 0.5 mm^3, 19.1 μg/kg YC-27 was administered via tail vein injection. NIR-guided laparoscopic resection of the xenograft was carried out in a laparoscopic training case (Global trade), using the LumiNIR 8 to 10 hours after i.v. injection. Images were taken before and after resection at 5 fps.

**Visualization of porcine kidney after YC-27 administration**

A 30-kg male Yorkshire pig was anesthetized with 1.32 mL of TKX (tiletamine HCl, 50 mg/mL; zolazepam HCl, 50 mg/mL; mannitol, 57.7 mg/mL; ketamine, 50 mg/mL; and xylazine, 50 mg/mL) given i.m. To suppress pain and prevent infection, 0.6 mg of buprenorphine and 660 mg of cefazolin was administered i.m. After intubation, a Veress needle was inserted into the peritoneal cavity, and CO₂ was used to insufflate the peritoneum to 15-cm H₂O. Three 10-mm ports were placed under laparoscopic vision. YC-27 was administered via i.v. injection at a dose of 3.33 μg/kg YC-27 and the kidney was observed over 30 minutes. Laparoscopic images were recorded with the LumiNIR.

**Detection of a prestained xenograft placed inside a porcine abdomen**

After establishing a 1,000 mm^3 LMD-PSMA xenograft in an athymic Nu/Nu mouse, 19.1 μg/kg YC-27 was injected i.v. 24 hours before the pig surgery. A 30-kg male Yorkshire pig was anesthetized with 1.32 mL of TKX (tiletamine HCl, 50 mg/mL; zolazepam HCl, 50 mg/mL; mannitol, 57.7 mg/mL; ketamine, 50 mg/mL; and xylazine, 50 mg/mL) given i.m. To suppress pain and prevent infection, 0.6 mg of buprenorphine and 660 mg of cefazolin was administered i.m. After intubation, a Veress needle was inserted into the peritoneal cavity, and CO₂ was used to insufflate the peritoneum to 15-cm H₂O. Three 10-mm ports were placed under laparoscopic vision. The murine YC-27 prestained tumor was surgically removed and placed behind the porcine peritoneum adjacent to the kidney. The prestained xenograft was visualized and removed with the guidance of the LumiNIR.

**Optimization of timing and dose**

A 2:1 suspension of 3 × 10^6 LMD in Matrigel was injected into the upper flanks of 20 athymic Nu/Nu mice, while an equivalent LMD-PSMA suspension was injected into the contralateral flank. When the tumors reached a volume of approximately 0.5 mL, YC-27 was administered via tail vein injection in varying doses (39.7, 19.1, and 9.5 μg/kg). Mice were sequentially imaged at 1, 2, 3, 4, 6, 8, 10, and 24 hours after i.v. injection using the LumiNIR at 5 fps. The images were captured at a constant gain setting using the “GigE Viewer” (Allied Vision Technologies GmbH) to obtain probe kinetics. The GigE Viewer interface allows the user to control the exposure time/frame rate and gain settings of the camera to the user’s preference. Regions of interest (ROI) were drawn around tumor sites, kidneys, muscle, and background. Arbitrary pixel count was used to evaluate dosing and timing for signal-to-noise ratio using ImageJ (18).

**Comparing the LumiNIR system to da Vinci Firefly**

A 2:1 suspension of 3 × 10^6 LMD and Matrigel (BD Biosciences) was injected into the upper flanks of athymic Nu/Nu mice, while an equivalent suspension of LMD-PSMA was injected into the contralateral flank. When the tumors were approximately 200 mm^3, 79.4 μg/kg YC-27 was administered i.v. Twenty-four hours after injection, the animals were scanned on the Pearl Impulse imager (Li-COR) at 170-μm resolution according to the manufacturer’s protocol, which requires about 30 seconds for image capture. Immediately afterwards, the animals were imaged using the LumiNIR at 10 fps and images were captured using the “GigE Viewer” (Allied Vision Technologies). Images captured on the Pearl and the LumiNIR were analyzed using the Pearl software and ImageJ (18), respectively.

**Comparing the LumiNIR system to the pearl**

A 2:1 suspension of 3 × 10^6 LMD and Matrigel (BD Biosciences) was injected into the upper flanks of athymic Nu/Nu mice, while an equivalent suspension of LMD-PSMA was injected into the contralateral flank. When the tumors were approximately 200 mm^3, 79.4 μg/kg YC-27 was administered i.v. Twenty-four hours after injection, the animals were scanned on the Pearl Impulse imager (Li-COR) at 170-μm resolution according to the manufacturer’s protocol, which requires about 30 seconds for image capture. Immediately afterwards, the animals were imaged using the LumiNIR at 10 fps and images were captured using the “GigE Viewer” (Allied Vision Technologies). Images captured on the Pearl and the LumiNIR were analyzed using the Pearl software and ImageJ (18), respectively.
well plate in duplicates and layered with 100 μL of 1% agarose. Two plates were made and one shipped to Intuitive on ice while the other was kept at 4°C. Both plates were imaged about the same time (48 hours after plating). One was imaged with the da Vinci Si System with the Firefly attachment that uses a proprietary image capture system that has a 1080p HD output and the exposure time/frame rate cannot be manually adjusted. The other was imaged with the LumiNIR at 5 fps. Arbitrary pixel count was analyzed with ImageJ (18). Wells containing cells but no dye were used to determine the noise of the systems.

Results

Detecting a PSMA-positive orthotopic tumor in a mouse

We had previously described the development and use of YC-27, a low-molecular-weight fluorescent agent that targets PSMA and enables NIR imaging of cells expressing PSMA in murine models of prostate cancer (17). Using the Fluobeam (Fluoptics), a commercially available preclinical NIR imaging system, we set up a more realistic surgical situation. To determine whether YC-27 is able to identify and aid in resection of orthotopic murine prostate tumors, 3 × 10^5 PC3-PIP cells were implanted in the dorsal lobe of the prostate of athymic Nu/Nu mice. Sixteen days after implantation, 79.4 μg/kg of YC-27 was administered via i.v. injection. Twenty-four hours after i.v. administration of YC-27, exploratory open surgery with the aid of the Fluobeam was performed and a 3-mm orthotopic prostate cancer xenograft was detected and surgically resected under NIR guidance (Fig. 1A and B). H&E staining of the xenograft confirmed the presence of malignant cells (Fig. 1C), and immunohistochemistry with an anti-PSMA antibody proved that they were derived from the PSMA-positive PC3-PIP xenograft (Fig. 1D). Interestingly, signal in the epididymis was observed, indicating YC-27 uptake, which was unexpected (Fig. 2A and B). Expression was confirmed by RT-PCR on RNA collected from the epididymis, kidney, and liver of athymic Nu/Nu mice. The kidney was used as a positive control and, as expected, expression of murine PSMA mRNA was detected (19), while the liver provided a negative control (Supplementary Fig. S2). The Fluobeam is not compatible with current laparoscopic surgical equipment, which led us to developing our own imaging system.

Development of the LumiNIR system

NIR imaging is based on exciting a fluorophore and detecting the light emitted after it is excited. To do this, we engineered and fabricated an NIR detection system, LumiNIR, which can easily be integrated into both laparoscopic and robotic equipment (Supplementary Fig. S1). The LumiNIR is composed of a novel class 4 laser based off a 780-nm light source with a total power output of 5.5 W, and a modified Prosilica GX1920 high-resolution CCD camera. The NIR fluorescence images are captured using the 3/4" Sony ExViewHAD II ICX674 sensor in the Prosilica GX1920 with a reported 31% quantum efficiency at 800 nm modified with a 800-nm long-pass filter in front of the sensor. The light source is engineered to provide more than 30 different angles of light oriented and focused to precisely enter a standard laparoscopic high-density fiber optic light cable. When coupled to a properly coated laparoscope, the light is diffused to more than 45° as it exits the laparoscope, resulting in a wide field of illumination without creating potential areas of heat injury to the host tissue.

Use of LumiNIR in animal models

To test the LumiNIR system in a surgical setting, we used small and large animal surgical models. Breast cancer cells engineered to
express PSMA (LMD-PSMA) were subcutaneously xenografted into the right axil of athymic Nu/Nu mice. Exogenous expression of PSMA did not appear to change the in vitro growth and migration characteristics when compared with the parental LMD cells (Supplementary Figs. S3–S6). When tumors reached a volume of 500 mm³, mice were administered 19.1 μg/kg (HED of 100 μg for a 70-kg male) YC-27 via tail vein injection and after a 10-hour uptake time, mice were placed in a laparoscopic training box in which the xenografts were resected with the guidance of the LumiNIR system (Supplementary Movie S1). Supplementary Figure S7 shows images of the tumor bed before and after resection. Minimal signal in the tumor bed after resection indicated a possibility of residual tumor.

We then moved on to testing the system in a porcine model, an appropriate model for laparoscopic surgery to assess the feasibility of using YC-27 with the LumiNIR. Within 5 minutes of administering 3.33 μg/kg of YC-27, NIR signal was easily visible in the porcine kidney with the LumiNIR (Fig. 2A and B). This finding was expected, as YC-27 is known to have renal clearance (17), and PSMA is expressed in the murine and human kidneys (19, 20). Expression in porcine kidney has not been extensively studied but there is one report that it has expression in porcine kidney (21). In addition, the signal intensity from the kidney was directly proportional to the amount of excitation by the light source (Supplementary Movie S2). To assess whether tissue absorption of NIR signal would limit utility of NIR imaging in vivo, a LMD-PSMA tumor xenograft was explanted from its murine host after YC-27 administration and implanted behind the porcine peritoneum during laparoscopic exploration (Fig. 2C and D). To further demonstrate the utility of LumiNIR, the prestained xenograft was easily visualized and removed through the guidance of the LumiNIR (Supplementary Movie S3).

Performance of LumiNIR compared with a dedicated small animal imager

Prior characterization of YC-27 was done on the LI-COR Biosciences Pearl, a dedicated small animal imager. To test the LumiNIR system and determine the optimal dose and timing for surgery, athymic Nu/Nu mice bearing contralateral PSMA-positive and -negative tumors were injected i.v. with 39.7, 19.1, and 9.5 μg/kg of YC-27 and imaged at regular intervals using the LumiNIR (images for all concentrations of YC-27, and at all time points were captured under identical settings at 5 fps). The three different doses are based on the human equivalent dose (HED) calculation (22) and would be approximately 2 ×, 1 ×, and 0.5 × of what is considered a microdose in human studies (100 μg, ref. 23). An initial whole-body, fluorescent blush was observed in all animals immediately after injection with clearance from non-target tissues, proceeding according to the anticipated biodistribution kinetics (Supplementary Fig. S8; ref. 17). Signal in the PSMA-positive tumor was dose-dependent and nonspecific signal was cleared by 6 to 10 hours after injection, depending on the dose administered (Supplementary Fig. S9). The highest signal-to-noise ratio of 11.37 was observed 6 hours after administration of 9.5 μg/kg of YC-27, while at the dose of 19.1 μg/kg, the signal-to-noise ratio was 10.94 at 8 hours after administration, and at the highest dose of 39.7 μg/kg the signal-to-noise ratio was 10.4 at 10 hours after administration. To compare the LumiNIR with the LI-COR Biosciences Pearl, athymic Nu/Nu mice bearing contralateral PSMA-positive and -negative tumors of about 200 mm³ were administered 39.7 μg/kg of YC-27 via i.v. injection. The animals were imaged with the LI-COR Biosciences Pearl 24 hours after injection and immediately afterwards using the LumiNIR system at 10 fps. ROIs were drawn around the PSMA-positive and -negative tumors from images generated from the LumiNIR and LI-COR Biosciences...
Pearl (Fig. 3A–C), and signal-to-noise ratios were calculated. Despite differences in exposure time between the Pearl imager and LumiNIR (~30 s/image vs. 0.1 seconds, respectively), the signal-to-noise ratio was nearly the same with both systems (Fig. 3D), supporting that the real-time laparoscopic LumiNIR system possesses the sensitivity necessary for application to a clinical setting.

Performance of LumiNIR compared with da Vinci Firefly

Currently, the only commercially available surgically guided NIR imaging system is the Intuitive Surgical NIR clinical device, the Firefly attachment to the da Vinci robot. This is a system that is equipped with filters optimized for indocyanine green (ICG) but can also detect YC-27. To compare the LumiNIR and da Vinci Firefly, identical plates containing dilutions of ICG (peak emission wavelength, 830 nm) and YC-27 (peak emission wavelength, 792 nm) were imaged on both systems. To quantify the signal, ROIs were drawn around each dilution series. In this setting, the LumiNIR could detect as little as 15.63 pmol of ICG, which is similar to the Firefly (Supplementary Fig. S10). When imaging YC-27, the LumiNIR was more sensitive than the da Vinci Firefly. When using a signal-to-noise ratio of 1.2 as a cutoff value for visual detection, the LumiNIR could detect 2.48 pg of YC-27 compared with 39.69 pg of the compound required for detection by the da Vinci system (Fig. 4).

LumiNIR can reduce PSM

The LumiNIR was developed with the goal of being able to reduce PSMs. To determine whether image-guided surgery using YC-27 and the LumiNIR was a means to reduce positive margins, we resected PSMA-positive xenografts after YC-27 administration with the guidance of LumiNIR system \((n = 8)\) or by conventional surgery \((n = 10)\). For animals resected under the guidance of the LumiNIR, tissue was resected until there was no residual signal (Fig. 5). Upon white light evaluation, there was no detectable residual tumor in any surgery. The animals were then followed for over a month, and only the animals resected by conventional surgery had recurrence at the primary site (Fig. 6 and Supplementary Table S1). The recurrence rate of 40% in the surgeries done under white light is in the range of what is seen with aggressive tumors. Treuting and colleagues (24) have seen 33% to 53.5% recurrence rates at the primary site after surgical resection of MDA-MB-435 xenografts in nude mice. We have previously seen 25% to 40% recurrence at the primary site after simple surgical resection with RenCa, CT-26, TrampC2, and B-16 xenograft models (Unpublished Data). These results demonstrate NIR image-guided surgery using the LumiNIR can be used to decrease PSMs resulting in decreased morbidity and mortality. A reduction in PSM would also reduce the costs associated with adjuvant therapies, and morbidities associated with them, which is the standard of care in patients with PSM.

Figure 3.
Comparing the LumiNIR with the Pearl imager. Athymic Nu/Nu mice \((N = 5)\) with established PSMA-positive (white arrow) and PSMA-negative (yellow arrow) subcutaneous tumors were imaged using the Pearl (A), and the LumiNIR: PSMA-positive (B) and PSMA-negative (C) 24 hours after i.v. administration of 39.7 μg/kg of YC-27. Comparing the PSMA-positive and -negative xenografts, similar signal-to-noise ratio was observed with both the systems (D).
Discussion

The primary objective in oncologic surgery is complete removal of malignant tissue at the time of resection. However, the ability of the human eye or even laparoscopically magnified imaging to discriminate malignant tissue from surrounding benign tissue often limits the completeness of resection, particularly for microscopic tumor burdens. The advent of tumor-specific, efficient NIR fluorophores, and increasingly sensitive CCD sensors, promises to allow detection of these microscopic extensions of tumor at the time of surgery, when they may be readily excised (25). This paradigm-shifting technology may enable more complete excisions and reduce the need for expensive and morbid adjuvant therapies.

Figure 4.
The Intuitive da Vinci Firefly System can be used to detect YC-27. Identical plates containing dilutions of YC-27 were used to compare the LumiNIR with Intuitive Surgical’s NIR clinical surgical system, the Firefly attachment of the da Vinci system. The Firefly has been optimized for compounds such as the ICG, whereas the LumiNIR has been optimized for compounds such as the YC-27. The LumiNIR can detect as little as 2.48 pg of the compound, whereas with the da Vinci system, we could detect 39.7 pg of the compound. The red line indicates a signal-to-noise ratio of 1.2 as a cutoff value for visual detection. This demonstrates the ability to use the da Vinci if enough probe is used. It might be possible to detect tumors using tracer doses in a patient with an optimized detection system.

Figure 5.
Comparison of surgeries with and without NIR illumination. Animals with established LMD-PSMA xenografts were given 37.9 mg/kg YC-27 about 20 hours before the surgery. The first (leftmost) four columns contain photographs of surgeries performed with NIR guidance so that there was no residual tumor left. The second (rightmost) four columns contain photographs of surgeries performed without NIR guidance. Under white light, both sets looked the same, that is, it was impossible to determine whether there was residual tumor under white light. All the animals were imaged with the NIR device described herein after surgery and with the Pearl imaging system after the animals were sutured. The animals were also imaged 7 days after surgery with the Pearl imaging system. Of note, 19.1 mg/kg YC-27 was administered i.v. 6 hours before the imaging on day 7. We resected tumors on 8 animals with the guidance of the LumiNIR, whereas there were 10 other animals on which the surgical resection was carried out under white light. This experiment was carried out only once.
Intraoperative NIR fluorescent surgical guidance has recently become feasible for a variety of reasons. First, fluorescent emission may be captured quickly (~30 ms), allowing real-time detection with frame rates of up to 30 fps, consistent with laparoscopic and robotic surgical technology. Second, NIR fluorescence uses CCD cameras at high spatial resolution, allowing high-definition images. Third, NIR fluorescence technology is readily compatible with existing laparoscopic and robotic surgical systems, and Intuitive Surgical has recently integrated the Firefly imaging technology (Novadaq Technologies) into the da Vinci system. The data presented in this study suggest the potential utility of the Firefly attachment in augmenting tumor visualization during radical prostatectomy after administration of YC-27. Alternatively, the LumiNIR is optimized for detection of YC-27 and provides even greater sensitivity to detect microscopic extension of tumors in vitro and may enable detection of smaller tumor burdens during oncologic surgery.

Sensitivity analysis found that YC-27 can distinguish as few as 3,125 PSMA-positive cells over PSMA-negative cells in vitro (Supplementary Figs. S11 and S12). Considering that 1 mm³ of tumor is estimated to contain approximately 100,000 tumor cells (26), this sensitivity may allow detection of very small tumor burdens, as would be expected at the site of a positive margin or in micrometastatic disease. In murine models, a signal-to-noise ratio of approximately 11 was seen after i.v. injection of YC-27, and when combining this high signal-to-noise ratio with the excellent spatial resolution allowed by a CCD camera, tumor borders had sharp contrast with surrounding tissue in real-time imaging. A proof-of-concept study was performed in a relevant laparoscopic porcine model by visualizing and removing a pre-stained xenograft from behind the peritoneum of a male pig. The LumiNIR was also able to facilitate the surgical removal of PSMA-positive prostate cancer xenografts in a murine model and decrease the rate of PSMs.

A similar urea-based agent has been used for positron emission tomography/computed tomography (PET/CT) imaging in humans and detected more putative metastatic lesions than the gold standard combination of CT and bone scintigraphy with minimal toxicity (13), suggesting that the small doses of YC-27 likely necessary in humans will be effective with limited side effects. Studies performed with dual modality single-photon emission computed tomography (SPECT)/optical (NIR) compounds demonstrate that with a single tracer dose minimal lesions could be detected (12). Using such compounds would allow a single administration to allow for SPECT imaging before surgery and fluorescent imaging during surgery with the potential benefit of preoperative surgical planning for potential sites of extracapsular extension and micrometastatic disease to local lymph nodes.

Previous studies have evaluated the use of NIR fluorescence imaging to guide detection and treatment of cancer, including ovarian cancer (27, 28), colorectal cancer (29), breast cancer (30), gastric cancer (31), head and neck cancer (32), and liver cancer (33). van Dam and colleagues (27) evaluated intraoperative fluorescence imaging in ovarian cancer using a folate-FITC agent, which fluoresces in the visible spectrum and targets FR-α. The authors detected all FR-α-positive tumors intraoperatively, with a signal-to-noise ratio of 3.1:1. With the combination of LumiNIR and YC-27, we can obtain a signal-to-noise ratio of up to 11:3:1. According to Eckelman and colleagues (34), the ideal signal-to-noise ratio for an imaging agent is 10:1.

To date, most reports using the da Vinci/SPY system have used nonspecific NIR dyes (35), but recently, Laydner and colleagues (15) reported a proof-of-concept study using a PSMA-targeting small molecule and the da Vinci/Firefly Surgical System in murine surgery. Weak signal was detected in 2 of 3 mice with large PSMA-positive xenografts. Although no signal-to-noise ratios were reported, background signal was noted to be strong, particularly from the kidney, liver, and bladder, which may limit utility during prostatectomy. Furthermore, a large quantity of the imaging agent was necessary to obtain these results (10 nmol, ~60× microdose) compared with 0.5× microdose (0.12 nmol) of NIR fluorescent agent in this study. Unfortunately, in the Laydner and colleagues study, the fluorescence signal detected was not reliable for surgical applications due to the weak signal despite large PSMA-positive xenografts. No signal was detectable from the base of the tumor, which questions whether the agent and technology could reliably detect PSM. In this study, NIR-guided laparoscopic surgery was accurate and reliable using very small doses of YC-27. In addition, in this study, we demonstrate large animal applications that closely approximate human laparoscopic surgery.

We report a practical NIR dye/light source/camera combination that could be easily implemented in contemporary prostate cancer surgery without disrupting the common clinical pathway, offering a novel strategy for the detection and treatment of prostate cancer. We also compare our system with the da Vinci Firefly attachment, the most widely used robotic surgical system. Our combination would enable exquisite detection of PSMA-expressing cells and has been evaluated in relevant animal models, including simulation of human laparoscopic extirpative surgery. This technology can be used to detect minimal disease not infrequently left in the surgical bed after Robotic Assisted Laparoscopic Prostatectomy (RALP), thereby minimizing or even eliminating a PSM and the
attendant morbidity and cost of adjuvant therapy. The ability to potentially eliminate PSM during RALP may represent the single biggest cost savings achievable. Moreover, as PSMA is expressed in most tumor neovasculature, this technology can also be extended to other malignancies to aid in tumor resection, where residual tumor portends not only morbidity and cost, but also increased mortality.

Disclosure of Potential Conflicts of Interest
Under a licensing agreement between I-I-COR and the Johns Hopkins University, Drs. Pomper, Chen, and Mease are entitled to a share of royalties received by the University on sales of products described in this article. The terms of this arrangement are being managed by the Johns Hopkins University in accordance with its conflict of interest policies. No conflicts of interest were disclosed by the other authors.

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Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): B.P. Neuman, J.B. Eifler, M. Castaneras, W.H. Chowdhury, A. Mukherjee, S.E. Lupold, R. Rodriguez

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