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Diarrhea-associated HIV-1 APIs potentiate muscarinic activation of Cl− secretion by T84 cells via prolongation of cytosolic Ca2+ signaling

Paul A. Rufo,1,5* Patricia W. Lin,2,5× Adriana Andrade,7† Lianwei Jiang,3,6,8 Lucia Rameh,4 Charles Flexner,7 Seth L. Alper,3,6,8 and Wayne I. Lencer1,5,8

1GI Cell Biology, Combined Program in Pediatric Gastroenterology and Nutrition, 2Division of Newborn Medicine, Children’s Hospital, 3Molecular and Vascular Medicine and Renal Units and 4Division of Signal Transduction, Beth Israel Deaconess Medical Center, and Departments of 5Pediatrics and 6Medicine, Harvard Medical School, Boston, Massachusetts 02115; 7Division of Clinical Pharmacology, Johns Hopkins University, Baltimore, Maryland 21205; and 8Harvard Digestive Diseases Center, Boston, Massachusetts 02115

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Rufo, Paul A., Patricia W. Lin, Adriana Andrade, Lianwei Jiang, Lucia Rameh, Charles Flexner, Seth L. Alper, and Wayne I. Lencer. Diarrhea-associated HIV-1 APIs potentiate muscarinic stimulation of Cl− secretion by T84 cells via prolongation of cytosolic Ca2+ signaling. Am J Physiol Cell Physiol 286: C998–C1008, 2004. First published December 30, 2003; 10.1152/ajpcell.00357.2003.—Aspartyl protease inhibitors (APIs) are important components of most highly active antiretroviral therapy (HAART) regimens used in the treatment of human immunodeficiency virus (HIV)-1 infection. These agents decrease plasma HIV viral load, increase peripheral CD4+ T lymphocyte counts, delay clinical progression, and extend life expectancy (17). However, the clinical utility of these agents has been limited by serious side effects, which include lipodystrophy, insulin resistance, and diarrhea (14). The mechanistic bases of these dose-limiting side effects of API treatments remain unexplained.

In these studies, we examine the effects of the API nelfinavir on the intestine and on intestinal epithelial cells. Intestinal fluid secretion in the human depends on the closely regulated transport of Cl− ions by epithelial cells lining the intestinal crypt. Crypt epithelia utilize the basolateral membrane Na+–K+-ATPase and Na+–K+–coupled cotransporter NKCC1 to accumulate intracellular Cl− above its electrochemical equilibrium potential. The regulated opening of apical membrane Cl− channels in that setting results in a net secretion of Cl− ions into the intestinal lumen. Coordinated opening of basolateral K+ channels to maintain an inside-negative membrane potential sustains the Cl− secretory response by enhancing both the electrical gradient favoring electrogenic apical Cl− exit and the chemical gradient favoring Na+–K+–coupled Cl− uptake by basolateral NKCC1. Water and Na+ are thought to follow Cl− passively into the intestinal lumen to effect net fluid secretion.

Neural, endocrine, paracrine, and autocrine mechanisms tightly regulate intestinal fluid secretion in the human via agonists that utilize either cyclic nucleotides or Ca2+ as second messengers. Agonists that depend on adenosine 3′,5′-cyclic monophosphate (cAMP) to initiate Cl− secretion activate the apical membrane Cl− channel CFTR (cystic fibrosis transmembrane receptor) and the basolateral membrane K+ channel KCNQ1/KCNE3 (2, 10, 32, 42). Agonists that utilize Ca2+ as a second messenger activate the apical membrane Ca2+-activated Cl− conductance and the basolateral membrane K+ channel IK1 (KCNN4) (22, 24, 25, 47).

Muscarinic innervation of intestinal crypts regulates Cl− secretion through local release of acetylcholine. The secretory response induced in the crypt epithelial cell requires an elevation of intracellular Ca2+ that initially activates an apical membrane Ca2+-sensitive Cl− conductance. However, coordinate generation of inositol 3,4,5,6-tetrakisphosphate (IP4) and phosphorylation of the MAP kinase intermediates extracellular signal-regulated kinase (ERK) and p38 rapidly downregulate this Ca2+-sensitive Cl− conductance to keep muscarinally induced Cl− secretory responses short-lived (2, 7, 23, 29–31).

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ASPARTYL PROTEASE INHIBITORS (APIs) are important components of most highly active antiretroviral therapy (HAART) regimens used in the treatment of human immunodeficiency virus (HIV)-1 infection. These agents decrease plasma HIV viral load, increase peripheral CD4+ T lymphocyte counts, delay clinical progression, and extend life expectancy (17). However, the clinical utility of these agents has been limited by serious side effects, which include lipodystrophy, insulin resistance, and diarrhea (14). The mechanistic bases of these dose-limiting side effects of API treatments remain unexplained.

* P. A. Rufo and P. W. Lin contributed equally to this work.
† A. Andrade was lead investigator for the clinical study.

Address for reprint requests and other correspondence: W. I. Lencer, GI Cell Biology, Combined Program in Pediatric Gastroenterology and Nutrition, Children’s Hospital, 300 Longwood Ave., Boston, MA 02115 (E-mail: wayne.lencer@childrens.harvard.edu).

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In the current study, we have found that the API nelfinavir induces a secretory form of diarrhea in HIV-1-infected patients. In vitro studies demonstrate that nelfinavir potentiates muscarinic stimulation of Cl\(^{-}\) secretion in the human intestinal cell line T84 through the prolongation of a long-lived, store-operated Ca\(^{2+}\) entry pathway. The resulting prolonged period of increased intracellular Ca\(^{2+}\) correlates with uncoupling of the apical membrane Ca\(^{2+}\)-dependent Cl\(^{-}\) conductance from effects of the downstream regulatory signals IP\(_{4}\), phosphorylated ERK (pERK), and phospho-p38, all present at normal levels. We propose that this prolonged, store-operated Ca\(^{2+}\) influx provokes in intestinal epithelium the enhanced Cl\(^{-}\) secretion and consequent secretory diarrhea observed clinically in patients treated with APIs.

METHODS

Clinical studies. Eight HIV-infected subjects (ages 21–54) with diarrhea (stool output ≥300 g/24 h) for longer than 1 mo while on nelfinavir-containing regimens were admitted for 48 h and received a controlled diet (~4,200 calories/day, 50% carbohydrates, 12% protein, and 38% fat). Subjects remained on their prescribed daily dose of nelfinavir (5 subjects received 1,250 mg twice daily, and 3 subjects received 750 mg 3 times daily). Antidiarrheal medications were discontinued 3 days before and during hospitalization. Subjects receiving APIs other than nelfinavir or with any condition known to cause diarrhea were excluded from study participation. Stool output was collected in preweighed containers and stored at 4°C. Specimens were weighed, homogenized, and centrifuged for 10 min at 2,000 rpm. Fecal supernatants were analyzed for [Na\(^{+}\)] and [K\(^{+}\)] by ion-selective electrodes (Hitachi 917; Boehringer Mannheim), and pH and osmotic content were measured. Fecal osmolar gap was defined as the difference between predicted ([Na\(^{+}\) + K\(^{+}\)] × 2) and estimated fecal osmolality (290 mosmol/kg H\(_{2}\)O) (15). Osmotic diarrhea was defined as a fecal osmolar gap of >60 mosmol/kg H\(_{2}\)O with stool [Cl\(^{-}\)] ≤ 15 meq/l and [Na\(^{+}\)] ≤ 30 meq/l and a stool pH ≥ 6.0. Secretory diarrhea was defined as a fecal osmolar gap ≤50 mosmol/kg H\(_{2}\)O, pH ≥ 6.0, with stool [Na\(^{+}\)] ≤ 60 meq/l and stool [Cl\(^{-}\)] ≥ 30 meq/l. This study was approved by the IRB at Johns Hopkins University, and all subjects provided informed consent before participation.

Materials. Nelfinavir (Agouron Pharmaceuticals, La Jolla, CA), saquinavir (Roche Pharmaceuticals, Nutley, NJ), indinavir (Merck, West Point, PA), and ritonavir (Abbot Laboratories, North Chicago, IL) were used without excipients as kindly provided by the manufacturers. Stock solutions (20 mM) were stored at 4°C in equal parts of ethanol and DMSO. Cells were pretreated for 30 min with nelfinavir (or other API) unless otherwise stated. Anti-pERK (New England Biolabs, Beverly, MA) and anti-phospho-p38 antibodies (Cell Signaling, Beverly, MA) were used at 1:1,000 dilution. [\(^{3}H\)]inositol was obtained from PerkinElmer (Boston, MA). All other reagents were obtained from Sigma-Aldrich (St. Louis, MO) unless otherwise specified.

Short-circuit measurement in intact monolayers. Short-circuit current (Isc) and transepithelial resistance were measured in confluent T84 cell monolayers grown on 0.33-cm\(^{2}\) inserts). CCh was used at 100 mM and forskolin at 10 μM. We routinely observe a variability of 10–15 μA/cm\(^{2}\) in maximal Isc elicited by the muscarinic agonist CCh in T84 monolayers due to cell culture and plating of T84 cells on filter inserts from sequential passages, consistent with previous studies (28, 48).

Short-circuit current measurement in semipermeabilized monolayers. T84 cell monolayers (grown on 0.33-cm\(^{2}\) inserts) were incubated in the presence of or absence of nelfinavir in buffers containing K\(^{+}\) or Cl\(^{-}\) as the sole permeant ions (Table 1). Basolateral membrane K\(^{+}\) conductances, measured as short-circuit current (Iscbasol), were studied in cells permeabilized apically with 20 μM amphotericin B, in the presence of asymmetrical buffers that imposed a basolaterally directed sevenfold K\(^{+}\) gradient (apical solution 4, basal solution 5; see Table 1) as previously described (41). Transmembrane potential was clamped at 0 mV, and Iscbasol was measured before and after stimulation with CCh. Apical Cl\(^{-}\) conductances, measured as short-circuit current (Iscapicl), were studied in cells permeabilized basolaterally with 100 μM amphotericin B, in the presence of symmetric high-Cl\(^{-}\) buffer (solution 1) with transmembrane potential clamped at +10 mV (apical) as previously described (34). Ipscocl was measured before and after thapsigargin stimulation. Anion selectivity was measured in asymmetrical nelfinavir-containing buffers that imposed an apically directed ~20-fold gradient of either I\(^{-}\) (basal solution 6, apical solution 7) or Cl\(^{-}\) (basal solution 2, apical solution 3) as the sole permeant ions. Transepithelial currents were measured during 1-s voltage clamp periods ranging from ~80 to +80 mV and normalized to baseline Isc at rest as described (34). Basal current-voltage (I-V) curves obtained in the absence of agonist were subtracted from those measured after agonist treatment to calculate agonist-induced currents.

| Table 1. Composition of solutions used for electrophysiology studies |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Compound, mM    | High Cl\(^{-}\) | Normal Cl\(^{-}\) | Low Cl\(^{-}\) | High K\(^{+}\)  | Low K\(^{+}\)  | Normal I\(^{-}\) | Low I\(^{-}\)  |
| Na\(^{+}\)       | 0.7             | 0.7             | 0.7             | 140            | 20             | 5.8             | 5.8             |                 |                 |                 |                 |
| K\(^{+}\)        | 0.43            | 5.8             | 5.8             | 140            | 20             | 5.8             | 5.8             |                 |                 |                 |                 |
| Ca\(^{2+}\)      | 1.25            | 1.25            | 1.25            | 1.25           | 1.25           | 1.25            | 1.25            |                 |                 |                 |                 |
| Mg\(^{2+}\)      | 0.4             | 0.4             | 0.4             | 0.4            | 0.4            | 0.4             | 0.4             |                 |                 |                 |                 |
| Cl\(^{-}\)       | 144.8           | 144.9           | 7.9             | 144.9          | 7.9            | 144.9           | 7.9             |                 |                 |                 |                 |
| I\(^{-}\)        |                 |                 |                 | 7.9            | 137            |                 |                 |                 |                 |                 |                 |
| Choline          | 142.3           | 137             |                 | 140            | 140            | 137             |                 |                 |                 |                 |                 |
| Glucosinate      |                 |                 |                 |                 |                 |                 |                 | 130             |                 |                 |                 |
| NMDG             |                 |                 |                 |                 |                 |                 |                 | 130             |                 |                 |                 |
| SO\(_{4}\)       | 0.4             |                 |                 |                 |                 |                 |                 |                 | 1.65            | 1.29            |                 |
| PO\(_{4}\)       | 1.13            | 0.4             | 0.4             |                 | 0.4            |                 |                 |                 | 0.4             |                 |                 |
| HEPES            | 10              | 0.4             |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| d-Glucose        | 5.6             | 5.6             | 5.6             | 5.6            | 5.6            | 5.6             | 5.6             |                 |                 |                 |                 |
| Total, mM        | 307             | 305             | 305             | 299            | 299            | 305             | 305             |                 |                 |                 |                 |

NMDG, N-methyl-n-glucamine.
**Immunoblots of pERK.** T84 cell monolayers (grown on collagen-coated 5-cm² filters) were preincubated in the presence or absence of nelfinavir (0.4 to 40 μM) at 37°C for 30 min. Five minutes after the subsequent addition of CCh, cells were transferred to ice-cold PBS. Total cell lysates were prepared by scraping cells into lysis buffer (1 mM NaF, 1 mM sodium vanadate, 1% Triton X-100, one protease inhibitor MiniTab with EDTA; Hoffman-La Roche, Nutley, NJ) and then clarified by centrifugation. Lysates were analyzed for pERK by SDS-PAGE and immunoblot. Equal protein loads were confirmed by Ponceau stain.

**Immunoblots of phospho-p38.** T84 cell monolayers (grown on collagen-coated 5-cm² filters) were preincubated in the presence or absence of 30 μM nelfinavir for 30 min at 37°C. After exposure to CCh (100 μM) for the indicated intervals (between 0 and 15 min), monolayers were transferred into ice-cold lysis buffer (1 mM NaF, 1 mM sodium vanadate, 1% Triton X-100, one protease inhibitor MiniTab with EDTA; Hoffman-La Roche). Cell lysates were clarified by centrifugation, and phosphorylated p38 was assayed by immunoblot.

**1P₄ measurements.** T84 cell monolayers (grown on collagen-coated 45-cm² filters) were labeled for 24 h in inositol-free DMEM containing 5% fetal calf serum and 5% FCS. Total cell lipids (5% fetal calf serum and 5% FCS) were then extracted in H₂O-saturated ether, dried overnight, and freeze-thawed using 5% FCS. These data show that HIV-1-infected patients on chronic nelfinavir therapy exhibited fecal electrolyte concentrations ([Na⁺] and [Cl⁻]) consistent with a secretory defect, we utilized the human intestinal T84 cell line. T84 cells were incubated at 37°C in growth medium containing 2% FCS in the absence of nelfinavir (40 μM) (Fig. 1, B and E) or adenosine (10 μM; see below). Stimulation of Iₑ by nelfinavir (at all tested concentrations) was observed only after CCh treatment (Fig. 1C). The EC₅₀ value for nelfinavir was 4.8 (30 min after 30-min preincubations approximating the peak plasma concentration (4 mg/l or 6 μM) measured in humans treated with 1.250 mg of nelfinavir twice daily (17). Nelfinavir (30 μM) did not change the EC₅₀ value of CCh, and the CCh-potentiating effect of nelfinavir was not reversed after 24 h (nelfinavir increased the peak response to CCh by 180%). Nelfinavir also potentiated the action of two other Ca²⁺-dependent secretagogues (Fig. 1D); thapsigargin (5 μM) and the bile acid taurodeoxycholate (500 μM). The effects of nelfinavir on agonist-stimulated Iₑ in T84 cells are summarized in Fig. 1E. The structurally related HIV APIs saquinavir and indinavir similarly potentiated muscular Cl⁻ secretion in T84 cells (Fig. 2). Nelfinavir pretreatment of the human intestinal cell line HT29 C119a also potentiated CCh-activated Iₑ (data not shown). Thus nelfinavir and other APls produce long-lasting stimulatory effects on Iₑ induced by Ca²⁺ agonists in two human colonocyte cell lines.

**Nelfinavir potentiates an apical Ca²⁺-dependent Cl⁻ conductance and uncouples it from downregulatory signals.** We assessed the relative contributions of basolateral and apical conductances to nelfinavir-stimulated Iₑ by studying selectively permeabilized monolayers. To test stimulation of basolateral K⁺ channels, we permeabilized selectively the apical membranes of T84 cells with the ionophore amphotericin B, and the monolayer was exposed to an apical-to-basolateral K⁺ gradient with K⁺ as the sole permeant ion, as previously discussed (29).

> To examine the cellular mechanisms underlying this secretory defect, we utilized the human intestinal T84 cell line. T84 cells model regulated Cl⁻ secretion in the human intestine (1). Exposure of resting T84 cells to nelfinavir (30 μM) produced no detectable effect on Cl⁻ secretion (Iₑ) or transepithelial resistance. Nelfinavir-pretreated monolayers subsequently exposed to CCh showed a three- to fourfold increase in peak Cl⁻ secretory response (Fig. 1A) and a prolonged duration of Cl⁻ secretion (30 min after CCh exposure, Iₑ was 3.5 ± 0.3 μA/cm² in control and 9.1 ± 0.83 μA/cm² in nelfinavir-pretreated monolayers, means ± SE, n = 7 experiments, P ≤ 0.001). Nelfinavir pretreatment did not alter the decrease in transepithelial resistance observed after subsequent treatment with CCh (598 ± 74 and 723 ± 133 Ω/cm², means ± SE, in control and nelfinavir-treated T84 cell monolayers, respectively). Nelfinavir had no effect on Cl⁻ secretion elicited by the Ca²⁺-dependent agonists vasoactive intestinal peptide (VIP; 5 nM) (Fig. 1, B and E) or adenosine (10 μM; see below). Stimulation of Iₑ by nelfinavir (at all tested concentrations) was observed only after CCh treatment (Fig. 1C). The EC₅₀ value for nelfinavir was 4.8 (30 min after 30-min preincubations approximating the peak plasma concentration (4 mg/l or 6 μM) measured in humans treated with 1.250 mg of nelfinavir twice daily (17). Nelfinavir (30 μM) did not change the EC₅₀ value of CCh, and the CCh-potentiating effect of nelfinavir was not reversed after 24 h (nelfinavir increased the peak response to CCh by 180%). Nelfinavir also potentiated the action of two other Ca²⁺-dependent secretagogues (Fig. 1D); thapsigargin (5 μM) and the bile acid taurodeoxycholate (500 μM). The effects of nelfinavir on agonist-stimulated Iₑ in T84 cells are summarized in Fig. 1E. The structurally related HIV APIs saquinavir and indinavir similarly potentiated muscular Cl⁻ secretion in T84 cells (Fig. 2). Nelfinavir pretreatment of the human intestinal cell line HT29 C119a also potentiated CCh-activated Iₑ (data not shown). Thus nelfinavir and other APls produce long-lasting stimulatory effects on Iₑ induced by Ca²⁺ agonists in two human colonocyte cell lines.

**RESULTS**

Nelfinavir induces secretory diarrhea through selective potentiation of signaling by muscarinic and other Ca²⁺-dependent agonists. Stool samples collected from eight HIV-infected individuals on chronic nelfinavir therapy exhibited fecal electrolyte concentrations ([Na⁺] and [Cl⁻]) consistent with a secretory process. Stool pH and the fecal supernatant osmotic gap were consistent with a secretory process in seven subjects (Table 2). These data show that HIV-1-infected patients on chronic nelfinavir therapy have a secretory diarrhea.

**Table 2. Stool output in HIV-infected patients treated with nelfinavir**

<table>
<thead>
<tr>
<th>Subject No. (Sex)</th>
<th>Stool Output, g/day</th>
<th>Osmotic Gap, mosmol/kgH₂O</th>
<th>Stool pH</th>
<th>Na⁺, meq/l</th>
<th>Cl⁻, meq/l</th>
<th>K⁺, meq/l</th>
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<tr>
<td>1 (M)</td>
<td>408</td>
<td>−12</td>
<td>6.0</td>
<td>121</td>
<td>37</td>
<td>30</td>
</tr>
<tr>
<td>2 (M)</td>
<td>273</td>
<td>−38</td>
<td>6.0</td>
<td>84</td>
<td>49</td>
<td>79.9</td>
</tr>
<tr>
<td>3 (M)</td>
<td>302</td>
<td>16</td>
<td>7.8</td>
<td>68</td>
<td>41</td>
<td>69</td>
</tr>
<tr>
<td>4 (F)</td>
<td>368</td>
<td>62</td>
<td>7.0</td>
<td>79</td>
<td>39</td>
<td>34.8</td>
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<td>5 (F)</td>
<td>332</td>
<td>32</td>
<td>5.0</td>
<td>73</td>
<td>48</td>
<td>56.1</td>
</tr>
<tr>
<td>6 (F)</td>
<td>475</td>
<td>−15</td>
<td>6.5</td>
<td>98</td>
<td>44</td>
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<td>116</td>
<td>75</td>
<td>47.1</td>
</tr>
<tr>
<td>8 (M)</td>
<td>3,940</td>
<td>−4</td>
<td>7.5</td>
<td>111</td>
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<td>36.1</td>
</tr>
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</table>

Calculated osmotic gap is defined as 290 mosmol/kgH₂O [(fetal [Na⁺] + [(fetal [K⁺]) × 2]. HIV, human immunodeficiency virus; M, male; F, female.
described (41). After achievement of steady state, CCh was added and basolateral K\(^+\) conductance was measured as the short-circuit current \(I_s\). These apically permeabilized monolayers exhibited similar basolateral K\(^+\) conductances after muscarinic stimulation in the presence or absence of nelfinavir (Fig. 3, A and B). Thus nelfinavir has no effect on basolateral K\(^+\) conductance activated by CCh stimulation (believed to be mediated by the Ca\(^{2+}\)-dependent K\(^+\) channel IK\(^1\)/KCNN4) (12). Nonetheless, Cl\(^-\) secretion elicited by nelfinavir requires basolateral K\(^+\) conductance and is blocked fully by high concentrations of the K\(^+\) channel inhibitor clotrimazole (Fig. 4).

Nelfinavir could also act by increasing the apical membrane Ca\(^{2+}\)-dependent Cl\(^-\) conductance or possibly (though less

Fig. 1. Nelfinavir acts synergistically with muscarinic agonists to potentiate Cl\(^-\) secretion. A: time course of 100 \(\mu\)M carbachol (CCh)-induced short-circuit current \(I_s\) in intact T84 cell monolayers pretreated for 90 min with (●) or without (○) nelfinavir (30 \(\mu\)M). Data are representative of 6 independent experiments. B: time course of 5 nM vasoactive intestinal peptide (VIP)-induced \(I_s\) in monolayers pretreated with (●) or without (○) nelfinavir. Data are representative of 3 independent experiments. C: nelfinavir concentration-response curve for monolayers stimulated with CCh (●) and VIP (○). Data are means ± SE; \(n = 3\) experiments. D: time courses of \(I_s\) induced by thapsigargin in cells pretreated with (●) or without (○) nelfinavir. E: agonist-induced \(I_s\) in T84 monolayers pretreated with (light shaded bars) or without (dark shaded bars) nelfinavir. Data are means ± SE; \(n = 3\) experiments for each agonist. * \(P < 0.05\). TDC, tauro-deoxycholate; Thaps, thapsigargin.

Fig. 2. Human immunodeficiency virus (HIV)-1 protease inhibitors potentiate Cl\(^-\) secretion elicited by the muscarinic agonist CCh. Time courses of CCh-induced \(I_s\) are shown in intact T84 monolayers pretreated (●) or untreated (○) with 100 \(\mu\)M saquinavir (A) or indinavir (B). Data for both inhibitors are representative of 2 independent experiments.

Fig. 3. Nelfinavir does not inhibit basolateral K\(^+\) conductance in T84 cells. A: time course of CCh-induced basolateral membrane K\(^+\) conductance \([I_{bl\text{K}}]\) in apically permeabilized T84 monolayers pretreated with (●) or without (○) nelfinavir. B: peak increase in \(I_{bl\text{K}}\) above baseline \([\Delta I_{bl\text{K}}]\). Data are means ± SE; \(n = 3\) experiments. NS, nonsignificant.
likely, in view of Fig. 1B) through activation of the apical cAMP-dependent CFTR. We therefore permeabilized selectively the basolateral membrane of T84 cell monolayers with amphotericin B. Cells were then studied in symmetrical solutions containing Cl\(^-\) as the only permeant ion, and apical Cl\(^-\) conductance, measured as \(I_{\text{ap}}(\text{Cl})\), was measured as previously described (41). Basolateral permeabilization precludes the use of the muscarinic agonist CCh in studies assessing apical Ca\(^{2+}\)-activated Cl\(^-\) conductances. Thus we used the endoplas-
The transient elevation of $I_{sc}$ that typifies muscarinically induced Cl$^{-}$ secretion in T84 cells is generally attributed to rapid downregulation of apical membrane Cl$^{-}$ channels by the parallel synthesis of IP$_4$ and the phosphorylation of the MAP kinase intermediates ERK and p38 (29–31). These downregulators of apical Ca$^{2+}$-dependent Cl$^{-}$ conductance render it refractory to further stimulation by Ca$^{2+}$-dependent agonists for up to 30 min after withdrawal of muscarinic activation (26).

Downregulation of basolateral membrane K$^{+}$ channels by transactivation of the EGF receptor also follows muscarinic activation in T84 cells and also contributes to the transient nature of CCh-elevated $I_{sc}$. However, basolateral K$^{+}$ conductance is unaltered in nelfinavir-pretreated cells as shown in Fig. 3, A and B. We therefore tested whether nelfinavir potentiation of apical Cl$^{-}$ conductance might be explained by inhibition of the muscarinic activation of IP$_4$ synthesis or by inhibition of phosphorylation of ERK and p38.

We first tested whether nelfinavir had any effect on the refractory period to Ca$^{2+}$-dependent agonists observed after muscarinic activation. Control monolayers stimulated with CCh exhibited a typical increase in $I_{sc}$ followed by a rapid return to baseline. There followed a period refractory to subsequent treatment with thapsigargin (Fig. 6A). In contrast, nelfinavir-pretreated monolayers failed to exhibit such a refractory period after muscarinic stimulation (Fig. 6A). The nelfinavir-pretreated cells displayed normal sensitivity to thapsigargin exposure only 15 min after the initial exposure to CCh. This response resembles that of cells exposed to thapsigargin without pretreatment with nelfinavir or CCh (Fig. 6A). The mean results from three independent studies (Fig. 6B) show that nelfinavir abrogates the refractory period seen normally in T84 cells after stimulation with CCh. Despite abolition of the post-CCh-refractory period of T84 cells by nelfinavir pretreatment, nelfinavir had no detectable effect on CCh-induced

![Graph A](image1)

**Fig. 6.** Nelfinavir uncouples Ca$^{2+}$-activated $I_{sc}$ from downregulation by phosphorylated ERK (pERK), phospho-p38, and inositol 3,4,5,6-tetra(kisphosphate (IP$_4$). A: time course of $I_{sc}$ in intact T84 monolayers treated without CCh (●) or with CCh in the presence (●) or absence (○) of nelfinavir. Thapsigargin was applied to all monolayers at 45 min. B: peak $I_{sc}$ induced by thapsigargin. Data are means ± SE; n = 3 experiments. C: Western blot of total cell extracts for pERK prepared from intact T84 cell monolayers pretreated with or without the indicated concentrations of nelfinavir and subsequently exposed or not exposed to 100 μM CCh for 5 min. Data are representative of 2 independent experiments. D: Western blot of total cell extracts for phospho-p38 prepared from intact T84 cell monolayers pretreated with or without the indicated concentrations of nelfinavir and subsequently exposed or not exposed to 100 μM CCh for 5 min. Data are representative of 2 independent experiments. E–H: HPLC analyses of [3H]IP$_4$ in total cell extracts prepared from control (E and G) or nelfinavir-pretreated monolayers (F and H) and subsequently exposed (G and H) or not to CCh (E and F). IP$_4$ controls were run in parallel (not shown). IP$_4$ levels were similar in control (14,268 dpm) and nelfinavir-pretreated (15,191 dpm) T84 cell monolayers. Data are representative of 2 independent experiments.
levels of pERK (Fig. 6C), phospho-p38 (Fig. 6D), or IP$_3$ (Fig. 6, E–H). These data demonstrate that the Ca$^{2+}$-activated Cl$^-$ conductance in nelfinavir-pretreated cells is functionally uncoupled from normal levels of these physiological downregulatory signals.

**Nelfinavir potentiates cytosolic [Ca$^{2+}$]$_i$ signaling.** Because the effects of nelfinavir pretreatment were observed only in cells exposed to Ca$^{2+}$-dependent agonists, we examined the effect of nelfinavir on intracellular Ca$^{2+}$ signaling in fura-2-loaded T84 cells. Nelfinavir itself had no detectable effect on [Ca$^{2+}$]$_i$ in resting cells (not shown). After muscarinic stimulation, however, Ca$^{2+}$ transients in nelfinavir-pretreated cells were increased in magnitude and duration compared with those observed in cells not exposed to nelfinavir (Fig. 7A). The peak increase in [Ca$^{2+}$]$_i$, induced by CCh in nelfinavir-pretreated cells was 138 ± 10 nM (n = 9) vs. 56 ± 4 nM (n = 4; mean ± SE) in cells unexposed to nelfinavir. In contrast, nelfinavir pretreatment had no detectable effect on intracellular Ca$^{2+}$ transients induced by CCh in a Ca$^{2+}$-free bath (increase in [Ca$^{2+}$]$_i$: 43 ± 7 vs. 45 ± 5 nM, respectively, n = 3; mean ± SE) (Fig. 7B). Thus the enhanced [Ca$^{2+}$]$_i$ response induced by CCh in nelfinavir-pretreated cells was entirely dependent on influx of extracellular Ca$^{2+}$. The enhanced muscarinic Cl$^-$ secretion observed in nelfinavir-pretreated monolayers was inhibited by the Ca$^{2+}$-permeable cation channel inhibitor SKF-96365 (50 μM) (Fig. 8, n = 3, P < 0.05). In contrast, the L-type Ca$^{2+}$ channel blockers verapamil (25 μM) and nifedipine (1 μM) were without apparent effect on nelfinavir-induced secretory responses (not shown).

Basolateral addition of Ba$^{2+}$ (3 mM) to T84 monolayers inhibited the enhancement of the muscarine-induced $I_{\mathrm{sc}}$ observed in nelfinavir-pretreated monolayers (Fig. 9A), whereas apical Ba$^{2+}$ had no effect (not shown). As expected, basolateral application of Ba$^{2+}$ to untreated monolayers failed to inhibit normal CCh-induced Cl$^-$ secretion (Fig. 9A; summarized in Fig. 9B). Moreover, basolateral Ba$^{2+}$ did not inhibit the CCh-triggered increase in basolateral K$^+$ conductance in apically permeabilized T84 cells pretreated with nelfinavir (Fig. 9, C and D) confirming directly that Ba$^{2+}$ does not affect IK1 in this experimental system. The inhibitory effect of Ba$^{2+}$ is also not due to inhibition of the K$^+$ channel KCNQ1/KCNE3, because the chromanol inhibitor of this channel, 293B, similarly had no effect on the potentiation of the CCh-induced $I_{\mathrm{sc}}$ in intact monolayers pretreated with nelfinavir (not shown). Thus the inhibition by Ba$^{2+}$ of the enhanced Ca$^{2+}$ transient in nelfinavir-pretreated T84 cells did not appear secondary to inhibition of either the cAMP-regulated K$^+$ channel KCNQ1/KCNE3 or the Ca$^{2+}$-gated K$^+$ channel IK1.

We then considered the possibility that Ba$^{2+}$ blocks a CCh-activated Ca$^{2+}$ entry pathway in nelfinavir-pretreated cells. As shown in Fig. 7A, CCh induced [Ca$^{2+}$]$_i$, transients in nelfinavir-pretreated, fura-2-loaded T84 cells that exceeded both in magnitude and duration those observed in cells unexposed to nelfinavir. Addition of Ba$^{2+}$ to the bath rapidly reduced [Ca$^{2+}$]$_i$, toward baseline levels (Fig. 7A). Thus Ba$^{2+}$ exposure of nelfinavir-pretreated T84 cells inhibits in parallel the nelfinavir-potentiated $I_{\mathrm{sc}}$ across monolayers and the nelfinavir-potentiated [Ca$^{2+}$]$_i$, transient recorded on coverslips, without detectable inhibition of basolateral K$^+$ conductance. This correlation suggested that Ba$^{2+}$ might also inhibit the nelfinavir-associated escape from the refractory period that follows muscarinic activation. Indeed, Ba$^{2+}$ inhibited fully the $I_{\mathrm{sc}}$ induced by thapsigargin added soon after muscarinic activation (Fig. 9, E and F). These data suggest that nelfinavir pretreatment potentiates Ca$^{2+}$ entry in CCh-stimulated T84 cell monolayers via a mechanism that can be inhibited by basolateral exposure to Ba$^{2+}$. However, in T84 cells not pretreated with nelfinavir, Ba$^{2+}$ has no effect on CCh-activated $I_{\mathrm{sc}}$ or on the CCh-induced [Ca$^{2+}$]$_i$, transient. Thus nelfinavir-elicited, Ba$^{2+}$-sensitive, CCh-activated Ca$^{2+}$ entry is not part of the normal response to muscarinic stimulation in untreated T84 cells.

We tested the role of intracellular Ca$^{2+}$ stores in the regulation of the nelfinavir-elicited Ca$^{2+}$ entry pathway. Intracellular Ca$^{2+}$ stores of T84 cells grown on coverslips were depleted by muscarinic stimulation in nominally Ca$^{2+}$-free bath. In the absence of extracellular Ca$^{2+}$, CCh induced small [Ca$^{2+}$]$_i$, transients with

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**Fig. 7.** Nelfinavir enhances plasma membrane Ca$^{2+}$ influx induced by CCh. A: CCh (added at filled arrows) elicited intracellular Ca$^{2+}$ concentration ([Ca$^{2+}$]$_i$) transients in clusters of T84 cells pretreated with (●) or without (□, right-displaced trace) nelfinavir. The increased [Ca$^{2+}$]$_i$, in nelfinavir-pretreated cells was reversed (●) by 3 mM BaCl$_2$ (added at open arrow). Each trace is representative of 4–5 cell clusters imaged on 2–4 separate coverslips. B: CCh-induced [Ca$^{2+}$]$_i$, transients in T84 cells in nominally Ca$^{2+}$-free medium pretreated with (●) or without (□) nelfinavir. Each trace is representative of 3 cell clusters imaged on 3 coverslips.

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**Fig. 8.** Nelfinavir-induced $I_{\mathrm{sc}}$ is blocked by the Ca$^{2+}$-permeable cation blocker SKF-96365 (SKF). CCh-induced Cl$^-$ secretion in control and nelfinavir-pretreated intact T84 monolayers is shown in the absence (solid bars) or presence (shaded bars) of SKF-96365. Data are means ± SE; n = 3 experiments. *P < 0.05.
indistinguishable peak $[\text{Ca}^{2+}]_i$ values 134 ± 58 nM above baseline in nelfinavir-pretreated cells and 108 ± 38 nM in untreated cells ($n = 4$, mean ± SE) that rapidly returned to baseline levels (Fig. 10, A and B). Readdition of 2.7 mM extracellular Ca$^{2+}$ in the continued presence of CCh rapidly increased $[\text{Ca}^{2+}]_i$ to peak values of 229 ± 31 and 183 ± 27 nM above baseline in nelfinavir-pretreated and untreated cells, respectively ($n = 4$, means ± SE) (Fig. 10, A and B). However, the rate of the subsequent decline in $[\text{Ca}^{2+}]_i$ in nelfinavir-pretreated cells was much slower than that in untreated cells. $[\text{Ca}^{2+}]_i$ in the absence of nelfinavir fell 78 ± 4% (mean ± SE) from peak values within 8 min after bath Ca$^{2+}$ readdition (Fig. 10, A and C). In contrast, $[\text{Ca}^{2+}]_i$ in nelfinavir-pretreated cells decreased only 30 ± 3% from peak levels during the same period ($P < 0.0005$; Fig. 10, B and C). Thus influx-dependent elevation of $[\text{Ca}^{2+}]_i$, following bath Ca$^{2+}$ readdition to CCh-stimulated T84 cells was prolonged by nelfinavir pretreatment.

After depletion of intracellular Ca$^{2+}$ stores by thapsigargin exposure of T84 cells in a nominally Ca$^{2+}$-free medium, readdition of bath Ca$^{2+}$ induced an elevation of $[\text{Ca}^{2+}]_i$, larger than that observed after CCh stimulation, with a peak value of 402 ± 11 nM above baseline ($n = 4$, mean ± SE; Fig. 10D). This store depletion-activated Ca$^{2+}$ influx was larger still in nelfinavir-pretreated cells, with a peak value of 816 ± 125 nM above baseline ($n = 4$, mean ± SE, $P < 0.05$; Fig. 10E).

Moreover, the rate of subsequent $[\text{Ca}^{2+}]_i$ decline in nelfinavir-pretreated cells was again much slower than that in untreated cells. Whereas 15 min after bath Ca$^{2+}$ readdition, $[\text{Ca}^{2+}]_i$ had declined 52 ± 6% from peak values in untreated cells, this decline was only 26 ± 4% in nelfinavir-pretreated cells (means ± SE, $P < 0.0005$; Fig. 10F). Thus nelfinavir pretreatment enhanced both the magnitude and duration of thapsigargin-induced store depletion-activated Ca$^{2+}$ influx in T84 cells. These data suggest activation by nelfinavir of a store-operated plasmalemmal Ca$^{2+}$ entry pathway.

**DISCUSSION**

These studies provide the first mechanistic insights into the pathophysiology of API-induced diarrhea in HIV-infected patients. Nelfinavir potentiates muscarinic Cl$^{-}$ secretion in intestinal epithelial cells by recruitment of a slowly inactivating basolateral Ca$^{2+}$ entry pathway that can be further activated by depletion of intracellular Ca$^{2+}$ stores and is inhibited by basolateral exposure to Ba$^{2+}$. This additional Ca$^{2+}$ uptake pathway differs from that activated by CCh in the normal muscarinic signal transduction cascade, because Ba$^{2+}$ has no detectable effect on CCh-activated $I_{\text{op(C)}}$ in untreated cells. The enhanced $[\text{Ca}^{2+}]_i$ signal induced by nelfinavir may cause or contribute to the uncoupling of a CaCC-like apical Cl$^{-}$-
conductance from normal downregulation by IP_4, pERK, and phospho-p38. The resulting prolonged activation of apical Cl^- conductance contributes to (and may suffice to explain) the enhanced Cl^- secretory response. This mechanism of action is distinct from that recently proposed for the chemotherapeutic agent flavopiridol, which elicits a secretory response in T84 cells via inhibition of the downregulatory signals affecting the apical Ca^{2+}-activated Cl^- conductance (27).

On the basis of these results, we propose that nelfinavir acts in vivo directly on the intestinal mucosa to enhance the activity of muscarinic and other Ca^{2+}-dependent agonists by recruiting an additional store-operated plasmalemmal Ca^{2+} entry pathway to potentiate an otherwise normal secretory response. Such a mechanism of action on intestinal Cl^- secretion should initiate a secretory form of diarrhea, a prediction confirmed by our clinical studies in hospitalized HIV-infected adults. At peak in vivo plasma concentrations of 6 μM for nelfinavir, the Cl^- secretory response would be near the ED_{50} for nelfinavir's in vitro effect on T84 cells. Thus small differences among individual patient plasma nelfinavir concentrations due to differences in drug metabolism or excretion may have large effects on Cl^- secretion and diarrhea severity.

Other tested APIs also potentiate the muscarinically induced Cl^- secretory response in T84 cells. Furthermore, nelfinavir effectively potentiates the Cl^- secretory responses elicited by a wide range of Ca^{2+}-dependent agonists, including those induced by bile acids often present in the human colon. Thus the secretory diarrhea described in up to 30% of API-treated patients may be the result of enhanced secretion by normal neurocrine and paracrine secretory regulators, triggered by subclinical degrees of bile acid malabsorption as well as other genetic, dietary, or environmental factors.

The apical membrane conductance potentiated by nelfinavir in T84 cells exhibits several properties characteristic of the CLCA family of Ca^{2+}-activated Cl^- conductances, including Ca^{2+} dependence, a preference for I^- over Cl^-, and sensitivity to inhibi-
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tion by DTT. Although the molecular identity of the intestinal crypt cell Ca2+-activated Cl− conductance remains uncertain, members of the CLCA gene family have been proposed as candidates (3, 19). This apical Ca2+-activated Cl− conductance is thus a therapeutic target, but specific inhibitors for it and for the cloned CLCA channels remain unidentified. Chlorotoxin, active against the Ca2+-activated Cl− conductance of gliomas and astrocytes, appears inactive in T84 cells (33). Our results also show that nelfinavir effectively uncouples the apical Cl− conductance from downregulation by the intracellular mediators IP3, pERK, and phospho-p38 but has no apparent effect on basolateral K+ conductance after muscarinic activation. Thus nelfinavir may elevate levels of intracellular antagonists of these downregulatory signals to potentiate the physiological agonists of Ca2+-dependent intestinal Cl− secretion.

The reversal potential of thapsigargin-activated apical membrane currents in nelfinavir-pretreated cells (Fig. 5C) suggests that nelfinavir may potentiate in parallel an apical membrane Ca2+-activated cation conductance and an apical Ca2+-activated Cl− conductance, as suggested also by our previous studies in the absence of nelfinavir (34). Merlin et al. (34) also showed that gluconate permeability of the thapsigargin-induced T84 cell apical membrane conductance is minimal. Similarly, CCh-induced increase in Iec across intact, nelfinavir-pretreated T84 cell monolayers is abrogated in nominally Cl−-free, symmetrical sodium gluconate solutions (not shown). Activation of apical cation currents is consistent with previous reports of nonspecific cation currents in T84 cells (4, 8, 11, 45, 46).

We have previously shown that the imidazole antifungal clotrimazole and its des-imidazolyl metabolite block intestinal Cl− secretion by inhibition of both the cAMP-activated K+ conductance (likely mediated by KCNQ1/KCNNE3) and the Ca2+-gated K+ conductance likely mediated by IK1 (KCNN4) (41). Blockade of the appropriate K+ channel(s) fully inhibits Cl− secretion induced by either cAMP or Ca2+-dependent agonists in vitro and by cAMP-dependent agonists in vivo. Basolateral K+ channel activity is also required for nelfinavir-stimulated Cl− secretion by T84 cells and is blocked fully by 30 μM clotrimazole, although at this concentration clotrimazole is nonspecific. At the more specific concentration of 1 μM, clotrimazole had no effect on CCh-induced Cl− Iec in cells pretreated with nelfinavir or (as previously reported) without nelfinavir (not shown). Clotrimazole has been administered in humans at doses sufficient to block IK1 with minimal toxicity (5, 6). Thus clotrimazole or other more specific IK1 blockers (16, 44) may be useful for treatment of the secretory diarrhea induced by nelfinavir and other APIs used in the treatment of HIV.

Direct blockade of the nelfinavir-recruited Ca2+ entry pathway, however, might affect more selectively the adverse effects of APIs on regulation of intestinal Cl− secretion. Such blockade would allow for specific inhibition of API-induced potentiation of Ca2+-dependent Cl− secretory responses without affecting the normal muscarine-inhibited secretory response. Thus molecular identification of this Ca2+ entry pathway might facilitate development of specific inhibitors of this pathway as well as APIs that do not increase its activity.

One family of plasmalemmal Ca2+-permeable cation channels is the transient receptor potential (TRP) superfamily (9, 36). TRPV6 (ECaC2/CaT1) and TRPV5 (ECaC1/CaT2) are the most extensively studied TRP channels of the intestine. ECaC2/CaT1 has been localized by in situ hybridization to surface enterocytes of the rat (37) but appears to be absent from human colon (21, 38). ECaC1/CaT2 has been immunolocalized to the apical membrane of villous tip enterocytes in rabbit duodenum (20) and in transverse and distal colon of the human (21, 38). In addition, TRPV6 overexpressed in some cultured cells confers increased store-operated cation channel activities. However, the pathway recruited by nelfinavir in T84 cells may represent a basolateral pathway of intestinal crypt cells.

This novel pathway is notable for the ability of Ba2+ to block the nelfinavir-associated enhancement of apical Cl− secretion as well as for the enhanced magnitude and prolonged duration of muscarically induced [Ca2+]i elevation. In contrast, Ba2+ has no effect on the muscarically induced Iec in cells not treated with nelfinavir. Thus the inhibitory effect of Ba2+ on nelfinavir-potentiated Cl− secretion may represent a Ba2+ block of the nelfinavir-induced Ca2+ entry pathway. It is also possible that Ba2+ may permeate the nelfinavir-induced Ca2+ entry pathway. Once inside the cell, Ba2+ might then block a nelfinavir-induced, Ca2+-dependent reversal of the normal inactivation processes for the apical membrane Ca2+-activated Cl− conductance. Thus the molecular identity of the nelfinavir target(s) remains to be determined.

The effects of nelfinavir on Ca2+ signaling in intestinal epithelial cells may similarly apply to other cell types affected by API-based therapeutics. If so, altered Ca2+ signaling in adipocytes, myocytes, or hepatocytes may contribute to other API-associated dose-limiting side effects including lipodystrophy and insulin resistance (13, 43).

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Present address of A. Andrade: Division of Infectious Diseases, Johns Hopkins University, Baltimore, MD 21205.

REFERENCES

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