Research Article

Integrin Alpha V Beta 3 Targeted Dendrimer-Rapamycin Conjugate Reduces Fibroblast-Mediated Prostate Tumor Progression and Metastasis[1]

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Running head: G5-rapamycin reduces PCa progression

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Abstract

Therapeutic strategies targeting both cancer cells and associated cells in the tumor microenvironment offer significant promise in cancer therapy. We previously reported that generation 5 (G5) dendrimers conjugated with cyclic-RGD peptides target cells expressing integrin alpha V beta 3. In this study, we report a novel dendrimer conjugate modified to deliver the mammalian target of rapamycin (mTOR) inhibitor, rapamycin. *In vitro* analyses demonstrated that this drug conjugate, G5-FI-RGD-rapamycin, binds to prostate cancer (PCa) cells and fibroblasts to inhibit mTOR signaling and VEGF expression. In addition, G5-FI-RGD-rapamycin inhibits mTOR signaling in cancer cells more efficiently under proinflammatory condition compared to free rapamycin. *In vivo* studies established that G5-FI-RGD-rapamycin significantly inhibits fibroblast-mediated PCa progression and metastasis. Thus, our results suggest the potential of new rapamycin-conjugated multifunctional nanoparticles for PCa therapy.

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In the progression of prostate cancer, metastasis often represents a fatal step, with 90% of deaths resulting from metastases rather than from the primary tumor [Sporn, 1996; Tse and Kalluri, 2007]. This finding has generated great interest in developing targeted cancer therapeutics. Effective therapies would target both the metastatic cells and cells of the microenvironment that permit their survival [Bhowmick et al., 2004; Bussard et al., 2008; Canon et al., 2007; Dai et al., 2017; Doehn et al., 2009]. Angiogenesis is an essential factor in tumor cell growth and survival, and the correlation between neovascularization, micro-vessel density, and metastatic carcinoma [Folkman, 1992; Weidner et al., 1992]

has been confirmed as an important parameter in tumor progression [Dai et al., 2004; Kaplan et al., 2005]. Several studies demonstrate that growth factors in the tumor microenvironment and the local host tissues are active participants in this process [Hattori et al., 2002; Liotta and Kohn, 2001]. One such growth factor, vascular endothelial growth factor (VEGF), is known to enhance the tumor angiogenic potential and has emerged as a target for anticancer therapy with several drugs currently in clinical trials [Decaussin et al., 1999; Kuhn et al., 2007]. Taken together, these findings have led to an intense interest in identifying innovative methods to modulate both the source and the impact of these angiogenic factors on tumor progression [Dai et al., 2004; Decaussin et al., 1999; Ito et al., 2007; Kaplan et al., 2005; Yang et al., 2008].

Macrophages, infiltrating eosinophils, and fibroblasts are implicated in tumor progression [Gleave et al., 1991; Hwang et al., 2008; Pollard, 2008; Tuxhorn et al., 2002]. More recently, stromal fibroblasts, the most abundant cell type in the stroma of carcinomas, have been identified as a source of VEGF and other factors that promote an angiogenic response to neoplasms [Bhowmick et al., 2004; Hwang et al., 2008; Ito et al., 2007; Orimo et al., 2005]. Proliferating fibroblasts, enhanced capillary density, and deposition of type-1 collagen and fibrin are hallmarks of a tissue stroma response to tumor progression and metastasis [Kalluri and Zeisberg, 2006; Kaplan et al., 2005; Zeisberg et al., 2007]. Recent studies illustrate that these changes are, in part, regulated by integrin-fibroblast interactions [Scaffidi et al., 2001]. Yet these fibroblasts have, until recently, been largely overlooked as targets in cancer therapy.

The mammalian target of rapamycin (mTOR) is a serine/threonine protein kinase that participates in the formation of two distinct signaling complexes; mTOR complex 1 (mTORC1), containing the regulatory-associated protein of mTOR (Raptor), and mTOR complex 2 (mTORC2), containing the rapamycin-insensitive companion of mTOR

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(Rictor). mTORC1 phosphorylates ribosomal S6 Kinase (S6K) and activated S6K phosphorylates ribosomal protein S6 (rpS6), stimulating protein synthesis, cell growth, and cell proliferation. In contrast, mTORC2 phosphorylates Akt and PKCα, promoting cell survival and cytoskeleton reorganization. Rapamycin, a specific inhibitor of mTOR, directly binds to mTORC1 and inhibits its activity. However, mTORC2 is insensitive to rapamycin, although prolonged treatment can inhibit mTORC2 in many cell types [Laplante and Sabatini, 2012].

Integrins play a key role in cell adhesion to RGD motifs within proteins of the extracellular matrix (ECM), triggering signal transduction mechanisms involved in stem cell self-renewal [Krebsbach and Villa-Diaz, 2017; Villa-Diaz et al., 2016], cell proliferation and survival [Hynes, 2002], and tumor metastasis [Kwakwa and Sterling, 2017]. We previously reported that generation 5 dendrimers can be conjugated with cyclic-RGD peptides that target and bind with specificity to cells that express high levels of the receptors for integrin alpha V beta 3 [Hill et al., 2007; Rameshwer Shukla, 2008]. Here, we report the synthesis of a novel dendrimer conjugate with rapamycin, G5-FI-RGD-rapamycin. Furthermore, we report that G5-FI-RGD-rapamycin binds to prostate cancer cells as well as the fibroblasts that support them to suppress tumor progression. We also demonstrate that G5-FI-RGD-rapamycin blocks the mTOR signaling pathway that modulates VEGF expression and subsequently impedes metastatic tumor progression.

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MATERIALS AND METHODS

DENDRIMER SYNTHESIS

Commercially available generation 5 (G5) poly amido amine (PAMAM) dendrimer (Dendritech, Midland, MI) was prepared and analyzed at the Michigan Nanotechnology

Institute of Medicine and Biological Sciences as previously described. Briefly, G5 amine terminated dendrimer was partially neutralized via acetylation (0.01 mmol G5 amine dendrimer and 0.085 mmol triethy amine/0.074 mmol acetic anhydride). The reaction was run overnight in anhydrous MeOH at room temperature. Subsequently, the reaction mixture was purified via dialysis (10,000 MWCO) and the average number of acetyl groups (75) was determined via a ^{1}HNMR calibration curve. G5Ac (75) was further modified via 1:3 molar addition of fluorescein isothiocyanate (FI) in DMSO overnight. Free FI dye was removed by an elution column (G25 sephadex). An active ester was prepared by reacting G5Ac (75) with an excess of gluaric anhydride, repeating purification via dialysis then reacting the conjugate with an excess of 1-[3-(Dimethylamino) propyl]-3-ethylcarbodiimide methiodide (EDC) and again repeating dialysis. Finally, a commercially available αVβ3 specific cyclic arginine-glycine-aspartic acid (RGD) peptide (cRGDyK, Peptides International, Louisville, KY) was added in a 5:1 molar ratio to G5Ac (75)-FI ester and purification steps were repeated. The esterfication steps were repeated, then commercially available rapamycin (Sigma-Aldrich, St. Louis, MO) was added in a 8:1 ratio to the G5Ac (75)-FI-RGD conjugate and the final compound (G5-FI-RGD-rapamycin) was purified via dialysis.

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CELL CULTURE

Primary bone marrow-derived stromal fibroblasts were collected from human or mouse bone marrow [Jung et al., 2013; Wang et al., 2010]. Primary fibroblasts and cancer cell lines (PC3, C4-2B, MDA-MB-231, and HeLa; American Type Culture Collection) were grown in Dulbecco's modified Eagle's medium (DMEM, Invitrogen, Carsbad, CA) supplemented with 10% FBS and 1% penicillin/streptomycin. Human dermal

microvascular endothelial cells (HDMEC; Cambrex, Walkersville, MD) were cultured in endothelial growth medium-2 for microvascular cells (EGM2-MV; Cambrex).

FLOW CYTOMETRY

Human fibroblast cells were treated with 200 nM G5-FI-RGD-rapamycin for 6 h with/without pre-treatment with 1 μM free RGD peptide. Cells were then disassociated from the culture dish by trypsinization, washed in PBS and analyzed via flow cytometry for mean fluorescent intensity (Beckman Coulter, Fullerton CA).

IMMUNOFLUORESCENCE

Approximately 5 x 10^5 human fibroblastswere seeded onto six well culture dishes (Matek Corp., Ashland MA) and cultured in 3 ml of medium for at least 24 h before the initiation of the experimental conditions. Samples were treated with G5-FI-RGD-rapamycin (200 nM) for 6 h with/without pre-treatment with 1 μM free RGD peptide and examined for G5-conjugate uptake using a Carl Ziess confocal microscope.

WESTERN BLOT ANALYSIS

Whole cell lysates were prepared from cells, separated on 10% SDS-polyacrylamide gel and transferred to PVDF membrane. The membranes were incubated with 5% milk for 1 h and incubated with primary antibodies overnight at 4°C. Primary antibodies used were as follows: VEGF (1:1000; Santa Cruz, Santa Cruz, CA), FGF-2 (1:1000; Santa Cruz), phospho-S6K1 (Thr389) (1:1000; Cell Signaling, Danvers, MA), S6K1 (1:1000; Cell Signaling), phospho-S6 (Ser 240/244) (1:4000; Cell Signaling), and S6 (1:4000; Cell Signaling). Blots were incubated with peroxidase-coupled secondary antibodies (Promega, Madison, WI) for 1 h, and protein expression was detected with SuperSignal

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West Pico Chemiluminescent Substrate (Thermo Scientific, Rockford, IL). Membranes were reprobed with anti-GAPDH antibody (Chemicon, Temecula, CA) to control for equal loading.

ELISA

HDMEC and human or mouse fibroblasts were treated with 200 nM G5-FI-RGD-rapamycin for 24 h. Supernatants of cell cultures were collected and centrifuged to eliminate cell debris. VEGF expression was determined by a human VEGF Quantikine ELISA kit (R&D systems, Minneaplis, MN) following the manufacturer's instructions. The fluorescence was quantified via a TECAN microplate reader (TECAN US, Durham, NC).

IN VIVO TUMOR GROWTH AND ANGIOGENESIS ASSAY

PC3 cells (1.5 x 10^6) with or without pretreatment with G5-FI-RGD-rapamycin (200 nM) for 12 h, were implanted in the flank of SCID mice. Subsequently, human or mouse fibroblasts (1.5 x 10^6) with/without pretreatment with G5-FI-RGD-rapamycin (200 nM) for 12 h were co-implanted with PC3 cells. Tumor volume was calculated twice a week for the duration of the experiment using the formula: Volume (mm^3) = length x $(width)^2/2$.

After three weeks, mice were euthanized and tumors were harvested, fixed, and processed for standard immunohistochemistry. Histological sections were incubated in antigen retrieval solution for 30 min at 90^0C, followed by incubation with polyclonal anti-human factor VIII antibody (Lab Vision, Fremont, CA) over night at 4^0C [Nor et al., 1999]. The number of blood vessels in six random fields was counted per experimental condition under light microscope. The care and treatment of experimental animals was in

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accordance with University of Michigan institutional guidelines. At least three independent experiments were performed to verify reproducibility of results.

IN VIVO METASTASIS ASSAY

PC3 cells that were stably transfected with luciferase ($PC3^{luc}$) cells were injected into the left cardiac ventricle of SCID mice. Four experimental groups were established; group one received 1 mg/kg G5-FI-RGD-rapamycin treatment 48 h before inoculation with tumor cells, group two received treatment at the time of tumor cell inoculation, group three received treatment 48 h after tumor cell inoculation and group four was inoculated with tumor cells and afterwards untreated. G5-FI-RGD-rapamycin was intraperitoneally treated 2 times per week for four weeks. At 1, 2, 3 and 4 week time points, bioluminescence imaging was performed to follow prostate cancer-derived bone metastases as a primary outcome. Immediately prior to each imaging session, the mice were injected intraperitoneally with luciferin (100 μl at 40 mg/ml in PBS). Mice were then anesthetized with 1.5% isoflurane/air, using the Xenogen IVIS (Caliper Life Science, Hopkinton MA. USA) cryogenically cooled imaging system. Bioluminescence generated by the luciferin/luciferase reaction was used for quantification of cancer growth using the LivingImage software (Caliper Life Science, Hopkinton MA. USA). Signal intensity was quantified as the sum of all detected photons during a 1-minute luminescent integration time.

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STATISTICAL ANALYSES

Results are presented as mean ± standard deviation (SD) or standard error (SE) of mean. Significance of the difference between two measurements was determined by unpaired

the Student's *t*-test, and multiple comparisons were evaluated by the Newman-Keuls multiple comparison test. Values of $p < 0.05$ were considered significant.

RESULTS

SYNTHESIS OF G5-FI-RGD-RAPAMYCIN DENDRIMER

To eliminate non-specific binding, generation 5 (G5) dendrimers were partially surface modified with acetic anhydride (75) and subsequently conjugated with fluorescein isothiocyanate (FI), RGD, and rapamycin (Fig. 1A). Gel-permeation chromatography (GPC) was used to confirm dendrimer conjugate homogeneity (Fig. 1B). Data generated via a GPC eluogram demonstrated a monodispersed conjugate population with a poly-dispersity index (PDI) of 1.04. To demonstrate that G5 dendrimers functionalized with RGD and rapamycin bind to human bone marrow-derived fibroblasts, the cells were treated with 200 nM G5-FI-RGD-rapamycin for 6 h. Confocal microscopy analysis revealed robust binding and internalization of the conjugate after treatment with 200 nM G5-FI-RGD-rapamycin (Fig. 1C). The observed binding was inhibited when the cells were pre-incubated with 1 μM of free RGD peptide for 30 min prior to G5-FI-RGD-rapamycin treatments, confirming specificity (Fig. 1C). Flow cytometry analysis confirmed dendrimer binding to fibroblasts as indicated by an increase in fluorescent intensity relative to untreated fibroblasts (Fig. 1D). The binding was also blocked when the fibroblasts were pre-incubated with 1 μM of free RGD peptide for 30 min prior to G5-FI-RGD-rapamycin treatments (Fig. 1D). Together, these results strongly indicate the successful conjugation of a multifunctional G5-FI-RGD-rapamycin dendrimer that specifically targeted cells that express integrin αVβ3.

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G5-FI-RGD-RAPAMYCIN INHIBITS mTOR SIGNALING IN FIBROBLASTS AND CANCER CELLS

Rapamycin alters protein translation by inhibiting mammalian target of rapamycin complex 1 (mTORC1) signaling [Guertin and Sabatini, 2007; Martin et al., 2004; Schmelzle and Hall, 2000]. Therefore, G5-FI-RGD-rapamycin was tested as an mTORC1 inhibitor. Western blot analysis revealed that treatment with G5-FI-RGD-rapamycin (0.5 nM, 1 nM, 10 nM or 50 nM) blocked mTORC1-mediated S6K1 phosphorylation (Thr389) at levels similar to free rapamycin treatments in human fibroblasts (Fig. 2A). G5-FI-RGD-rapamycin (20 nM and 200 nM) also strongly inhibited S6K1-mediated phosphorylation of ribosomal protein S6 (rpS6) at levels similar to free rapamycin treatments in HeLa (cervical cancer), PC3 (prostate cancer), and MDA-MB-231 (breast cancer) cells in normal culture conditions (Fig. 2B). Interestingly, when cancer cells were stimulated with with TNF-α stimulation to mimic proinflammatory conditions, the sensitivity to free rapamycin (both 20 nM and 200 nM) was significantly reduced (Fig. 2B). Critically, in TNF-α stimulated PC3 cells treated with 20 nM or 200 nM G5-FI-RGD-rapamycin and in TNF-α stimulated HeLa and MDA-MB-231 cells treated with 200 nM G5-FI-RGD-rapamycin, sensitivity to rapamycin was sustained (Fig. 2B). These results suggest that G5-FI-RGD-rapamycin significantly inhibits mTOR signaling in cancer cells under proinflammatory conditions more efficiently than unconjugated rapamycin.

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G5-FI-RGD-RAPAMYCIN REDUCES VEGF EXPRESSION IN RAPAMYCIN SENSITIVE CELLS

Growing evidence demonstrates that two key regulators of angiogenesis, vascular endothelial growth factor (VEGF), and fibroblast growth factor (FGF) are up-regulated in

both advanced tumor cells and their reactive stromal fibroblast cells [Ferrara and Kerbel, 2005; Fukumura et al., 1998; Nor and Polverini, 1999]. To determine how VEGF and FGF-2 expression from the cancer cells or fibroblast cells respond to G5-FI-RGD-rapamycin, rapamycin sensitive cells (PC3, C42B, and human fibroblast) and rapamycin insensitive cells (HDMEC, MDA-MB-231, and HeLa) [Sarbassov et al., 2006] were treated with 200 nM G5-FI-RGD-rapamycin for 24 h and VEGF and FGF-2 expression were analyzed by Western blotting. Under these conditions, G5-FI-RGD-rapamycin inhibited VEGF expression in rapamycin-sensitive prostate cancer cells, PC3, C4-2B, and human fibroblast cells (Fig. 3A), but there was no impact on the rapamycin-insensitive cells, HDMEC, MDA-MB-231, and HeLa cells (Fig. 3B). Distinctively, FGF2 expression was not altered by G5-FI-RGD-rapamycin in both rapamycin sensitive cells (Fig. 3A) and rapamycin-insensitive cells (Fig. 3B).

To investigate the effects of prostate cancer cell-secreted factors on VEGF secretion in human fibroblasts, cells were cultured for 24 h with conditioned medium from PC3 or G5-FI-RGD-rapamycin (200 nM) treated PC3 and analyzed by Western blotting for detection of VEGF and FGF2. Results demonstrated that treatment with conditioned medium from PC3 cells increased VEGF protein levels from human fibroblasts and that conditioned medium from G5-FI-RGD-rapamycin treated PC3 did not increase VEGF protein levels from human fibroblasts (Fig. 3C). HDMEC and human or mouse fibroblast cells were treated with 200 nM G5-FL-RGD-rapamycin for 24 h and culture supernatants were assayed by ELISA for detection of secreted VEGF. Results indicated a 50% reduction in VEGF secretion from both human and mouse fibroblasts following G5-FI-RGD-rapamycin treatment (Fig. 3D). Taken together, these results suggest that VEGF secretion from fibroblasts is influenced by tumor-secreted factors and that G5-FI-RGD-rapamycin treatment inhibits this effect.

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G5-RGD-RAPAMYCIN INHIBITS FIBROBLAST MEDIATED PCa PROGRESSION *IN VIVO*

Next, we determined how fibroblasts play a role in tumor progression *in vivo*, and the extent to which this role is dependent of mTOR signaling. PC3 cells were pretreated with or without 200 nM G5-FI-RGD-rapamycin for 12 h and were injected with either human or mouse fibroblasts into the flanks of SCID mice. In parallel experiments, human or mouse fibroblasts were pre-treated with 200 nM G5-RGD-rapamycin for 12 h prior to co-implantation with PC3 cells. The volume of these tumor xenografts was monitored for 22 days. Treating PC3 cells with 200 nM G5-FL-RGD-rapamycin did not affect tumor progression when compared to PC3 without treatment (Fig. 4A). PC3 cells co-implanted with either human or mouse fibroblasts demonstrated a fourfold increase in tumor growth compared to PC3 cells alone (Fig. 4A). Pre-treating either the human or mouse fibroblasts with G5-FI-RGD-rapamycin prior to co-implantation did not affect the viability of fibroblasts but reduced fibroblast-mediated tumor growth twofold (Fig. 4A). These results suggest that fibroblasts enhance tumor progression and indicate that this enhancement is mTOR signaling dependent.

Because enhanced capillary density is a hallmark of tissue stroma reacting to and promoting tumor progression toward metastasis [Kalluri and Zeisberg, 2006; Kaplan et al., 2005; Zeisberg et al., 2007], we analyzed the effects of treatment with G5-FL-RGD-rapamycin on blood vessel density in tumor xenografts in SCID mice. Xenografts from PC3 cells with or without co-implantation with fibroblasts were collected, sectioned, and stained for factor VIII, an essential clotting factor found in blood vessels. In parallel experiments, xenografts from tumors formed from PC3 cell co-implanted with fibroblasts pre-treated with G5-FL-RGD-rapamycin (200 nM) were also sectioned and stained for factor VIII. Blood vessel density of these samples were subsequently quantified. Results

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revealed that co-implanting PC3 cells with human or mouse fibroblasts increases blood vessel density showing both increased size and number of blood vessels (Fig. 4B and C). The density was significantly reduced when fibroblasts were treated with G5-FL-RGD-rapamycin before implantation (Fig. 4B and C).

G5-RGD-RAPAMYCIN INHIBITS PCa METASTASIS *IN VIVO*

We extended our *in vivo* studies to include G5-FI-RGD-rapamycin. Luciferase tagged PC3 cells were injected into the left ventricle of the hearts of SCID mice. These mice were then treated with 1 mg/kg G5-FL-RGD-rapamycin under one of the following conditions: Group 1 served as a control in which the animals were untreated to the PC3 cell injections. Group 2 animals were treated with the G5 conjugates 48 h prior to the PC3 cell injections. Group 3 animals were treated with the G5 conjugates at the time of PC3 cell injections. Group 4 animals were treated with the G5 conjugates 48 h after PC3 cell injections. Thereafter, the G5-FI-RGD-rapamycin was intraperitoneally treated 2 times per week for four weeks in group 2, group 3, and group 4. Results were compared to controls that were injected with PC3 cells but not treated with G5 conjugates. Bioluminescence data showed that treatment with G5-FL-RGD-rapamycin significantly reduced tumor burden in the post-treatment group (Group 4) and dramatically reduced tumor burden in the pre-treatment group (Group 2) and immediate-treatment group (Group 3) compared to controls (Group 1) (Fig. 5). Taken together, these data suggest G5-FI-RGD-rapamycin is effective in modulating prostate tumor progression and metastasis.

DISCUSSION

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Groundbreaking research using dendritic nano-polymers for the targeted delivery of therapeutic drugs has demonstrated promising therapeutic potential. Dendritic polymers are currently being evaluated for many *in vivo* biological applications including scaffolds used in tissue engineering, imaging (magnetic resonance, near-infrared, and positron emission), boron-neutron capture therapy, and cancer therapy [Lee et al., 2005; Paleos et al., 2007; Pan et al., 2014; Tomalia et al., 2007] and several first generation nano-carriers are now approved by the FDA [Ellerhorst et al., 1999; Fassas and Anagnostopoulos, 2005; Green et al., 2006]. However, the development of dendritic polymers that target fibroblasts is just now emerging. Furthermore, using these polymers to modify specific cellular and molecular mechanisms by which fibroblasts modify the microenvironment and enhance tumor metastasis is only beginning to materialize.

In a recent study, investigators described a novel type of fibroblast activation in response to a growing tumor that led to an increased production of growth factors and pro-inflammatory and proteolytic proteins, while at the same time cytoskeletal proteins were degraded [Rasanen et al., 2009]. VEGF, HGF/SF, and FGF7 mRNA levels were upregulated to variable degrees in tumor-activated fibroblasts. These activated cells caused an increase in colony unit formation of primary tumor cell lines (UT-SCC-43A and UT-SCC-74A). These results shed light on a study that suggested that human prostatic carcinoma-associated fibroblasts grown with initiated human prostatic epithelial cells dramatically stimulated growth and altered histology of the epithelial population [Olumi et al., 1999]. In addition, they are consistent with our results, which demonstrate that accessory fibroblasts are necessary for prostate tumor progression. We observed that co-implantation of PC3 with human fibroblasts exhibited a fourfold increase in tumor volume as compared to PC3 cells alone. In addition, treating these fibroblasts with G5-FI-RGD-rapamycin prior to implantation resulted in a twofold reduction in tumor volume

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and a marked reduction of blood vessel density in tumor. Together, these data support published reports suggesting that fibroblasts play an important role in tumor progression and further indicate that mTOR signaling may play an important role. Our analysis of two cytokines, VEGF and FGF2, known to play a role in fibroblast-mediated tumor progression revealed that only VEGF is upregulated in fibroblasts by conditioned medium from cancer cells and this increase is eliminated by G5-FI-RGD-rapamycin. Recent studies showed that insulin-like growth factor 2 (IGF2) secreted from cancer cells increases VEGF secretion from cancer-associated fibroblasts [Xu et al., 2017] and that mTOR promotes IGF2 expression [Dai et al., 2013; Dai et al., 2011]. Thus, IGF2 in PC3 conditioned medium may induce VEGF expression from fibroblasts and IGF2 secretion from PC3 cancer cells may be inhibited by G5-FI-RGD-rapamycin. Inflammatory cytokines such as TNFα activate mTOR signaling and promote tumor angiogenesis via VEGF production [Lee et al., 2007]. In addition, TNFα increases αVβ3 integrin expression and migration in human cancer cells [Hou et al., 2011]. Because αVβ3 integrin signaling activates mTOR signaling [Lee et al., 2010], it is possible that G5-FI-RGD-rapamycin inhibit mTOR signaling more efficiently than free rapamycin by targeting αVβ3 under inflammatory condition. Indeed, further analysis showed that unlike free rapamycin, G5-FI-RGD-rapamycin retains its mTOR signaling inhibitory effects in the presence of TNFα. *In vivo* results confirmed *in vitro* data by showing that treatment with G5-FI-RGD-rapamycin reduces tumor burden and metastasis in a mouse model. Interestingly, published reports of free rapamycin treatment for this model do not reflect the efficacy we observed in reduction of tumor burden leading us to suspect that there is a dendrimer effect in the observed results. Further investigations are required to reveal what mechanisms are responsible for these observations and the results should

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have important implications for the development of therapies for the treatment of metastatic prostate cancers.

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CONFLICT OF INTEREST

The authors have no potential conflicts of interest.

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FIGURE LEGENDS

Fig. **1.** Synthetic scheme and characterization of G5-FI-RGD-rapamycin. (A) Synthetic scheme. (B) Dendrimer homogeneity was confirmed via GPC with a poly-dispersity

index of 1.04. (C) Human fibroblasts (HFs) were treated with 200 nM G5-FI-RGD-rapamycin for 6 h. Confocal images. Robust binding was observed after 6 h (left panel) and eliminated by pre-incubation with 1 μM free RGD peptide (right panel). Scale bars, 50 μm. (D) Conjugate binding to HFs was confirmed via flow cytometry (left panel) and eliminated by pre-incubation with 1 μM free RGD peptide (right panel).

Fig. **2.** G5-FI-RGD-rapamycin inhibits mTOR signaling in fibroblasts and cancer cells. (A) G5-FI-RGD-rapamycin blocked S6K1 phosphorylation at the similar levels to free rapamycin treatment. Human fibroblasts were treated with the indicated concentration of free rapamycin or G5-FI-RGD-rapamycin for 24 h and analyzed by Western blotting with the indicated antibodies. (B) G5-FI-RGD-rapamycin renders cancer cells sensitive to rapamycin-mediated inhibition of rpS6 phosphorylation under proinflammatory condition. Human cancer cells were treated with the indicated concentration of free rapamycin (Rapa) or G5-FI-RGD-rapamycin (G5-Rapa) with/without TNF-α (20 ng/ml) for 24 h and analyzed by Western blotting with the indicated antibodies. Band intensity for rpS6 phosphorylation was quantified using Image J software and normalized to rpS6.

Fig. **3.** G5-FI-RGD-rapamycin reduces VEGF expression in rapamycin sensitive cells. (A) Rapamycin sensitive cells (PC3, C42B, and human fibroblast (HF)) and (B) rapamycin insensitive cells (HDMEC, MDA-MB-231, and HeLa) were treated with 200 nM G5-FI-RGD-rapamycin (G5-Rapa) for 24 h and analyzed by Western blotting for detection of VEGF and FGF-2 expression. (C) HFs were cultured for 24 h with conditioned medium (CM) from PC3 or G5-FI-RGD-rapamycin (G5-Rapa, 200 nM) treated PC3 and analyzed by Western blotting for detection of VEGF and FGF2. (D) HDMEC and human or mouse fibroblast cells (HF or MF) were treated with G5-FL-

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RGD-rapamycin (G5-Rapa, 200 nM) for 24 h and culture supernatants were assayed by ELISA for detection of secreted VEGF. Data represent average mean ± SD from duplicate assays, and the experiments were performed twice. * $P < 0.001$; $^{\#} P < 0.002$; n.s., not significant.

Fig. **4.** G5-RGD-rapamycin inhibits fibroblast mediated PCa progression in vivo. PC3 cells treated with/without G5-FI-RGD-rapamycin (G5-R, 200 nM) for 12 h were injected or co-injected with either human or mouse fibroblast cells (HF or MF) treated with/without G5-FI-RGD-rapamycin (G5-R, 200 nM) for 12 h into the flank of SCID mice. (A) The volume of tumor xenografts was monitored for 22 days. Data represent average mean ± SE. * $P < 0.005$; $^{\#} P < 0.05$; n.s., not significant. The number of mice analyzed is indicated. (B) Representative micrographs of factor VIII stained tumor sections at 10X magnification. Scale bars, 200 μm. (C) The number of blood vessels in six random fields was counted per experimental condition under light microscope. Data represent average mean ± SD. * $P < 0.001$; n.s., not significant.

Fig. **5.** G5-RGD-rapamycin inhibits PCa metastasis in vivo. $PC3^{luc}$ cells were injected into the left cardiac ventricle of SCID mice. Experimental groups for G5-FI-RGD-rapamycin treatment (1 mg/kg) were as follows; Con: untreated after $PC3^{luc}$ cell inoculation, Pre: 48 h before $PC3^{luc}$ cell inoculation, Im: at the time of $PC3^{luc}$ cell inoculation, Post: 48 h after $PC3^{luc}$ cell inoculation. G5-FI-RGD-rapamycin was intraperitoneally treated 2 times per week for four weeks in Pre, Im, and Post. At 1, 2, 3 and 4 week time points, bioluminescence imaging was performed. Data represent average mean ± SD. * $P < 0.01$; $^{\#} P < 0.02$; $^{\#\#} P = 0.05$. The number of mice analyzed is indicated.

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Figure 1

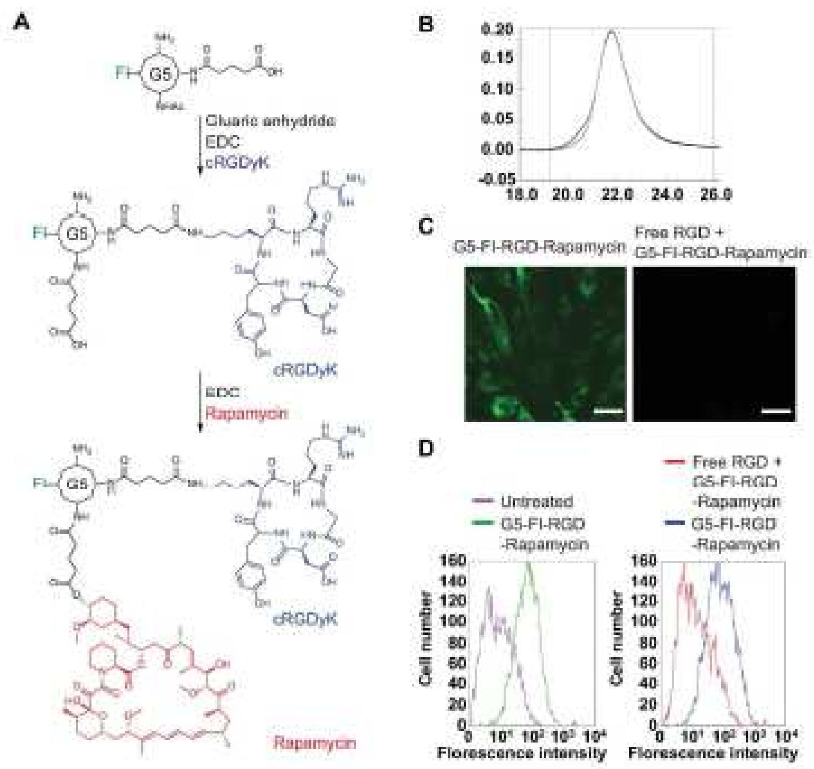

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Figure 2

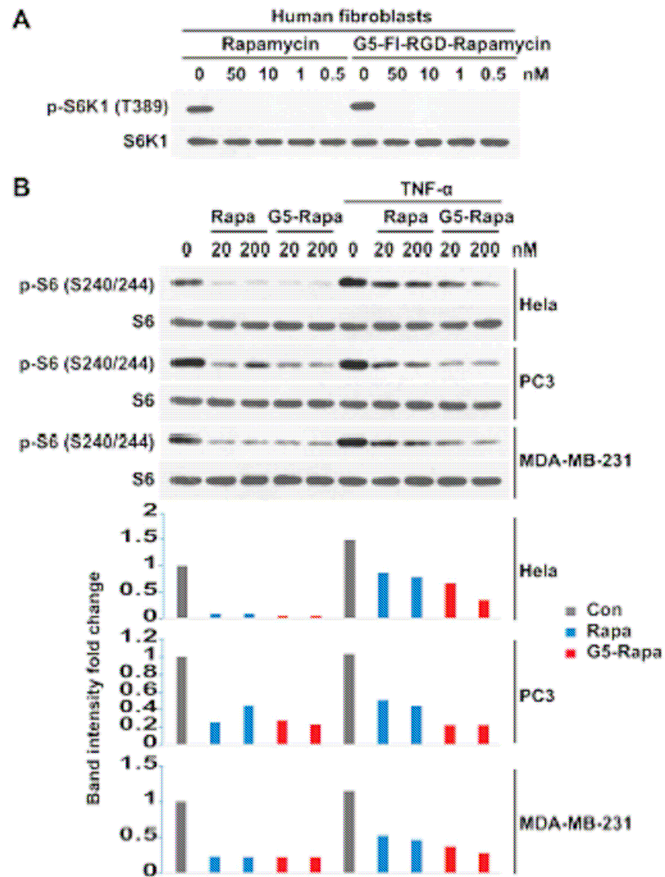

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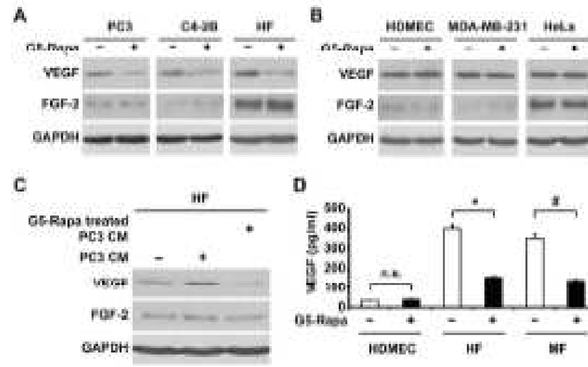
Figure 3



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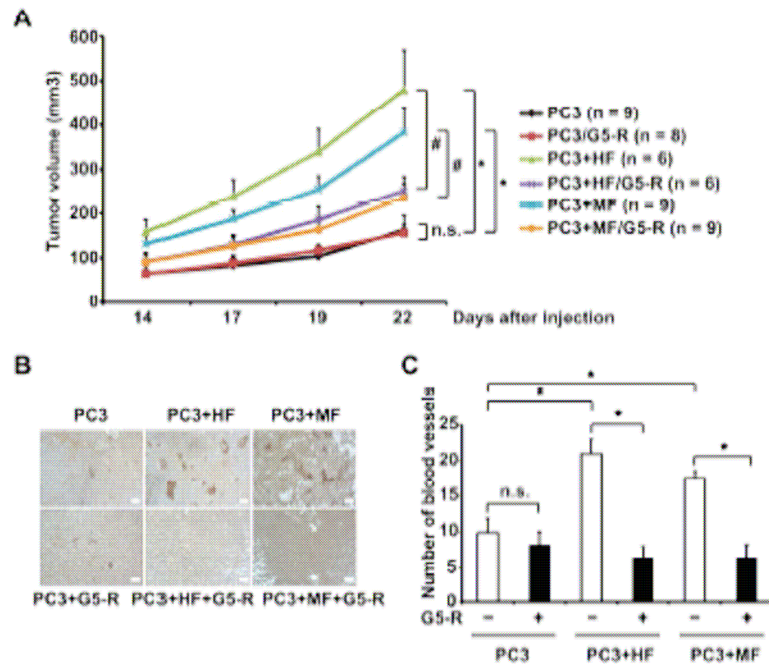
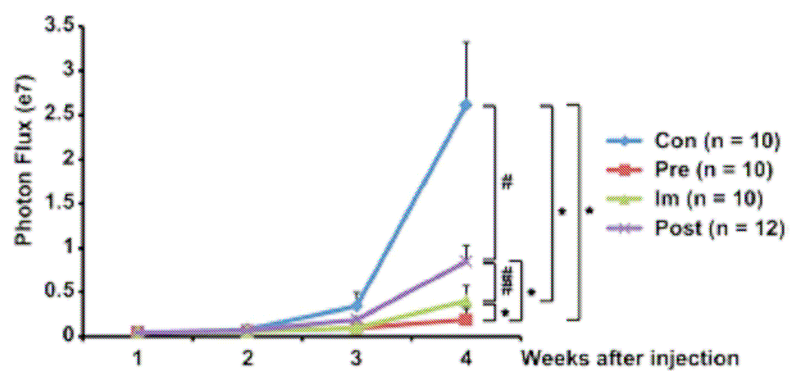


Figure 5



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