

Ursodeoxycholic acid attenuates colonic epithelial secretory function

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Key points

- Although diarrhoeal diseases represent a significant health and economic burden to society, therapeutic options remain limited.
- While several bile acids are known to stimulate epithelial Cl[−] secretion, the major driving force for fluid secretion in the intestine, the effects of ursodeoxycholic acid (UDCA) on epithelial transport function are not well described.
- We report that in contrast to other bile acids, UDCA exerts anti-secretory actions on colonic epithelial cells *in vitro*.
- In contrast, *in vivo* administration of UDCA enhances epithelial secretory function, an effect we ascribe to being due to its bacterial metabolism to lithocholic acid. In keeping with this hypothesis, *in vivo* administration of a metabolically stable analogue of UDCA, 6 α -methyl-UDCA, was anti-secretory.
- Our findings reveal novel anti-secretory actions of UDCA and suggest that metabolically stable analogues of bile acid may be useful for development as a new class of anti-diarrhoeal drug.

Abstract Dihydroxy bile acids, such as chenodeoxycholic acid (CDCA), are well known to promote colonic fluid and electrolyte secretion, thereby causing diarrhoea associated with bile acid malabsorption. However, CDCA is rapidly metabolised by colonic bacteria to ursodeoxycholic acid (UDCA), the effects of which on epithelial transport are poorly characterised. Here, we investigated the role of UDCA in the regulation of colonic epithelial secretion. Cl[−] secretion was measured across voltage-clamped monolayers of T₈₄ cells and muscle-stripped sections of mouse or human colon. Cell surface biotinylation was used to assess abundance/surface expression of transport proteins. Acute (15 min) treatment of T₈₄ cells with bilateral UDCA attenuated Cl[−] secretory responses to the Ca²⁺ and cAMP-dependent secretagogues carbachol (CCh) and forskolin (FSK) to 14.0 ± 3.8 and 40.2 ± 7.4% of controls, respectively ($n = 18$, $P < 0.001$). Investigation of the molecular targets involved revealed that UDCA acts by inhibiting Na⁺/K⁺-ATPase activity and basolateral K⁺ channel currents, without altering their cell surface expression. In contrast, intraperitoneal administration of UDCA (25 mg kg^{−1}) to mice enhanced agonist-induced colonic secretory responses, an effect we hypothesised to be due to bacterial metabolism of UDCA to lithocholic acid (LCA). Accordingly, LCA (50–200 μ M) enhanced

agonist-induced secretory responses *in vitro* and a metabolically stable UDCA analogue, 6 α -methyl-UDCA, exerted anti-secretory actions *in vitro* and *in vivo*. In conclusion, UDCA exerts direct anti-secretory actions on colonic epithelial cells and metabolically stable derivatives of the bile acid may offer a new approach for treating intestinal diseases associated with diarrhoea.

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Abbreviations 4-PB, 4-phenylbutyrate; 6 α -MUDCA, 6 α -methyl-UDCA; CCh, carbachol; CDCA, chenodeoxycholic acid; CFTR, cystic fibrosis transmembrane conductance regulator; ENaC, epithelial sodium channel; FSK, forskolin; I_{sc} , short-circuit current; LCA, lithocholic acid; SGLT-1, sodium glucose co-transporter; TTX, tetrodotoxin; TUDCA, taurine-conjugated derivative of UDCA; UDCA, ursodeoxycholic acid.

Introduction

Appropriate regulation of intestinal epithelial fluid and electrolyte transport is important for normal digestive function, mucosal protection and whole body fluid homeostasis. Under normal circumstances fluid absorption, driven mainly by Na⁺ absorption, predominates. However, fluid secretion, driven by Cl⁻ secretion, also occurs and is important for lubricating and protecting the mucosa (Barrett & Keely, 2000). The balance between absorption and secretion is highly dynamic and is regulated by an array of neuronal, immunological and hormonal messengers. Many intestinal disorders exist that perturb the balance between absorption and secretion, leading to the onset of diarrhoea. While infectious diarrhoea is responsible for ~2 million child deaths each year in developing countries, common causes of diarrhoea in Western societies include intestinal pathogens, inflammatory diseases, irritable bowel syndrome, and digestive and metabolic disorders. However, even though the social and economic burdens of such diseases are immense (Sandler *et al.* 2002), there are still relatively few well tolerated and effective therapeutic options for their treatment.

At the molecular level, intestinal fluid secretion is coordinated by the activity of several transport proteins (Barrett & Keely, 2000). Energy for the process comes from the activity of basolateral Na⁺/K⁺-ATPase pumps which maintain low intracellular Na⁺ concentrations by pumping Na⁺ from the cell in exchange for K⁺. This provides a favourable gradient for basolateral Na⁺/K⁺/2Cl⁻ co-transporter activity, which carries Na⁺ into the cell along with K⁺ and 2Cl⁻. K⁺ does not accumulate intracellularly, since it exits through the basolateral K⁺ channels, KCNN4 and KCNQ1. Thus, the concerted activity of these basolateral transporters specifically increases intracellular Cl⁻ concentrations so that a gradient exists for its exit when channels, such as the cystic fibrosis transmembrane conductance regulator (CFTR), in the apical membrane open. Since Cl⁻ secretion drives intestinal fluid secretion, these transport proteins

represent excellent targets for the development of drugs to treat secretory diarrhoea.

Although classically known for their roles in lipid digestion, bile acids are becoming increasingly recognised as important regulators of intestinal epithelial function. The primary bile acids cholic acid (CA) and chenodeoxycholic acid (CDCA) are synthesised in the liver, stored in their conjugated forms in the gallbladder and released into the duodenum upon ingestion of food. As they pass through the small intestine, bile acids facilitate the digestion and absorption of lipids, and are reabsorbed in the terminal ileum to be recycled back to the liver. Normally, this enterohepatic circulation of bile acids is extremely efficient with <5% of circulating bile acids entering into the colon with each cycle. Here, they are metabolised by resident bacteria, primarily by deconjugation, dehydroxylation and epimerisation, to yield secondary bile acids. Cholic acid is metabolised to deoxycholic acid (DCA), while CDCA is metabolised to ursodeoxycholic acid (UDCA), which is then further metabolised to lithocholic acid (LCA) (Hofmann, 2009).

Previous studies have shown that conjugated and unconjugated bile acids rapidly induce colonic epithelial Cl⁻ secretion (Volpe & Binder, 1975; Chadwick *et al.* 1979; Dharmasathaphorn *et al.* 1989; Potter *et al.* 1991; Gelbmann *et al.* 1995; Mauricio *et al.* 2000; Venkatasubramanian *et al.* 2001; Moschetta *et al.* 2003). While there are considerable species differences in the potencies of different bile acids, it is clear that in humans, prosecretory effects occur only when bile acid levels enter the pathophysiological range (Mekhjian & Phillips, 1970). Such prosecretory effects are thought to underlie the diarrhoea that is associated with conditions of bile acid malabsorption. Mechanisms by which bile acids stimulate Cl⁻ secretion have been well studied *in vitro*, with both Ca²⁺- and cAMP-dependent mechanisms being implicated (Dharmasathaphorn *et al.* 1989; Devor *et al.* 1993; Huang *et al.* 1995; Moschetta *et al.* 2003). Furthermore, it appears that bile acids can exert their prosecretory effects either by acting directly on epithelial cells themselves or through stimulation of

regulatory cells within the mucosa (Karlstrom *et al.* 1986; Gelbmann *et al.* 1995).

Notably, there are strict structure–activity requirements for bile acids in promoting secretion, with only dihydroxy bile acids, such as DCA and CDCA, being effective (Chadwick *et al.* 1979; Gordon *et al.* 1979). However, UDCA, a dihydroxy bile acid that is formed by bacterially mediated epimerisation of the 7 α -OH group of CDCA, and which is also in widespread use as a therapeutic in liver disease, has been reported to be devoid of prosecretory actions *in vitro* (Gelbmann *et al.* 1995; Keely *et al.* 2007). In the current study, we more fully investigated the effects of UDCA on colonic epithelial secretory function.

Methods

Chemicals

CDCA-Na⁺ salt and LCA-Na⁺ salt were obtained from Calbiochem (San Diego, CA, USA). UDCA-Na⁺ salt, carbachol (CCh), forskolin (FSK), amiloride, phloridzin, tetrodotoxin, nystatin and amphotericin B were from Sigma-Aldrich Inc. (Gillingham, UK). Stock solutions of bile acids were prepared in deionised H₂O. Sulfo-NHS-Biotin was from Pierce Biotechnology (Rockford, IL, USA). Anti-Na⁺/K⁺-ATPase α_1 subunit antibodies (mouse) and anti-KCNN4 antibodies (rabbit) were obtained from AbCam (Cambridge, UK) and anti- β -actin was from Sigma-Aldrich (St Louis, MO, USA). All other reagents were of analytical grade.

Cell culture

T₈₄ colonic epithelial cells were cultured in DMEM/Hams F12 media (1:1) supplemented with 5% newborn calf serum (Keely *et al.* 2007). For electrophysiological studies, 5×10^5 cells were seeded onto 12 mm Millicel HA Transwells (Millipore, Bedford, MA, USA). For Western blot and surface biotinylation experiments, 1×10^6 cells were seeded onto 30 mm Millicell HA Transwells. Cells seeded onto filters were cultured for 10–15 days before use. Under these conditions, T₈₄ cells develop the polarised phenotype of native epithelial cells and vectorially secrete Cl[−] in a basolateral to apical direction.

Human tissues

Resected colonic tissue was obtained from adult patients undergoing colorectal surgery in Beaumont Hospital. Patients agreed to participate by written informed consent and this study was approved by Beaumont Hospital Medical Ethics Committee. Normal colonic mucosa was identified by pathologists and specimens were taken at least 3 cm clear of the tumour and resection margins. Patients receiving chemo/radiotherapy, or those with a history of inflammatory bowel disease, were excluded. Fourteen patients (10 male), with a median age of 63 years

(range 42–85 years), were included, none of whom were taking bile acid sequestrants or UDCA at the time of surgery.

Animals

Male C57 BL6 mice aged 6–12 weeks were used. Animals were maintained in an environmentally controlled facility (12/12 h light–dark cycle) with access to food and water *ad libitum*. Animals were fed 2018 Teklad Global 18% Protein Rodent Diet (Harlan Laboratories Inc., Indianapolis, IN, USA). Experiments were approved by the RCSI Ethics Committee. UDCA (25 mg kg^{−1}), 6 α -methyl-UDCA (6 α -MUDCA; 25 mg kg^{−1}) or endotoxin-free phosphate buffered saline as vehicle were injected intraperitoneally, and mice were killed 4 h later by cervical dislocation.

Electrophysiological measurements

T₈₄ monolayers were washed in serum-free medium and allowed to equilibrate for 1 h. Cells were mounted in Ussing chambers (aperture = 0.6 cm²), voltage-clamped to zero potential difference and monitored for changes in short-circuit current (I_{sc}) using a VCC-MC8 voltage clamp (Physiological Instruments, San Diego, CA, USA). Under such conditions, agonist-induced changes in I_{sc} are wholly reflective of changes in Cl[−] secretion (Cartwright *et al.* 1985). I_{sc} measurements were carried out in Ringer's solution containing (in mM): 140 Na⁺, 5.2 K⁺, 1.2 Ca²⁺, 1.2 Mg²⁺, 119.8 Cl[−], 25 HCO₃[−], 0.4 H₂PO₄[−], 2.4 HPO₄^{2−} and 10 glucose, at pH 7.4, and aerated with 95% O₂/5% CO₂. Results were expressed as ΔI_{sc} ($\mu A cm^{-2}$) or as a percentage of control responses.

Apical Cl[−] currents were measured as previously described (Rochwerger *et al.* 1994). Briefly, cell monolayers were mounted in Ussing chambers under an apical to basolateral Cl[−] gradient (119.8–4.8 mM), established by replacing NaCl in the basolateral solution with equimolar sodium gluconate. Monolayers were basolaterally permeabilised with nystatin (100 $\mu g ml^{-1}$), and after a 35 min re-equilibration period, cells were stimulated with FSK (10 μM). Under these conditions, changes in I_{sc} reflect apical Cl[−] currents (I_{Cl}).

Basolateral K⁺ currents were analysed as previously described (Kirk & Dawson, 1983). Voltage-clamped T₈₄ monolayers were apically permeabilised using amphotericin B (50 μM). A K⁺ gradient (123.2–5.2 mM) was then created across the basolateral membrane by addition of a high-K⁺ (123.2 mM) Ringer's solution, in which NaCl is substituted with potassium gluconate, to the apical reservoir. Ouabain (100 μM) was added basolaterally to inhibit Na⁺/K⁺-ATPase activity. Under these conditions, changes in I_{sc} are reflective of basolateral K⁺ currents (I_K).

Na⁺/K⁺-ATPase activity was measured as previously described (Lam *et al.*, 2003). T₈₄ monolayers

were bathed bilaterally in a low Na^+ (25 mM) Ringer solution, where NaCl was substituted with equimolar *N*-methyl-D-glucamine (NMDG)-Cl. Apical membranes were permeabilised with amphotericin B (50 μM), and under these conditions changes in I_{sc} reflect Na^+/K^+ -ATPase activity.

Sections of isolated human or mouse colonic mucosa were obtained by blunt micro-dissection of underlying muscle layers. Tissues were mounted in Ussing chambers (window area = 0.3 cm² for mouse and 0.5 cm² for human specimens) and bathed in Ringer's solution for measurements of I_{sc} . Tissues were allowed to equilibrate for 30 min before addition of pharmacological reagents.

For measurements of sodium glucose co-transporter (SGLT-1) activity in mice, whole thickness sections of proximal jejunum were mounted in Ussing chambers and bathed apically in glucose-free Ringer's, containing mannitol (5 mM), and basolaterally in normal Ringer's solution. To stimulate SGLT-1 activity, 25 mM glucose was added apically, with 25 mM mannitol being added basolaterally at the same time to maintain isosmolarity, and changes in I_{sc} were measured. Phloridzin (1 mM) was used to confirm increases in I_{sc} were due to SGLT-1 activity (Grubb, 1995).

Measurements of caecal bile acids

Caecal contents were collected from treated and control animals and stored in isopropanol at -20°C . Caecal bile acid levels were measured using HPLC-ES-MS/MS and the qualitative caecal bile acid composition was expressed as percentage total bile acid content, as previously described (Tadano *et al.* 2006).

Cell surface biotinylation

The protocol used was based on one previously published (Del Castillo *et al.* 2005). Following treatment, cells were washed with ice-cold PBS. Freshly prepared biotinylation buffer (1 mg ml⁻¹ Sulfo-NHS-Biotin in PBS) was added basolaterally and cells were incubated at 4°C for 15 min on a rotating platform after which the buffer was replenished. After another 15 min, cells were washed, incubated with quenching reagent (100 mM glycine), lysed (Triton lysis buffer; 45 min) and centrifuged (15,300 g, 6 min). After normalising for protein concentration, supernatants were then precipitated overnight on a rotator at 4°C with 100 μl of streptavidin-agarose beads (Pierce Biotechnology). Biotinylated proteins were detected by Western blotting.

Western blotting

T₈₄ monolayers were washed with ice-cold PBS and lysed (1% Nonidet P-40, 150 mM NaCl, 50 mM Tris base, 1 complete mini EDTA-free protease inhibitor

tablet, 0.1 mg ml⁻¹ phenylmethylsulfonyl fluoride (PMSF) and 1 mM Na₃VO₄). Lysates were sonicated, centrifuged (15,300 g, 10 min, 4°C), and the pellet discarded. After normalising for protein content, 2 $\times$ gel loading buffer (50 mM Tris HCl, 100 mM dithiothreitol (DTT), 40% glycerol, 4% SDS) was added, and samples were then separated by SDS-PAGE, followed by transfer to polyvinylidene difluoride (PVDF) membranes. Membranes were preblocked in 5% blocking buffer (Marvel in Tris-buffered saline with 1% Tween (TBST)) for 60 min at room temperature, followed by incubation with primary antibody in blocking buffer overnight at 4°C . The primary antibodies employed were anti- Na^+/K^+ -ATPase α_1 subunit antibodies (mouse, 1:10,000 dilution), anti-KCNN4 antibodies (rabbit; 1:1500 dilution) and anti- β -actin (1:10,000 dilution). After washing ($\times 4$) in TBST, membranes were incubated with horseradish peroxidase-conjugated secondary antibodies (1:3000 dilution) in blocking buffer for 60 min at room temperature. After further washing ($\times 4$) in TBST, immunoreactive proteins were detected by enhanced chemiluminescence (Amersham Biosciences, Little Chalfont, UK).

Statistical analysis

Results are expressed as mean $\pm$ standard error of the mean (SEM) for a series of *n* experiments. Statistical analyses were performed by paired *t*-tests or analysis of variance (ANOVA) with the Tukey multiple comparisons test, as appropriate (Instat Software; GraphPad, San Diego, CA, USA). *P* values ≤ 0.05 were considered to be significant.

Results

UDCA exerts anti-secretory actions on colonic epithelial cells *in vitro*

As previously reported, UDCA (500 μM) did not alter basal I_{sc} across cultured monolayers of T₈₄ cells (Fig. 1A), although its parent bile acid, CDCA (500 μM) stimulated responses of $40 \pm 2.69 \mu\text{A cm}^{-2}$ within 5 min. However, UDCA pretreatment significantly attenuated responses to the prototypical Ca^{2+} and cAMP-dependent secretagogues CCh (100 μM) and FSK (10 μM), to 14.0 ± 3.8 and $40.2 \pm 7.4\%$ of those in control cells, respectively (*n* = 18; Fig. 1A). The anti-secretory effect of UDCA was concentration dependent, with an EC₅₀ of approximately 200 μM , and was rapid in onset, occurring within 1 min after its addition (Fig. 1B and C). Interestingly, UDCA effects on cAMP-dependent responses were slower in onset, taking up to 30 min to become apparent (Fig. 1C). The anti-secretory actions of UDCA were reversible and were no longer apparent 120 min after removal of the

bile acid (data not shown). Furthermore, UDCA did not alter transepithelial resistance or lactate dehydrogenase release from the cells at any concentration tested (data not shown), suggesting its anti-secretory effects are not due to a loss of cell viability.

The effects of UDCA on voltage-clamped human colonic tissue were also examined. After mounting in Ussing chambers, tissues were first treated with tetrodotoxin (TTX) to remove the possible influence of enteric nerves. Similar to our findings in cultured epithelial cells, UDCA alone was without effect on basal I_{sc} (data not shown), but significantly attenuated subsequent agonist-induced responses in a concentration-dependent manner (Fig. 1D).

To determine the effects of UDCA on electrogenic Na^+ absorption through the epithelial sodium channel

(ENaC), a previously published approach was employed to induce ENaC expression in T₈₄ cells (Iordache & Duszyk, 2007). Pretreatment of cells with 4-phenylbutyrate (4-PB) for 24 h induced ENaC protein expression (data not shown) and a basal I_{sc} of $7.7 \pm 0.1 \mu\text{A cm}^{-2}$. While this 4-PB-induced current was abolished by the ENaC blocker amiloride (10 μM), treatment with UDCA (500 μM) was without effect (Fig. 1E).

In vivo administration of UDCA enhances colonic secretory responses in mice

To examine the effects of UDCA administration *in vivo*, mice were injected intraperitoneally with UDCA (25 mg kg^{-1}), and after 4 h their colons were removed, stripped of smooth muscle and mounted in Ussing

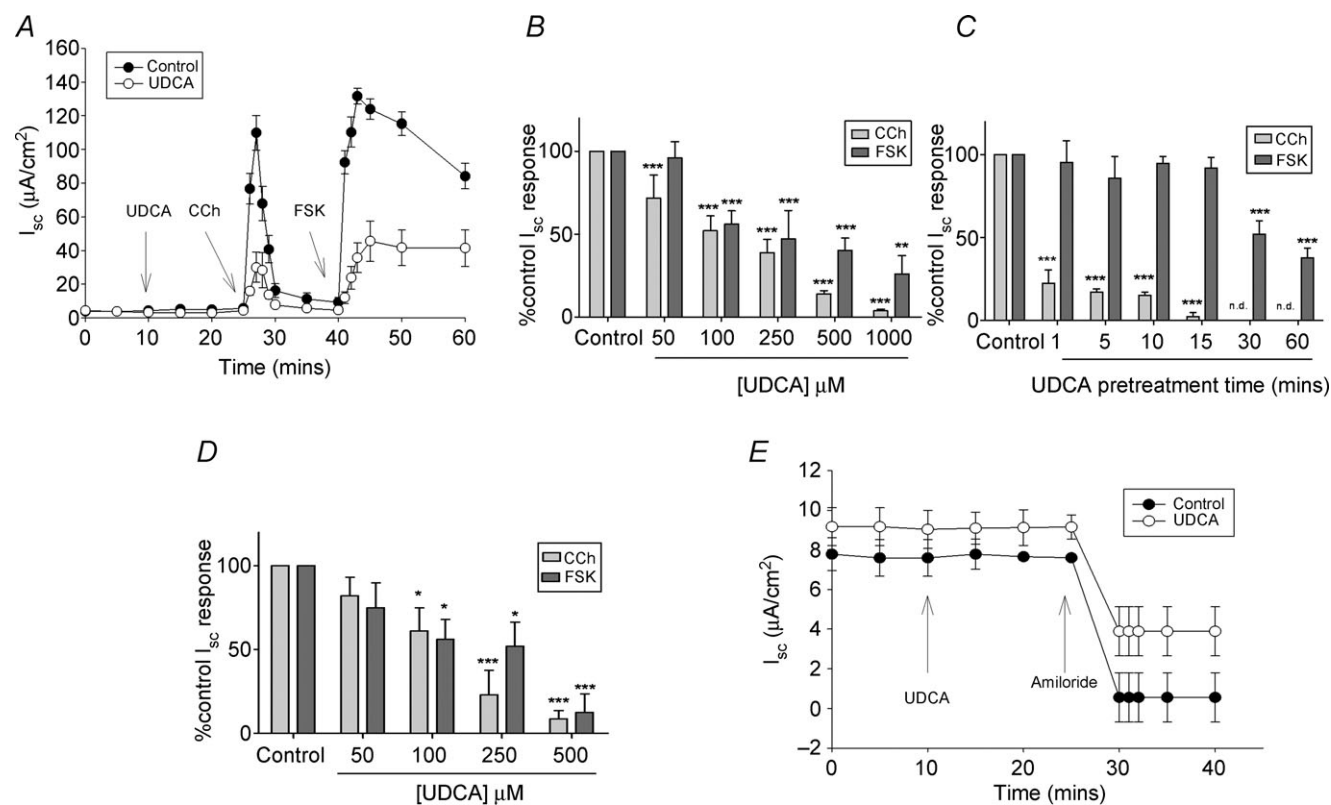


Figure 1. UDCA inhibits colonic epithelial secretory responses *in vitro*

A, T₈₄ cell monolayers were mounted in Ussing chambers and treated bilaterally with ursodeoxycholic acid (UDCA; 500 μM) for 15 min, before Cl^- secretory responses to basolateral carbachol (CCh; 100 μM) and apical forskolin (FSK; 10 μM) were measured as changes in short circuit current (ΔI_{sc}) ($n = 18$). B, T₈₄ cells were exposed to bilateral UDCA at differing concentrations (50 μM –1 mM) for 15 min and subsequent I_{sc} responses to CCh and FSK were measured ($n = 6$ –18). C, UDCA (500 μM) was added bilaterally to voltage-clamped monolayers of T₈₄ cells for various periods of time before measuring secretory responses to CCh and FSK ($n = 4$). D, muscle-stripped sections of human colon were mounted in Ussing chambers and monitored for changes in I_{sc} . The basolateral solution contained tetrodotoxin (TTX; 1 μM) to remove the influence of enteric nerves. After stabilisation of the I_{sc} , tissues were treated bilaterally with UDCA at various concentrations for 15 min prior to stimulation with CCh and FSK ($n = 8$). E, T₈₄ cells were pretreated with 4-phenylbutyrate (5 mM; 24 h) to induce amiloride-sensitive Na^+ channel (ENaC) activity before mounting in Ussing chambers. Cells were then sequentially treated with UDCA (500 μM) and amiloride (10 μM) and changes in I_{sc} were noted ($n = 8$). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. n.d. denotes 'not determined'.

chambers for I_{sc} measurements. Interestingly, in direct contrast to its anti-secretory effects in cultured epithelia, UDCA enhanced secretagogue-induced responses in *ex vivo* colonic tissues (Fig. 2A). We hypothesised that such contrasting effects could be due to bacterial metabolism of UDCA to LCA *in vivo*. This hypothesis was supported by our findings that colonic LCA levels were significantly increased in UDCA-treated mice from $9.7 \pm 1.6 \text{ nmol g}^{-1}$ (4% of total bile acids) to $33.4 \pm 6.5 \text{ nmol g}^{-1}$ (16% of total bile acids) in UDCA-treated mice (Fig. 2B). Of the caecal bile acids measured, LCA alone showed significant alterations after treatment with UDCA, and total caecal bile acid

levels were similar in control ($206 \pm 15.5 \text{ nmol g}^{-1}$) and UDCA-treated mice ($215 \pm 18.0 \text{ nmol g}^{-1}$). Interestingly, when we tested its effects in Ussing chambers, we found that, in direct contrast to UDCA, LCA significantly potentiated agonist-induced secretory responses in T_{84} cells (Fig. 2C) and human tissue (Fig. 2D).

***In vivo* administration of a metabolically stable UDCA analogue inhibits colonic secretory responses in mice**

To further test the hypothesis that prosecretory effects of UDCA *in vivo* are due to its bacterial metabolism,

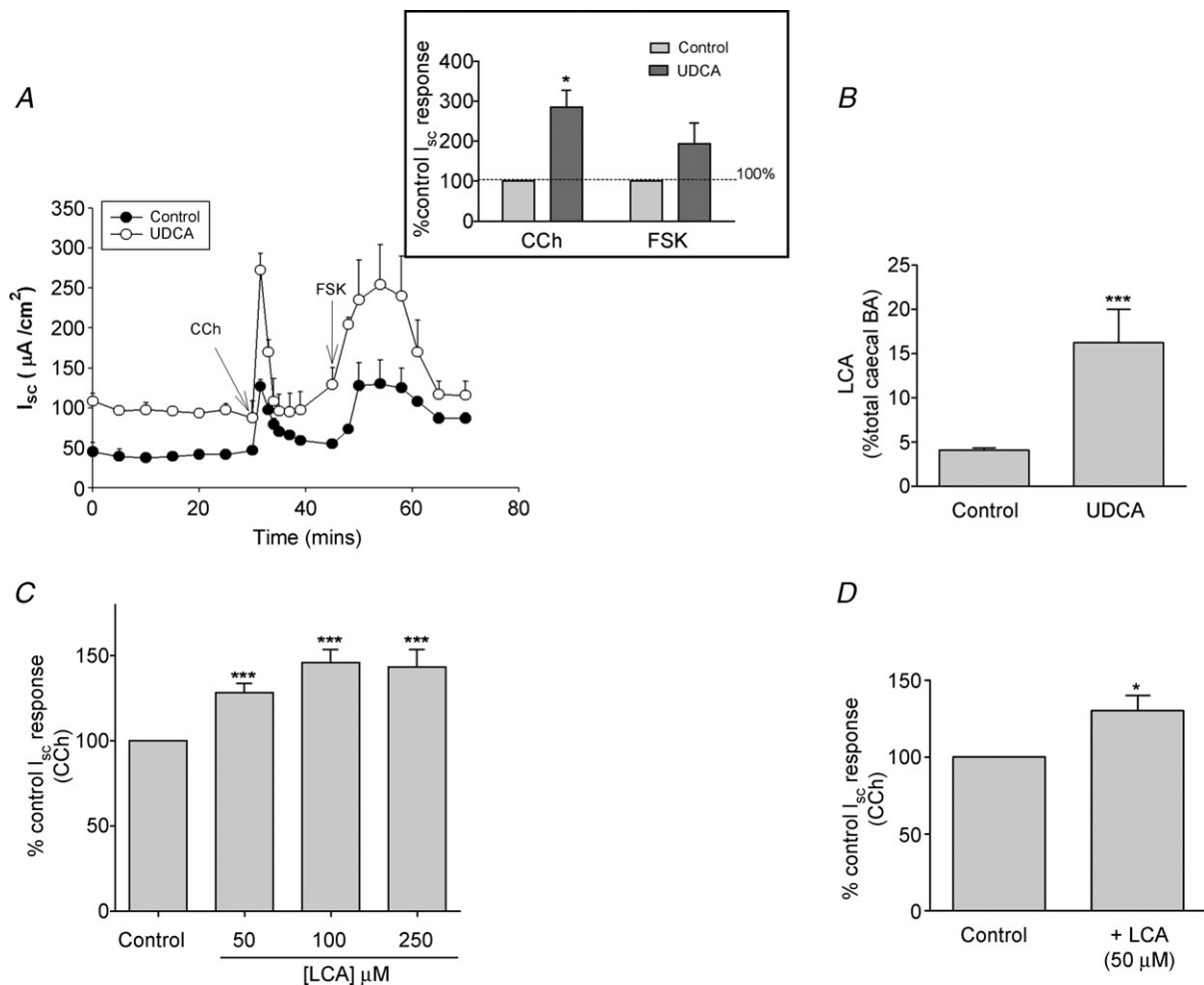


Figure 2. UDCA administration *in vivo* potentiates colonic epithelial secretory responses

A, male C57/BL6 mice were intraperitoneally injected with UDCA (25 mg kg^{-1}) or PBS vehicle, and were then killed after 4 h. Muscle-stripped sections of colonic mucosa were mounted in Ussing chambers and changes in CCh ($100 \mu M$)- and FSK ($10 \mu M$)-induced I_{sc} were measured ($n = 5$). The inset shows peak changes in I_{sc} induced by CCh and FSK in UDCA-treated mice expressed as a percentage of control responses. B, the caecal contents from control and UDCA-treated mice were collected and LCA levels were measured by HPLC mass spectrometry ($n = 4$). C, monolayers of T_{84} cells were mounted in Ussing chambers and were treated bilaterally with LCA (50 – $250 \mu M$) for 15 min before measuring I_{sc} responses to CCh ($100 \mu M$) ($n = 9$). D, muscle-stripped sections of human colon were mounted in Ussing chambers in the presence of basolateral TTX ($1 \mu M$) to remove the influence of enteric nerves. After stabilisation of the I_{sc} , tissues were treated bilaterally with LCA ($50 \mu M$) for 15 min prior to stimulation with basolateral CCh ($100 \mu M$) ($n = 5$). * $P < 0.05$; *** $P < 0.001$.

we employed a non-metabolisable UDCA analogue, 6α -MUDCA. Methylation of UDCA in the 6-position sterically hinders bacterial 7-dehydroxylases, thereby preventing its metabolism to LCA (Roda *et al.* 1994). We confirmed the stability of the compound in mice where, in contrast to UDCA, intraperitoneal administration of 6α -MUDCA did not alter caecal LCA levels (Fig. 3A). Treatment of voltage-clamped T_{84} cells with 6α -MUDCA inhibited both CCh- and FSK-stimulated secretory responses to a similar degree as did UDCA (Fig. 3B), confirming that it retains the anti-secretory actions of UDCA. However, in contrast to our findings with UDCA,

in vivo administration of 6α -MUDCA significantly attenuated agonist-induced secretory responses in *ex vivo* colonic tissues (Fig. 3C). Interestingly, 6α -MUDCA did not alter SGLT-1 activity in *ex vivo* mouse jejunal tissues, suggesting the compound specifically inhibits epithelial secretory function (Fig. 3D).

Sidedness of anti-secretory actions of UDCA

To further characterise anti-secretory actions of UDCA on colonic epithelial cells, we examined the sidedness

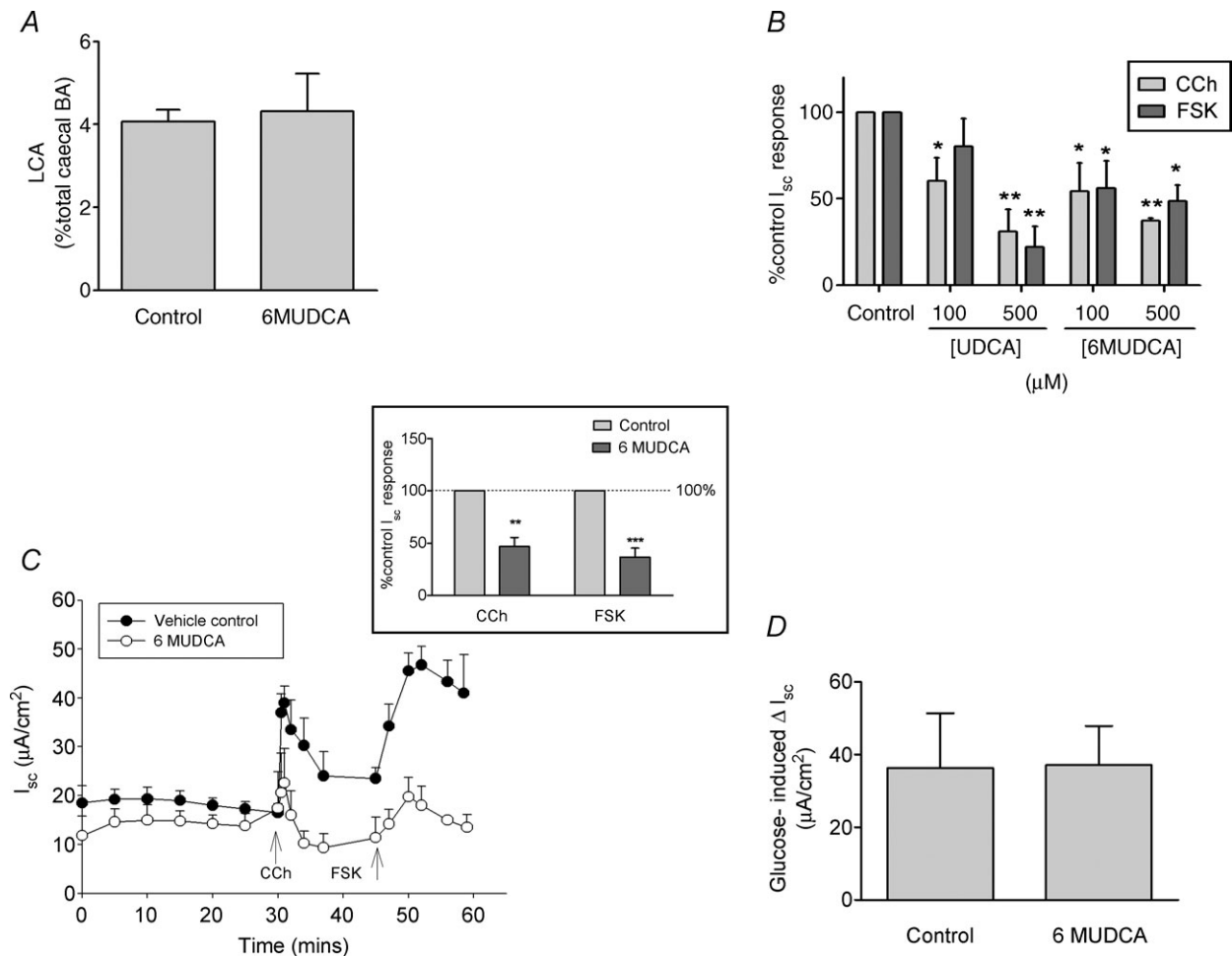


Figure 3. 6α -Methyl UDCA inhibits colonic epithelial Cl^- secretion *in vitro* and *in vivo*

A, male C57/BL6 mice were intraperitoneally injected with 6α -MUDCA (25 mg kg^{-1}) or PBS vehicle, and were then killed after 4 h. The caecal contents from control and 6α -MUDCA-treated mice were collected and LCA levels were measured by mass spectrometry ($n = 4$). B, voltage-clamped monolayers of T_{84} cells were pretreated with UDCA or 6α -MUDCA (100 – $500 \text{ }\mu\text{M}$) for 15 min before measuring CCh ($100 \text{ }\mu\text{M}$)- or FSK ($10 \text{ }\mu\text{M}$)-stimulated I_{sc} responses. Maximal changes in I_{sc} in response to CCh and FSK were expressed as a percentage of responses in controls ($n = 7$). C, mice were injected intraperitoneally with 6α -MUDCA (25 mg kg^{-1}) and after 4 h muscle-stripped sections of colonic mucosa were mounted in Ussing chambers and changes in I_{sc} in response to CCh and FSK were measured. The inset shows peak changes in I_{sc} induced by CCh and FSK in 6α -MUDCA-treated mice expressed as a percentage of control responses ($n = 5$). D, sections of jejunum from control or 6α -MUDCA-treated mice were mounted in Ussing chambers for measurements of SGLT-1 activity. After a 20 min equilibration period, glucose (25 mM) was added apically and mannitol (25 mM) basolaterally and subsequent changes in I_{sc} were measured ($n = 6$). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

of responses to the bile acid. Basolateral addition of UDCA was more effective in inhibiting agonist-induced secretory responses than was apical addition (Fig. 4A). Interestingly, however, the taurine-conjugated derivative of UDCA (TUDCA; 500 μM), which is unable to cross cell membranes unless a transporter is present, was ineffective when added apically, but was equipotent to UDCA when added basolaterally (Fig. 4B). We also examined the sidedness of UDCA effects on agonist-induced secretory responses across sections of human colon in Ussing chambers. Similar to its effects in cultured T₈₄ cells, UDCA was more effective when applied basolaterally, with secretory responses to CCh being inhibited to $40.4 \pm 8.1\%$ of controls compared with $69.3 \pm 14.1\%$ inhibition after apical addition ($n = 4$; $P < 0.05$).

UDCA inhibits Na⁺/K⁺-ATPase pump activity and K⁺ channel currents in colonic epithelial cells

To begin to elucidate how UDCA exerts its anti-secretory effects, we analysed the effects of the bile acid on the activity of several transport proteins that comprise the

Cl[−] secretory pathway. Under conditions that specifically isolate basolateral Na⁺/K⁺-ATPase pump activity or K⁺ conductances, UDCA (500 μM) significantly inhibited CCh (100 μM)-stimulated I_{sc} responses to 16.2 ± 3.9 and $13.7 \pm 4.1\%$ of controls, respectively (Fig. 5A, B). In contrast, UDCA did not alter FSK-stimulated apical Cl[−] currents, which were $100.9 \pm 22.2\%$ of control responses (Fig. 5C).

Finally, to determine if UDCA has its anti-secretory effects by altering the surface expression of Na⁺/K⁺-ATPase pumps and K⁺ channels at the cell surface, we employed a cell surface biotinylation approach to quantify expression of these proteins in the basolateral membrane. However, these experiments revealed that there were no significant alterations in surface expression of either the Na⁺/K⁺-ATPase α subunit or KCNN4 in UDCA-treated cells (Fig. 5D and E).

Discussion

It is well established that dihydroxy bile acids stimulate intestinal fluid and electrolyte secretion and that their increased colonic delivery in conditions of bile acid malabsorption causes diarrhoea (Chadwick *et al.* 1979; Keely *et al.* 2007). However, a notable exception is UDCA, which based on its lack of secretory actions in guinea pig, rabbit, and canine colon *in vitro* and *in vivo*, has been previously characterised as a 'non-secretory' bile acid (Mekjian *et al.* 1971; Rahban *et al.* 1980; Gelbmann *et al.* 1995). Here, we present new data to show that in addition to being non-secretory, UDCA also exerts potent anti-secretory effects on colonic epithelial cells. The actions of UDCA were observed both in cultured cells and in pharmacologically denervated human colonic tissue, suggesting they are due to a direct action of the bile acid on the epithelial cells. It was interesting to note that the time course by which UDCA has its anti-secretory actions depends on the particular type of secretagogue in question, with inhibition of Ca²⁺-dependent responses occurring more rapidly than that of cAMP-dependent responses. This suggests that different mechanisms might underlie the anti-secretory effects of UDCA on Ca²⁺- and cAMP-dependent agonists. Although the concentrations at which UDCA has its anti-secretory actions (50 μM –1 mM) might not normally occur *in vivo* (De Kok *et al.* 1999), during conditions of bile acid malabsorption or when it is used therapeutically, levels of the bile acid increase significantly in the colonic lumen and serum (van Gorkom *et al.* 2002; Hess *et al.* 2004).

Intriguingly, we found that, in contrast to its anti-secretory actions *in vitro*, intraperitoneal injection of UDCA to mice potentiated secretagogue-induced responses across *ex vivo* colonic tissues. Such prosecretory

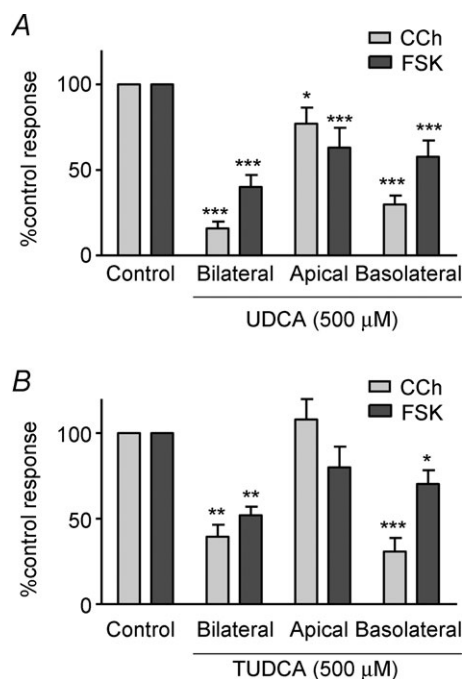


Figure 4. Sidedness of the anti-secretory effects of UDCA and TUDCA on colonic epithelial cells

A, T₈₄ cell monolayers were mounted in Ussing chambers and treated apically, basolaterally or bilaterally with UDCA (500 μM) for 15 min, before Cl[−] secretory responses to basolateral CCh (100 μM) or FSK (10 μM) were measured as changes in I_{sc} ($n = 13$). B, voltage-clamped T₈₄ cell monolayers were treated apically, basolaterally or bilaterally with tauro-UDCA (TUDCA; 500 μM) for 15 min, before Cl[−] secretory responses to basolateral CCh (100 μM) or FSK (10 μM) were measured ($n = 10$). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

effects of UDCA when administered *in vivo* may provide new insights into the diarrhoeal side effects that can occur when the bile acid is used therapeutically (Alberts *et al.* 2005). While the underlying cause of this diarrhoeal effect is not known, it has been hypothesised to be due to bacterially mediated re-epimerisation of the 7 β -OH group of UDCA to give CDCA, which is prosecretory (Hempfling *et al.* 2003). However, UDCA is preferentially metabolised *in vivo* to the monohydroxy bile acid LCA, which has been shown to be the predominant colonic bile acid in humans treated with UDCA (van Gorkom *et al.* 2002). We also found caecal LCA levels to increase dramatically upon administration of UDCA to mice.

Although known to be a hepatotoxic bile acid, the effects of LCA on colonic transport function are poorly defined. Here, we found that LCA potentiates epithelial responses to secretagogues and it therefore may act to oppose the anti-secretory actions of UDCA. Thus, we hypothesised that metabolism to LCA might underlie the prosecretory effects of UDCA *in vivo*, and further that derivatives of UDCA, which cannot be metabolised by 7-dehydroxylation, should have anti-secretory actions *in vivo*. To test this hypothesis we used 6 α -MUDCA, a 6-methylated derivative of UDCA that is completely resistant to bacterial dehydroxylation (Roda *et al.* 1994), but which retains the anti-secretory effects of UDCA

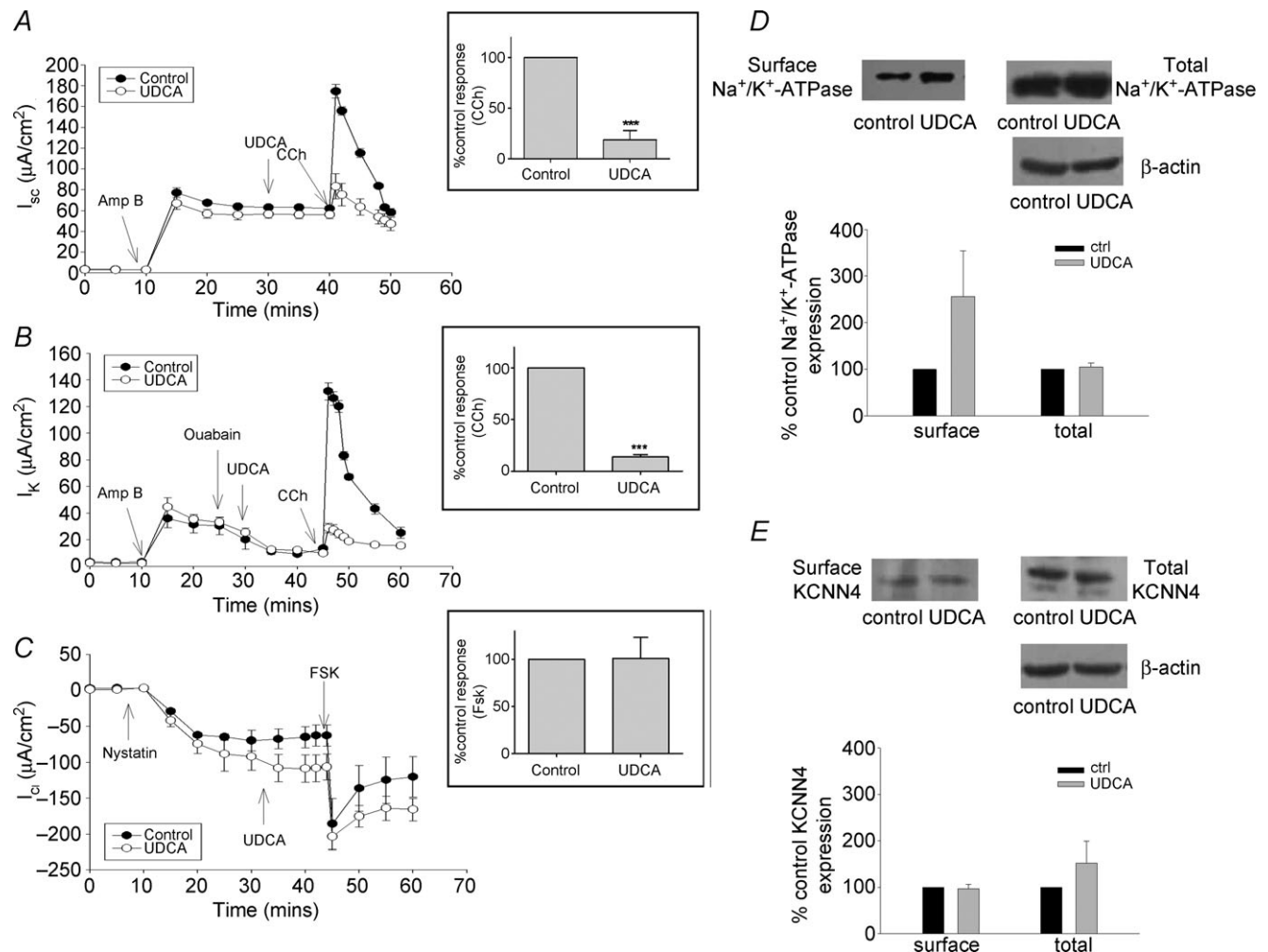


Figure 5. UDCA inhibits Na⁺/K⁺-ATPase pump activity and basolateral K⁺ currents in colonic epithelial cells

A–C, monolayers of T₈₄ cells were mounted in Ussing chambers for measurements of (A) Na⁺/K⁺-ATPase activity ($n = 7$), (B) basolateral K⁺ currents (I_K ; $n = 5$) or (C) apical Cl[−] currents (I_{Cl} ; $n = 10$) as described in Methods. The insets to each panel show maximal changes in I_{sc} (ΔI_{sc}) in response to agonist stimulation under each experimental condition expressed as a percentage of control responses. D, after treatment with UDCA (500 μM ; 15 min) total cellular and basolateral surface expression of the Na⁺/K⁺-ATPase α_1 subunit was analysed by Western blotting or cell surface biotinylation, respectively. The lower panel shows densitometric analysis of eight similar experiments. E, after treatment with UDCA (500 μM ; 15 min) total cellular and basolateral surface expression of KCNN4 was analysed. The lower panel shows densitometric analysis of three similar experiments.

in vitro. Upon administration to mice, 6 α -MUDCA did not alter caecal LCA levels and significantly inhibited secretagogue-induced responses across voltage-clamped colonic tissues. Thus, our data support the hypothesis that it is because of its metabolism to LCA that UDCA enhances colonic secretion *in vivo*, and that this effect may underlie the diarrhoeal side effects that occur when UDCA is used therapeutically for liver disease. Importantly, our data also suggest that non-metabolisable analogues of UDCA may be good candidates for development into a new class of anti-diarrhoeal drug.

Although significant inhibition of agonist-induced responses was observed upon apical addition of UDCA, the bile acid was found to be more effective when added basolaterally. A similar pattern of responses to apical and basolateral UDCA was observed in voltage-clamped human colonic tissues. Interestingly, the taurine conjugate of UDCA, TUDCA, was only effective when applied basolaterally to T₈₄ monolayers. TUDCA is more hydrophilic than UDCA, and unlike UDCA it cannot enter cells by passive diffusion across the lipid membrane. However, bile acid transporters are expressed on the basolateral membrane of colonic epithelia (Weihrauch *et al.* 2006), which probably explains the increased efficacy of both TUDCA and UDCA when applied basolaterally. These data are consistent with our previous findings which show that conjugated bile acids do not cross the apical membrane of T₈₄ cells and that uptake of UDCA occurs more rapidly across the basolateral than apical membrane (Keely *et al.* 2007). Importantly, these data also suggest that UDCA, and its derivatives, must enter the cells before they can exert their anti-secretory actions. Furthermore, conditions which disrupt tight junction integrity would be expected to result in enhanced epithelial delivery of UDCA or its conjugates to the basolateral membrane, thereby increasing their biological actions.

Using well-established approaches to specifically measure Na⁺/K⁺-ATPase activity, K⁺ channel currents and Cl⁻ channel currents, we found that UDCA significantly inhibited both Na⁺/K⁺-ATPase activity and Ca²⁺-activated K⁺ channel currents, but not FSK-stimulated apical Cl⁻ channel currents. Thus, upon entry into colonic epithelial cells, UDCA rapidly inhibits key transport proteins required for Cl⁻ secretion to occur. We hypothesised that such effects of UDCA could be mediated by altered trafficking of transport proteins to the cell surface, and therefore carried out cell surface biotinylation analyses. However, we detected no reductions in the surface localisation of either Na⁺/K⁺-ATPase pumps or K⁺ channels after UDCA treatment, suggesting that the anti-secretory effects of the bile acid are not mediated by altered trafficking of transport proteins to the cell surface. Thus, how UDCA inhibits the activity of Na⁺/K⁺-ATPase pumps and K⁺ channels remains to be determined but several possibilities exist. For

example, UDCA may alter the generation of signals that activate these transport proteins or alternatively could alter their association with regulatory proteins. Several proteins are known to bind to and regulate Na⁺/K⁺-ATPase activity, including FXYD proteins (Garty & Karlish, 2006), translationally controlled tumour protein (Jung *et al.* 2004) and MONAKA (modulator of Na⁺/K⁺-ATPase) (Mao *et al.* 2005). Indeed, such regulatory proteins provide an attractive mechanism for inhibition of the Na⁺/K⁺-ATPase pump, since many are expressed in a cell-specific manner and could explain why UDCA specifically inhibits Cl⁻ secretory responses, while Na⁺ absorptive processes, including electrogenic Na⁺ absorption through ENaC and SGLT-1 activity, remain unaltered. Similarly, proteins that regulate the activity of KCNN4, the Ca²⁺-dependent K⁺ channel, are known to exist and could represent targets for UDCA action (Joiner *et al.* 2001). Future studies will focus on elucidating the molecular mechanisms by which UDCA inhibits the activities of these transport proteins and also to characterise the effects of UDCA on Na⁺/K⁺/2Cl⁻ co-transporter activity, which is also a key component of the epithelial secretory pathway.

In summary, UDCA is an anti-secretory bile acid that has its effects by inhibition of multiple components of the Cl⁻ secretory pathway. However, anti-secretory actions of UDCA are not likely to be observed under normal conditions *in vivo* due to its rapid metabolism by colonic bacteria to LCA, which, in contrast to UDCA, enhances epithelial secretory function. Thus, our data provide new insights that may explain the occurrence of diarrhoea in patients on UDCA therapy, and also suggest that metabolically stable analogues of the bile acid may be good candidates for development of a new class of anti-diarrhoeal drug. By virtue of their direct actions on epithelial secretory function, along with the well-established safety profile of UDCA in humans, such drugs could have distinct advantages over currently available anti-diarrhoeal therapies.

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Author contributions

O.K.: study design/data acquisition/analysis/interpretation, manuscript preparation; M.M., J.W., C.C., M.S.: data acquisition/analysis/interpretation/ manuscript preparation; A.R., R.P.: development of 6-MUDCA, data acquisition/interpretation; P.F., F.M., J.G.: study concept and design; A.H.: study concept and design, manuscript preparation; S.K.: obtained funding, study concept and design, manuscript preparation.

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Translational perspectives

These current studies reveal new roles for the bile acids ursodeoxycholic acid (UDCA) and lithocholic acid (LCA) in regulating colonic epithelial secretory function. While UDCA exerts direct anti-secretory effects, LCA has contrasting actions that enhance agonist-induced secretion. Since UDCA is rapidly metabolised *in vivo* by colonic bacteria to LCA, our data provide a new explanation as to why UDCA can cause diarrhoea when it is used in clinical settings. Furthermore, our data suggest that UDCA analogues that cannot be metabolised by colonic bacteria may be of therapeutic use in treating intestinal disorders associated with secretory diarrhoea. Further studies are now required to translate our findings into animal models of intestinal disease to determine if metabolically stable UDCA analogues could ultimately be useful in treating secretory diarrhoeal diseases in humans. Finally, the data reported here should also be considered in a wider context where, as a consequence of its well-established cytoprotective actions, UDCA is under investigation for a range of intestinal and extra-intestinal pathological conditions, including cancer, neurological diseases and atherosclerosis. In such settings, the potential benefits of an absorbable, non-metabolisable analogue that retains the therapeutic activity of UDCA are clear.