Prostate-specific Membrane Antigen Directed Selective Thrombotic Infarction of Tumors


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ABSTRACT

Prostate-specific membrane antigen (PSMA), a glutamyl preferring carboxypeptidase, is found in prostate and other carcinomas present on both tumor cells and associated microvascular lining cells. We find that the channel structures delineated by PSMA-expressing cells in human and rat prostate tumors are in functional continuity with the vasculature and thus form part of tumor microvasculature. The PSMA-positive cell-outlined channels are CD31 negative and mutually exclusive of CD31-positive cell-lined channels elsewhere in the tumor consistent with tumor cells adapted to a pseudoendothelial phenotype in vasculogenic mimicry. To assess the functional potential of such PSMA-lined microvasculature to selectively direct infarctive tumor therapy, we coupled the soluble extracellular domain of tissue factor to a PSMA catalytic site inhibitor to create a PSMA-directed selective tumor vascular thrombogen (STVT). This protein induced selective local in vivo infarctive necrosis of the rat Mat Lu prostate tumor when administered i.v. The combination of administration of this STVT with low-dose doxorubicin produced a profound tumoricidal effect, resulting in complete eradication of some tumors. This is consistent with the therapeutic potential for a PSMA-directed STVT and expands the potential for selective infarctive ablation of tumors.

INTRODUCTION

The PSMA protein is a marker of prostate epithelial cells that are more highly expressed by CaP, especially in more advanced tumors (1). First identified by monoclonal antibody 7E11C-5 where it was found to be up-regulated in poorly differentiated, metastatic, and recurrent CaP (1–3). The cDNA was cloned and found to encode a type II transmembrane protein (1, 2), a glutamyl preferring carboxypeptidase that releases glutamate by hydrolysis of γ or α linkages (1, 4). This protein also has been described in brain as a neuropeptidase (1, 5), as well as in small intestine as folate hydrolase (1, 4). In normal prostatic epithelium, a cytosolic form of PSMA is found, whereas in CaP, there is a nearly 100-fold increase of the membrane form (6). There is evidence that indicates PSMA expression is up-regulated not only in tumor cells but also is found associated with local, what appear to be, microvascular lining cells in CaP and other tumors (1, 7, 8). We here explore whether PSMA-positive cells constitute, in part, intratumoral vasculature structures and what have been thought to be PSMA-expressing endothelial cells may be tumor cells adapted to vasculo-

The inappropriate expression of a novel gene product on the luminal surface of intratumoral microvascular lining cells provides a potential target to localize and assemble molecules for imaging or therapy. We have previously demonstrated the feasibility of localizing TF to tumor microvasculature to induce local tumor vasculature thrombosis (10). This strategy has successfully induced selective infarctive necrosis of tumors and frequent complete eradication in a proof of principle murine tumor model and without undesirable effects (10–12). We have characterized PSMA expression in both the human LuCaP tumor model and the rat Mat Lu prostate tumor model. Using a STVT incorporating a PSMA catalytic site inhibitor as the selective targeting element, i.v. administration induced selective local infarction of Mat Lu tumors. Combined therapy with doxorubicin significantly enhanced tumor eradication and prolonged the tumor-free status.

MATERIALS AND METHODS

Reagents. Murine monoclonal antibody J591, specific for the extracellular domain of PSMA, was kindly provided by Dr. N. Bander (School of Medicine, Cornell University). Monoclonal antibodies against mouse CD31 (MEC 13.3) and rat CD31 (TLD-3A12) were from PharMingen (La Jolla, CA). Bioti

5 The abbreviations used are: PSMA, prostate-specific membrane antigen; CaP, carcinoma of the prostate; TF, tissue factor; STVT, selective tumor vascular thrombogen; GuHCl, guanidinium hydrochloride; DTTaagcttTCACGTGCCCATACACTCTACCGG-3. The resulting 639-bp fragment was isolated by gel electrophoresis and subjected to a second PCR with BM33 and BM51: 5'-AAATggatccTGGTGCCTAGGGGCCCGG-GACTACAAATACTGTGGCAGCA-3'. The resulting 670-bp fragment was digested with BamHI and HindIII and ligated into the BamHI and HindIII sites of the vector pTrcHisC (Invitrogen, Carlsbad, CA). The BM51 oligo also encodes a thrombin cleavage site (Val-Pro-Arg-Gly-Ser) for selective proteolytic deletion of the His tag from the expressed protein. This plasmid (NuV120) is further modified to contain a linker sequence with three repeats of GlySer between the thrombin cleavage sequences and those of TF. The following overlapping oligos were annealed and inserted into the BamHI and Avai sites of NuV120: nuv20–1: 5'-GATCTTGGTCCCTAGGGGACCAA-3'; nuv20–2: 5'-PO4-AATGGCTCGGTTAATACTGCCG-3'; nuv20–3: 5'-PO4-GTGACCCGAGAGG-GCGGTTCAGTGTTGAGGTTCA-3'; nuv20–4: 5'-PO4-GGAGGTGGAGGGTTGTC-3'; nuv20–5: 5'-PO4-TCTCGGATCCCTAGGGACCAA-3';
fluoresce of a LuCap xenograph. The PSMA-positive cells (arrows). The expression is more intense at the lumenal surface of these cells, which are formed by tumor cells, and the PSMA expression is also more intense at the lumenal surface of these tumor cell-lined channels in B).

Body 7E11C-5 illustrates PSMA-delineating microchannels (arrows). CD31-positive endothelial cells (arrows). The two classes of cells are mutually exclusive, indicating that PSMA is not expressed on the vascular endothelium, which is consistent with the observation that PSMA is expressed only on the luminal surface of these tumor cell-lined channels.

Lu tumor-bearing rats were injected i.v. with 10^12 A. The resulting plasmid (NuV127) encodes a His-tag, a thrombin cleavage site, three repeats of the spacer Gly 4 Ser, and TF residues 3\text{CTCCA-3}. The resulting plasmid (NuV127) encodes a His-tag, a thrombin cleavage site, three repeats of the spacer Gly 4 Ser, and TF residues 3\text{CTCCA-3}. The protein construct was purified in two steps with a Source 15Q 16/10 column followed by a Sephacryl S-200 gel filtration. The purified protein was then concentrated with a Pellicon XL concentrator (MWCO, 10,000). The His tag is removed by thrombin digestion, and the protein is then further purified by gel filtration.

Preparation of STVT. Biotinylated D\text{βE} peptide (biotin-GSGSD\text{βE}) was synthesized using Fmoc chemistry and validated by mass spectrometry. Biotin-D\text{βE} was mixed at a 10:1 molar ratio with strep-TF fusion protein at 1 mg/ml in physiological saline for 30 min. The resulting D\text{βE}:strept-TF conjugate was freed of free biotin-D\text{βE} by dialysis. Immediately before injection, the D\text{βE}:strept-TF conjugate was mixed with an equimolar concentration of factor VIIa for 10 min to generate D\text{βE}:strept-TF:VIIa complex.

Cell Culture. The LuCap cells were cultured in RPMI 1640 supplemented with 10% FCS, 2 mM HEPES, 10 mM sodium pyruvate (1 mM), and glucose (4.5 g/liter). Mat Lu cells were cultured in RPMI 1640 with 10% FCS, glutamine (2 mM), and 250 nM dexamethasone.

Factor Xa Generation Assay. Factor Xa generation assays were performed as described previously (12) with modification provided for association of the STVT constructs to PSMA-expressing LnCap cells. Cells were plated at 8 × 10^5/well in 96-well plates and allowed to attach for 4 h in medium above. Medium was replaced with HBSA buffer [150 mM NaCl, 5 mM CaCl_2, 0.5% BSA, and 20 mM HEPES (pH 7.4)], and serial concentrations of D\text{βE}:strept-TF:VIIa or Strept-TF:VIIa complex were added to the wells. After 5 min of incubation, factor X was then added to a final concentration of 1 μM. After 5 min at 37°C, the limited proteolytic conversion of factor X to factor Xa was measured.

Animal Models. The LuCap human prostate tumor was cultured as a xenograft in WEHI nude mice (The Scripps Research Institute Breeding Facility). The tumors were passaged by implantation of 2-mm^3 fragments in the s.c. tissue of the back of the mice. The rat Mat Lu prostate carcinoma, carried in male Copenhagen rats ages 4–6 weeks (Harlan Sprague Dawley, Germantown, NY), was inoculated with 5 × 10^5 Mat Lu cells s.c./site in the back of the rats. Treatment was initiated once tumors reached 200 mm^3 through bolus i.v. injection of the STVT or control protein (0.1 mg/kg based on strep-TF protein) and repeated twice at 2-day intervals. For combination therapy,
liposomal doxorubicin (Doxil) at 2 mg/kg was separately injected i.v. Tumor growth and other physical signs were monitored daily, including gross evidence of tumor necrosis, local tumor ulceration, as well as evidence of toxicity, including mobility, response to stimulus, eating, and weight of each animal. The studies have been reviewed and approved by the Institutional Animal Care and Use Committee of The Scripps Research Institute. The work was conducted in the Scripps Research Institute facilities, which are accredited by the Association for the Assessment and Accreditation of Laboratory Animal Care. The Scripps Research Institute maintains an assurance with the U.S. Public Health Service and is registered with the United States Department of Agriculture and is in compliance with all regulations relating to animal care and welfare.

Statistical Analysis. Statistical significance was determined by the two-tailed Student’s t test, except for statistical significance of survival curves, which used the logrank test using GraphPad Prism version 3.00 (GraphPad Software, San Diego, CA).

RESULTS

PSMA-positive Cells Delineate some Intratumoral Microchannels. Immunohistochemical analysis of the human LuCap tumors clearly identified PSMA-positive cells that line and thereby delineate the microscopical channels with structural characteristics not unlike microvascular channels (Fig. 1A). The lumens of these channels are formed by tumor cells, and PSMA expression is more intense on the aspect of tumor cell membranes that constitute the lumenal surface of the channels (Fig. 1B). Double staining of the LuCap tumor with antimouse CD31 antibody and PSMA-specific antibody suggests these PSMA-delineated microchannels are distinct and mutually exclusive of microvascular channels lined by CD31-positive cells (Fig. 1C). Similar microchannels lined by PSMA-positive cells were also observed in syngeneic rat Mat Lu tumors (Fig. 1D).

To address the issue of whether the PSMA-positive microchannels are valid elements of the intratumoral microvasculature and directly continuous with the general vasculature, we infused bacteriophage i.v. as a vascular marker in tumor-bearing rats. Tumors were harvested ~2 min after infusion, rapidly frozen, and sectioned. Double immunostaining for PSMA and bacteriophage revealed that the PSMA-positive cell-lined microchannels contained phage (Fig. 1D) indicative of immediate functional continuity with the general vasculature.

The STVT Functionally Associates with PSMA-positive Cells. To confer cell surface assembly of the designed STVT to PSMA positive cells, a known suicide inhibitor of PSMA glutamyl carboxypeptidase, namely DβE, was incorporated (14–16). The biotin-GSGSDβE inhibitor structure was coupled to Strep-TF protein (Fig. 2, A and B) through the high affinity binding of biotin to the streptavidin domain. However, targeting alone is not sufficient for function because the STVT must also align properly on an anionic cell membrane surface and associate with factor X substrate that has localized to the same locus. The specific activity of the assembled DβE:strep-TF:VIIa complex on PSMA-expressing LnCap cells (Fig. 2C) was analyzed in a factor Xa generation assay that requires the functional assembly. Unlike most tumor cells, LnCap cells do not express TF as indicated by the coagulation assays and examined by Western blot (data not shown) and do not directly activate substrate factor X to the active product factor Xa and thereby drive the thrombogenic cascade (Fig. 2D). The dose dependent increase of factor Xa generation in the presence of LnCap cells was striking in comparison to the control Strep-TF lacking the PSMA-targeting element, indicating that the PSMA-directed STVT functionally assembles on the cell surface via binding of DβE to PSMA (Fig. 2D) and functionally initiates the thrombogenic cascade.

Tumor Infarction in Vivo. The control Strep-TF protein was not toxic in rats over a wide range of concentrations, thereby permitting evaluation of the potential for selective tumor thrombosis and infarctive necrosis in tumor-bearing rats. i.v. administration of the PSMA-
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directed STVT was associated with a rapid wave of microthrombosis and resultant infarction of Mat Lu tumors (Fig. 3A) with significant retardation in tumor growth (Fig. 3B). An average 70% reduction in tumor mass was observed compared with controls (Fig. 3C). The center of the tumors in the experimental group showed gross signs of ischemic necrosis. In contrast, there was no microthrombosis or areas of necrosis in these highly cellular tumors from the control group (Fig. 4A). Occluded tumor microvessels were widespread in the experimental group (Fig. 4B), with platelet aggregates, packed erythrocytes, and fibrin (Fig. 4C). The tumor interstitium that commonly contained a few erythrocytes was infiltrated with inflammatory cells (Fig. 4D).

After the standard three infusions at 2-day intervals, tumors showed very extensive necrosis with liquefaction of the entire central region of the tumors. However, at the growth edge of tumors from the treated animals, a rim of viable tumor tissue remained.

Combined STVT Plus Doxorubicin Therapy. To address the potential to enhance selective tumor microvascular thrombosis and infarction of tumors, infusions of both STVT and low-dose liposomal doxorubicin (2 mg/kg) were conducted. Three infusions of each were administered at 2-day intervals as above. There was a virtually complete arrest of tumor growth and even gross eradication of tumors in some rats (Fig. 5). This same combination therapy had a significant beneficial effect on survival of the tumor-bearing animal hosts ($P < 0.001$). The prolongation of survival of rats treated with STVT alone was modest but was significant. Therapy with low-dose liposomal doxorubicin alone had no measurable benefit (Fig. 6).

DISCUSSION

PSMA protein is synthesized by normal prostate epithelial cells; however, it is more highly expressed after neoplastic transformation of these cells (1). The protein is a glutamyl, preferring carboxypeptidase that hydrolyzes γ or α linkages to release glutamate (1, 4). Whereas normal prostate epithelial cells produce a cytosolic form of PSMA, transformation results in a nearly 100-fold increase of the membrane isoform (6). Some recent studies have suggested that PSMA expression is up-regulated not only in prostate carcinomas but also is associated with the local endothelial cells in prostate carcinomas and even in association with other tumors (1, 7, 8).

We have demonstrated in this study that PSMA-positive cells are found lining intratumoral microchannels that are not lined by conventional CD31-positive endothelial cells. Tumor cell surface expression of PSMA is more intense on that aspect of tumor cell membranes that delineate the luminal surface of these tumor cell-lined channels. These PSMA-delineated microchannels are continuous with the general vasculature based on the very rapid entry of bacteriophage into these channels after infusion by the tail vein. Additional studies demonstrate that extensive thrombotic infarction occurs after administration of a PSMA-localizing STVT. It is reasonable to hypothesize that the PSMA-positive cell delineated channels, which lack the usual endothelial marker CD31, are likely tumor cells adapted to a pseudoendothelial phenotype. Such adaptation has been described as vasculogenic mimicry (17–23) wherein tumor cells, rather than endothelial cells, adapt and line intratumoral microvascular channels. A recent study showed heterogeneous-invasive prostate carcinoma cell lines have the potential to form perfusable vasculogenic-like networks in culture (9). Existence of such networks in aggressive rat and human tumors in vivo, similar to this study, were observed (9). Although a current topic of some interest and debate (24–27), a greater degree of elucidation of the intrinsic cell biology and vasculogenic characteristics remain to be developed (28–30). However, in addition to the vasculogenic mimicry hypothesis, tumor cell surface molecules may be directly accessed by molecules in blood, including therapeutic agents, through direct transmigration of tumor cells through the microvascular lining cells to the lumen and subsequent detachment into the circulation during metastasis. These tumor cells initially localize to endothelial cells locally before releasing into circulation (29). In one study, it was estimated that ~15% of perfused vessels of a colon carcinoma xenograft were mosaic vessels with focal regions where tumor cells appeared to contact the microvessel lumen (30). Tumor cells accounted for ~4% of the total vascular surface area in these colon carcinomas. Similar numbers of mosaic vessels were found in human colon carcinoma biopsies (30), underscoring the complexity of...
intratumoral microvasculature and differences from normal vasculogenic rules.

A selective tumor microvascular thrombotic infarction strategy was used to determine whether tumor cell surface-expressed molecules, in this case PSMA, could both localize and properly assemble the cell surface TF:VIIa:X:membrane complex to initiate the thrombogenic cascade in vivo. Using this PSMA-directed STVT, we observed robust and highly selective tumor microvascular thrombosis and infarctive necrosis of syngeneic prostate tumors in the rats. The gross and histopathological changes observed were similar to those previously described by us and others for selective infarctive therapy of tumors (10, 31). Signs of tumor vasculature thrombosis occurred immediately after initial infusion of the STVT followed by infarction and necrosis. The adopted three-dose protocol was without any general adverse effect on the rats. However, despite the rapid tumor destruction, there remained viable tumor cells at the tumor periphery. However, host survival was significantly extended.

Combination therapy of the PSMA-directed STVT with low-dose liposomal doxorubicin was far more effective. Doxorubicin alone had no observable effect on tumor growth or survival. However, separate bolus infusions of doxorubicin at the time of STVT infusion greatly potentiated the effect on the tumors. Abrupt infarctive features of the tumors were observed. Although not directly addressed, the doxorubicin appears to facilitate eradication of tumor cells at the peripheral edge of the tumors where microthrombosis and necrosis appears to be less effective. However, the more attractive interpretation is that because doxorubicin is known to induce endothelial cell apoptosis (32), it may also have injured the tumor microvascular endothelium thereby increasing exposure of the tumor cells to plasma proteins to potentiate the local thrombotic activity of the PSMA-directed STVT.

These experiments underscore the potential importance of tumor cell exposure and even participation in intratumoral microvasculature.

Fig. 4. A, H&E-stained section of untreated Mat Lu tumor. Tumor cells are very poorly differentiated, and the tumor microvasculature is not easily identified. B, Mat Lu tumor after treatment exhibiting extensive necrosis and frequent microvessel thrombotic occlusion (arrows). C, treated tumor at higher magnification demonstrating a thrombosed vessel containing platelet aggregates, packed RBCs, and fibrin. D, higher magnification of treated tumor illustrating characteristic infiltration of inflammatory cells (arrows).

Fig. 5. Low-dose liposomal doxorubicin augmentation of the tumoricidal effect of PSMA-directed STVT therapy. In representative experiments, combination therapy resulted in nearly complete growth arrest of tumors in the treated animals (○, n = 12) in striking contrast to those treated only with low-dose liposomal doxorubicin (□, n = 12). The data points represent mean ± SE of 12 rats (P < 0.001). The experiment was reproducible with comparable results.

Fig. 6. Survival analysis of Mt Lu tumor-bearing rats. Combination treatment with PSMA-directed STVT with low-dose liposomal doxorubicin demonstrated significantly increased survival (n = 10) of tumor-bearing hosts. Low-dose doxorubicin alone (n = 10) had no significant effect. Survival was modestly prolonged in rats treated with STVT alone (n = 10) in contrast to the control saline-treated group (n = 10) or the doxorubicin group. The statistical significance between saline treated and STVT treated as well as between STVT treated and combination STVT plus doxorubicin treatment are significant with P < 0.0001 by logrank test.
Such exposure to the blood supports the therapeutic potential to target large molecules such as proteins to tumor cell surface molecules. The success of targeting the present STVT to a tumor cell surface-specific molecule expands the possible application of this approach to include other tumor cell surface molecules as the facilitators and targets. Dual therapy of a functional STVT and a cytotoxic agent shows promise in enhancing the infarctive eradication of tumors. Infarctive tumor eradication as been reported by us and others (10, 31) has the potential to develop as an effective therapeutic tactic.

ACKNOWLEDGMENTS

We thank Barbara Parker for her assistance in preparation of the manuscript.

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