Possible Mechanisms of Diarrheal Side Effects Associated with the Use of a Novel Chemotherapeutic Agent, Flavopiridol

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ABSTRACT

The novel cyclin-dependent kinase inhibitor flavopiridol has recently completed Phase I trials for the treatment of refractory neoplasms. The dose-limiting toxicity observed with this agent was severe diarrhea. Because the compound otherwise showed promise, the present study sought to determine possible mechanisms underlying the diarrheal side effects. Flavopiridol was tested for its ability to modify chloride secretory responses of the human colonic epithelial cell line, T84. Studies were conducted in vitro in modified Ussing chambers. High concentrations of flavopiridol (10^{-4} M), above those likely to be clinically relevant, had a direct stimulatory effect on chloride secretion, probably ascribable to an increase in cyclic AMP. Lower, clinically relevant concentrations of flavopiridol (10^{-6} M) had no effect on chloride secretion by themselves but potentiated responses to the calcium-dependent secretagogue, carbachol. The drug also potentiated responses to thapsigargin and taurodeoxycholate and reversed the inhibitory effects of carbachol and epidermal growth factor on calcium-dependent chloride secretion. Pretreatment with the cyclic AMP-dependent secretagogue, forskolin, potentiated responses to flavopiridol, but not vice versa. Thus, diarrheal side effects induced by flavopiridol are likely multifactorial in origin and may involve interactions with endogenous secretagogues such as acetylcholine and bile acids. A better understanding of the diarrheal side effects induced by flavopiridol should allow optimization of therapy with this otherwise promising drug and/or the development of related agents with improved toxicity profiles.

INTRODUCTION

The external environment manipulates cellular proliferation and differentiation by stimulating or inhibiting certain signal transduction pathways that impinge on the cell cycle (1–3). Each component of the cell cycle machinery, as a final executor in cell division, has the potential to elicit or to contribute to a neoplastic phenotype (4). When normal cells sense external stimuli, such as contact inhibition, they stop proliferating. However, in transformed cells, some of the controls exerted on progression through the cell cycle are lost. Checkpoints at the G1-S and G2-M transitions are surveillance mechanisms that monitor the completion of critical cell cycle transitions (5). In transformed cells, these checkpoints are less stringent or even absent (6). Because transformed cells have handicapped checkpoints, cancer has been described as a cell cycle disease (6).

Cell division involves the recruitment of a group of serine/threonine kinases, called CDKs. These are activated and inactivated in an orderly manner at specific time points throughout the cell cycle (6). The kinase activity of CDKs is controlled by their association with cyclins, proteins that are present at particular times in the cell cycle, as well as by posttranslational modifications (4). To date, nine CDKs have been discovered, each correlating with specific cyclins during different stages of the cell cycle. Most of the cyclin-CDK complexes remain well-regulated in transformed cells, in terms of their coordination with DNA replication and mitosis. What is lacking is the ability to modulate the complexes in response to external factors and to DNA damage, most obviously at the G1-S and G2-M checkpoints. Approximately 90% of human tumors are associated with aberrations in cell cycle signaling pathways such as deletion of the retinoblastoma gene product (a tumor suppressor that normally blocks cell cycle progression), deletion of CDK inhibitors (such as p15 or p16), overexpression of cyclin D, or amplification of cdk4 or cdk6 with consequent activation of the G1 kinase and retinoblastoma inactivation (1, 2). Thus, CDKs are attractive chemotherapeutic targets, and drugs that could act as CDK inhibitors might be expected to be effective cytostatic drugs (7).

Flavopiridol is a recently discovered agent that, at doses attained in clinical settings, acts as a specific inhibitor of several CDKs including cdk1, cdk2, cdk4, and cdk7 (8). As such, the drug inhibits cell cycle progression in G1 and G2 (8). Recent studies have also revealed that flavopiridol also inhibits expression of cyclin D1, an effect which would also contribute to the ability of the drug to cause cell cycle arrest (9). At low concentrations, flavopiridol is not toxic to resting or confluent cells in vitro. However, at higher concentrations (~1 μM) toxicity can occur in resting as well as cycling cells (10). Initial clinical trials...
have suggested antineoplastic effects of this agent against refractory cancers, in particular prostate, renal, and colon cancers, as well as lymphoma (11, 12). The major dose-limiting toxicity of the drug was severe diarrhea, which necessitated the cessation of treatment in some cases (11, 12). However, unlike diarrhea associated with the use of more classical chemotherapeutic agents, the diarrheal side effects of flavopiridol were associated with little or no apparent damage to the intestinal epithelium and instead had “secretory” electrolyte features (11). We therefore hypothesized that flavopiridol might have direct effects on the chloride secretory properties of epithelial cells, and that these effects might result in diarrhea in vivo. The present study represents an in vitro approach, using the human colonic epithelial cell line T$_{84}$, to test this hypothesis.

**MATERIALS AND METHODS**

**Materials.** Carbachol and forskolin (Sigma Chemical Co., St. Louis, MO), EGF (Genzyme, Cambridge, MA), genistein, and thapsigargin (LC Laboratories, Woburn, MA) were purchased from the sources indicated. Taurodeoxycholic acid was the generous gift of Dr. Alan Hofmann (University of California, San Diego, CA). Flavopiridol was supplied by Dr. Jennifer Dumont (Hoechst Marion Roussel, Bridgewater, NJ). All other reagents used were of at least analytical grade and were obtained commercially.

**Cells.** The human colonic epithelial cell line T$_{84}$ was used for all experiments in this study. Cells were maintained in DMEM/F12 media with 5% newborn calf serum and in a humidified atmosphere of 95% air, 5% CO$_2$. For chloride secretion experiments and cAMP assays, T$_{84}$ cells were seeded onto 12-mm Millicell-HA culture plate inserts (permeable supports) and grown for 8–12 days. At the time of study, cell monolayers had stable values of transepithelial resistance in excess of 1000 Ω·cm$^2$.

**Measurement of Chloride Secretion.** Chloride secretory responses of T$_{84}$ cell monolayers grown on permeable supports were measured by mounting the cells in modified Ussing chambers, as described previously (13), and quantitated as changes in short circuit current (I$_{sc}$). Previous studies have shown that I$_{sc}$ is wholly reflective of changes in transepithelial chloride secretion in response to a variety of agonists in this model (14, 15). Studies were conducted under short-circuited conditions except during brief intervals (3–5 s at each time point) when the open circuit potential difference across the monolayer was assessed. All studies were conducted in Ringers’ solution (140 mM Na$^+$, 5.2 mM K$^+$, 1.2 mM Ca$^{2+}$, 0.8 mM Mg$^{2+}$, 119.8 mM Cl$^-$, 25 mM HCO$_3^-$, 2.4 mM H$_2$PO$_4^-$, 0.4 mM HPO$_4^{2-}$, and 10 mM glucose).

**cAMP Assay.** cAMP was measured in lysates of stimulated or control cell monolayers using a commercially available cAMP enzyme immunoassay kit (Amersham, Arlington Heights, IL). Cells grown on Millipore inserts were rinsed thoroughly with Ringers’ solution and allowed to equilibrate in this solution at 37°C for 15 min. Cells were then stimulated with flavopiridol (10$^{-4}$ M) on the apical side or forskolin (10$^{-3}$ M) on the apical and basolateral sides as a positive control for various times as indicated by the experimental design. Ice-cold ethanol/ Ringers’ (2:1, v/v) solution was added to stop the reaction, and the lysates were kept at −70°C for no longer than 24 h before completing the assay.

**Statistical Analysis.** All data are expressed as means ± SE for a series of experiments. Statistically significant differences between mean values were analyzed by Student’s $t$ test or ANOVA with Bonferroni post-hoc tests, as appropriate.

**RESULTS**

**Effect of Flavopiridol on Chloride Secretion.** We first examined whether flavopiridol alone could stimulate chloride secretion across T$_{84}$ cell monolayers. Various doses of the drug were applied to either the apical or basolateral side and any change in I$_{sc}$ noted. Flavopiridol stimulated a slow but sustained chloride secretory response when applied apically to T$_{84}$ monolayers (Fig. 1). The maximal I$_{sc}$ response of 17.9 ± 1.6 μA/cm$^2$ ($n = 27$) was recorded at a dose of 10$^{-4}$ M. Flavopiridol stimulated dose-dependent increases in I$_{sc}$ when added to either the apical or basolateral side of T$_{84}$ cells, but the apical response was more pronounced (data not shown). To determine the mechanism of this direct effect on chloride secretion, cAMP levels were measured. As shown in Fig. 2, flavopiridol (10$^{-4}$ M) caused a significant increase in intracellular cAMP levels that was similar to the increase in cAMP induced by forskolin, used as the positive control. However, this dose of flavopiridol has a smaller effect on I$_{sc}$ than does forskolin, underscoring the complexity inherent in the regulation of chloride secretion, and the fact that simple correlations between second messenger levels and transport responses are not possible. Moreover, the concentration of flavopiridol (10$^{-3}$ M) that caused increases in I$_{sc}$ and cAMP is considerably in excess of blood levels of the drug measured in clinical settings (11, 12); therefore, the significance of these findings is somewhat unclear. At lower doses of flavopiridol (≤10$^{-6}$ M) that might be seen in patients treated with
the drug (11, 12), flavopiridol had no direct effect on chloride secretion ($I_C < 1 \mu A/cm^2$) and no measurable effect on cAMP levels (data not shown).

**Effect of Flavopiridol on Chloride Secretion Induced by Calcium-dependent Agonists.** Because flavopiridol had little independent effect on chloride secretion at clinically achievable doses, it was unlikely that its direct effect on secretion could account for its diarrheal side effects. We therefore tested whether flavopiridol might instead potentiate responses to other known chloride secretagogues. Initial studies focused on calcium-dependent stimuli of chloride secretion, pretreatment with flavopiridol on chloride secretory responses to the cAMP-dependent agonist, forskolin. In contrast to findings obtained with calcium-dependent stimuli of chloride secretion, pretreatment with flavopiridol did not potentiate the secretory response to forskolin; in this case, the response to forskolin was not statistically different from that obtained with forskolin alone (data not shown). Interestingly, however, pretreatment with forskolin significantly potentiated a subsequent response to flavopiridol (Fig. 8).

**DISCUSSION**

The experiments described in this report were designed to examine the possibility that diarrheal side effects experienced by patients taking flavopiridol could be related to alterations in chloride secretion. In keeping with this hypothesis, flavopiridol...
was shown to modify various aspects of chloride secretion in an in vitro model, although some of the effects that were seen occurred at concentrations of the drug that are likely to be in excess of any that can be obtained clinically (11, 12).

Flavopiridol is a flavonoid, and other known flavonoids such as genistein are either direct chloride secretagogues at high doses or potentiate responses to other stimuli at low doses (23–25). In general, the ability of flavonoids to modify chloride secretion in T84 cells as well as in other systems has been ascribed to their ability to act as tyrosine kinase inhibitors. Some studies, however, also suggest a direct effect of the flavonoid genistein, at least, on CFTR chloride channels localized to the apical membrane of epithelial cells (23). Furthermore, we and others have determined that tyrosine kinase activity, including that induced by binding of EGF to its receptor, serves to limit calcium-dependent chloride secretion (22, 26, 27). The mechanism of this effect is still the subject of investigation, although it appears likely to involve the tyrosine kinase-dependent generation of inhibitory intracellular messengers such as inositol 3,4,5,6-tetrakisphosphate and the products of phosphatidylinositol 3-kinase (20, 25, 27). In turn, these intracellular mediators directly or indirectly inhibit the activity of membrane chloride and potassium channels required for the overall process of chloride secretion (20, 28, 29). It is possible, therefore, that the ability of flavopiridol to potentiate responses to calcium-dependent secretagogues and to reverse inhibitory effects on chloride secretion might be related to some activity of the compound as a tyrosine kinase inhibitor. However, previous studies on this

Fig. 3 Effect of flavopiridol on chloride secretion induced by carbachol (CCh, $10^{-4}$ M). A, time course of chloride secretory responses to carbachol in the absence (○) or presence (●) of flavopiridol (Flavo, $10^{-4}$ M). Values are means for four experiments; bars, SE. B, effect of various nonsecretory doses of flavopiridol on chloride secretory responses to carbachol ($10^{-4}$ M). Values are expressed as a percentage of the response obtained in the absence of flavopiridol pretreatment and are means for two to five experiments; bars, SE. * values that represent significant potentiation of the response to carbachol, $P < 0.05$ by ANOVA with Bonferroni post-hoc test.

Fig. 4 Effect of flavopiridol on chloride secretion induced by thapsigargin (TG, $2 \times 10^{-6}$ M). A, time course of chloride secretory responses to thapsigargin in the absence (○) or presence (●) of flavopiridol pretreatment (Flavo, $10^{-4}$ M). Values are means for four experiments; bars, SE. B, increases in chloride secretion ($\Delta I_{sc}$) induced by flavopiridol or thapsigargin alone or the combination of these agents (Actual). Pred., the predictive additive response calculated by addition of the individual responses to flavopiridol and thapsigargin. The response obtained with the combined agents significantly exceeded the predicted response, $P < 0.001$ by Student’s t test. Values are means for four to five experiments; bars, SE.
agent suggest that although flavopiridol can inhibit EGF receptor tyrosine kinase activity, this effect occurs at concentrations of the drug that do not correspond to the lower range of doses examined here (IC50 < 1 μM; Ref. 8). Similarly, flavopiridol does not inhibit binding of EGF to its receptor, even at concentrations in excess of 2 mM (8). In contrast, effects of flavopiridol on ErbB2 could conceivably be involved in its diarrheal effects, because we have shown that this receptor tyrosine kinase is pivotally involved in the inhibitory effects of EGF on epithelial chloride secretion (30, 31).

Alternative mechanisms of the effect of flavopiridol on chloride secretion can be considered. The drug is a weak inhibitor of the chloride channel, and it is possible that flavopiridol could potentiate the effects of other agents on chloride secretion. For example, flavopiridol could increase the permeability of the channel by disrupting the channel subunit, or it could increase the expression of the channel subunit. Alternatively, flavopiridol could increase the activity of the channel by increasing the intracellular calcium concentration.

Fig. 5  Effect of flavopiridol on chloride secretion induced by taurodeoxycholate (TDC, 5 × 10^{-4} M). A, time course of chloride secretory response to taurodeoxycholate in the absence (○) or presence (●) of flavopiridol pretreatment (Flavo, 10^{-4} M). Values are means for five to six experiments; bars, SE. B, increases in chloride secretion (ΔIsc) induced by flavopiridol or taurodeoxycholate alone or the combination of these agents (Actual). Pred., the predictive additive response calculated by addition of the individual responses to flavopiridol and taurodeoxycholate. The response obtained with the combined agents significantly exceeded the predicted response, P < 0.05 by Student’s t test. Values are means for five to six experiments; bars, SE.

Fig. 6  Increases in chloride secretion (ΔIsc) induced by thapsigargin (TG) alone or after pretreatment with carbachol (CCh, 10^{-4} M), flavopiridol (Flavo, 10^{-4} M), or the combination of carbachol plus flavopiridol. Values are means for 3–10 experiments; bars, SE. * responses to TG that differed from the response obtained with TG alone (*, P < 0.05; **, P < 0.01 by ANOVA with Bonferroni post-hoc test). The response to TG in the presence of flavopiridol plus carbachol did not differ significantly from that obtained in the presence of flavopiridol alone (P > 0.05).

Fig. 7  Increases in chloride secretion (ΔIsc) induced by thapsigargin (TG) alone or after pretreatment with EGF (100 ng/ml), flavopiridol (Flavo, 10^{-4} M), or the combination of EGF plus flavopiridol. Values are means for three to five experiments; bars, SE. *, responses to TG that differed from the response obtained with TG alone (*, P < 0.05; ***, P < 0.001 by ANOVA with Bonferroni post-hoc test). The response to TG in the presence of flavopiridol plus EGF did not differ significantly from that obtained in the presence of flavopiridol alone (P > 0.05).
The ability of flavopiridol to potentiate the chloride secretory response to taurodeoxycholate has an interesting clinical correlate. In preliminary clinical studies with flavopiridol, it was discovered that the administration of cholestyramine reduced the intensity of patients’ diarrhea and in some cases, permitted escalation of the dose of flavopiridol that could be given (11, 12). In fact, this therapeutic strategy was prompted, in part, by the in vitro studies reported here, attesting to the validity of this approach to understand the adverse effects encountered (12). The clinical efficacy of cholestyramine might reflect an ability of the resin to bind flavopiridol and its known biliary metabolite, which would decrease the exposure of intestinal epithelial cells to flavopiridol (11). However, it is also tempting to speculate that at least part of the efficacy of cholestyramine in this setting correlates to removal of endogenous secretagogues (i.e., secretory bile acids) that might otherwise synergize with, and thereby uncover, a prosecretory action of flavopiridol. Similarly, anecdotal evidence suggests that flavopiridol-induced diarrhea could be diminished in some patients by administration of anticholinergic drugs (11).

In summary, flavopiridol, a cyclin-dependent kinase inhibitor, has demonstrated promising antineoplastic effects toward certain malignancies (11, 12). However, patients administered flavopiridol experience severe diarrheal side effects (11, 12). The current studies have shown that high doses of flavopiridol directly stimulate chloride secretion across monolayers of human colonocytes in modified Ussing chambers. This may be a result, at least in part, of the ability of flavopiridol to raise intracellular cAMP levels. Additionally, flavopiridol potentiates chloride secretory responses to calcium-dependent agonists and reverses cellular inhibitory mechanisms that normally limit the extent of calcium-dependent chloride secretion. Because these latter actions of flavopiridol can occur at doses that are clinically relevant (11, 12), they may well contribute to the side effects seen in patients treated with the drug. Whatever the intracellular/biochemical mechanism(s) of these effects, they could certainly provide an explanation as to why this medication causes severe diarrhea. A better understanding of the diarrhea induced by flavopiridol should allow optimization of therapy with this promising drug and/or the development of related agents with improved toxicity profiles (40).

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