PI3K/mTOR dual inhibitor VS-5584 preferentially targets cancer stem cells

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Abbreviations: CSC, cancer stem cells; PI3K, phosphoinositide 3-kinase; mTOR, mammalian target of rapamycin; PIK3CA, catalytic subunit of PI3Kα; ALDH, aldehyde dehydrogenase; SP, side population; TIF, tumor initiating frequency; ER, estrogen receptor; SCLC, small cell lung cancer; FACS, fluorescence-activated cell sorting; MTD, maximum tolerated dose
Abstract

Cancer stem cells (CSC) have been implicated in disease recurrence, metastasis and therapeutic resistance, but effective targeting strategies for these cells are still wanting. VS-5584 is a potent and selective dual inhibitor of mTORC1/2 and Class I PI3K kinases. Here we report that VS-5584 is up to 30-fold more potent in inhibiting the proliferation and survival of CSC compared to non-CSC in solid tumor cell populations. VS-5584 preferentially diminished CSC levels in multiple mouse xenograft models of human cancer, as evidenced by marked reduction of tumor-initiating capacity in limiting dilution assays. Likewise, VS-5584 treatment ex vivo preferentially reduced CSC in surgically resected breast and ovarian patient tumors. In contrast, chemotherapeutics such as paclitaxel and cisplatin were less effective in targeting CSC than bulk tumor cells. Mechanistic investigations revealed that preferential targeting of CSC required inhibition of multiple components of the PI3K/mTOR pathway: coordinate RNAi-mediated silencing of PI3Kα, PI3Kβ and mTOR phenocopied the effect of VS-5584, exhibiting the strongest preferential targeting of CSC, while silencing of individual PI3K isoforms or mTOR failed to replicate the effect of VS-5584. Consistent with CSC ablation, VS-5584 delayed tumor regrowth following chemotherapy in xenograft models of small cell lung cancer. Taken together, the preferential targeting of CSC prompts a new paradigm for clinical testing of VS-5584: clinical trials designed with CSC-directed endpoints may facilitate demonstration of the therapeutic benefit of VS-5584. We suggest that combining VS-5584 with classical chemotherapy that debulks tumors may engender a more effective strategy to achieve durable remissions in cancer patients.
Introduction

Chemo-resistance and cancer relapse represent significant challenges in cancer management, and are attributable in part to the presence of subpopulations of cancer cells termed cancer stem cells (CSC) or tumor-initiating cells. CSC were first identified in acute myeloid leukemia (1, 2) and are operationally defined by their self-renewal and tumor initiation capacities. The presence of CSC in solid tumors was first described in breast cancer (3) and has since been identified in a wide variety of solid tumors, and implicated in resistance to anticancer therapies, cancer recurrence, and metastasis. (4-7)

The phosphoinositide 3-kinase/mammalian target of rapamycin (PI3K/mTOR) pathway is one of the most frequently activated signaling pathways in cancer, playing a central role in tumorigenesis by regulating the proliferation, survival, differentiation and migration of cancer cells as well as tumor angiogenesis (8). AKT and mTOR are the major effector kinases in the PI3K/mTOR pathway. mTOR exists in two distinct protein complexes, mTORC1 and mTORC2, each with different downstream substrates (9). The PI3K/mTOR pathway also plays a role in cancer stem cells (8, 10-14). Activation of the PI3K/mTOR pathway in adult blood cells through PTEN deletion led to the generation of leukemia-initiating cells (11). Similarly, activation of PI3K/mTOR signaling, achieved by knocking down PTEN, enriched breast cancer stem cells (13).

VS-5584 is a highly potent and selective dual PI3K/mTOR inhibitor, exhibiting approximately equal low nanomolar potency against mTOR kinase and all four Class I isoforms of PI3K. VS-5584 was shown to target the mTORC1 and mTORC2 complexes as well as PI3K in cells, as evidenced by inhibition of phosphorylation of cellular targets of these kinases including AKT (Ser473 and Thr308) and ribosomal protein S6 (Ser240/244) (15). VS-5584
shows no significant inhibitory activity against over 400 other protein and lipid kinases, including closely related lipid kinases such as DNA-PK and VSP34, underscoring the high selectivity of VS-5584(15). Simultaneous inhibition of mTORC1/2 and PI3K by VS-5584 is expected to more effectively shut down PI3K/mTOR signaling than isoform-selective PI3K or mTOR inhibitors that block only a subset of these targets. This approach should also overcome the feedback activation of PI3K signaling that is thought to limit the effectiveness of rapamycin analogs (8, 9). It was reported recently that activation of mTOR accounted for the resistance of breast cancer to the PI3Kα–selective inhibitor BYL719 in the clinic, further arguing the importance of simultaneous inhibition of mTOR and PI3K (16).

Here we report that in addition to exhibiting potent anti-cancer activity in a broad set of tumor models, VS-5584 preferentially targets CSC as demonstrated using a panel of orthogonal CSC assays, including the limiting dilution tumor-initiating assay, a gold standard for CSC. Consistent with the observation that VS-5584 preferentially abolishes CSC, VS-5584 delayed tumor regrowth in small cell lung xenograft models after cessation of treatment with cisplatin. These results provide compelling rationale for the clinical development of VS-5584 as a cancer stem cell targeting agent.

Materials and Methods

Cell lines, primary human tumor tissues, compounds and reagents

All cancer cell lines used were obtained from ATCC (Manassas, VA) with the exception of SUM159 which was acquired from Asterand (Detroit, MI). Cell lines were authenticated by STR (short tandem repeat) analysis at either ATCC or IDEXX Radil (Columbia, MO). V12-H-Ras transformed human mammary epithelial cells (HMLER) were obtained from the Broad Institute
and maintained as described (17). Primary human breast and ovarian tumor specimens were obtained from Tissue Solutions Ltd. (Glasgow, UK) after patient’s consent and institutional IRB approval. VS-5584 was synthesized by S*Bio (15). Other compounds were purchased from Selleckchem (Munich, Germany). Reverse-Phase Protein Microarray (RPMA) was conducted at Theranostics Health Inc (Rockville, MA).

**Aldefluor assays**

An imaging-based Aldefluor assay was conducted using the Aldefluor assay kit (STEMCELL Technologies, Vancouver, BC) with the following modifications: Cells were plated in collagen treated plates. Following compound treatment, Aldefluor reagents supplemented with 10 ng/ml Hoechst 33342 dye were added. Plates were incubated at 37°C for 20 min. After washing, Aldefluor+ and total cells (in buffer containing Hoechst 33342) were quantified using Celigo (Nexcelom Bioscience, Lawrence, MA). ALDH inhibitor diethylamino benzaldehyde (DEAB) treated cells were used as a negative control. FACS-based Aldefluor assay was conducted following manufacturer’s instructions (STEMCELL Technologies).

**Side Population (SP) assays**

Hoechst 33342 exclusion (Side Population) assay was carried out as previously described (18).

**HMLER assay**

HMLER cells were treated with compounds for 4 days. Following a 4-day compound wash-off and cell recovery period, cells were stained with PE-labeled anti-CD24, APC-labeled anti-CD44 antibody (BD Biosciences) and 7-AAD+ live cells were subject to FACS analysis.
APC-labeled IgG 2\textsubscript{b}K and PE labeled IgG2\textsubscript{a}K (BD Biosciences) were used as isotype controls for CD44 and CD24, respectively.

**Tumorsphere assay**

To determine tumorsphere forming efficiency, cells from tissue culture or dissociated tumors were plated in tumorsphere forming medium as previously described (17). Spheres were enumerated using Celigo.

**Apoptosis assays and siRNA transfection**

Standard methods were used for Annexin V and Caspase 3/7 assays and siRNA transfection with details in Supplementary Materials and Methods.

**In vivo Tumor xenograft studies, cell dissociation and limiting dilution assay**

For the SCLC PDX study: $10^5$ cells of p2 SCLC PDXact\textsuperscript{TM} tumor (Molecular Response, San Diego, CA) admixed with Cultrex ECM (Trevigen, Gaithersburg, MD) were subcutaneously injected into NOD-SCID mice (Harlan, Livermore CA). When tumors reached an average size of 200 mm\textsuperscript{3}, mice were randomized with 5 mice per group and treated with vehicle control, cisplatin ([i.p. once a week for 2 weeks], or cisplatin followed by VS-5584 (PO, 3 times weekly for 4 weeks). Details of other tumor xenograft studies are in Supplementary Materials and Methods. To dissociate single cells, tumor tissue was minced into smaller pieces and incubated with Liberase (Roche Applied Science, Indianapolis, IN) or dispase for 1h at 37$^\circ$C under agitation. Mouse cells were removed from xenograft human tumors using mouse antibodies and magnetic beads.

For the limiting dilution assay, cells dissociated from xenograft tumors were admixed with matrigel and injected into the mammary fat pad (for MDA-MB-231 and MCF-7 breast tumors)
or subcutaneously (NCI-H841 tumors) of immunodeficient SHrN mice (Harlan). Tumor-initiating frequency (TIF) was calculated using the ELDA Software (19).

Results

Preferential targeting of cancer stem cells by VS-5584 in vitro.

In a previous screening of over 300,000 compounds using an HMLE CSC assay (17), a number of PI3K/mTOR pathway inhibitors were found to preferentially target CSC. This historical observation prompted our initial interest in exploring the PI3K/mTOR pathway to target CSC. We therefore determined the effect of VS-5584, a highly potent and selective dual inhibitor of PI3K/mTOR (15), on CSC in multiple orthogonal CSC assays that have been validated by limiting dilution implantation in mice.

Cancer stem cells have high aldehyde dehydrogenase (ALDH) activity, which can be measured by the Aldefluor enzymatic assay (20). Aldefluor+ cells from several breast cancer cell lines have been shown to display CSC characteristics (21). We also show that Aldefluor+ SUM159 triple negative breast cancer cells display enhanced self-renewal and tumor-initiating capability relative to Aldefluor- cells in immunodeficient mice (Fig. S1). To quantify CSC that harbor high ALDH activity, we developed an imaging-based Aldefluor assay. As shown in Fig. 1A, although VS-5584 dose-dependently reduced both Aldefluor+ and Aldefluor- cell populations, it was far more potent against the Aldefluor+ CSC within the SUM159 cell line. A similar preferential effect of VS-5584 on Aldefluor+ CSC was observed using the estrogen receptor-positive (ER+) MCF7 and carcinosarcoma Hs578T cell lines (Fig. 1A), indicating that VS-5584 exerts an approximately 10- to 30-fold more potent inhibitory effect on CSC than bulk
tumor cells across these cell lines. In contrast, exposure to the cytotoxic agents paclitaxel or cisplatin, increased the percentage of Aldefluor+ cells (Fig. 1B), consistent with CSC being resistant to conventional chemotherapy. Importantly, VS-5584 attenuated paclitaxel-induced enrichment of Aldefluor+ cells (Fig. 1C).

A tumorsphere assay can be used to measure self-renewal of CSC (22). SUM159 and MCF-7 tumorspheres were treated with VS-5584, paclitaxel, or combination of both agents, and the effect of these treatments on CSC was determined in a secondary tumorsphere assay. Tumorsphere forming efficiency was decreased by VS-5584 but increased by paclitaxel. Strikingly, combination of VS-5584 and paclitaxel almost completely abolished tumorsphere formation, indicating a marked reduction of CSC (Fig. 1D).

Enhanced drug efflux is another attribute of CSC. Thus CSC, when assayed by their ability to exclude the Hoechst 33342 dye, are found to reside in a side population (SP) with greater dye exclusion capacity (18). As with the Aldefluor assay, we first validated that SP of SUM159 cells indeed exhibited elevated tumor-initiating capability relative to non-SP (Fig. S2). To determine the effect of VS-5584 on SP CSC, SUM159 cells were cultured under hypoxic conditions (1% O2) to enrich for CSC (23). VS-5584 markedly reduced the proportion of SP cells with less than 1% SP remaining following treatment with 100 nM VS-5584 and no detectable SP CSC following 1 μM VS-5584 treatment. Similarly VS-5584 also reduced the proportion of SP cells in MCF-7 cells (Fig. 1E).

In the HMLER cell line model, the CD44hi/CD24lo subpopulation has been demonstrated to possess characteristics of CSC (17). A distinct CD44hi/CD24lo population was most evident in the HMLER cells that survived paclitaxel treatment, and this helped to set the gate for FACS
analysis across all samples. While paclitaxel treatment significantly increased the percentage of CD44^{hi}/CD24^{lo} cells compared to the control sample, VS-5584 abolished the CD44^{hi}/CD24^{lo} cells with greater than 10-fold reduction (Fig. 1F). Taken together, these data demonstrate that VS-5584 has a strong preferential inhibitory effect on CSC in direct contrast to the cytotoxic agents paclitaxel and cisplatin, suggesting that CSC have an increased dependency on PI3K/mTOR signaling compared to non-CSC.

**Preferential induction of apoptosis by VS-5584 in cancer stem cells.**

Since VS-5584 dramatically reduced the proportion of CSC-containing population, we surmised that VS-5584 might induce stronger apoptosis in CSC. To test this hypothesis, SUM159 cells were treated with VS-5584 or DMSO control for 24h and the percentage of Annexin V-positive apoptotic cells was determined for both the Aldefluor+ and Aldefluor-subpopulations. VS-5584 (500 nM) induced apoptosis in 11% of Aldefluor+ cells compared to less than 2% of Aldefluor- cells (Fig. 2A), indicating that VS-5584 selectively induced apoptosis in CSC. In addition, SUM159 cells were sorted for Aldefluor+ and Aldefluor- cells and each subpopulation was treated with VS-5584 for 24h. Apoptosis was assessed by a Caspase 3/7 assay. VS-5584 induced 2-fold greater Caspase activation in Aldefluor+ cells compared to Aldefluor- cells (Fig. 2B). Similarly, VS-5584 caused more pronounced apoptosis induction in SP cells as compared to non-SP cells (Fig. 2C-D). In contrast, paclitaxel induced slightly more apoptosis in non-CSC than CSC (Fig. 2B-D). Altogether, these results indicate that VS-5584 preferentially induces apoptosis in CSC relative to non-CSC.

**Preferential targeting of CSC by VS-5584 in the MDA-MB-231 triple-negative breast cancer model in vivo.**
We subsequently determined if similar preferential targeting of CSC occurs \textit{in vivo}. We first used MDA-MB-231 triple negative human breast cancer cells implanted orthotopically in the mouse mammary fat pad. After tumors reached a volume of approximately 200 mm$^3$, VS-5584 was administered orally at 25 mg/kg once daily for 9 days. Tumors were harvested and dissociated into single cells and subjected to CSC assays without further compound treatment (Fig. 3A). Results of Aldefluor assay showed that the percentage of Aldefluor$^+$ cells was relatively low with an average of 0.7% in control tumors, VS-5584 treatment caused significant reduction of the proportion of Aldefluor$^+$ CSC to 0.2% ($p = 0.015$, Fig. 3B, S5). A more rigorous and functional test for CSC is the limiting dilution assay. Accordingly, cells dissociated from either VS-5584- or vehicle-treated tumors were injected into immunodeficient mice in limiting dilutions. Cells from VS-5584-treated tumors displayed a 7-fold reduction of tumor-initiating frequency (TIF), confirming reduction of CSC in tumors by VS-5584 treatment (Fig. 3C).

\textbf{Differential effects of VS-5584 and everolimus on CSC in the ER$^+$ MCF7 breast cancer model \textit{in vivo}.}

Similar to our observations using the MDA-MB-231 model, VS-5584 treatment also reduced the proportion of CSC in the MCF7 ER$^+$ breast tumor xenograft model, as evidenced by a significant decrease in the percentage of Aldefluor$^+$ cells, tumorsphere forming efficiency, and TIF in a limiting dilution assay (Fig. 3D-F).

Since VS-5584 inhibits multiple nodes of the PI3K/mTOR signaling pathway, we reasoned that inhibition of CSC by VS-5584 might involve effects on more than one of these pathway components. To test this hypothesis, we investigated effects of the potent mTORC1
inhibitor everolimus on CSC in the same MCF7 xenograft model. In contrast to VS-5584, oral daily dosing of everolimus at 5 mg/kg, shown to inhibit mTORC1 activity in tumors as evidenced by reduction of S6 phosphorylation (Fig. 3G), did not reduce the proportion of CSC, as measured by multiple assays (Fig. 3D-F). Collectively, these data suggest that inhibition of components of the PI3K/mTOR pathway other than mTORC1 might be important for the preferential reduction of CSC observed with VS-5584.

The role of PI3K isoforms and mTOR in the preferential targeting of CSC by VS-5584.

To further assess the contribution of individual PI3K isoforms and mTOR in mediating the CSC effect of VS-5584, SUM159 cells were transfected with siRNA specific for PI3Kα, PI3Kβ, or mTOR individually or in combination. Two different siRNA sequences were used per gene. An Aldefluor assay was carried out 3 days post siRNA transfection. PI3Kδ and PI3Kγ were not examined because they are mostly expressed in leukocytes and their role in epithelial cells is not established (24). Single isoform knock-down of PI3Kα, PI3Kβ or mTOR resulted in a moderate increase in the percentage of Aldefluor+ cells compared to scrambled control siRNA. Importantly, double knockdown of PI3Kα and PI3Kβ, PI3Kα and mTOR or PI3Kβ and mTOR decreased the percentage of Aldefluor+ CSC to some extent, whereas triple knockdown of PI3Kα, PI3Kβ and mTOR, which mirrors the kinase inhibition profile of VS-5584, showed the most striking 70% reduction of the proportion of Aldefluor+ cells (Fig. 4A). Effective target knockdown by all siRNAs was confirmed by western blot analysis (Fig. 4B). These data further support the notion that inhibition of multiple components of the PI3K/mTOR pathway by VS-5584 is critical for the observed preferential targeting of CSC.

Preferential targeting of CSC by VS-5584 in primary human tumor tissue samples.
Having demonstrated that VS-5584 preferentially reduced CSC in both cell line models and *in vivo* tumor xenografts, we determined if *ex vivo* treatment with VS-5584 preferentially targets CSC in surgically removed primary human tumor specimens. *Ex vivo* treatment of breast tumor tissue fragments with VS-5584 for 5 days reduced the proportion of both CD44<sup>hi</sup>/CD24<sup>lo</sup> (Fig. 5A) and Aldefluor<sup>+</sup> (Fig. 5B) CSC. The modest effect on the tumor of patient 3 (Fig. 5A-B) may be explained by a sample quality issue, as there were significantly fewer live cells available for FACS analysis compared to tumors of patients 1 and 2 (Fig. 5A). We reasoned that other carcinomas, such as ovarian cancer, might depend on similar CSC signaling pathways. Accordingly, *ex vivo* treatment with VS-5584 was undertaken using ovarian tumor tissue, surgically removed from two patients who had received prior taxane- and platinum-based chemotherapy. *Ex vivo* treatment with 100 nM VS-5584 for 5 days reduced the proportion of CD44<sup>hi</sup>/CD117<sup>hi</sup> cells, previously validated as a CSC marker in ovarian cancer (25), in both ovarian cancer patient tumor specimens (Fig. 5C). To further evaluate the effect of VS-5584 on tumor-initiating cells, 10,000 cells dissociated from the above control- or VS-5584-treated ovarian tumor specimens were implanted subcutaneously into immunodeficient mice. After 17 weeks, mice injected with cells from control-treated ovarian tumor specimens 1 and 2 developed tumors, whereas no tumors formed in mice injected with cells from VS-5584-treated tumor specimens (Fig. 5D). Thus the results from *ex vivo* treatment of primary patient tumor specimens are in agreement with our findings with cell lines and xenograft tumors, and indicate that VS-5584 preferentially reduces CSC populations.

**Effects of VS-5584 on tumor regrowth after chemotherapy**

CSC have been postulated to account for tumor recurrence after chemotherapy (4). We therefore hypothesized that, by preferentially eliminating CSC, VS-5584 might delay tumor
regrowth after initial treatment with chemotherapy. Small cell lung cancer (SCLC) represents a logical setting to test this hypothesis since most patients with SCLC initially respond to chemotherapy but subsequently experience tumor recurrence (26). The effect of VS-5584 on tumor-initiating CSC of SCLC was therefore assessed in the NCI-H841 SCLC xenograft model in vivo. VS-5584 treatment caused significant tumor growth inhibition (p = 0.003, Fig. 6A) and reduced the proportion of CSC in NCI-H841 tumors as evidenced by a significant decrease in the percentage of SP cells (p = 0.006; Fig. 6B). Furthermore, cells dissociated from NCI-H841 tumors of VS-5584-treated mice showed a striking 67-fold reduction in tumor-initiating frequency when injected in limiting dilutions into immunodeficient mice, indicating a marked depletion of CSC by VS-5584 in xenograft tumors (Fig. 6C).

Subsequently, we sought to determine if VS-5584 can delay tumor regrowth after initial de-bulking by cisplatin, a standard-of-care first line chemotherapeutic agent, in human SCLC xenograft models. Prior to in vivo experiments, we confirmed that cisplatin or etoposide were not effective in depleting CSC of SCLC cell lines; in fact, both agents enriched CSC whereas VS-5584 depleted CSC in vitro (Fig. S3). In the NCI-H69 SCLC xenograft study, weekly i.p. dosing of 5 mg/kg cisplatin for 2 weeks induced initial tumor regression, but these tumors regrew quickly after cessation of cisplatin treatment (26). Single agent VS-5584 at 15 mg/kg dosed orally once daily caused significant inhibition of NCI-H69 tumor growth (p < 0.05). In combination, VS-5584 substantially delayed the regrowth of NCI-H69 tumors following cessation of cisplatin treatment (Fig. 6D). Patient-derived-xenograft (PDX) models, which preserve the histology and heterogeneity of patient tumors, may be more relevant models for CSC research (27, 28). We therefore tested VS-5584 in a SCLC PDX model established from a lymph node metastasis of a patient with SCLC. In keeping with our observations with the NCI-
H69 model, VS-5584 administered following cessation of cisplatin dosing delayed tumor regrowth (Fig. 6E). These results are consistent with the suppression of cisplatin-resistant CSC by VS-5584, resulting in a longer delay of tumor regrowth after cessation of cisplatin treatment.

Discussion

Intensive efforts have been devoted to targeting the PI3K/mTOR pathway due to its critical importance in the proliferation and survival of cancer cells. Here we report that, in addition to exhibiting broad and robust antitumor activity in animal models (15), VS-5584, a potent dual PI3K/mTOR kinase inhibitor, also exerts a preferential effect on CSC present in cell culture, in human tumor xenografts, and in surgically excised human tumor specimens. In stark contrast, the cytotoxic chemotherapeutic agent paclitaxel, cisplatin and etoposide increased the proportion of CSC. Our observation that VS-5584 inhibited tumor regrowth after effective treatment with cisplatin in SCLC models, including a patient-derived primary tumor model, is consistent with the notion that VS-5584 may delay tumor recurrence at least in part through the suppression of CSC. To our knowledge, this is the first comprehensive evaluation of the effect of a highly selective PI3K/mTOR inhibitor on cancer stem cells.

The PI3K/mTOR pathway has been shown to be important for the proliferation of cancer stem cells in both solid tumors and leukemias (10-14). In prostate cancer, a CD133+/CD44+ sub-population with progenitor/stem cell characteristics was shown to exhibit higher PI3K/mTOR pathway activity, and treatment with the PI3K/mTOR inhibitor BEZ-235 suppressed the proliferation of such prostate cancer stem cells (10). PF-04691502, another dual PI3K/mTOR inhibitor, was recently shown to inhibit the proliferation of CSC in vitro and to inhibit tumor
growth in a colon CSC-derived xenograft model (29). However, in these various studies, a critical unanswered question remained whether PI3K/mTOR inhibitors exert a general anti-proliferative effect against both CSC and non-CSC, or whether the CSC are more dependent on the PI3K/mTOR pathway than are non-CSC. Interestingly, Wicha and colleagues reported that the AKT inhibitor perifosine reduced the proportion of ALDH+ CSC as well as tumor-initiating cells in breast tumor models (13), suggesting that perifosine has preferential effects on breast cancer stem cells. In light of the fact that perifosine was subsequently reported to also inhibit EGFR and c-Met phosphorylation (30), the CSC effect of perifosine could be due to inhibition of these other molecular targets in addition to AKT.

VS-5584 is highly selective for Class I PI3K isoforms and mTOR kinase with no significant activity against over 400 other protein and lipid kinases profiled (15). We provide clear evidence that inhibition of mTORC1, mTORC2 and PI3K isoforms by VS-5584 confers a strong preferential inhibitory effect on CSC across different carcinoma types, including breast, ovarian and small cell lung cancer. While VS-5584 preferentially abolished CSC in the MCF7 breast tumor model, an mTORC1-selective inhibitor everolimus did not reduce the proportion of CSC. Rapamycin, a closely related mTORC1 inhibitor, also did not impact the self-renewal of mammary stem cells (13). These data therefore suggest that inhibiting PI3K isoforms, mTORC1 and mTORC2 simultaneously may be important to exert a strong preferential effect on CSC. This hypothesis was further substantiated by our result that triple knockdown of PI3Kα, PI3Kβ, and mTOR by siRNA showed the strongest preferential reduction of CSC while knockdown of PI3Kα, PI3Kβ or mTOR individually did not exert a preferential effect on CSC (Fig. 4).

Multiple, distinct subpopulations of leukemic stem cells have previously been identified (4). In solid tumors, CSC have been identified using a variety of markers and functional
attributes even within the same type of cancer; e.g. breast or ovarian cancer. While these markers may identify overlapping states of CSC, a more plausible explanation is that CSC are also heterogeneous in solid tumors. An ideal CSC-targeting agent should optimally reduce all CSC pools. The PI3K/mTOR dual inhibitor VS-5584 appears to be such an agent, since we have demonstrated that VS-5584 reduced CSC based on multiple independent measurements, including Aldefluor, Hoechst-dye exclusion and CSC surface markers (CD44<sup>hi</sup>/CD24<sup>lo</sup> for breast cancer and CD44<sup>hi</sup>/CD117<sup>hi</sup> for ovarian cancer). Furthermore, VS-5584 also preferentially reduced the proportion of cells with self-renewal potential as measured by tumorsphere assays and by tumor-initiating capability following limiting dilution re-implantation of cells into secondary immunodeficient mice.

Our findings have implications for the clinical development of VS-5584. The observation that CSC exhibited 10- to 30- fold greater sensitivity to VS-5584 than non-CSC (Fig. 1) suggests that clinical trials designed with CSC-directed endpoints may facilitate demonstration of efficacy at sub-MTD doses. One such clinical trial concept is to test VS-5584 in a maintenance setting following cessation of front-line chemotherapy with survival endpoints, rather than conventional tumor shrinkage endpoints which primarily assess targeting of the bulk tumor burden. Current first-line chemotherapy generally consists of cytotoxic agents, such as taxanes (e.g. paclitaxel) and platinum agents (e.g. cisplatin). While these agents may effectively de-bulk tumors and control disease initially, tumors invariably recur due to ineffective control of CSC. A CSC-targeting agent is expected to block CSC-mediated tumor recurrence. Our results generated using two SCLC xenograft models (Fig. 6) provide proof-of-concept that inhibition of PI3K and mTOR kinase activities by VS-5584 after de-bulking tumors with a cytotoxic agent may substantially extend antitumor response and delay tumor regrowth. Our findings thus provide
strong rationale for the clinical development of VS-5584, currently in a Phase 1 clinical trial (NCT01991938), for the treatment of cancer with the goal of achieving more durable responses through the preferential targeting of cancer stem cells.

Authors’ Contributions

Conception and design: Q. Xu, V.N. Kolev, and J.A. Pachter

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REFERENCES


**Figure Legends**

**Figure 1. VS-5584 preferentially targets CSC in vitro.** (A) VS-5584 markedly reduced the viability of Aldefluor+ cells but had weaker effect against Aldefluor- cells. SUM159, MCF7, and Hs578T breast cancer cells were treated with VS-5584 for 2 days and an imaging-based Aldefluor assay was carried out. (B) Paclitaxel and cisplatin enriched for Aldefluor+ CSC. SUM159 cells were treated with paclitaxel or cisplatin for 2 days followed by an Aldefluor assay. (C) VS-5584 attenuated paclitaxel-induced Aldefluor+ cells. SUM159 cells were treated
with 100 nM VS-5584 and 10 nM paclitaxel alone or in combination and analyzed as in (B). (D) VS-5584 alone or in combination with paclitaxel decreased tumorsphere forming efficiency. SUM159 and MCF-7 tumorspheres were treated with 100 nM VS-5584, 10 nM paclitaxel alone or in combination. Results of secondary tumorsphere assay are shown. (E) Preferential targeting of SP CSC by VS-5584. SUM159 and MCF-7 cells were cultured under hypoxia (1% O₂) and treated with VS-5584 for 2 days. Cells were incubated with Hoechst 33342 dye and SP was determined by FACS. (F) VS-5584 preferentially targeted CD44 hi/CD24 lo cells. HMLER cells were treated with VS-5584 or paclitaxel for 4 days. Following a 4-day recovery period cells were co-stained with CD44 and CD24 antibodies and subject to FACS analysis.

**Figure 2. VS-5584 induced apoptosis preferentially in CSC.** (A) SUM159 cells were treated with VS-5584 or vehicle for 24h, co-stained with Annexin V and Aldefluor reagents. (B-D) SUM159 cells were first FACS-sorted into Aldefluor+ and Aldefluor- cells (B) or SP and non-SP cells (C, D) and treated with VS-5584 or paclitaxel for 24h. Apoptosis induction was analyzed using either an Annexin V (C) or Caspase 3/7 assay (B, D).

**Figure 3. VS-5584 preferentially abolishes CSC in two human breast tumor xenograft models in vivo.** (A) Experimental design. Rx compound or vehicle. (B-D) Mice bearing MDA-MB-231 tumors were treated with either vehicle or 25 mg/kg VS-5584 QD for 7 days. Cells were dissociated from tumors and subject to CSC assays shown in (A). (B) Aldefluor assay data showing that VS-5584 preferentially reduced Aldefluor+ CSC in MDA-MB-231 tumor xenografts. Shown is a scatter plot of % Aldefluor+ cells. *, denotes significant p value of 0.015 based unpaired t test. (C) Limiting dilution assay showing that VS-5584 reduced tumor-initiating
capability of CSC in vivo. Cells dissociated from MDA-MB-231 tumors were re-implanted in limiting dilutions into the mammary fat pad of SHrN immunodeficient mice. The number of mice grew tumors at week 8 out of total of 4 mice per group (in parenthesis) is tabulated. Tumor-initiating frequency (TIF) was calculated using the ELDA software. (D-G) Mice bearing MCF7 tumors were dosed orally with vehicle (Control), 20 mg/kg VS-5584 or 5 mg/kg everolimus daily for 10 days. Cells were dissociated from tumors and subject to a panel of CSC assays as shown in (A). (D) Aldefluor assay results showing preferential reduction of CSC by VS-5584 (p = 0.007) but not everolimus. (E) Secondary tumor sphere assay showing that VS-5584 but not everolimus significantly suppressed self-renewing capability of CSC (p = 0.001). (F) In vivo limiting dilution assay showing that VS-5584 reduced while everolimus increased TIF. (G) Results of reverse phase protein microarray array (RPMA) showing that both VS-5584 and everolimus reduced pS6 (Ser240/244) levels in MCF-7 tumors.

Figure 4. Inhibition of PI3Kα, PI3Kβ and mTOR is required for strong preferential targeting of CSC. (A) SUM159 cells were transfected with siRNA against PI3Kα, PI3Kβ and mTOR, individually or in combination. Aldefluor+ cells as a percentage of control, averaged from 2 independent experiments, is shown (Y axis). (B) Confirmation of siRNA knockdown of PI3K isoforms and mTOR. Lysates from cells transfected with various siRNA were subjected to western blot analysis. β-actin served as a loading control.

Figure 5. VS-5584 reduces the proportion of CSC in ex vivo human tumor specimens. (A-C) Breast tumor tissue from 3 patients (A, B) or ovarian tumor tissue from 2 patients (C) was treated ex vivo with 100 nM VS-5584 for 5 days. Dissociated cells were subjected to CD44 and CD24 FACS analysis (A) and Aldefluor assay (B) or CD44 and CD117 FACS analysis (C).
Aldefluor assay was not performed on Patient 2 tumor (B) due to insufficient number of cells obtained after tumor dissociation. (D) 10,000 dissociated cells from ex vivo treated ovarian tumor tissue as described in (C) were implanted subcutaneously into immunodeficient mice. The number of mice that grew tumors at week 17 out of total of 3 mice per group (in parenthesis) is tabulated.

**Figure 6.** VS-5584 targets small cell lung cancer CSC and delays tumor regrowth after chemotherapy in SCLC models. (A-C) Mice bearing NCI-H841 SCLC tumors were treated with either vehicle or 20 mg/kg VS-5584 thrice weekly for 3 weeks. Cells were dissociated from tumors and subject to CSC assays. (A) Tumor volume plot showing that VS-5584 caused significant tumor growth inhibition ($p = 0.003$). (B) SP analysis showing that VS-5584 significantly reduced the proportion of SP cells in tumors ($p = 0.006$). (C) in vivo limiting dilution assay showing that VS-5584 caused a 67-fold reduction in tumor-initiating frequency ($p = 5 \times 10^{-6}$). (D-E) Tumor weight plots showing that VS-5584 delayed tumor regrowth following weekly dosing of 5 mg/kg cisplatin for 2 weeks. VS-5584 was dosed orally at either 15 mg/kg on a QDx5 schedule for 8 weeks starting on day 1 as a single agent group (red) and in combination with cisplatin (green) (D) or at 25 mg/kg on a thrice weekly schedule for 4 weeks starting on day 9 (E).
Figure 1

A. SUM159

Viability, % of Control

0.001 0.01 0.1 1 VS-5584, μM

B. SUM159

% Aldefluor+ Cells

DMSO 1 nM 3 nM 10 nM Paclitaxel

C. SUM159

% Aldefluor+ Cells

Control VS-5584 Paclitaxel VS-5584+Paclitaxel

D. SUM159

2° Tumorspheres

Control VS-5584 Paclitaxel VS-5584+Paclitaxel

MCF-7

2° Tumorspheres

Control VS-5584 Paclitaxel VS-5584+Paclitaxel

E. VS-5584

SUM159

DMSO 0.03 μM 0.1 μM 0.3 μM

MCF-7

DMSO 0.03 μM 0.1 μM 0.3 μM

F. 0.3 μM VS-5584

Control

CD44

0.3 μM VS-5584

CD24

2% CSC

0.15% CSC

15% CSC
Figure 2

A. Annexin V+ Cells (Fold Change)

B. Caspase 3/7 Activation (Fold Change)

C. SP vs. non-SP

D. Caspase 3/7 Activation (Fold Change)
**Figure 3**

A. Tumor-bearing mice treated with Rx lead to residual tumors, which are then treated with Liberase to isolate viable cells. These cells are assessed using Aldefluor assay and Tumorsphere assays.

B. MDA-MB-231 cells treated with Liberase show a significant increase in Aldefluor+ Cells compared to control, with p = 0.04.

C. MDA-MB-231 cells treated with Liberase show a significant increase in Aldefluor+ Cells compared to control, with p = 0.04.

D. MCF-7 cells treated with Liberase show a significant increase in Aldefluor+ Cells compared to control, with p = 0.04.

E. MCF-7 cells treated with Liberase show a significant increase in Tumorspheres per 2,000 cells compared to control, with p = 0.04.

F. MCF-7 cells treated with Liberase show a significant increase in Tumorspheres per 2,000 cells compared to control, with p = 0.04.

G. MCF-7 cells treated with Liberase show a significant increase in pS6(Ser240/244) compared to control, with p < 0.0001.
A.

![Graph showing the effect of PI3Kα, PI3Kβ, and mTOR siRNA on Aldolase+ Cells (% of Control).]

B.

![Western blots showing the expression of PI3Kα, PI3Kβ, and mTOR in Control and siRNA-treated samples.]

Figure 4
Figure 5

A. Control

Br. Patient 1  Br. Patient 2  Br. Patient 3

CD44-APC

VS-5584

CD24-PE

B. Br. Patient 1  Br. Patient 3

% Adelfluor+ Cells

0.0 0.1 0.2 0.3 0.4

Control VS-5584

C. Ov. Patient 1  Ov. Patient 2

% CD44^hi/C117^hi Cells

0.0 0.2 0.4 0.6

Control VS-5584

D.

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Kolev et al.
Figure 6

A. NCI-H841

B. NCI-H841

C. NCI-H841

Limiting dilutions

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<tr>
<td>p</td>
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D. NCI-H69

E. SCLC-PDX

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PI3K/mTOR dual inhibitor VS-5584 preferentially targets cancer stem cells

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