Murine epithelial sodium (Na\(^{+}\)) channel regulation by biliary factors

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The epithelial sodium channel (ENaC) mediates Na\(^{+}\) transport in several epithelia, including the aldosterone-sensitive distal nephron, distal colon, and biliary epithelium. Numerous factors regulate ENaC activity, including extracellular ligands, post-translational modifications, and membrane-resident lipids. However, ENaC regulation by bile acids and conjugated bilirubin, metabolites that are abundant in the biliary tree and intestinal tract and are sometimes elevated in the urine of individuals with advanced liver disease, remains poorly understood. Here, using a Xenopus oocyte-based system to express and functionally study ENaC, we found that, depending on the bile acid used, bile acids both activate and inhibit mouse ENaC. Whether bile acids were activating or inhibiting was contingent on the position and orientation of specific bile acid moieties. For example, a hydroxyl group at the 12-position and facing the hydrophilic side (12\(\alpha\)-OH) was activating. Taurine-conjugated bile acids, which have reduced membrane permeability, affected ENaC activity more strongly than did their more membrane-permeant unconjugated counterparts, suggesting that bile acids regulate ENaC extracellularly. Bile acid–dependent activation was enhanced by amino acid substitutions in ENaC that depress open probability and was precluded by proteolytic cleavage that increases open probability, consistent with an effect of bile acids on ENaC open probability. Bile acids also regulated ENaC in a cortical collecting duct cell line, mirroring the results in Xenopus oocytes. We also show that bilirubin conjugates activate ENaC. These results indicate that ENaC responds to compounds abundant in bile and that their ability to regulate this channel depends on the presence of specific functional groups.

Epithelial Na\(^{+}\) channel (ENaC)\(^{2}\)-mediated Na\(^{+}\) transport is rate-limiting for Na\(^{+}\) reabsorption in principal cells in the aldosterone-sensitive distal nephron, where the channel plays a key role regulating total extracellular fluid volume (1). ENaC expression in the epithelia of the airways, colon, and biliary tree has also been implicated in regulating total luminal Na\(^{+}\) and fluid volume (2–4). The channel’s activity is directly regulated by several environmental factors, including extracellular ions (e.g. H\(^{+}\), Na\(^{+}\), and Cl\(^{-}\)), mechanical forces, and proteases (5). It has recently emerged that amphipathic compounds, including bile acids, also regulate ENaC-mediated currents (6–8).

Primary bile acids are synthesized in hepatocytes and are ultimately secreted into the duodenum to emulsify dietary lipids and facilitate excretion of toxic metabolites (9). Gut microbes metabolize these and generate secondary bile acids by modifying key functional groups (10). Approximately 95% of bile acids are reabsorbed in the ileum and are transported back to the liver via the portal vein, completing the enterohepatic loop. Bile is also composed of conjugated bilirubin (c-bilirubin), an end product of heme catabolism that allows for its aqueous phase excretion (11). Under physiologic conditions, high concentrations of bile acids and c-bilirubin are restricted to the bile ducts, gall bladder, and gut. Blood and urine concentrations of both increase in liver disease or injury, whereupon urine becomes a major vehicle for their elimination (12–16). Whether increased biliary factor levels contribute to the pathology of liver disease remains unclear.

Bile acids influence numerous physiologic processes through the nuclear farnesoid X receptor and the G protein–coupled receptor TGR5 (17–20). Recent reports have shown that bile acids regulate several members of the ENaC/degenerin family (6, 7, 21, 22). ENaC belongs to a family of trimeric cation channels, which include acid-sensing ion channels (ASICs) and the bile acid–sensitive ion channel (BASIC) (23, 24). ENaC is a heterotrimer composed of α, β, and γ subunits. Each subunit contributes two transmembrane helices to a single pore, with the bulk of each subunit contained in the extracellular domains (25, 26). Gating regulation by extracellular factors is emblematic of this protein family. Numerous studies have identified sites and structures key to regulation by extracellular factors (27).

Here we examined the molecular determinants of ENaC regulation by amphipathic compounds found in bile. We found...
that specific bile acids regulate mouse ENaC, both heterologously expressed in *Xenopus* oocytes and endogenously expressed in a mouse cortical collecting duct cell line (mpkCCDc14). When systematically screening bile acids, we found that both channel activation and inhibition were associated with specific moieties and that neither activation nor inhibition depended on membrane permeability. We also found that conjugates of bilirubin activated ENaC. Other known modes of ENaC regulation, including proteolytic processing, influenced bile acid activation of the channel. Deoxycholic acid (DCA) robustly activated uncleaved channels, which have a low basal open probability ($P_o$), whereas DCA and taurocholic acid (t-CA) failed to activate fully cleaved channels, which have a high $P_o$. Our data suggest that biliary factors may be natural ligands for the channel and bind to the extracellular side of the channel to influence its $P_o$.

**Results**

*Biliary factors regulate ENaC expressed in Xenopus oocytes*

It has previously been reported that bile acids activate human and rat ENaC, ASIC1, and BASIC expressed in *Xenopus* oocytes (6, 7, 21, 22). Here, we investigated bile acid regulation of mouse ENaC, which has been extensively studied and is relevant in key model systems. We expressed WT mouse α, β, and γ subunits in oocytes and measured the effect of 1 mM DCA, cholic acid (CA), chenodeoxycholic acid (CDCA), and hyodeoxycholic acid (HDCA) (Fig. 1A) on whole-cell currents by two-electrode voltage clamp (TEVC). We found that bile acids enhanced ENaC currents in the order DCA > CA > CDCA and that HDCA inhibited ENaC currents (Fig. 1B). Bile acid regulation of ENaC currents occasionally demonstrated oocyte batch dependence (note the bimodal distribution of CA data), suggesting that differences in protein biosynthesis may influence bile acid regulation. DCA activation was dose-dependent, with evident activation at 10 μM DCA and more than half-maximal activation at 100 μM DCA (Fig. 1C).

Because bilirubin conjugated to glucuronic acid (c-bilirubin) is also a major bile component, we determined whether c-bilirubin activates ENaC (Fig. 2A). Bilirubin conjugation allows for aqueous phase excretion of the heme catabolite into bile. We found that c-bilirubin reversibly activated ENaC and that activation was dose-dependent (Fig. 2, B and C). ENaC activation by c-bilirubin required higher doses than DCA for equivalent increases in current and did not saturate even at 5 mM c-bilirubin (Figs. 1C and 2C). To test whether ENaC activation...
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Figure 2. Conjugated bilirubin activates mouse ENaC in Xenopus oocytes. A and B, oocytes expressing WT ENaC were perfused with 5 mM bilirubin conjugated with either glucuronic acid (c-bilirubin) or taurine (t-bilirubin) and then washed out before the addition of 10 μM amiloride. C, concentration-dependent activation of ENaC by bilirubin conjugates. The basal amiloride-sensitive current was \(-2.7 \pm 1.9 \mu\text{A} (n = 14)\). Data are mean ± S.D. \((n = 5–9)\). Lack of saturation suggests an \(EC_{50} > 1 \text{mM}\). ****, \(p < 0.0001\) by two-way ANOVA with Sidak’s multiple-comparison post hoc test.

Depended on the opened porphyrin ring of bilirubin or the glucuronide moieties introduced by conjugation, we tested the ability of taurine-conjugated bilirubin to activate the channel (t-bilirubin; Fig. 2A). We found that t-bilirubin activated ENaC more potently than c-bilirubin (Fig. 2, B and C). These data suggest that bilirubin itself mediates activation of ENaC by c-bilirubin and t-bilirubin. Taken together, our data show that specific biliary factors activate mouse ENaC expressed in Xenopus oocytes.

Preventing ENaC palmitoylation enhances activation by DCA

Schmidt et al. (28) proposed that bile acids activate BASIC by facilitating interactions between a cytosolic amphipathic helix and the plasma membrane. Palmitoylation (post-translational modification by hydrophobic palmitate) of the ENaC β and γ subunits has been proposed to activate ENaC through an analogous mechanism (29, 30). ENaC β and γ subunits are palmitoylated at specific intracellular cysteine residues (βCys-43, βCys-557, γCys-33, and γCys-41), and mutating these sites to alanine prevents palmitoylation. We hypothesized that DCA could activate ENaC through a similar mechanism and that there might be overlap between the two modes of regulation. We expressed ENaC subunits with all four palmitoylation sites mutated to alanine (ENaCΔP) in oocytes and tested whether mutation affected activation by DCA (Fig. 3). We found that removing all four palmitoylation sites potentiated DCA activation of ENaC currents by 7.5-fold (Fig. 3C). We also tested ENaCs lacking palmitoylation sites in only the β (βΔP) or γ (γΔP) subunits (Fig. 3). We found that γΔP recapitulated the effect of removing all four sites, whereas βΔP had an intermediate effect. When we mutated individual palmitoylation sites, we found the greatest effects at the N-terminal palmitoylation sites flanking a conserved His-Gly sequence. These results suggest that palmitoylation affects ENaC regulation by DCA.

Trypsin treatment precludes ENaC activation by DCA

Preventing ENaC palmitoylation may have affected DCA activation through overlapping mechanisms of activation (i.e. by enhancing membrane association of key intracellular structures). Alternatively, preventing palmitoylation may simply reduce the channel’s basal \(P_o\), leaving greater potential for activation (note the lower basal currents in Fig. 3B). We tested the ability of DCA to activate channels forced into a low-\(P_o\) state through an independent mechanism: by preventing ENaC cleavage. ENaC α and γ subunits undergo double cleavage that releases autoinhibitory tracts (31–33). Cleavage occurs in the periphery of the extracellular domains, far from the palmitoylation sites (25, 34–37). Uncleaved channels are “nearly silent” and have a very low \(P_o\) (38, 39). Mutating the furin sites in the α and the γ subunits (ENaCΔF: αR205A, R231AβγR143A) prevents cleavage by furin but leaves channels susceptible to cleavage by less stringent proteases like trypsin (33, 40). We found that DCA robustly increased ENaCΔF currents (Fig. 4, A and B). We also found that preventing cleavage greatly increased activation by DCA as compared with WT (Fig. 4C), similar to the effect of preventing palmitoylation. We then measured the effect of DCA activation before and after trypsin activation (Fig. 5A). As before, DCA activated ENaC currents, and the effect was reversible (Fig. 5A, DCA #1). Trypsin addition (2 μg/ml) irreversibly activated ENaC currents, consistent with cleavage. However, subsequent DCA addition (DCA #2) failed to activate currents further. Notably, trypsin activa-
tion was comparable with the first DCA activation. We confirmed these results by testing channels lacking autoinhibitory tracts in the α and γ subunits (ENαCaΔP; αΔ206–231βγΔ144–186). Channels lacking both tracts have a high open probability (39) and were not further activated by DCA (Fig. 5B). Taken together, our data suggest that preventing palmitoylation or cleavage indirectly enhanced DCA activation by suppressing activity and that trypsin treatment prevented DCA activation by “locking” the channel open.

**DCA activates ENaC independent of purinergic signaling**

Purinergic signaling regulates ENaC activity on a time scale similar to DCA-dependent activation (41). ATP inhibits ENaC through purinergic receptor signaling that ultimately depletes phosphoinositide 4,5-bisphosphate necessary for ENaC activity (42). DCA could inhibit purinergic signaling to activate ENaC. However, purinergic receptor-dependent ENaC regulation has not been demonstrated in *Xenopus* oocytes, and deep proteomics of *Xenopus* eggs did not detect P2Y receptors (43). To test this idea, we used apyrase at concentrations sufficient to activate ENaC 3-fold in other cells (4) to scavenge extracellular ATP and reduce purinergic signaling in our cells. When we perfused 5 units/ml apyrase to the cell bath, whole-cell currents increased by 13 ± 6% (Fig. 6), consistent with modest ATP

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**Figure 3. Removal of palmitoylation sites increases ENaC activation by DCA.** Oocytes were injected with cRNA encoding β or γ subunits with palmitoylation site cysteines mutated to alanine along with complementary WT ENaC subunits. The effect of 1 mM DCA on amiloride (a)-sensitive currents was measured the following day. A, representative current traces showing the effect of DCA on currents from WT ENaC or various palmitoylation-deficient mutants, where all sites have been mutated (ENαCaΔP), both sites in a single subunit have been mutated (βΔP and γΔP), or individual sites have been mutated (βC33A, βC557A, γC33A, and γC41A). Oocytes were clamped at a holding potential of −70 mV due to high WT basal currents. B, amiloride-sensitive currents are shown before and after exposure to DCA for each oocyte. Baseline amiloride-sensitive currents were −6.1 ± 2.4 μA for WT ENaC, −0.98 ± 0.65 μA for ENαCaΔP, −2.4 ± 1.2 μA for βΔP, −1.1 ± 0.6 μA for βC33A, −2.0 ± 1.4 μA for βC557A, −1.0 ± 1.1 μA for γΔP, −0.8 ± 0.2 μA for γC33A, and −1.2 ± 0.7 μA for γC41A (n = 11–15 for all groups). All groups showed significant increases in current upon DCA addition (p < 0.001 by Wilcoxon matched-pairs signed rank test). C, DCA activation of ENaC currents was determined as a percentage of the amiloride-sensitive baseline current. Individual experiments are shown with bars indicating the mean. *, p < 0.05; ***, p < 0.001; ****, p < 0.0001 by Kruskal–Wallis test followed by Dunn’s multiple-comparison test.

**Figure 4. Removal of ENaC furin cleavage sites increases DCA activation of the channel.** A, oocytes were injected with cRNA encoding WT ENaC subunits or ENaC subunits lacking the furin cleavage sites in the α and γ subunits (ENαCaΔF: αR205A,R231AγR143A). Whole-cell currents were measured by TEVC at −100 mV. Representative current traces of oocytes perfused with 1 mM DCA for 40 s, followed by 10 μM amiloride (amil) are shown. B, amiloride-sensitive currents are shown before and after exposure to DCA for each oocyte. Baseline amiloride-sensitive currents were −4.6 ± 1.21 μA for WT ENaC (n = 11) and −0.6 ± 0.3 μA for ENαCaΔF (n = 19). ***, p < 0.001; ****, p < 0.0001 by Wilcoxon matched-pairs signed rank test. C, DCA activation of ENaC current was determined as a percentage of the amiloride-sensitive baseline current. Individual experiments are shown with bars indicating the mean. ****, p < 0.0001 by Mann–Whitney U test.
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inhibition of ENaC. When we added 1 mM DCA in the continued presence of apyrase, amiloride-sensitive currents nevertheless increased. The magnitude of current increase was similar to DCA-dependent activation in the absence of apyrase (see Figs. 1 and 7). These data suggest that purinergic signaling has a modest effect on ENaC currents in oocytes and that DCA activates ENaC independent of purinergic signaling.

**ENaC activation by bile acids depends on specific moieties, but not on membrane permeability**

CA and CDCA are synthesized from cholesterol in the liver. These primary bile acids may then be conjugated to taurine or glycine in the liver and further modified into secondary bile acids (e.g., DCA) and/or deconjugated in the gut (10). Bile acids are differentiated based on the presence and orientation (facing the hydrophilic α side or hydrophobic β side) of hydroxyl groups on the steroid rings and whether they are conjugated at position 24 (Fig. 7A). Data in Fig. 1 suggested that ENaC activation depends on the presence of specific functional groups. We tested this idea by screening conjugated and unconjugated bile acids that varied by the presence and orientation of hydroxyl groups at positions 6, 7, and 12. These bile acids varied in the lipophilicity of the nonionized form, indicated by the partition coefficient (log P; Table 1) and the propensity to cross the membrane at pH 7.4, indicated by the distribution coefficient (log D; Table 1). We applied each bile acid at 1 mM and determined the effect on amiloride-sensitive currents in oocytes (Fig. 7, B and C). Although bile acids had varied effects on ENaC currents (Fig. 7C and Table 2), neither the bile acid’s partition coefficient nor distribution coefficient was predictive of that effect (Fig. 7, D and E).

To determine the contribution of the various functional groups to the effect on ENaC current, we performed a multiple linear regression analysis of our data in Fig. 7C. Each functional group (with either α or β orientation) was included in the linear regression model as an independent factor (Table 3, “Main effects”). A model without interactions between functional groups fit the data poorly and was characterized by strongly heteroscedastic residuals (Fig. 7F). For example, the fitted values at −40 that represent the HDCA data had largely positive residuals, whereas the fitted values at −33 that represent the t-HDCA data had largely negative residuals (Fig. 7F, right). A model including interactions between functional groups fit the
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Table 1

| Bile acid   | LogP | pKa | LogD |
|-------------|------|-----|------|
| DCA         | 3.50 | 5'  | 1.10 |
| CA          | 2.02 | 5'  | -0.38|
| t-CA        | 0.79 | 5'  | -7.49|
| g-CA        | 1.65 | 3.9 | -1.85|
| CDCA        | 3.28 | 5'  | 0.88 |
| t-CDCA      | 1.38 | 5'  | -6.82|
| t-LCA       | 2.10 | 5'  | -5.93|
| UCA         | 0.92 | 5'  | -1.48|
| 12βHCA      | 2.36 | 5'  | -0.14|
| HDCA        | 3.08 | 5'  | 0.68 |
| t-HDCA      | 1.43 | 5'  | -6.69|

* Partition coefficient values determined previously (44).
* Partition coefficient values calculated using ALOGPS (55).
* pKa values determined previously (44).
* pKa values calculated using MarvinSketch (ChemAxon, Cambridge, MA).

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Figure 7. ENaC-activating bile acids possess specific moieties. A, schematic of cholic acid structure. Solid wedges connect groups facing the hydrophobic side of the molecule, termed the β side. Dashed wedges connect groups facing the hydrophilic side of the molecule, termed the α side. Bile acids can be conjugated with taurine or glycine at position 24, B, representative recordings of the effect of various taurine-conjugated bile acids at 1 mM, followed by 10 μM amiloride (amil), C, bile acid–driven changes in current were determined as a percentage of the amiloride-sensitive baseline current. Individual experiments are shown with bars indicating the mean. The position and orientation (facing the α or β side) of hydroxyl groups in the tested bile acids and the presence of taurine or glycine conjugation at position 24 are summarized. All bile acids tested had a 3α-OH. Data were analyzed by one-way ANOVA with Tukey’s multiple-comparison test, with results summarized in Table 1. D and E, the effect on ENaC currents for each bile acid was plotted against the bile acid’s logP and logD values (see Table 1). Neither correlation was significant. Data were also analyzed by multiple linear regression, with functional groups as independent factors. Models with no interactions between functional groups (F) or with interactions between functional groups (G; see Table 2) were evaluated. F and G (left), kernel density plot of Studentized residuals (blue line) to evaluate distribution of residuals, with normal density (red line) overlaid. Both models gave normally distributed residuals, as determined by the Shapiro–Wilk W test (p = not significant). F and G (right), residuals versus fitted values plot to evaluate heteroscedasticity in models. White’s test for heteroscedasticity gave p = 0.0003 for the model without interactions and p = 0.049 for the model with interactions.

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data well and had smaller residuals that were normally distributed and nearly homoscedastic (Fig. 7G) (e.g., the residuals for each bile acid were symmetrically distributed about the red model line at zero) (Fig. 7G, right). In this model, the HDCA and t-HDCA data were fit with values approximating the averages for their groups. Although all possible interactions were considered, most were automatically omitted due to collinearity with other factors in the model. Our linear regression model fit the data with R² = 0.93, with parameters reported in Table 3.

With an intercept of 20, our model predicts that a bile acid lacking all of the functional groups considered (i.e., lithocholic acid (LCA)) would moderately activate ENaC. We could not test LCA due to its low aqueous solubility; however, taurolithocholic acid (t-LCA) increased ENaC currents by 27 ± 8%. The presence of the 12α-OH group was strongly associated with an increase in ENaC activity in the model (Table 3). Indeed, compounds that possessed a 12α-OH (DCA, CA, t-CA, glycocholic acid (g-CA), and ursodeoxycholic acid (UC)) generally activated ENaC more than other compounds (Fig. 7C and Table 2). Both 6α-OH and 7β-OH were associated with inhibition in the model. Our data show that 6α-OH–bearing HDCA and t-HDCA both decreased ENaC currents. UCA, which bears 7α-OH and taurine conjugation had mild main effects but interacted with other functional groups in our model. Our data show that adding a 7α-OH to t-LCA, creating t-CDCA, had little effect (not significant). However, adding 7α-OH to 12α-OH–bearing CA, making CA, decreased activation by 28% (p = 0.0004). Interest-
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Table 2

Adjusted p values for each pair in Fig. 7C using one-way ANOVA with Tukey’s multiple-comparison test

|       | t-HDCA | HDCA | 12βHICA | UCA | t-LCA | t-CDCA | CDCA | g-CA | t-CA | CA  |
|-------|--------|------|----------|-----|-------|--------|------|------|------|-----|
| DCA   | <0.0001| <0.0001| <0.0001  | <0.0001| <0.0001| <0.0001 | <0.0001| <0.0001| <0.0001| 0.003|
| CA    | <0.0001| <0.0001| <0.0001  | <0.0001| <0.0001| <0.0001 | <0.0001| <0.0001| <0.0001| 0.0004|
| t-CA  | <0.0001| <0.0001| <0.0001  | <0.0001| <0.0001| <0.0001 | <0.0001| <0.0001| <0.0001| 0.0001|
| g-CA  | <0.0001| <0.0001| NS*      | NS   | NS    | NS     | NS   | 0.0003|
| CDCA  | <0.0001| <0.0001| NS       | 0.002| 0.02  | NS     | NS   |       |
| t-CDCA| <0.0001| <0.0001| NS       | NS   | NS    | NS     | NS   |       |
| t-LCA | <0.0001| <0.0001| NS       | NS   | NS    | NS     | NS   |       |
| UCA   | <0.0001| <0.0001| NS       | NS   | NS    | NS     | NS   |       |
| 12βHICA| <0.0001| <0.0001| NS       | NS   | NS    | NS     | NS   |       |
| HDCa  | 0.02   |       |          |      |       |        |      |       |      |

* NS, not significant.

Table 3

Linear regression model parameters of Fig. 7 data (143 data points)

Functional groups at various sites on the lithocholic acid backbone were included as independent variables in the model. Interactions between functional groups were also included. Several interactions were automatically omitted due to collinearity. R² was 0.93 with a root mean squared error of 9.5.

| Coefficient | p value |
|-------------|---------|
| Main effects|         |
| 6α-OH      | −47 ± 0.5| <0.0001 |
| 7α-OH      | −7 ± 0.3 | 0.01    |
| 7β-OH      | −36 ± 0.5| <0.0001 |
| 12α-OH     | 44 ± 0.5 | 0.2     |
| 12β-OH     | 6 ± 0.2  | 0.01    |
| Glycine conjugation | 16 ± 0.3 | <0.0001 |
| Taurine conjugation | 6 ± 0.3  | 0.01    |
| Model intercept | 20 ± 0.3 | <0.0001 |

| Interactions|         |
|-------------|---------|
| 7α-OH–12α-OH| −11 ± 0.5| 0.04    |
| 6α-OH–taurine conjugation | −19 ± 0.5| <0.0001 |
| 12α-OH–taurine conjugation | 29 ± 0.5| <0.0001 |

Bile acids regulate ENaC endogenously expressed in mpkCCDc14 cells

ENaCs expressed in Xenopus oocytes have recapitulated many of the channel’s functional properties observed in other cells (e.g. ion selectivity, blocker sensitivity, and proteolytic activation). Because ENaC regulation by bile acids has only been reported in oocytes, we determined whether bile acids activate ENaC in a mouse cortical collecting duct cell line (mpkCCDc14), which endogenously expresses ENaC (45, 46). We cultured cells on permeable supports for 5 days and measured ENaC-mediated short-circuit currents (I_SC) in Ussing chambers. Experiments with DCA failed due to irreversible loss of electrical resistance across the monolayer. We then tried t-CA due to its low membrane permeability. Our initial experiments showed no effect with t-CA, which robustly activated ENaC expressed in oocytes (see Fig. 7). We hypothesized that ENaC subunits expressed in mpkCCDc14 cells may be cleaved, leaving the channel “locked open” and insensitive to channel modulators (see Fig. 5 and below). Indeed, observing trypsin activation of ENaC currents in cultured cells has required inhibiting endogenous proteases to circumvent this issue (32, 47). Nevertheless, there is strong evidence that cleavage of ENaC subunits is dynamically regulated in vivo and that channels at the luminal surface of the distal nephron are not fully cleaved (48–54). We therefore incubated cells overnight with the serine protease inhibitors aprotinin and camostat before measuring the effect of t-CA on ENaC-mediated I_SC. We found that t-CA added to the apical side in the continued presence of camostat activated amiloride-sensitive I_SC in a dose-dependent manner, with 1 mM t-CA activating by 54 ± 14% (Fig. 8). The t-CA dose–response curve from mpkCCDc14 cells was similar to the t-CA dose–response curve in oocytes (Fig. 8B).

To test the specificity of the effect, we also tested t-HDCA, which inhibited ENaC expressed in oocytes (Fig. 7). We found that t-HDCA inhibited amiloride-sensitive I_SC in a dose-dependent manner with 1 mM t-HDCA inhibiting by 13 ± 6% (Fig. 8). The relative changes in current are smaller than those measured in oocytes in both cases. We also observed modest increases in I_SC upon adding 2 μM trypsin. Before adding trypsin, we replaced the apical solution with a solution lacking camostat and waited until currents stabilized before proceeding. During this period, we observed a consistent increase in I_SC even after reversal of t-CA stimulation. We speculate that this resulted from cleavage by endogenous proteases after removal of the protease inhibitor. Still, our data clearly show that t-CA and t-HDCA regulation of ENaC endogenously expressed in mpkCCDc14 cells is analogous to their regulation of ENaC heterologously expressed in Xenopus oocytes.

To confirm that locking the channel open precludes ENaC activation by t-CA in mpkCCDc14 cells, we tested the effect of t-CA on ENaC currents after trypsin treatment. One day before current measurements, cell culture medium was supplemented with protease inhibitors as before or with vehicle. For cells cultured with protease inhibitors, recording medium was supplemented with 5 μM camostat on the apical side. When we tested cells that had not been exposed to protease inhibitors, we observed no change in I_SC after the addition of 2 μM trypsin or after the subsequent addition of 1 mM t-CA (Fig. 9). When we tested cells that were cultured with protease inhibitors, we observed a robust increase in I_SC after trypsin addition in excess of camostat but no change in I_SC after the subsequent addition...
of 1 mM t-CA. Taken together with data in Fig. 8, these data suggest that t-CA activates ENaC by increasing ENaC \( P_o \).

**Discussion**

Recent reports have shown that ENaC/degenerin family members are regulated by a variety of amphipathic molecules (6–8, 21, 22). In this study, we show that specific biliary factors regulate ENaC. Our results suggest that regulation by bile acids depends on specific moieties and that these compounds affect the channel \( P_o \). We also found that bilirubin conjugates regulate the channel and that bile acids regulate ENaC endogenously expressed in cultured polarized epithelial cells.

Bile acids are synthesized by hepatocytes and are modified by gut bacteria, giving rise to a family of compounds that vary with respect to hydroxyl groups at key positions. Our results show that bile acids with a 12α-OH activate ENaC, whereas bile acids with a 6α-OH inhibit it. Rat and human ENaCs were also activated by bile acids bearing 12α-OH (6, 7). Sensitivity to bile acid dosing was similar for mouse ENaC, rat ENaC, and human ASIC1a (6, 22). Our results also suggest that taurine conjugation had mixed effects on mouse ENaC. Whereas taurine conjugation had a mild independent stimulatory effect, it also amplified the effect of the underlying bile acid. The independent stimulatory effect of taurine conjugation appears to be larger for human ENaC (7). In contrast to mouse ENaC, glycine and taurine conjugation of CA had no effect on the activation of rat ENaC (6). Conjugation to taurine or glycine increases bile acid hydrophilicity and lowers the compound’s \( pK_a \), resulting in reduced membrane permeability. Given the effect to enhance both activation and inhibition we observed with taurine conjugation, our data suggest that membrane permeability is not required for ENaC regulation by bile acids. Our data also show that bilirubin conjugates activated ENaC currents. As compared with DCA, bilirubin conjugates required much higher concentrations to activate ENaC to similar levels. Because both the glucuronic acid and taurine conjugates activated ENaC with similar dose dependences, our data suggest that regulation likely depends on the pyrrole moieties of bilirubin. As with bile acids, our data with taurine-conjugated bilirubin suggest that membrane permeability is not required for ENaC regulation.

**Figure 8. Bile acids regulate ENaC in mpkCCDc14 cells.** Polarized mpkCCDc14 cells grown on permeable supports were mounted in an Ussing chamber for \( I_{sc} \) measurements. A, representative recordings shown. Increasing concentrations of t-CA or t-HDCA were added to Ringer’s buffer supplemented with 10 μM camostat on the apical side of the chamber, as indicated. After the last bile acid addition, bile acids were removed by replacing the solution on the apical side with Ringer’s buffer lacking camostat. 2 μM trypsin was then added, followed by 10 μM amiloride. Baseline amiloride-sensitive \( I_{sc} \) was 16 ± 9 μA/cm². \( B \), changes in current in response to t-CA (\( n = 6 \)) or t-HDCA (\( n = 6 \)) were determined as a percentage of the amiloride-sensitive baseline current, while correcting for time-dependent changes in current. Linear estimates of the time-dependent change in current under each condition were determined using a 30-s window during the steady-state period just before each bile acid addition and were used to account for run-down during each experiment. A dose–response experiment for t-CA activation of ENaC-expressing oocytes is overlaid for comparison (\( n = 5 \)) and was performed analogously to the experiment in Fig. 1C. Data for t-CA were fit to the Hill equation, \( E_{C50} = 210 ± 100 \) μM in mpkCCDc14 cells and 148 ± 5 μM in oocytes.

**Figure 9. Trypsin precludes t-CA activation of amiloride-sensitive \( I_{sc} \) in mpkCCDc14 cells.** Cells were incubated with or without 500 μg/ml aprotinin and 20 μM camostat 24 h before recordings. A, representative recordings shown. 5 μM camostat was maintained on the apical side for the protease inhibitor–treated cells. After the currents stabilized, 7 μM trypsin was added, followed by 1 mM t-CA. For untreated cells, no camostat was present during the recording, during which 2 μM trypsin was added, followed by 1 mM t-CA. 10 μM amiloride was applied at the end of each recording. \( B \), amiloride-sensitive \( I_{sc} \) values are calculated based on currents measured just prior to the addition of the subsequent agent. Baseline amiloride-sensitive currents were 22.1 ± 6.2 μA/cm² for untreated cells (\( n = 11 \)) and 6.3 ± 2.8 μA/cm² for protease inhibitor–treated cells (\( n = 11 \); \( p < 0.0001 \) versus untreated cells by repeated-measures two-way ANOVA with Sidak’s multiple-comparison test). ***, \( p < 0.001 \); ****, \( p < 0.0001 \) by repeated measures two-way ANOVA with Sidak’s multiple-comparison test.
Our bile acid data are consistent with regulation through effects on channel $P_o$. Suppressing $P_o$ by preventing palmitoylation or furin processing markedly increased the response to DCA. In contrast, elevating $P_o$ through trypsin treatment or mutagenesis prevented a response to both DCA and t-CA. These results accord with previous studies that used trypsin to prevent bile acid activation and showed that bile acids increase $P_o$ in single-channel recordings (7). However, they contrast with earlier single-channel experiments suggesting that bile acids activate only furin-processed channels, and not uncleaved near-silent channels (6, 7). Notably, lower bile acid concentrations (250 $\mu M$ t-DCA or 500 $\mu M$ DCA) were used as compared with experiments presented here. Nonetheless, our data clearly show that bile acids robustly activate channels lacking furin processing.

Several lines of evidence suggest that bile acids regulate ENaC by directly binding to an extracellular site to affect the $P_o$ of the channel. Here we showed that bile acids likely regulate ENaC independent of purinergic signaling. The Wiemuth group (8) recently reported that while amphipathic compounds influenced membrane properties, no effect on membrane properties predicted effects on the function of ENaC/degenerin channels. We did not find that channel regulation correlated with differences in the biophysical properties of the bile acids tested. Instead, the presence of specific moieties accounted for differences between the effects of different bile acids. Our results with taurine conjugates limit the likely sites of interaction to the extracellular domains and the outer portion of the transmembrane helices. We showed that altering channel function through mutations at opposite ends of the channel profoundly affects ENaC regulation by bile acids, illustrating cross-talk between all three modes of regulation. The Haerteis group (7) recently proposed that bile acids bind ENaC near the degenerin site on the basis of functional analysis and molecular modeling. This region of the protein, long implicated in ENaC function, lies in the transmembrane helices of the pore and is consistent with these data.

ENaC is expressed in epithelia that are exposed to high concentrations of bile acids and c-bilirubin. ENaC is robustly expressed in the aldosterone-sensitive distal colon and was recently reported to be expressed in cholangiocytes, which line the bile ducts and gallbladder (4, 56). ENaC-mediated Na$^+$ transport has been proposed to regulate the viscosity of bile and stool fluid content (4, 57). Additionally, cholestasis, cirrhosis, and hepatitis are often associated with elevated biliary factor levels in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60). Urinary bile acid concentrations are well-correlated with serum total bile acids and conjugated bilirubin in blood (13, 16, 58–60).

ENaC functional expression in Xenopus laevis oocytes

Oocytes from X. laevis were harvested and defolliculated using standard protocols. 1–4 ng of cRNA encoding each ENaC subunit was injected into stage V or VI oocytes using a Nanoject II (Drummond Scientific, Broomall, PA). After injection, oocytes were incubated at 18 °C for 20–24 h in modified Barth’s saline (88 mM NaCl, 1 mM KCl, 2.4 mM NaHCO$_3$, 15 mM HEPES, 0.3 mM Ca(NO$_3$)$_2$, 0.41 mM CaCl$_2$, 0.82 mM MgSO$_4$, 10 $\mu g$/ml sodium penicillin, 10 $\mu g$/ml streptomycin sulfate, 100 $\mu g$/ml gentamicin sulfate, pH 7.4) prior to current measurements. The protocol for harvesting oocytes from X. laevis was approved by the University of Pittsburgh’s Institutional Animal Care and Use Committee.

Two-electrode voltage clamp (TEVC) recordings

TEVC was performed using an Axoclamp 900A voltage clamp amplifier and DigiData 1550A (Molecular Devices,
Sunnyvale, CA) interfaced to a personal computer. Data acquisition and analyses were performed using pClamp 10.5 software (Molecular Devices). Pipettes for electrophysiological recordings were pulled from borosilicate glass capillaries (World Precision Instruments, Inc., Sarasota, FL) using a model p-87 micropipette puller (Sutter Instrument Co., Novato, CA) and had resistances of 0.5–5 milliohm when filled with 3 M KCl and inserted into the bath solution. Oocytes were maintained in a recording chamber (Automate Scientific, San Francisco, CA) with 20 μl of bath solution and continuously perfused with Na-110 buffer (110 mM NaCl, 2 mM KCl, 2 mM CaCl2, 10 mM HEPES, pH 7.4) at a flow rate of 5–8 ml/min. Various compounds were diluted into Na-110 solution from 100 mM stock solutions in water (t-CA, g-CA, DCA, HDCA, and t-HDCA) or DMSO (amiloride, CA, CDCA, t-CDCA, t-LCA, UCA, and 12βHICA). At the end of each experiment, currents were measured in 10 μM amiloride to determine the amiloride-sensitive component of the current. All experiments were performed at ambient temperatures (20–24 °C). The DMSO cosolvent used for some compounds at 1% final concentration did not significantly affect ENaC currents (∆I = –10 ± 5%; n = 8; p = 0.08 by paired Student’s t test).

**mpkCCD14 cell culture**

Cells were cultured in Dulbecco’s modified Eagle’s medium/F12 (Thermo Fisher Scientific) supplemented with 2% fetal calf serum, 50 nM dexamethasone, 60 nM selenium, 1 nM triiodothyronine, 5 μg/ml insulin, 5 μg/ml transferrin, 10 ng/ml epidermal growth factor, and 1% penicillin/streptomycin (Millipore-Sigma), as described previously (33). Cells were seeded at confluent density onto 1.2-cm diameter Costar Transwell inserts (0.4–μm pore size, Corning, NY). The subcultured cells were grown for at least 5 days. 24 h before I_sc measurements, growth medium was replaced with unsupplemented Dulbecco’s modified Eagle’s medium/F12. At the same time, serine protease inhibitors (5 mg/ml aprotinin and 20 μM camostat mesylate) were added to both the upper and lower compartments of the transwells, as indicated.

**Short-circuit current measurements**

Transwell inserts covered by cell monolayers were mounted in modified Ussing chambers and continuously short-circuited using a VCC MC6 voltage clamp system (Physiologic Instruments, San Diego, CA) (33). Each hemic-chamber was bathed in 5 ml of Ringer’s solution (110 mM NaCl, 25 mM NaHCO3, 5.8 mM KCl, 1.2 mM KH2PO4, 2 mM MgSO4, 2 mM CaCl2, and 11 mM glucose, pH 7.4). A gas mixture of 95% O2 and 5% CO2 at ambient temperatures (20–24 °C). The DMSO cosolvent used for the sodium channel (ENaC) by bile acids involves the degenerin site. J. Biol. Chem. 291, 19835–19847 CrossRef Medline

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