Activation of nano-photosensitizers by Y-90 microspheres to enhance oxidative stress and cell death in hepatocellular carcinoma

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While radioembolization with yttrium-90 (Y-90) microspheres is a promising treatment for hepatocellular carcinoma (HCC), lower responses in advanced and high-grade tumors present an urgent need to augment its tumoricidal efficacy. The purpose of this study was to determine whether clinically used Y-90 microspheres activate light-responsive nano-photosensitizers to enhance hepatocellular carcinoma (HCC) cell oxidative stress and cytotoxicity over Y-90 alone in vitro. Singlet oxygen and hydroxyl radical production was enhanced when Y-90 microspheres were in the presence of several nano-photosensitizers compared to either alone in cell-free conditions. Both the SNU-387 and HepG2 human HCC cells demonstrated significantly lower viability when treated with low activity Y-90 microspheres (0.1–0.2 MBq/0.2 mL) and a nano-photosensitizer consisting of both titanium dioxide (TiO2) and titanocene (TC) labelled with transferrin (TiO2-Tf-TC) compared to Y-90 microspheres alone or untreated cells. Cellular oxidative stress and cell death demonstrated a linear dependence on Y-90 at higher activities (up to 0.75 MBq/0.2 mL), but was significantly more accentuated in the presence of increasing TiO2-Tf-TC concentrations in the poorly differentiated SNU-387 HCC cell line (p < 0.0001 and p = 0.0002 respectively) but not the well-differentiated HepG2 cell line. Addition of TiO2-Tf-TC to normal human hepatocyte THLE-2 cells did not increase cellular oxidative stress or cell death in the presence of Y-90. The enhanced tumoricidal activity of nano-photosensitizers with Y-90 microspheres is a potentially promising adjunctive treatment strategy for certain patient subsets. Applications in clinically relevant in vivo HCC models are underway.

Hepatocellular carcinoma (HCC) is a primary liver malignancy that is the fourth leading cause of cancer-related death worldwide, and expected to further increase in Western populations with the significant rise in chronic liver disease secondary to non-alcoholic steatohepatitis1-4. Despite recent advances in systemic agents such as immunotherapy, there persists a substantial cohort of non-responders or poor responders to these agents, necessitating the need for therapeutic innovations5. Yttrium-90 (Y-90) radioembolization involves the minimally invasive, image-guided delivery of microspheres embedded with the high-energy pure beta-emitting radionuclide Y-90 to liver tumors in a precise and selective fashion directly through their arterial supply resulting in highly concentrated internal radiation therapy6. Effective and long-lasting objective responses are achieved when Y-90 microspheres are delivered to HCC tumors at high absorbed radiation doses7-9. Despite this, there are several limitations to Y-90 radioembolization, including lower response rates in patients with advanced stages of HCC, those with poorly differentiated tumors, and when adequate Y-90 radiation tumor dose is unable to be achieved either due to poor vascular conduits or significant dose heterogeneities on a micro-dosimetry level10-14. This highlights the need to innovate this treatment paradigm to enhance the cytotoxic efficacy of Y-90 at lower radiation doses to extend its treatment benefits to these more vulnerable and high-risk patients.

Beta-emitting radionuclides emit near ultraviolet to blue visible light, known as Cerenkov Radiation (CR)15-17. This light, along with the direct energy of the beta particle can activate light sensitive drugs known as nano-photosensitizers to generate tumoricidal reactive oxygen species (ROS) through a photodynamic therapy (PDT)
In vivo, PDT results in tumor death through a multi-dimensional processes involving direct cell damage, microvascular shutdown, and activation of anti-tumor immune response through immunogenic cell death\(^1\). Prior work has shown that positron emitters such as F-18, Zr-89, and Ga-68 can serve as effective nano-photosensitizer activation sources to produce reactive oxygen species (ROS) from H\(_2\)O and O\(_2\), potentially introducing additional therapeutic mediators for cancer cell death. (B) Broad spectrum optical output of Y-90 (in Y-90\(\text{Cl}_3\) form) versus that of FDG and Zr-89 at equal activities (0.925 MBq) as measured on an IVIS Illumina (4 min exposure, 4 binning, 10 cm field-of-view, f-stop 1, open filter, excitation blocked). (C) Y-90 exhibited photon fluxes over fivefold greater than Zr-89 and over 16-fold greater than FDG. (D) Y-90 exhibited average radiances over sixfold greater than Zr-89 and over 17-fold greater than FDG. Values represent mean ± standard deviation of three measurements.

In this study, we determined whether Y-90 in its clinically used microsphere form could activate UV-responsive nano-photosensitizers to generate tumoricidal ROS and induce HCC cell death in vitro at activities approximating absorbed radiation doses lower than typically required for HCC tumor response in the clinic according to the Medical Internal Radiation Dose (MIRD) model (<180 Gy). Our results showed that Y-90 has a luminescence output several folds greater than that of other clinically used beta-emitters. Treatment of various nano-photosensitizers with Y-90 microspheres generated tumoricidal singlet oxygen and hydroxyl radicals in cell-free media. Using a dual nano-photosensitizer consisting of titanium dioxide (TiO\(_2\)) and titanocene (TC) labelled with transferrin (Tf) to facilitate tumor cell uptake (TiO\(_2\)-Tf-TC), we show Y-90 microsphere treatment activated cellular and mitochondrial oxidative stress to enhance cell death in highly malignant and poorly differentiated SNU-387 HCC cells. Interestingly, well-differentiated HepG2 HCC cells showed greater cell death with Y-90 microspheres alone compared to SNU-387 cells, and this was not enhanced with nano-photosensitizers. Importantly, addition of nano-photosensitizers did not increase oxidative stress or cell death from Y-90 in normal human liver cells. These results indicate that Y-90, in its clinically used microsphere form can activate nano-photosensitizers resulting in enhanced HCC cell death with potentially greater impact in certain histologic subtypes. These results support further investigations into the use of nano-photosensitizers as an adjunctive treatment and the differential responses of Y-90 alone amongst various HCC subtypes.
Materials and methods

Measuring bioluminescence output of radionuclides. Y-90Cl₃ was obtained from Eckert and Ziegler Radiopharma (Berlin, Germany). Both F-18 fluorodeoxyglucose (FDG) and Zr-89 were obtained and produced in compliance with good manufacturing practices (GMP) from a CS-15 biomedical cyclotron at our local institution. Phantoms containing 0.925 MBq of each radionuclide in triplicate were imaged in 96-well clear bottom, black walled plates, on an IVIS Illumina (PerkinElmer, Waltham, MA) with an open filter, 4 min exposure, 4 binning, 10 cm field-of-view, f-stop 1, excitation block. Broad spectrum optical output was measured using region-of-interest analysis using Living Image Software version 2.60.1 (PerkinElmer, Waltham, MA) to obtain photon flux (photons/s) and radiance (photons/s/cm²/sr) values.

Nano-photosensitizer formulations. For cell-free ROS assays, hypericin (Millipore Sigma, Burlington, MA), TiO₂ anatase 25 nM nanoparticles (Sigma Aldrich, St. Louis, MO), and titanocene (TC) formulated into human serum albumin were used as nano-photosensitizers. TiO₂-based nano-photosensitizers were synthesized in a manner described previously. Briefly, 25 nm diameter anatase TiO₂ nanoparticles (Sigma Aldrich Co.) were suspended in deionized water to form a 10 mg/mL stock solution, which was then mixed vigorously with human apo-transferrin (TI, Athens Research and Technology, Athens, GA), dissolved in phosphate buffered saline (PBS) using a 1:3 TiO₂ to TI mass ratio and dispersed by sonication at 3 W for 60 s with a Cole Parmer Ultrasonic Processor GE 130 PB (Cole Parmer, Vernon Hills, IL). The mixture was immediately filtered through a 0.22 μm polyethersulfone (PES) syringe filter (VWR Scientific, Batavia, IL), and 2% by volume of a 12 mM TC (Alfa Aesar, Tewksbury, MA) solution in DMSO was added, yielding TiO₂-Tf-TC. Suspensions were characterized for size with dynamic light scattering (DLS) using a Malvern Zetasizer Nano ZS system (Supplemental Fig. 1). A similar protocol was used with a 12 μM Alexa680-tagged Ti (ThermoFisher Scientific, Waltham, MA) using the 1:3 TiO₂ to Tf mass ratio to yield TiO₂-Alexa-TF.

HSA-TC was synthesized and characterized in the same way described previously. Briefly, 80 mg TC was taken in 16 mL 0.5% aqueous solution of HSA and the mixture was shaken for 6 h at 560 oscillation per min in IKA KS 130 basic plate shaker at room temperature. The mixture was then immediately subjected to lyophilization in Thermo Fischer SAVANT RVTS105 refrigerated vapor trap lyophilizer to obtain the HSA-TC nanoparticle as orange red dry powder. The dry powders were reconstituted in DPBS immediately prior to use in the cell free assays or in cell studies. The size distributions and concentrations were confirmed in the same way as described previously.

Cell-free ROS assays. Resin Y-90 microspheres (SirSpheres, Sirtex, Woburn, MA) were obtained as unused leftover vial doses after routine clinical use and were transferred to our lab under institutional and radiation safety approval and protocol. Y-90 SirSpheres was the only form of microsphere used in this study. Both singlet oxygen and hydroxyl radical cell-free assays were performed in 96-well, clear bottom, black walled plates (Corning, Corning NY) with appropriate concentrations of nano-photosensitizers and activities of Y-90 microspheres in a total volume of 0.2 mL in phosphate-buffered saline (PBS, Life Technologies, Carlsbad, CA). For singlet oxygen radical measurement, singlet oxygen sensor green (SOSG) reagent (ThermoFisher Scientific, Waltham, MA) was added for a final concentration of 5 μM to each experimental condition well. Activation of SOSG reagent by singlet oxygen radical was determined by measuring 504 nm excitation/525 nm emission fluorescence according to manufacturer instructions using a Synergy HT multimode plate reader (BioTek Instruments Inc) immediately before and at several time points after addition of Y-90 microspheres up to 72 h. Experimental conditions included PBS alone, nano-photosensitizer alone (Hypericin 500 nM, TC 0.1 μM or 1 μM, or TiO₂ 10 μg/mL or 50 μg/mL) added to Y-90 microspheres. The activities of 0.26 MBq and 0.52 MBq were chosen as they approximately correspond 65 Gy and 130 Gy previously.

For hydroxyl radical measurement, hydroxyphenyl fluorescein (HPF) reagent (ThermoFisher Scientific, Waltham, MA) was added at a final concentration of 5 μM to each experimental condition well. Activation of HPF reagent by hydroxyl radical was determined by measuring 490 nm excitation/515 nm emission fluorescence according to manufacturer instructions using the above plate reader (BioTek Instruments Inc, Winooosti, VT) immediately before and at several time points after addition of Y-90 microspheres up to 72 h. Experimental conditions were identical to that for singlet oxygen except with the absence of the sodium azide (NaN₃) experimental condition. Each experimental condition was repeated five times.

Cell culture. SNU-387 HCC cells were a generous gift from Dr. Terence Gade (Department of Radiology, University of Pennsylvania). HepG2 HCC cells were obtained from ATCC (Manassas, VA). STR profiling performed at our institution indicated that both cell lines matched reference standards per ATCC guidelines. Differentiation status of both cell lines was based off transcriptomic classifications by Caruso et al., with HepG2 cells characterized by well-differentiated, with hepatoblast-like features and SNU-387 as less-differentiated, invasive, with mesenchymal-like features. SNU-387 and HepG2 cells were maintained in Roswell Park Memorial Institute (RPMI) (Gibco Life Technologies, Carlsbad, CA) and Eagle’s Minimum Essential (EEM) media (Corning Life Sciences, Tewksbury, MA) respectively, both supplemented with 10% fetal bovine serum (Gibco) and 0.5% penicillin/streptomycin. The normal human liver epithelial cell line THLE-2 was obtained from ATCC (Manassas, VA) and maintained in Bronchial Epithelial Cell Growth media (Lonza, Basel, Switzerland) supplemented...
with 10% fetal bovine serum (Gibco) and 0.5% penicillin/streptomycin. All cell lines were maintained in a jacketed humidified CO₂ (5%) incubator at 37 °C and passaged when confluent. Core facility testing at our institution for contaminants such as mycoplasma was negative.

**Internalization of TiO₂-Tf constructs in SNU-387 cells.** After grown to confluence, SNU-387 cells were plated at a density of 8000 cells/well on black-walled clear bottom 96 well plates and incubated at 37 °C for 24 h. Cells were then treated with TiO₂-Alexa-Tf nano-photosensitizers. Both brightfield and fluorescence confocal microscopy were performed at 4, 24, and 72 h post treatment using an Olympus FV1000 confocal microscope using the AlexaFluor 633 excitation/emission channel. Fluorescence and bright-field image overlay with false color was performed using Fluoview FV10-ASW software from Olympus.

**Cell-based ROS and death assays.** After grown to confluence, all cell lines were plated at a density of 8000 cells/well on black-walled clear bottom 96 well plates (Corning, Corning NY) and incubated at 37 °C for 24 h. The dual nano-photosensitizer TiO₂-Tf-TC was then added at either 0 μg/mL (control), 10 μg/mL, or 50 μg/mL final concentration, then incubated for 2 h at 37 °C. Y-90 microspheres were then added at low or high anticipated activities. Given the marked heterogeneity and settling of Y-90 microspheres, the exact activity for each experimental well was obtained by measuring the open filter luminescence on a Synergy HT multimode plate reader (BioTek Instruments Inc, Winooski, VT) immediately after adding Y-90 microspheres and normalizing to that obtained from standard curves generated from Y-90Cl₃ at identical plate reader gains (Supplemental Fig. 2). After 72 h of incubation at 37 °C, HPF (ThermoFisher Scientific, Waltham, MA) was added to each well for a final concentration of 5 μM to assess for hydroxyl radical. After 30 min of incubation at 37 °C, fluorescence was measured using 490 nm excitation/515 nm emission using the above plate reader. These same experimental steps and conditions were performed to assess for mitochondrial superoxide production, except after the 72 h incubation, media was suctioned off and MitoSOX Red (ThermoFisher Scientific, Waltham, MA) reagent was added at a final concentration of 5 μM according to manufacturer’s instructions. After 30 min incubation at 37 °C, fluorescence was measured using 510 nm excitation/580 nm emission. Cell death was assessed using propidium iodide (PI) staining (Millipore Sigma, Burlington, MA) according to manufacturer’s instructions using the same experimental conditions. For each nano-photosensitizer concentration, there were at least 5 experiments without Y-90 and 10 experiments with various Y-90 microsphere activities.

**HCC cell viability assays at low Y-90 activities.** After grown to confluence, the two HCC cell lines (SNU-387 and HepG2) were plated at a density of 8000 cells/well on black-walled clear bottom 96 well plates (Corning, Corning NY) and incubated at 37 °C for 24 h. The dual nano-photosensitizer TiO₂-Tf-TC was then added at either 0 μg/mL (control) or 50 μg/mL final concentration, then incubated for 2 h at 37 °C. Y-90 microspheres were then added at low (less than 0.2 MBq/0.2 mL) activities and incubated for 72 h. Exact Y-90 activity was obtained by luminescence readings in each condition with reference to Y90-Cl standards as described above. Cell viability was assessed using the CellTitre-Glo Luminescence assay (Promega, Madison, WI) according to manufacturer’s instructions. Luminescence from Y-90 alone was accounted for by subtracting the background luminescence obtained just before adding the Cell-Titre-Glo reagent. Each experimental condition was performed in at least triplicate.

**Live-dead cell confocal microscopy in SNU-387 cells.** After grown to confluence, SNU-387 cells were plated at a density of 10,000 cells/well on an 8-well chambered slide (Corning, Corning NY) and incubated at 37 °C for 24 h. Cells were then treated with either Y-90 microspheres (0.52 MBq/0.2 mL) alone, TiO₂-Tf-TC (50 μg/mL) alone, Y-90 microspheres combined with TiO₂-Tf-TC, or untreated for 72 h. Following this, a live/dead cell stain consisting of Cyto-dye to stain live cells and propidium iodide (PI) to stain dead cells (Millipore Sigma, Burlington, MA) was added to each condition and incubated at 37 °C for 10 min according to manufacturer’s instructions. The media was suctioned off, washed with PBS, and the cells were fixed with para-formaldehyde (Sigma Aldrich, St. Louis, MO). Cells were then stored at 4 °C until the Y-90 had fully decayed (greater than 10 half-lives, approximately 30 days). Live and dead cell fluorescence confocal microscopy was performed using 488 nm excitation/518 nm emission and 488 nm excitation/632 nm emission respectively according to manufacturer’s instructions using an Olympus FV1000 confocal microscope. Fluorescence and bright-field image overlay with false color was performed using Fluoview FV10-ASW software from Olympus.

**Statistical analysis.** Statistical analysis was performed using GraphPad Prism 9.2 (GraphPad Software, Inc., La Jolla, CA). All data for radionuclide optical output, cell-free ROS production, and cell viability is expressed as assay signal in mean ± standard deviation. Statistical significance between experimental groups was assessed using one-way ANOVA followed by Tukey’s multiple comparison tests. Cell-based HPF, MitoSox, and PI values were plotted versus Y-90 microsphere activity for each nano-photosensitizer concentration. Simple linear regression was performed for each nano-photosensitizer concentration, and differences in slopes were determined using one-way ANOVA. Statistical significance was set as alpha less than 0.05.

**Results**

Y-90 exhibited high luminescence output and reactive oxygen species (ROS) production that was markedly enhanced with nano-photosensitizers and Y-90 microspheres in cell-free conditions. Broad spectrum luminescence demonstrated that Y-90 had a bright optical output several times greater than F-18 or Zr-89. Phantoms containing equal activities (0.925 MBq) of F-18 fluorodeoxyglucose
(FDG), Zr-89, and Y-90 (in Y-90Cl₃ form) were imaged on an IVIS Illumina (4 min exposure, 4 binning, 10 cm field-of-view, f-stop 1, open filter, excitation blocked). As shown in Fig. 1, Y-90 optical luminescence was over fivefold higher compared to Zr-89 and over 16-fold high compared to F-18 (Fig. 1B), as measured by both photon flux (photon/s) (Fig. 1C) and radiance (photon/s/cm²/sr) (Fig. 1D), in keeping with prior calculations and measurements.

Generation of singlet oxygen radical, the primary tumoricidal mediator of photodynamic therapy (PDT), was assessed using the singlet oxygen sensor green (SOSG) assay with and without different Y-90 microsphere activities (0.26–0.52 MBq/0.2 mL, approximating 65–130 Gy assuming MIRD) and nano-photosensitizer concentrations (Fig. 2). Significant increase in singlet oxygen radical production was seen with higher nano-photosensitizer concentrations (over threefold with Hypericin 500 nM Fig. 2A, over twofold with TC 1 μM, Fig. 2B; and up to twofold with TiO₂ 50 μg/mL, Fig. 2C) when combined with both low (0.26 MBq/0.2 mL) and higher (0.52 MBq/0.2 mL) activities of Y-90 microspheres after 48-h treatment (all p < 0.0001). This effect was abolished in the presence of the singlet oxygen radical scavenger sodium azide (NaN₃), indicating that this signal was indeed due to ROS production. Generation of hydroxyl radical over time was assessed using the hydroxyphenyl fluorescein (HPF) assay with and without various activities of Y-90 microspheres and concentrations of nano-photosensitizers. As shown in Fig. 3, increased hydroxyl radical was seen with higher concentrations of each

Figure 2. Combining Y-90 microspheres with nano-photosensitizers results in enhanced singlet oxygen radical production in cell-free media. Marked increase in singlet oxygen radical production was seen in the presence of nano-photosensitizers (A) hypericin 500 nM, (B) titanocene bound to human serum albumin (TC) 1 μM, and (C) TiO₂ 50 μg/mL with both low and high Y-90 microsphere activities compared to either alone. This effect was diminished in the presence of the singlet oxygen radical scavenger sodium azide (NaN₃). Values represent mean ± standard deviation of five measurements. ***p < 0.001, ****p < 0.0001.
nano-photosensitizer and Y-90 microsphere activities and increased over time up to 72 h (just over one Y-90 half-life). Similar to singlet oxygen production, hydroxyl radical production from hypericin or TC did not appear to be influenced by higher Y-90 microsphere activities (Fig. 3A, B). However, TiO₂ generation of hydroxyl radical was increased at higher Y-90 microsphere activities (Fig. 3C). Neither singlet oxygen or hydroxyl radical was significantly generated by Y-90 microspheres or nano-photosensitizer alone in cell-free media (Figs. 2 and 3), similar to other results utilizing therapeutic beta-emitting radionuclides such as I-131 as a platform for PDT³². Overall, this data demonstrated that Y-90 exhibited high luminescence output and reactive oxygen species (ROS) production was markedly enhanced with nano-photosensitizers and Y-90 microspheres in cell-free conditions.

Cellular oxidative stress from Y‑90 microspheres is enhanced in the presence of nano-photosensitizers in poorly-differentiated SNU-387 but not well-differentiated HepG2 HCC cells. For experiments involving HCC cells in vitro, we utilized a transferrin (Tf) labelled dual nano-photosensitizer con-
sisting of both TiO₂ and TC (TiO₂-Tf-TC), given previous work demonstrating greater tumoricidal efficacy compared to single nano-photosensitizers with lower radiance radionuclides18. In addition, transferring receptor (TfR) has found to be overexpressed in HCC and prior work with Tf-labelled nanoparticles showed high accumulation within HCC tumors versus non-targeted formulations in vivo33,34. We showed that this nano-photosensitizer construct labelled with AlexaFluor-680 internalized within SNU-387 HCC cells (Supplementary Fig. 3). Cellular oxidative stress as assessed by hydroxyl radical and mitochondrial superoxide production in both poorly differentiated SNU-387 and well-differentiated HepG2 HCC cells at 72 h was tested using the HPF and MitoSox assays respectively with various Y-90 microsphere activities and increasing concentrations of TiO₂-Tf-TC. Analysis at 72-h was chosen given the significant increase in hydroxyl radical generation in cell-free media (Fig. 3) at this time point and it was just over one half-life of Y-90. As shown in Fig. 4A,B, hydroxyl radical generation was increased in the presence of Y-90 microspheres alone without TiO₂-Tf-TC and demonstrated a linear dependence on Y-90 activity (Fig. 4A, increase of 69,337 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 65,145–73,529, r² = 0.99 for SNU-387 cells and Fig. 4B, increase of 4094 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 2932–5255, r² = 0.92 for HepG2 cells). In poorly differentiated SNU-387 cells, conditions with increasing concentrations of TiO₂-Tf-TC showed significantly greater hydroxyl radical generation in the presence of Y-90 microspheres compared to that without TiO₂-Tf-TC, and was linearly related with Y-90 activity (Fig. 4A, increase of 88,426 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 83,815–93,037 for TiO₂-Tf-TC 10 μg/mL, and increase of 111,557 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 105,464–117,650 for TiO₂-Tf-TC 50 μg/mL, both r² = 0.99, p < 0.0001), indicating that TiO₂-Tf-TC enhanced oxidative stress in HCC cells in vitro. Interestingly, the addition of TiO₂-Tf-TC to the well differentiated HepG2 cells did not result in a significant increase in hydroxyl radical generation (Fig. 4B, increase of 5209 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 83,815–93,037, r² = 0.92 for TiO₂-Tf-TC 10 μg/mL, and increase of 5327 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 105,464–117,650, r² = 0.91 for TiO₂-Tf-TC 50 μg/mL, p = 0.1744).

Production of mitochondrial superoxide in SNU-387 cells was also increased in the presence of Y-90 microspheres alone without TiO₂-Tf-TC, and was linearly related with Y-90 activity (Fig. 4C, increase of 88,426 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 83,815–93,037 for TiO₂-Tf-TC 10 μg/mL, and increase of 111,557 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 105,464–117,650 for TiO₂-Tf-TC 50 μg/mL, both r² = 0.99, p < 0.0001), indicating that TiO₂-Tf-TC enhanced oxidative stress in HCC cells in vitro. Interestingly, the addition of TiO₂-Tf-TC to the well differentiated HepG2 cells did not result in a significant increase in hydroxyl radical generation (Fig. 4B, increase of 5209 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 83,815–93,037, r² = 0.92 for TiO₂-Tf-TC 10 μg/mL, and increase of 5327 HPF a.u. per Y-90 MBq/0.2 mL, 95% CI 105,464–117,650, r² = 0.91 for TiO₂-Tf-TC 50 μg/mL, p = 0.1744).

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Nano-photosensitizers enhance Y-90 microsphere-mediated HCC cytotoxicity. We sought to determine whether TiO$_2$-TF-TC would induce HCC cell death in combination with otherwise non-toxic Y-90 microsphere activities. To test this, we determined cell viability of SNU-387 and HepG2 cells by ATP quantification treated with TiO$_2$-TF-TC with and without low activities of Y-90 microspheres (0.1–0.2 MBq/0.2 mL). Both cell lines demonstrated a significant decrease in cell viability with the combination of Y-90 microspheres and TiO$_2$-TF-TC after 72 h treatment but not with either alone, compared to untreated cells (Fig. 5A, p = 0.0002 for SNU-387 cells, Fig. 5C, p = 0.0035 for HepG2 cells). At higher Y-90 activities (up to 0.75 MBq/0.2 mL), we determined cell death utilizing propidium iodide (PI) staining given the increased interference from Y-90's Cerenkov emission with luminescence-based cell-viability assays. As demonstrated in Fig. 5B, SNU-387 cell death was linearly dependent on Y-90 activity (increase of 60,793 PI a.u. per Y-90 MBq/0.2 mL, 95% CI 44,126–77,459, $r^2 = 0.84$), similar to the cell-based hydroxyl radical and mitochondrial superoxide findings. However, conditions
with increasing concentrations of TiO$_2$-TF-TC showed significantly greater SNU-387 cell death in the presence of Y-90 microspheres compared to that without TiO$_2$-TF-TC, and was also linearly related with Y-90 activity (Fig. 5B, increase of 81,450 PI a.u per Y-90 MBq/0.2 mL, 95% CI 71,662–91,238, $r^2 = 0.96$ for TiO$_2$-TF-TC 10 μg/mL and increase of 99,371 PI a.u per Y-90 MBq/0.2 mL, 95% CI 88,702–110,039, $r^2 = 0.97$ for TiO$_2$-TF-TC 50 μg/mL, $p = 0.0002$). Live/dead cell stain confocal microscopy of untreated SNU-387 cells or those treated with TiO$_2$-TF-TC alone (50 μg/mL) showed mostly live cells (green Cyto-dye stain, Supplemental Fig. 4). In contrast, cells treated with Y-90 microspheres alone showed minimal live cells remaining, while those treated with combined Y-90 microspheres and TiO$_2$-TF-TC showed complete absence of live cells, presence of necrotic cells (red PI stain), and an abundance of cellular debris (Supplemental Fig. 4). HepG2 cells demonstrated a linear and increased rate of cell death with Y-90 activity alone compared to SNU-387 cells (Fig. 5D, increase of 120,334 PI a.u per Y-90 MBq/0.2 mL, 95% CI 106,360–134,309, $r^2 = 0.9234$ for HepG2 vs increase of 60,793 PI a.u per Y-90 MBq/0.2 mL, 95% CI 44,126–77,459, $r^2 = 0.8404$ for SNU-387 cells, $p < 0.0001$). Similar to that observed with hydroxyl radical and mitochondrial superoxide production, cell death was not enhanced with the addition of nano-photosensitizers in HepG2 cells (Fig. 5D, increase of 118,912 PI a.u per Y-90 MBq/0.2 mL, 95% CI 102,727–135,097, $r^2 = 0.89$ for TiO$_2$-TF-TC 10 μg/mL and increase of 141,732 PI a.u per Y-90 MBq/0.2 mL, 95% CI 123,651–159,814, $r^2 = 0.9009$ for TiO$_2$-TF-TC 50 μg/mL, $p = 0.0886$). Overall, we demonstrated that nano-photosensitizers significantly enhanced Y-90 microsphere-mediated HCC cytotoxicity.

Nano-photosensitizers do not increase oxidative stress or cell death in normal human hepatocytes.

We sought to determine whether TiO$_2$-TF-TC increased oxidative stress and cell death in normal human liver cells, which would have implications with added unwanted toxicities from this combined treatment. As shown in Fig. 6A, there was a linear relationship with Y-90 activity and hydroxyl radical generation in THLE-2 cells, but this was not increased when co-treating with increased concentrations of TiO$_2$-TF-TC (increase of 24,593 HPF a.u per Y-90 MBq/0.2 mL, 95% CI 17,438–31,748, $r^2 = 0.81$ for Y-90 without TiO$_2$-TF-TC, increase of 26,016 HPF a.u per Y-90 MBq/0.2 mL, 95% CI 20,808–31,224, $r^2 = 0.90$ for TiO$_2$-TF-TC 10 μg/mL, and increase of 24,593 HPF a.u per Y-90 MBq/0.2 mL, 95% CI 17,438–31,748, $r^2 = 0.81$ for TiO$_2$-TF-TC 50 μg/
Discussion

Given that Y-90 is one of the brightest and most efficient Cerenkov emitters of clinically used beta-emitting radionuclides, we hypothesized that it would also be a viable activator of nano-photosensitizers to enhance tumoricidal activity of HCC. Here we demonstrate that Y-90, specifically in its clinically used microsphere form (SirSpheres), activates light sensitive nano-photosensitizers to generate tumoricidal singlet oxygen radical among other ROS in cell-free media, which is a key mediator of PDT. Furthermore, this resulted in differential effects in HCC cell lines in vitro, with increased cellular hydroxyl and mitochondrial superoxide production along with increased cytotoxicity in the poorly differentiated SNU-387 HCC cell line but not in the well-differentiated HepG2 HCC cell line. This corroborates prior work demonstrating that low radiance beta-emitters such as F-18, Zr-89, and Cu-64 can activate nano-photosensitizers to enable depth-independent PDT to treat various malignancies. The time dependent increase in hydroxyl radical generation when nano-photosensitizers were combined with Y-90 microspheres up to 72 h is in keeping with its relatively long half-life of 64.1 h, and it is conceivable that even greater and effective tumoricidal ROS would be realized in the clinical scenario of liver tumor radioembolization where the effective half-life of Y-90 is far greater than its physical half-life.

Contrary to observations in cell-free media, the presence of Y-90 alone without nano-photosensitizer resulted in generation of hydroxyl and mitochondrial superoxide radicals and HCC cell death in vitro and was linearly dependent on Y-90 activity. This is not unexpected given the high energy beta particle interaction in a cellular environment likely results in persistent and elevated downstream oxidative byproducts, mirroring the tumoricidal activity seen with Y-90 alone in the clinic. Interestingly, our results demonstrate enhanced oxidative stress with increasing concentrations of TiO₂-Tf-TC both on a broad level with increased cellular hydroxyl radical production and specifically at the mitochondrial level with increased mitochondrial superoxide production in the poorly differentiated SNU-387 cells. While both of these oxidative products are to an extent nonspecific given the complex and convergent cellular oxidative pathways, it is in keeping with prior observations that the mitochondria is a therapeutic target of PDT. Importantly, there was significantly decreased viability at Y-90 activities up to 0.75 MBq/0.2 mL, which approximately corresponds to 170 Gy according to the MIRD model, also below the perfused liver volume absorbed dose considered for ablative purposes in HCC and may show enhanced activity against tumors that require higher doses for response. Importantly, addition of TiO₂-Tf-TC did not increase oxidative stress or cell death in normal human hepatocytes. Along with the favorable biodistribution profile of TiO₂-Tf-TC demonstrated in prior work showing minimal off target lung or background liver deposition, we anticipate a low likelihood that this novel treatment strategy would increase the toxicity profile of Y-90.

We did not observe a significant increase in cellular ROS production and cytotoxicity by adding nano-photosensitizers at higher activities of Y-90 (above 0.2 MBq/0.2 mL) in the well differentiated HepG2 cell line, which contrasts with that seen in the poorly differentiated SNU-387 cell line. However, HepG2 cells were more sensitive to the cytotoxic effects of Y-90 alone compared to SNU-387 cells. These two observations may indicate that there may be less room for therapeutic improvements by introducing adjunctive therapies such as nano-photosensitizers in the more sensitive HepG2 cell line. While these results need to be confirmed in a greater number of samples, limited clinical data has shown patients with more poorly differentiated histological grade HCC tumors, as indicated by dual tracer FDG/C-11 acetate positron emission tomography (PET)/CT, had poorer response rates and survival after Y-90 radioembolization than their well-differentiated counterparts.
The enhanced oxidative stress and cytotoxicity of poorly differentiated SNU-387 cells with nano-photosensitizers indicates that this novel adjunctive therapy may exert greater therapeutic benefits with certain histologic subtypes, who may already be in critical need for additional therapeutic options. These findings and the substantial genetic heterogeneity of HCC also calls for the careful design of in vivo studies utilizing different orthotopic animal models and patient-derived xenografts of varying malignant potential and genetic profiles to capture which patient cohorts may benefit.

Regarding implementing depth-independent PDT with Y-90, using its microsphere form (SirSpheres) is advantageous as it is already widely used in the clinic worldwide, avoiding the need to innovate and re-translate the beta-emitting source with often costly and elaborate radiochemistry. Furthermore, we show that activation of nano-photosensitizers is achieved when Y-90 most likely remains extracellular (SirSphere mean diameter 35 μm, with Y-90 permanently imbedded within the resin microsphere preventing leaching), likely as a result of its high decay energy (mean 0.94 MeV, maximum 2.28 MeV) and beta-minus particle tissue penetration of 2–11 mm (mean 2.5 mm). This obviates the need to reformulate Y-90 to internalize in cancer cells, which is likely required to enable activation of nano-photosensitizers with other lower energy or penetration radionuclides. Therefore, clinical translation efforts can focus on nano-photosensitizer formulation and can be more readily combined with the clinical workflow of widely implemented Y-90 microspheres either in resin or glass forms. The use of TiO₂ and TC as nano-photosensitizers is advantageous as both absorb light in the UV range where Cerenkov emission is highest and most efficient, and the former is less susceptible to photobleaching seen with organic photosensitizers. In addition, TiO₂ is a photosensitizer capable of regenerative production of hydroxyl and singlet oxygen radicals. This effect can be initiated by irradiation of TiO₂ with UV-spectrum radiation within 250–350 nm produced by the Cerenkov emission from Y-90 decay. The relative abundance of singlet oxygen and hydroxyl radicals is dependent on the size of the TiO₂ nanoparticle and the availability of O₂ with hydroxyl being favored in a hypoxic environment. However, our demonstration of enhanced ROS production with a variety of photosensitizers, including the naturally occurring and clinically used hypericin, provides justification to explore additional nano-photosensitizer formulations. In keeping with prior work, TiO₂-Tf-TC internalizes into HCC cells in vitro, where PDT is likely to be most efficacious, and may ultimately spatially enhance the tumoricidal activity of Y-90 microspheres. However, studies examining uptake and retention of nano-photosensitizers over a sufficient time period of Y-90’s decay are needed in clinically relevant in vivo orthotopic models of HCC.

The use and handling of Y-90 microspheres (SirSpheres) for in vitro experiments presents substantial logistical challenges due to their high energy hazards, heterogeneity and microsphere settling, requiring specialized equipment and radiation safety approvals. These hazards proved prohibitive for certain assays that involved luminescence at higher Y-90 activities, flow cytometry, and was a challenge for microscopy studies as the Y-90 had to fully decay (greater than 30 days) before analysis. Settling and heterogeneity of microspheres was controlled for by determining the background luminescence of each experimental condition for cell studies and normalizing to a standard luminescence to activity curve generated with Y-90-Cl₂. However, the invariably present spatial heterogeneity of Y-90 microspheres in our experimental conditions reflects common working assumptions of microsphere microdosimetry in current practice.

The in vitro data in this study provides motivation to investigate Y-90 microsphere activation of nano-photosensitizers in clinically relevant in vivo HCC models. Given the different effects in two HCC cell lines of different malignant potential and cancer etiology, in vivo models with more aggressive tumor subtypes and patient derived xenografts of similar nature that may be more relevant to Y-90 therapy should be prioritized. Given that administering Y-90 microspheres via the hepatic artery in small animals is resource-intensive and highly technically challenging, efforts to select the correct and most informative in vivo model is of critical importance. These efforts are ongoing. While we demonstrated enhanced cellular oxidative stress and death in HCC cells in vitro compared to Y-90 microspheres alone, this difference was more modest compared to that seen in our cell-free media results and compared to positron beta-emitting radionuclides that do not exhibit cytotoxicity at relevant activities alone in other studies. However, we anticipate the therapeutic effects of Y-90 microspheres combined with nano-photosensitizers to be further apparent in vivo and in the clinic due to the multi-dimensional tumoricidal mechanisms of PDT such as microvascular shutdown and generation of immunogenic cell death which are not captured in in vitro experiments. In addition, we did not assess differences in cell death mechanisms or signaling pathways between Y-90 microspheres alone or combined with nano-photosensitizers, which would likely be more revealing in vivo HCC models.

In conclusion, stimulation of nano-photosensitizers by Y-90 microspheres generated marked enhancement of ROS production in cell-free media which in turn resulted in enhanced oxidative stress and cell death in highly malignant SNU-387 HCC cells compared to Y-90 microspheres alone. We anticipate these therapeutic effects to be further apparent in vivo and in the clinic due to multi-dimensional tumoricidal mechanisms of PDT, with the ultimate goal of enhancing Y-90 radioembolization for HCC and other liver tumors. In addition, tumor penetration and intracellular uptake of TiO₂-Tf-TC nano-photosensitizers may improve the spatiotemporal tumoricidal activity of Y-90 microspheres. Applications in clinically relevant in vivo HCC models are underway.

Data availability
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions
C.M., C.E., K.B., and S.A. conceived the research concept and experimental design. C.M., C.E., J.P., P.K., and K.B. performed the experiments. C.M., C.E., J.P., A.Z., K.B., M.S. and S.A. analyzed and reviewed the data. C.M. wrote the manuscript. All authors reviewed and revised the manuscript.

Competing interests
The authors declare no competing interests.

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