Inhibition of Colon Cancer Cell Growth by Phosphodiesterase Inhibitors Is Independent of cGMP Signaling

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Received December 22, 2021; accepted December 29, 2021

ABSTRACT
There is growing interest in the potential use of phosphodiesterase (PDE) inhibitors for colorectal cancer (CRC) prevention and treatment. The present study has tested the idea that PDE inhibitors inhibit growth and viability of CRC cell lines by increasing cyclic guanosine monophosphate (cGMP) and activating cGMP-dependent protein kinase (PKG). Colon cancer cell lines and those with ectopic PKG2 expression were treated with membrane-permeable 8Br-cGMP or inhibitors of PDE5, PDE9, and PDE10a. Levels of cGMP capable of activating PKG were measured by immunoblotting for phosphorylation of vasodilator-stimulated phosphoprotein (VASP). The effects of treatment on CRC cell proliferation and death were measured using hemocytometry with trypan blue. Treatment with 8Br-cGMP had no effect on CRC cell proliferation or death. Endogenous PKG activity was undetectable in any of the CRC cell lines and those with ectopic PKG2 expression were treated with membrane-permeable 8Br-cGMP or inhibitors of PDE5, PDE9, and PDE10a. Levels of cGMP capable of activating PKG were measured by immunoblotting for phosphorylation of vasodilator-stimulated phosphoprotein (VASP). The effects of treatment on CRC cell proliferation and death were measured using hemocytometry with trypan blue. Treatment with 8Br-cGMP had no effect on CRC cell proliferation or death. Endogenous PKG activity was undetectable in any of the CRC cell lines, but expression of ectopic PKG2 conferred modest inhibition of proliferation but did not affect cell death. Extremely high concentrations of all the PDE inhibitors reduced proliferation in CRC cell lines, but none of them increased cGMP levels, and the effect was independent of PKG expression. The inability of the PDE inhibitors to increase cGMP was due to the lack of endogenous cGMP generating machinery. In conclusion, PDE inhibitors that target cGMP only reduce CRC growth at clinically unachievable concentrations, and do so independent of cGMP signaling through PKG.

SIGNIFICANCE STATEMENT
A large number of in vitro studies have reported that PDE inhibitors block growth of colon cancer cells by activating cGMP signaling, and that these drugs might be useful for cancer treatment. Our results show that these drugs do not activate cGMP signaling in colon cancer cells due to a lack of endogenous guanylyl cyclase activity, and that growth inhibition is due to toxic effects of clinically unobtainable drug concentrations.

Introduction
Cancers of the colon and rectum (CRC) are some of the most commonly diagnosed, and are responsible for 9% of all cancer deaths due to the late stage of diagnosis, when treatments are largely ineffective. It is therefore widely recognized that both primary prevention and the development of new therapeutics to treat advanced CRC are top priorities to reduce the health burden. Phosphodiesterases (PDEs) comprise a large family of enzymes that degrade cyclic nucleotides. They are also established therapeutic targets owing to diverse expression and functions in a variety of biologic processes (Lugnier, 2006; Maurice et al., 2014). A large and growing body of literature supports the idea that PDE inhibitors have antitumor effects in the gastrointestinal tract.

Some of the earliest studies demonstrated that a weak PDE5 inhibitor called sulindac sulphoxide (exisulind) could cause regression of colorectal polyps in human patients (Stoner et al., 1999; van Stolk et al., 2000). While exisulind was not approved for use in patients owing to toxicity at levels required for therapeutic effects (Stoner et al., 1999; van Stolk et al., 2000), efforts continued to understand the antitumor mechanism. Exisulind was reported to inhibit growth and induce apoptosis of colon cancer cell lines grown in vitro by increasing cGMP and activating type-1 cGMP-dependent protein kinase (PKG1) (Thompson et al., 2000; Joe et al., 2003). PKG1-dependent suppression of Wnt/β-catenin signaling and activation of cJun-N-terminal kinase were shown to mediate the proapoptotic effects of PDE5 inhibition (Soh et al., 2000; Thompson et al., 2000; Whitt et al., 2012; Li et al., 2013). While PDE5 is specific to cGMP, more recently, inhibition of the dual-specificity enzyme PDE10A has also been reported to inhibit colon cancer cell growth by a cGMP-dependent inhibition of β-catenin/T cell factor signaling (Li et al., 2015a; Li et al., 2015b; Lee et al., 2016).

ABBREVIATIONS: ATCC, American Type Culture Collection; CRC, colorectal cancer; ERK, extracellular signal-regulated kinase; GC-C, guanylyl cyclase C; PDE, phosphodiesterase; PKG, cGMP-dependent protein kinase; VASP, vasodilator-stimulated phosphoprotein.
Observations made by several independent groups are incongruent with the idea that activation of cGMP/PKG signaling by PDE inhibitors can inhibit colon cancer cell growth and viability. It has been suggested that the anticancer effect of exisulind is independent of cGMP signaling (Pitari et al., 2006). Others have shown that PDE5 inhibitors can synergize with the cytotoxic effects of chemotherapeutic drugs, but do not affect growth of colon cancer cell lines when used as a single agent (Booth et al., 2014; Booth et al., 2016; Booth et al., 2017). The importance of PDE5 downstream of PDE5 inhibitors has also been questioned, since both isoforms (PKG1 and PKG2) have been shown to be downregulated in colon cancer tissue compared with normal colon epithelium and are undetectable in colon cancer cell lines (Hou et al., 2006; Wang et al., 2012). In normal colon epithelium, cGMP is produced upon activation of the receptor guanylyl-cyclase (GC-C) by the peptide hormones guanylin and uroguanylin (Forte, 2004). Epithelial PDE5 antagonizes the effects of GC-C agonists by degrading cGMP (Bakre et al., 2000). Treatment of mice with PDE5 inhibitors has been shown to increase epithelial cGMP levels and suppress the proliferation in the colon crypt in a PKG2-dependent manner (Wang et al., 2014). In addition, it was recently reported that treatment with the PDE5 inhibitor sildenafil can inhibit carcinogenesis in two different models of colon cancer in mice (Islam et al., 2017; Sharman et al., 2018).

In contrast to in vitro studies with colon cancer cell lines, the role of cGMP signaling in colon cancer in mice (Islam et al., 2017; Sharman et al., 2018) has also been questioned, since both isoforms (PKG1 and PKG2) have been shown to be downregulated in colon cancer cell lines (Hou et al., 2006; Wang et al., 2017). The importance of PKG downstream of PDE5 inhibitors was shown to reduce proliferation of colon cancer cell lines at extremely high concentrations that are clinically irrelevant. However, even at the high levels of PDE inhibitors, treatment did not activate cGMP signaling because the colon cancer cell lines lack endogenous cGMP-generating machinery. Taken together, it is concluded physiologic doses of PDE inhibitors do not activate cGMP signaling or affect the proliferation of colon cancer cell lines grown in vitro.

Materials and Methods

Tissue Culture and Reagents. The colon cancer cell lines LS174T, Caco2, HCT116, HT29, and SW480 were obtained from the American Type Culture Collection (ATCC); maintained in 5% CO2 in RPMI-1640 medium containing 10% FBS; and supplemented with 2 mM L-glutamine, 10 IU/ml penicillin, and 10 μg/ml streptomycin. ATCC-derived colon cancer cell lines were made inducible for type 2 PDE inhibitors were shown to reduce proliferation of colon cancer cell lines at extremely high concentrations that are clinically irrelevant. However, even at the high levels of PDE inhibitors, treatment did not activate cGMP signaling because the colon cancer cell lines lack endogenous cGMP-generating machinery. Taken together, it is concluded physiologic doses of PDE inhibitors do not activate cGMP signaling or affect the proliferation of colon cancer cell lines grown in vitro.

Intracellular cGMP Does Not Inhibit Colon Cancer Cell Proliferation in the Absence of Ectopic PKG2 Expression. Several studies have reported that PDE inhibitors inhibit colon cancer cell proliferation, with the implication that elevated cGMP levels and activation of PKG mediate the effect. To directly interrogate the effects of increased intracellular cGMP on colon cancer cell growth, the membrane-permeable, PDE-resistant analog 8Br-cGMP was used. Treatment of parental LS174T colon cancer cells with 8Br-cGMP did not cause phosphorylation of VASP at the PKG-preferred site, Ser239, which demonstrates the absence of endogenous PKG.
Expression of ectopic PKG2 in these cells (LS174T-PKG2) conferred a dose-dependent phosphorylation of VASP in response to 8Br-cGMP (Fig. 1A). The lower mobility band observed at higher concentrations of 8Br-cGMP represents additional phosphorylation of Ser157 that causes a change in mobility on SDS-PAGE gels (Smolenski et al., 1998). Treatment with 8Br-cGMP did not affect proliferation or viability of the parental LS174T cells. However, 8Br-cGMP dose-dependently inhibited proliferation of the LS174T-PKG2 cells, with a maximum effect of 30% at 10 μM, but did not affect cell death (Fig. 1B, C). This effect was not unique to LS174T cells as similar studies using Caco2 and HCT116 cells were also unable to detect PKG activity, and there was no observed effect of cGMP on proliferation or cell death in the parental cell lines (Fig. 2). Ectopic expression of PKG2 conferred reduced proliferation of HCT116 cells and viability in Caco2 cells in response to 8Br-cGMP treatment, but these effects were modest.

PDE Inhibitors Suppress Colon Cancer Cell Growth Independent of cGMP/PKG2. The inability of high levels of intracellular cGMP to significantly affect proliferation or viability in several colon cancer cell lines is incongruent with published reports describing the growth-inhibitory effects of cGMP-elevating PDE inhibitors (Thompson et al., 2000; Li et al., 2013; Li et al., 2015b; Lee et al., 2016). To investigate this discrepancy, inhibitors of cGMP-specific PDE5 (sildenafil) and PDE9 (PF-04447943), as well as dual specificity PDE10A (TAK-063) were used to treat parental and PKG-expressing LS174T cells (Fig. 3). Surprisingly, all three inhibitors inhibited cell proliferation at concentrations higher than 10 μM in both parental and PKG2-expressing cells (Fig. 3A). At the highest dose (200 μM), the inhibition of proliferation in the parental LS174T cells was least for sildenafil (50%) and maximal for PF-04447943 (80%), with TAK-063 in between (65%). Results were similar in the LS174T-PKG2 cells, except that sildenafil was less effective (25% inhibition). Trypan blue staining showed that these drugs had marginal effects on cell viability that were typically less than 20% at all concentrations, except for the highest concentration of TAK-063, which was toxic (Fig. 3B). The ability of the PDE inhibitors to suppress proliferation in the parental cells contrasted with the effect of 8Br-cGMP, which did not affect parental cells, and only moderately inhibited growth in PKG2-expressing cells. These observations indicated that the antiproliferative effect of PDE inhibitors might be independent of cGMP and PKG. To test this, the ability of the PDE inhibitors to activate PKG in LS174T cells was determined using VASP phosphorylation as a readout (Fig. 3C). While 8Br-cGMP treatment caused robust VASP phosphorylation in the LS174T-PKG2 cells, none of the PDE inhibitors were effective except for 50 μM TAK-063, which caused a faint band in some experiments. This effect was not unique to LS174T cells, as similar results were obtained using Caco2 and HCT116 cells (Fig. 4). Treatment of HCT116 or Caco2 with 50 μM of the PDE inhibitors reduced proliferation to varying degrees in both parental and PKG2-expressing cells, with TAK-063 as the most effective in both cell lines. However, none of the PDE inhibitors caused VASP phosphorylation, indicating that the antiproliferative effect was independent of both cGMP and PKG.

Colon Cancer Cell Lines Lack Endogenous cGMP-Generating Machinery. The inability of the PDE inhibitors to elicit a functional cGMP response as measured by PKG-dependent phosphorylation of VASP was unanticipated based upon previous studies (Thompson et al., 2000; Li et al., 2013; Lee et al., 2016). Phosphodiesterases antagonize guanylyl-cyclases by hydrolytically cleaving the cGMP to produce GMP. The source of cGMP in the colon epithelium is membrane-bound GC-C following activation by guanylin (Forte, 2004). GC-C is maintained in colon tumors (Carrithers et al., 1996; Cagir et al., 1999; Birbe et al., 2005), but expression is more variable in colon cancer cell lines (Waldman et al., 1998). However, the GC-C agonist guanylin is rapidly downregulated during tumorigenesis (Cohen et al., 1998; Steinbrecher et al., 2000; Wilson et al., 2014). To determine whether functional GC-C is expressed in colon cancer cell lines, we measured VASP phosphorylation following treatment with the GC-C agonist linaclotide in combination with the PDE5 inhibitor sildenafil in different colon cancer cell lines that we engineered to express ectopic PKG2 (Fig. 5A). Out of four cell lines that were used in previous studies of PDE inhibitors, only LS174T and Caco2 produced phospho-VASP bands that were comparable to positive controls treated with 8Br-cGMP. LS174T cells expressing ectopic PKG2 were subsequently treated with different doses of linaclotide to identify the lowest concentration capable of activating cGMP/PKG signaling (Fig. 5B). The cells were then treated with the PDE inhibitors, together with the low dose of linaclotide (10 nM), to determine whether these drugs could amplify the basal cGMP production (Fig. 5C). Sildenafil produced a robust VASP phosphorylation at both 1 and 10 μM, whereas the PF-04447943 and TAK-063 were much less effective, with weak bands appearing only at the higher 10 μM dose. Taken together, these results strongly support the idea that the growth-inhibitory effects of PDE inhibitors in colon cancer cells does not involve activation of cGMP signaling, and is more likely to result from off-target effects at higher doses.

The Effect of PDE Inhibitors on Survival Signaling in Colon Cancer Cells. The mechanisms that have been proposed to mediate the antiproliferative effects of PDE inhibitors and cGMP in colon cancer cells have centered upon growth and survival pathways downstream of receptor-tyrosine kinases, and Wnt signaling. The effect of PDE inhibitors on these pathways was examined in the GC-C-expressing LS174T and Caco2 cell lines (Fig. 6). These studies showed that phospho-ERK levels were transiently suppressed by treating cells with 200 μM of Sildenafil or 100 μM of the PDE9, 10 inhibitors in both cell lines. This inhibition was more pronounced in Caco2 cells treated with PF-04447943 and TAK-063 (40%–70% inhibition), compared with sildenafil (10% inhibition), but in all cases the phospho-ERK normalized after 24 hours. Phospho-AKT and total β-catenin levels were not inhibited in either cell line by any of the drugs.

Discussion

A large body of work spanning two decades has highlighted cGMP-elevating PDE inhibitors for the prevention and treatment of colorectal cancer. Building on this foundation, recent large-cohort retrospective epidemiologic studies support their efficacy in humans and provide the impetus for prospective clinical studies to interrogate their utility in patients (Huang et al., 2019; Sutton et al., 2020). However, there are inconsistencies in the literature regarding the potential utility of cGMP-PDE inhibitors as a primary prevention modality or as...
Fig. 1. Ectopic PKG2 is required for cGMP to inhibit the growth of LS174T colon cancer cells. Parental LS174T colon cancer cells and those engineered to express ectopic PKG2 were treated with 8Br-cGMP at the indicated concentrations. (A) The cGMP signaling was measured by immunoblotting for VASP phosphorylation at Ser239 (VASP-239P). The effect of 8Br-cGMP of parental and PKG2-expressing LS174T cells on (B) cell proliferation and (C) cell viability. Data show means, and error bars are S.D. **P < 0.0001.
Fig. 2. The inability of cGMP to affect proliferation is common among colon cancer cell lines. (A) Parental Caco2 and HCT116 colon cancer cells and those with inducible PKG2 expression were treated with 8Br-cGMP (100 μM) and doxycycline (Dox) to induce PKG2 expression as indicated. The cGMP signaling was measured by immunoblotting for VASP phosphorylation at Ser239 (VASP-239P). The effect of 8Br-cGMP treatment on (B) cell proliferation (hemocytometer), and (C) cell viability (trypan blue exclusion) is shown. Data show means, and error bars are S.D. *P < 0.05.
Fig. 3. High doses of cGMP-PDE inhibitors suppress growth of LS174T colon cancer cells by a cGMP-independent mechanism. Parental and PKG2-expressing LS174T colon cancer cells were treated for 3 days with different doses of PDE inhibitors. Sildenafil (Sil)-PDE5, PF-04447943 (PF)-PDE9, and TAK-063 (TAK)-PDE10a. The effect of PDE inhibitor treatment on (A) cell proliferation (hemocytometer), and (B) cell viability (trypan blue exclusion). (C) The effect of PDE inhibitors on cGMP levels in LS-174T-PKG2 cells was measured by immunoblotting for phosphorylation of VASP (VASP-239P). Data show means, and error bars are S.D. ***P < 0.0001, **P < 0.005, *P < 0.05.
Fig. 4. The cGMP/PKG-independent inhibition of proliferation by PDE-inhibitors is a common feature of colon cancer cell lines. HCT116 and Caco2 colon cancer cells were either untreated or treated with the PDE5 inhibitor sildenafil (Sil), the PDE9 inhibitor PF-04447943 (PF), and the PDE10a inhibitor TAK-063 (TAK) as indicated. The ability of the drugs to increase cGMP in (A) HCT116-PKG2 and (C) Caco2-PKG2 was measured by immunoblotting for VASP phosphorylation at Ser239 (VASP-239P) using 8Br-cGMP as a positive control. The effect of 50 μM of the PDE inhibitors on proliferation and viability was measured in both parental and PKG2-expressing (B) HCT116 and (D) Caco2 colon cancer cells. Cells were treated with 50 μM of Sil, PF, or TAK for 3 days. Cell death was measured using trypan blue exclusion. Data show means, and error bars are S.D. ***P < 0.0001, **P < 0.005.
PDE inhibitors do not increase cGMP in colon cancer cell lines due to a lack of endogenous cGMP production. The expression of functional guanylyl-cyclase-C (GC-C) in colon cancer cells engineered to express ectopic PKG2 was determined by measuring VASP phosphorylation in response to treatment with the GC-C agonist linaclotide. (A) Different cell lines induced to express PKG2 as indicated below, were either untreated (control, C), treated with 8Br-cGMP (cG), or with the combination of linaclotide and sildenafil (L+S). Western blots were probed for β-actin as a loading control for PKG2 expression. (B) Dose-response study of linaclotide stimulation of LS174T-PKG2 cells to determine the dose required to generate minimal cGMP/PKG2 activity as measured by VASP phosphorylation. (C) LS174T-PKG2 cells were treated with PDE inhibitors as indicated, in the presence of 10 nM linaclotide. Relative cGMP levels were then measured by immunoblotting for VASP-239P. All immunoblots were reprobed with antitotal VASP to indicate relative phosphorylation.
Fig. 6. The effect of high-dose PDE inhibitors on proliferation/survival signaling in colon cancer cell lines. (A) LS174T and Caco2 colon cancer cells were treated with 200 μM Sildenafil (Sil), 100 μM PF-04447943 (PF), or 100 μM TAK-063 (TAK) for different times as indicated. The effects of treatment on ERK, AKT, and β-catenin were determined by immunoblotting. (B) Densitometric analysis of blots, where ratios of band intensities for ERK-P/ERK, AKT-P/AKT, and β-catenin/β-actin were calculated and expressed as a percent of the basal level (0 hour time point; dashed line).
chemotherapy for cancer treatment. The present study provides new information that impacts the interpretation of foundational in vitro studies of PDE inhibitors in colon cancer cell lines.

A key observation shown here is that high levels of intracellular cGMP do not inhibit proliferation or affect the viability of ATCC-derived colon cancer cell lines. In addition, the colon cancer cell lines do not express detectable PKG activity that has been reported to mediate antiproliferative signaling. Ectopic expression of PKG2 in colon cancer cells conferred a modest antiproliferative response to cGMP treatment in some colon cancer cell lines, but did not affect viability. While the number of cell lines used in these studies is not exhaustive, the results were similar between cells of different genetic etiology and are supported by observations from several independent groups using diverse gastrointestinal cancer cell lines (Wang et al., 2012; Wu et al., 2013; Booth et al., 2014).

Another key observation from the present study is that inhibitors of PDE5, PDE9, and PDE10a all suppressed colon cancer cell proliferation, but only at concentrations exceeding 10 μM. These results are consistent with observations made by several independent laboratories, which have reported EC50 values for inhibiting colon cancer cell growth ranging from 20 μM to over 500 μM for different PDE inhibitors (Table 1). Notably, these concentrations are between 10,000 to almost 100,000 times the published IC50 for the target PDE enzyme. This massive disconnect in effective concentration suggests that the inhibitory mechanism is due to off-target effects. Most importantly, the EC50 values for inhibiting colon cancer cell growth in vitro are almost 50 times the published peak plasma concentrations (Cmax) of these drugs when administered at high doses to human patients. The results shown here are consistent with the antiproliferative effects of PDE5 and PDE10a inhibitors on colon cancer cell lines as published by other laboratories, but the doses required are clinically unachievable.

The notation that the antiproliferative effect of the cGMP-PDE inhibitors is due to off-target effects is supported by the lack of effect of 8Br-cGMP on colon cancer cell growth. The present study measured activation of PKG as a functional readout for cGMP because the biologic significance of absolute cGMP levels is unclear. A surprising observation was that none of the PDE inhibitors studied were able to increase cGMP levels to activate PKG in the colon cancer cell lines. The underlying reason was clearly shown to be due to the lack of endogenous cGMP-generating machinery. Without a basal rate of cGMP production to provide a substrate for PDEs, their inhibition had no effect. In agreement with previous studies, it was shown here that functional GC-C was only expressed in 2 of the cell lines tested (Waldman et al., 1998). GC-C is the main source of cGMP in the colon epithelium, which is activated by peptide hormone guanylin, which is universally lost in colon cancer (Wilson et al., 2014). In the presence of GC-C and the synthetic agonist linaclotide, a physiologic dose (1 μM) of the PDE5 inhibitor sildenafil potently activated cGMP signaling as measured by VASP-phosphorylation. The lack of effect of PDE9 and PDE10a inhibitors in the linaclotide-treated cells demonstrated that PDE5 is the central enzyme controlling cGMP levels in colon cancer cells, as has been reported by others (Bakre et al., 2000; Piazza et al., 2000; Mei et al., 2015). The slight increase in cGMP detected at very high concentrations of the PDE9 and PDE10a inhibitors in the present study likely reflects crossover inhibition of PDE5.

The antiproliferative effect of high doses of PDE inhibitors was shown here to be an off-target effect of these drugs, but specific signaling pathways have previously been implicated as important. The most prevalent mechanism proposed is the cGMP/PKG-mediated downregulation of β-catenin protein levels, leading to suppression of TCF-target gene expression (Thompson et al., 2000; Whitt et al., 2012; Li et al., 2015b). However, inhibition of AKT and ERK pathways in cells expressing ectopic PKG2 has also been reported (Wu et al., 2012; Wu et al., 2013; Wang et al., 2017). There was no obvious effect on any of these signaling pathways that was common to the inhibitors, or across cell lines with any single inhibitor. A recent study showed that treating SW480 and

### TABLE 1

Effective doses of cGMP-PDE inhibitors

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<tr>
<th>Target</th>
<th>Drug</th>
<th>IC50</th>
<th>EC50&lt;sub&gt;a&lt;/sub&gt;</th>
<th>Human Plasma [C&lt;sub&gt;max&lt;/sub&gt;]</th>
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<tr>
<td>PDE5</td>
<td>Sildenafil</td>
<td>3.9 nM(Gupta et al., 2005)</td>
<td>66-271 μM</td>
<td>1.2 μM(Gupta et al., 2005)</td>
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<td>(100 mg dose)</td>
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<td></td>
<td></td>
<td>1-5 nM(Gupta et al., 2005; Ahmed, 2018)</td>
<td>38 μM(Li et al., 2013)</td>
<td>0.87 μM(Gupta et al., 2005)</td>
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<td>(20 mg dose)</td>
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<td></td>
<td>115 μM(Soh et al., 2000)</td>
<td>165-557 μM(Thompson et al., 2000)</td>
<td>13-27 μM(van Stolk et al., 2000)</td>
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<td></td>
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<td>(40-200 mg dose)</td>
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<tr>
<td>PDE9</td>
<td>PF-04447943</td>
<td>12 nM(Charnigo et al., 2019)</td>
<td>90 μM&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.12-0.63 μM(Charnigo et al., 2019)</td>
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<td></td>
<td>BI-409306</td>
<td>52 nM(Rosenbrock et al., 2019)</td>
<td>ND</td>
<td>1.37 μM(Moschetti et al., 2016)</td>
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<td></td>
<td>PDE10</td>
<td>TAK-063</td>
<td>0.3 nM(Harada et al., 2015)</td>
<td>22 μM&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>(100 mg dose)</td>
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<td>0.16 nM(Lee et al., 2016)</td>
<td>14-20 μM(Lee et al., 2016)</td>
<td>0.1-0.52 μM(Delnomdedieu et al., 2017)</td>
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<sup>a</sup>Inhibition of colon cancer cell growth.

<sup>b</sup>From the present study. ND: Not determined.
HCT116 colon cancer cells with 300 μM sildenafil for 48 hours inhibited proliferation, which was associated with reduced β-catenin levels (Mei et al., 2015). The mechanism was shown to involve increased redox stress and G1 arrest, but no specific pathway was indicated. It is possible that higher inhibitor concentrations over a longer period might have resulted in additional toxicity, but our results demonstrate that direct targeting of specific proliferative signaling pathways is unlikely to have a role.

An important conclusion from the present work is that the effective concentration of cGMP-PDE inhibitors used in colon cancer studies must be a critical factor when evaluating the significance of in vitro observations. The present study did not address the potential benefits of using PDE5 inhibitors in combination with traditional chemotherapy (Booth et al., 2014; Booth et al., 2017) or as immunomodulatory agents (Serafini et al., 2006; Lin et al., 2017). However, the concentrations of cGMP-PDE inhibitors that are needed to directly suppress colon cancer cell growth are clinically unachievable. Studies using knockout mice with defective cGMP signaling have shown that cGMP activation of PKG2 regulates intestinal homeostasis by slowing epithelial turnover (Steinbrecher et al., 2002; Li et al., 2007; Wang et al., 2012). Increasing cGMP using physiologic doses of PDE5 inhibitors or GC-C agonists, inhibits colon carcinogenesis in mice (Chang et al., 2017; Islam et al., 2017; Sharman et al., 2018). The mechanism was proposed to involve the reducing tumor initiation rather than inhibiting the growth of existing tumors, suggesting that PDE5 inhibitors might be useful for colon cancer prevention (Islam and Browning, 2018; Browning, 2019).

In summary, the present results demonstrate that proliferation and viability of colon cancer cell lines are not affected by cGMP or physiologic doses of cGMP-elevating PDE inhibitors. Extremely high doses of PDE inhibitors can inhibit colon cancer cell proliferation using an off-target mechanism that does not involve cGMP/PKG signaling.

**Authorship Contributions**

Participated in research design: Hou, Wren, D. Browning.
Contributed new reagents or analytic tools: Vega, D. Browning.
Performed data analysis: Hou, Wren, D. Browning.
Wrote or contributed to the writing of the manuscript: Wang, Vega, D. Browning.

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