Activation of the Human Epithelial Sodium Channel (ENaC) by Bile Acids Involves the Degenerin Site

Received for publication, March 25, 2016, and in revised form, July 31, 2016. Published, JBC Papers in Press, August 3, 2016, DOI 10.1074/jbc.M116.726471

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The epithelial sodium channel (ENaC) is a member of the ENaC/degenerin ion channel family, which also includes the bile acid-sensitive ion channel (BASIC). So far little is known about the effects of bile acids on ENaC function. ENaC is probably a heterotrimer consisting of three well characterized subunits (αβγ). In humans, but not in mice and rats, an additional δ-subunit exists. The aim of this study was to investigate the effects of chenodeoxycholic, cholic, and deoxycholic acid in unconjugated (CDCA, CA, and DCA) and tauro-conjugated (t-CDCA, t-CA, and t-DCA) form on human ENaC in its αβγ-configuration. We demonstrated that tauro-conjugated bile acids significantly stimulate ENaC in the αβγ- and in the δβγ-configure. In contrast, non-conjugated bile acids have a robust stimulatory effect only on δβγENaC. Bile acids stimulate ENaC-mediated currents by increasing the open probability of active channels without recruiting additional near-silent channels known to be activated by proteases. Stimulation of ENaC activity by bile acids is accompanied by a significant reduction of the single-channel current amplitude, indicating an interaction of bile acids with a region close to the channel pore. Analysis of the known ASIC1 (acid-sensing ion channel) crystal structure suggested that bile acids may bind to the pore region at the degenerin site of ENaC. Substitution of a single amino acid residue within the degenerin region of βENaC (N521C or N521A) significantly reduced the stimulatory effect of bile acids on ENaC, suggesting that this site is critical for the functional interaction of bile acids with the channel.

The epithelial sodium channel (ENaC)³ belongs to the ENaC/degenerin superfamily of non-voltage-gated ion channels (1). The recently published crystal structure of chicken acid-sensing ion channel 1 (ASIC1) belonging to the same channel family suggests that ENaC is a heterotrimer composed of three homologous subunits: α, β, and γ (2–4). Atomic force microscopy data also support the assumption that ENaC is a heterotrimetric channel (5). Each subunit of ENaC consists of short intracellular N and C termini, a large extracellular domain, and two transmembrane domains (TM1 and TM2). All subunits are thought to contribute to the channel pore with their TM2 domains (1). The initial part of the TM2 domain is highly conserved among the ENaC/degenerin ion channel superfamily and contains the sites critically important for channel function including the selectivity filter (6–10), the binding site of the channel blocker amiloride (11), and the degenerin site (12–15). The degenerin site is a hallmark of channels of the ENaC/degenerin superfamily and is important for channel gating.

The well characterized αβγENaC plays a pivotal role in sodium transport across the apical plasma membrane in the aldosterone-sensitive distal nephron, respiratory epithelia, distal colon, and sweat and salivary ducts (16–19). In humans, an additional δ-subunit exists that can functionally replace the α-subunit in heterologous expression systems (20–24). δENaC has been found in various epithelial and non-epithelial tissues (20, 25). In particular, δENaC mRNA is highly expressed in the brain (20, 26, 27). However, the functional role of the δ-subunit remains unclear.

The regulation of ENaC is highly complex and involves several hormones, signaling pathways, and local mediators (28–30). In particular, local factors affecting ENaC function are likely to be important for tissue-specific ENaC regulation. Moreover, important species differences appear to exist in ENaC regulation and need to be considered when studying the underlying regulatory mechanisms (31–33). Interestingly, rat αβγENaC has recently been reported to be activated by bile acids (34). Bile acids have previously been shown to activate another member of the ENaC/degenerin ion channel family, the bile acid-sensitive ion channel (BASIC) (35, 36), previously named intestine Na⁺ channel (INaC) in humans (37), and brain liver intestine Na⁺ channel (BLINaC) in mouse and rat (38).

The physiological role and mechanism of ENaC activation by bile acids remain to be elucidated. In particular, it has not yet been shown whether bile acids also affect the function of human ENaC, which can occur in at least two configurations (αβγ or δβγ) in different tissues. Therefore, the aim of this study was to investigate whether major human bile acids (chenodeoxycholic, cholic, and deoxycholic acid) modulate human ENaC in its αβγ- and δβγ-configuration. We demonstrate that

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¹This work was supported by grants from the Deutsche Forschungsgemeinschaft (DFG) (HA 6655/1-1 to S. H.), the Johannes and Frieda Marohn Foundation (to C. K.), and Deutscher Akademischer Austauschdienst (DAAD) (to A.I.). The authors declare that they have no conflicts of interest with the contents of this article. Part of this work has been published in abstract form (65–67).

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The abbreviations used are: ENaC, epithelial sodium channel; ASIC1, acid-sensing ion channel 1; MTSET, 2-(trimethylammonium)ethyl methanethiosulfonate bromide; CDCA, chenodeoxycholic acid; t-CDCA, tauro-chenodeoxycholic acid; CA, cholic acid; t-CA, tauro-cholic acid; DCA, deoxycholic acid; t-DCA, tauro-deoxycholic acid; NMDD, N-methyl-D-glucamine; ANOVA, analysis of variance; n.s., not significant.
bile acids can activate human ENaC, probably by specifically interacting with the degenerin region.

Results

**Bile Acids Are More Potent Activators of ENaC in the δβγ-configuration**—To test the effect of bile acids on ENaC function, human αβγ- or δβγENaC was heterologously expressed in *Xenopus laevis* oocytes. Amiloride-sensitive whole-cell currents (I\textsubscript{am}) were measured using the two-electrode voltage clamp technique. Representative current traces for αβγ- or δβγENaC-expressing oocytes are shown in Fig. 1, A and C and Fig. 1, B and D, respectively. Whole-cell current recordings were started in the presence of amiloride in a concentration of 2 or 100 μM to inhibit αβγENaC or δβγENaC, respectively (22). Wash-out of amiloride revealed an ENaC-mediated sodium inward current. Interestingly, the current response to superfusion with chenodeoxycholic acid (CDCA) was different in αβγENaC-expressing oocytes when compared with that in δβγENaC-expressing oocytes. CDCA reduced αβγENaC currents by about 10% but resulted in 2.7-fold increase of δβγENaC currents (Fig. 1, A and B). In contrast, tauro-deoxycholic acid (t-DCA) stimulated ENaC in both subunit configurations (Fig. 1, C, D, and E). The effects of bile acids were reversible within about 2 min after wash-out. Re-addition of amiloride returned the whole-cell current toward the initial baseline level. The rapid onset and reversibility of the bile acid effect suggest that it is not caused by a permanent chemical modification of the channel or by a gradual accumulation of bile acids in the lipid bilayer of the plasma membrane. Control experiments demonstrated that bile acids had no effect on whole-cell currents in non-injected oocytes and that in ENaC-expressing oocytes the current stimulated by t-DCA was fully blocked by amiloride (data not shown). These control experiments confirm that the observed current responses are mediated by the effects of bile acids on ENaC activity. In addition to CDCA and t-DCA, we also tested the effect of cholic (CA), tauro-cholic (t-CA), deoxycholic (DCA), and tauro-chenodeoxycholic (t-CDCA) acid in similar experiments. Normalized data from these experiments are summarized in Fig. 1E. Interestingly, δβγENaC currents were stimulated more than 2-fold by non-conjugated as well as tauro-conjugated bile acids. In contrast, only the tauro-conjugated forms of bile acids (t-CA, t-DCA, and t-CDCA) markedly stimulated αβγENaC currents with t-DCA producing the largest effect (about 2-fold). The non-conjugated bile acids CA and DCA had a stimulatory effect of about 20% on αβγENaC currents, whereas CDCA even inhibited αβγENaC currents on average by more than 20%. Thus, a robust stimulatory effect on αβγENaC was only observed with tauro-conjugated bile acids (Fig. 1E).

The marked difference between the effects of DCA and t-DCA on αβγENaC may result from a lower binding affinity of DCA to the channel or from DCA binding without major effect on channel function. To address this question, we performed experiments in which we first applied DCA and subsequently applied t-DCA in the presence of DCA (Fig. 2A) or first applied t-DCA and subsequently applied DCA in the presence of t-DCA (Fig. 2C). As summarized in Fig. 2B, DCA stimulated ENaC-mediated currents by about 30%, whereas subsequent application of t-DCA in the presence of DCA resulted in a stimulation of ENaC activity by more than 2-fold. In contrast, when ENaC was first activated by t-DCA, subsequent DCA application did not further activate the channel (Fig. 2D). Importantly, the combined stimulatory effects of DCA and t-DCA on αβγENaC were similar in both cases (DCA followed by t-DCA: 2.18 ± 0.08-fold, n = 20, N = 2; t-DCA followed by DCA: 2.15 ± 0.09-fold, n = 20, N = 2) and were not significantly
different from that of t-DCA applied alone (2.11 ± 0.08-fold, n = 20, N = 2; Fig. 2, B and D). Thus, the effects of DCA and t-DCA were not additive. These data suggest that DCA and t-DCA modify channel activity by the same mechanism. The finding that an initial application of DCA does not reduce the stimulatory effect of t-DCA applied in the presence of DCA suggests that DCA does not prevent t-DCA binding to the channel. Thus, t-DCA is likely to have a higher binding affinity to the channel than DCA and binding of DCA may have a smaller stimulatory effect on αβγENaC than binding of t-DCA.

Taken together, these findings demonstrate that tauro-conjugated bile acids stimulate ENaC in the δβγ- and in the αβγ-configuration, whereas non-conjugated bile acids have a robust stimulatory effect only on δβγENaC.

**Tauro-deoxycholic Acid Activates Human αβγENaC by Increasing Open Probability (Po) of Active Channels but Not by Recruiting Additional Near-silent Channels**—Our whole-cell current measurements demonstrated that the effects of bile acids on human ENaC in both αβγ-subunit and δβγ-subunit configurations were rapid and reversible. This makes it unlikely that insertion of new channels in the plasma membrane contributes to the stimulatory effect of bile acids on ENaC. Instead, bile acids probably stimulate ENaC by increasing the Po of channels that are already present in the plasma membrane. Two functionally distinct ENaC populations are thought to be present in the plasma membrane: active channels with an average Po of about 0.5 and so-called near-silent channels with an extremely low Po (31, 39–41). Thus, bile acids may further increase the Po of the active channel population or may recruit additional near-silent channels by converting them into active channels. To investigate the biophysical mechanisms of ENaC activation by bile acids, we performed single-channel recordings in outside-out patches of ENaC-expressing oocytes and tested the effect of bile acids on ENaC. Fig. 3A shows a representative recording from an outside-out patch excised from an oocyte expressing αβγENaC. The initial wash-out of amiloride revealed single-channel activity with up to three apparent channel levels (Fig. 3A). After t-DCA application, the same number of active channels in the patch was observed. However, NPo was moderately increased from 1.04 to 1.64 (where N is the number of channels and Po is single-channel open probability), and the single-channel current amplitude (i) was reduced from 0.39 to 0.37 pA (Fig. 3A, insets 1 and 2). The observed increase in NPo is consistent with the stimulatory effect of t-DCA on ENaC whole-cell currents in oocytes expressing αβγENaC (Fig. 1E). Upon wash-out of t-DCA, NPo and i returned approximately to their initial values (0.88 and 0.39 pA, respectively; Fig. 3A, inset 3). It is well established that proteolytic activation of ENaC is associated with the recruitment of near-silent channels (31, 39, 41, 42). Indeed, subsequent application of the serine protease chymotrypsin led to the recruitment of additional channel levels and a strong increase of NPo from 0.88 to 5.28 (Fig. 3A, inset 4). The single-channel amplitude remained unchanged at 0.39 pA. On average, t-DCA reduced the single-channel current amplitude from 0.38 ± 0.003 to 0.35 ± 0.01 pA (p < 0.001; N = 4; n = 7), increased NPo by about 1.6-fold from 0.82 ± 0.17 to 1.36 ± 0.25 (p < 0.05; N = 4; n = 7), and did not significantly change the number of apparent channel levels from 2.4 ± 0.5 versus 2.7 ± 0.6 (n.s.; N = 4; n = 7) (Fig. 3B).

In some experiments with very low initial αβγENaC activity, the difference in the effects of t-DCA and chymotrypsin was particularly impressive (Fig. 3C). In this experiment, only a few, extremely brief single-channel openings were observed prior to the application of t-DCA (NPo < 0.01), which indicates that in this outside-out patch, only near-silent channels with a very low Po are present. Interestingly, application of t-DCA had no significant effect on channel activity in this patch, which suggests that near-silent channels are not markedly affected by t-DCA. In contrast, application of chymotrypsin resulted in the expected conversion of near-silent channels into active channels as evidenced by the appearance of up to four channel levels with long channel openings (NPo = 2.52). In summary, our single-channel data indicate that t-DCA stimulates αβγENaC activity by increasing the Po of active channels without recruiting additional near-silent channels, which distinguishes the effect of t-DCA from that of channel-activating proteases. Moreover, the small but significant reduction of single-channel current amplitude in the presence of t-DCA indicates a possible interaction of bile acids with a region close to the channel pore.

**Chenodeoxycholic Acid Reduces the Single-channel Current Amplitude of δβγENaC**—In outside-out patches from oocytes expressing δβγENaC, we confirmed our previously reported finding that for unknown reasons δβγENaC shows a high basal Po close to 1 (Fig. 4, A and B) (22). Indeed, in outside-out patches, the channel resides almost all the time in its open state.

**FIGURE 2. Stimulatory effects of non-conjugated DCA and tauro-conjugated DCA are not additive.** A and C, representative whole-cell current traces of oocytes expressing wild-type αβγENaC. Amiloride (Ami; 2 μM), DCA (250 μM), and t-DCA (250 μM) were present in the bath solution as indicated by the bars. B and D, normalized amiloride-sensitive current values (Iamiloride acid/Iamiloride initial) obtained from similar experiments as shown in A and C (individual data points belonging to the same experiment are connected with solid lines; N = 2; ***, p < 0.001, n.s., not significant, paired ratio t test).
with only brief closing events (Fig. 4, inset 1 demonstrating part of the trace on an expanded time scale). Under these conditions, it is not surprising that application of CDCA had no additional stimulatory effect on $P_\text{o}$ despite the large stimulatory effect of CDCA observed on ENaC whole-cell currents (Fig. 1B). However, the single-channel current amplitude of $\delta\beta\gamma$ENaC was slightly reduced from 0.95 to 0.84 pA (Fig. 4A, inset 2). The single-channel current amplitude of $\delta\beta\gamma$ENaC returned to its initial value upon wash-out of CDCA (Fig. 4A, inset 3). In outside-out patches, chymotrypsin also had no detectable effect on $P_\text{o}$ and single-channel current amplitude of $\delta\beta\gamma$ENaC (Fig. 4A, inset 4), which is consistent with our previously reported data (22). Importantly, the small but significant and reversible reduction of the single-channel current amplitude of $\delta\beta\gamma$ENaC by CDCA (Fig. 4C) suggests that CDCA interacts with $\delta\beta\gamma$ENaC in a similar way as t-DCA interacts with $\alpha\beta\gamma$ENaC (Fig. 3B). This further supports the hypothesis that bile acids interact with a region in ENaC close to the channel pore.

Analysis of the Crystal Structure of the Transmembrane Domains of ASIC1 Suggests a Putative Binding Site for Bile Acids in the Degenerin Region of ENaC—To identify a putative bile acid binding site, we analyzed the crystal structure of ASIC1 transmembrane domains. Analysis revealed the presence of hydrophobic crevices in the membrane-spanning region of the channel occupied by three maltose groups of the detergent $n$-dodecyl-$\beta$-D-maltoside used for channel isolation from the
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FIGURE 4. Chenodeoxycholic acid does not stimulate hyperactive δβγENaC in outside-out patches but reduces single-channel current amplitude. A, representative single-channel current recording obtained at a holding potential of −70 mV from an outside-out patch with only one active δβγENaC channel. Amiloride (Ami, 10 μM), CDCA (250 μM) and chymotrypsin (Chym, 2 μg × ml⁻¹) were present in the bath solution as indicated by the bars. The current level at which the channel is closed (C) was determined in the presence of amiloride. The open and closed channel levels are indicated by horizontal lines. The insets (1, 2, 3, and 4) show the indicated segments of the continuous current trace on an expanded time scale. Asterisks indicate single-channel events shown on the right side of the corresponding inset with higher time resolution. Binned current amplitude histograms (not shown) were obtained from the current traces depicted in the insets and were used to calculate Np, and single-channel current amplitude (i). With only one active channel in the patch, the Np, value corresponds to P,. The dotted lines in the insets indicate the closed and open channel levels. B, summary of P, values from similar experiments as shown in A with only one active channel in the patch (N = 6; n = 6). n.s., not significant, paired t test. C, summary of i values from similar experiments as shown in A but including experiments with more than one channel in the patch (N = 7; n = 7). ***, p < 0.001, n.s., not significant, repeated measures one-way ANOVA with Bonferroni post hoc test.

plasma membrane before crystallization (Protein Data Bank [PDB] ID 2QTS (3)) (Fig. 5A). Two of the putative detergent binding sites are located on the outer side of the transmembrane domains and are probably occupied by membrane lipids. Interestingly, the third site is located within the pore region formed by the second transmembrane domains (TM2) of all three subunits and is accessible from the extracellular solution.

Bile acids are amphiphilic substances and can behave as detergents (43). Therefore, we hypothesized that maltoside detergent may mimic the effect of bile acids on ENaC function. Indeed, similar to CDCA, application of maltoside in a non-solubilizing concentration (10 μM) significantly stimulated δβγENaC by about 1.5-fold and inhibited αβγENaC by about 10% (Fig. 5, C–E). Thus, it is tempting to speculate that bile acids may bind to ENaC at sites corresponding to those identified for maltoside detergent co-crystallized with ASIC1. Among the three putative binding sites, the site located within the pore region appeared to be the most likely candidate for bile acid binding, because of the rapid onset and reversibility of the bile acid effect on P, and single-channel current amplitude. Estimating the energy of interaction (MolDock score (44) using Molegro Molecular Viewer 2.5.0 from CLC bio) between the maltose group and the channel reveals that the aspartate residue in position 433 (Asp⁴³³) makes the highest contribution to binding at this site. Using protein sequence alignment, we identified residues homologous to ASIC1 Asp⁴³³ in all four human ENaC subunits (Fig. 5B). The homologous residues are Asn⁵⁵⁰, Ala⁵²⁷, Asn⁵²¹, and Asn⁵³⁰ in α, δ, β, and γ-ENaC, respectively (Fig. 5B). Interestingly, these residues belong to the degenerin region known to play an important role in ENaC gating (1, 8, 10, 13). Thus, we hypothesized that the amino acid residues in ENaC subunits homologous to ASIC1 Asp⁴³³ may be functionally important sites for the interaction between bile acids and ENaC.

Mutating the Asparagine Residue βAsn⁵²¹ to Cysteine or Alanine Reduces the Stimulatory Effect of Bile Acids on δβγENaC—As shown above, bile acids activate δβγENaC more potently than αβγENaC. Therefore, we initially focused on ENaC in its δβγ-configuration to investigate whether the amino acid residues homologous to Asp⁴³³ in ASIC1 are involved in bile acid-mediated activation of ENaC. The homologous amino acid residues δAla⁵²⁷, βAsn⁵²¹, and γAsn⁵³⁰ were mutated to cysteines. The substitution of these residues by cysteine was chosen, because cysteine does not change substantially the size and charge of the amino acid side chain. Moreover, the cysteine residue can be covalently modified by the sulfhydryl reagent...

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FIGURE 5. Analysis of the crystal structure of the transmembrane domains of ASIC1 suggests a putative binding site for bile acids in the degenerin region of ENaC. A, ribbon diagram of the transmembrane domains of chicken ASIC1 (gASIC1) with three maltose groups of the co-crystallized detergent maltoside. The arrow points to the aspartate residue (Asp433), the amino acid residue with the highest contribution to the total energy of interaction between ASIC1 and the detergent in the degenerin region. B, sequence alignment of chicken ASIC1, DEG-1 from C. elegans (c.DEG-1), and human ENaC subunits (h.αENaC, h.δENaC, h.βENaC, and h.γENaC) corresponding to the first part of the second transmembrane domains (TM2). Amino acid residues homologous to Asp433 in chicken ASIC1 are indicated by bold characters in red. C and D, maltoside detergent reversibly inhibits αβγENaC (C) and reversibly activates δβγENaC (D). Representative whole-cell current traces of oocytes expressing wild-type αβγENaC (C) or δβγENaC (D) are shown. Amiloride (Ami, 2 μM (C) or 100 μM (D)) and n-dodecyl-β-o-maltoside (MALT, 10 μM) were present in the bath solution as indicated by corresponding bars. E, normalized amiloride-sensitive current values (Iami(∆m)/Iami(initial)) obtained from similar experiments as shown in C and D (mean ± S.E. and individual data points; N = 2; 14 ≤ n ≤ 20; ***, p < 0.001; unpaired ratio test).

Next, we tested whether the substitution of βAsn521 by cysteine modulates the stimulatory effect of bile acids on δβγENaC. As shown in Fig. 7A, application of CDCA to control oocytes expressing δβγENaC without a mutation resulted in a more than 2-fold increase of ENaC-mediated currents consistent with the findings shown in Fig. 1. Subsequent application of chymotrypsin (2 μg/ml) in the presence of CDCA did not

FIGURE 6. MTSET activates mutant channels with cysteine residues in the degenerin region but not wild-type δβγENaC. A–C, representative whole-cell current traces of oocytes expressing wild-type (δβγ) or a mutant ENaC (δβN521Cγ or δβS520Cγ) are shown. D, normalized amiloride-sensitive current values (Iami(∆m)/Iami(initial)) obtained from similar experiments as shown in A–C (mean ± S.E. and individual data points; N = 2; n = 12; ***, p < 0.001; one-way ANOVA with Bonferroni post hoc test). Amiloride (Ami, 100 μM) and MTSET (1 mM) were present in the bath solution as indicated by corresponding bars.
cause a further current increase. We have previously shown that chymotrypsin in this concentration maximally activates ENaC by proteolytic cleavage, increasing channel $P_o$ from about 0.5 to almost 1 consistent with a 2-fold increase of ENaC-mediated whole-cell currents (22). We confirmed in the present study that chymotrypsin alone caused a 2-fold increase of ENaC-mediated whole-cell currents (data not shown) similar to the effect observed with CDCA alone or with CDCA in combination with chymotrypsin. Thus, our findings suggest that both chymotrypsin and CDCA can increase the $P_o$ of wild-type ENaC from 0.5 to almost 1. Importantly, substitution of Asn521 by cysteine ($\delta\text{N}_{521}\text{C}$ENaC) reduced the stimulatory effect of CDCA by about 50%. Subsequent application of chymotrypsin to $\delta\text{N}_{521}\text{C}$ENaC resulted in an additional stimulatory effect (Fig. 7, B and I). These findings indicate that the $\delta\text{N}_{521}\text{C}$ mutation partially prevents the stimulatory interaction of CDCA with the channel, whereas proteolytic channel activation is preserved.

The significant inhibitory effect of the $\delta\text{N}_{521}\text{C}$ mutation on ENaC stimulation by CDCA was confirmed by regression analysis of normalized current data (Fig. 8A) taken from similar experiments as shown in Fig. 7, A and B. This analysis demonstrates that ENaC currents measured in the presence of CDCA are proportional to those measured in the presence of both CDCA and chymotrypsin. Importantly, the proportionality coefficient was close to 1 for the wild-type channel (0.94 ± 0.01; $N = 3$; $n = 38$), confirming that chymotrypsin has no additional stimulatory effect on $\delta\text{N}_{521}\text{C}$ENaC after channel activation by CDCA. In contrast, the proportionality coefficient for $\delta\text{N}_{521}\text{C}$ENaC was significantly smaller (0.48 ± 0.01; $p < 0.001$; $N = 3$; $n = 29$). This supports the conclusion that the $\delta\text{N}_{521}\text{C}$ mutation reduces the stimulatory effect of CDCA by more than 50%. In additional experiments, we tested the effect of five other bile acids on $\delta\text{N}_{521}\text{C}$ENaC. Using similar regression analysis as illustrated in Fig. 8A (data not shown), we demonstrated that the $\delta\text{N}_{521}\text{C}$ mutation significantly reduced the stimulatory effects of all bile acids tested (Fig. 8B).

Next, we tested whether substitution of Asn521 by other amino acids also affected the stimulatory effects of bile acids. Substituting Asn521 by alanine appeared to decrease basal $P_o$.
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![Graph A](image)

**FIGURE 8.** Effect of bile acid alone versus combined effect of chymotrypsin and bile acid on wild-type or mutant δβγENaC. A, linear regression analysis of the relative stimulatory effects of CDCA versus chymotrypsin in the presence of CDCA in δβγ- (○) and δβN521Cγ-ENaC (■) expressing oocytes. Each point represents a single measurement (relative increase of \( I_{\text{lim}} \) by chymotrypsin + CDCA versus relative increase of \( I_{\text{lim}} \) by CDCA) from similar experiments as shown in 7, A and B. ■ ■ ■ ■ = mean values with S.E. for δβγ and δβN521Cγ-ENaC, respectively. Calculated linear regression coefficients (\( k \)) are depicted by dashed lines. B, linear regression coefficients (\( k \)) calculated similarly as in A for experiments using the indicated bile acids (CA, t-CA, DCA, t-DCA, CDCA, or t-CDCA) in oocytes expressing wild-type (δβγ) or different δβγ-ENaC mutants: δβN521Cγ-γ, δβN521Aγ-γ, δβN521Sγ-γ, δβN521Dγ-γ and δβN521Cγ-γ (δβN521Cγ-γ (\( k = 5.5; n = 27 - 31; 10 \leq n \leq 38; *** p < 0.001 \) when compared with wild-type δβγ-ENaC (δβγ), n.s., not significantly different when compared with wild-type δβγ-ENaC (δβγ); one-way ANOVA with Bonferroni post hoc test).

because the maximal current reached in the presence of CDCA and chymotrypsin was almost 6-fold larger than the baseline current (Fig. 7C). Under the assumption that the mutant channel reaches a \( P_o \) of almost 1 in the presence of CDCA and chymotrypsin, it can be concluded that the baseline \( P_o \) of the channel containing the βN521A mutation is considerably lower than that of wild-type δβγ-ENaC. This conclusion is consistent with the finding that basal \( I_{\text{lim}} \) in oocytes expressing δβN521Aγ-ENaC was significantly lower than in matched oocytes expressing wild-type δβγ-ENaC (0.28 ± 0.03 \( \mu \)A, \( n = 33 \) versus 0.84 ± 0.08 \( \mu \)A, \( n = 20, N = 2; p < 0.01 \). The lower initial \( P_o \) of δβN521Aγ-ENaC could explain why the relative stimulatory effect of CDCA on the mutant channel was larger than that on the wild-type channel (Fig. 7I). Importantly, the stimulation achieved by CDCA did not reach the level obtained by subsequent exposure to chymotrypsin. Thus, similar to the βN521C mutation, the βN521A mutation also resulted in a reduced stimulatory effect of CDCA on ENaC in the δβγ-configuration (Fig. 8B). In contrast, the mutant channel δβN521Sγ-ENaC behaved like the wild-type channel (Figs. 7, D and I, and 8B), and basal \( I_{\text{lim}} \) of δβN521Sγ-ENaC was similar to that of δβγ-ENaC in matched oocytes (0.81 ± 0.10 \( \mu \)A, \( n = 24 \) versus 0.84 ± 0.08 \( \mu \)A, \( n = 20, N = 2; n.s. \)), arguing against a nonspecific effect of mutating βAsn521. Furthermore, substitution of βAsn521 by aspartate (βN521D) resulted in a large reduction of the stimulatory effect of both CDCA and chymotrypsin (Fig. 7, E and I). The decreased responsiveness of this mutant channel to two different stimuli suggests that introducing a negative charge at this site increased baseline \( P_o \) close to 1. This conclusion is consistent with the finding that basal \( I_{\text{lim}} \) in oocytes expressing δβN521Dγ-ENaC was significantly larger than in matched oocytes expressing wild-type δβγ-ENaC (2.04 ± 0.20 \( \mu \)A, \( n = 23 \) versus 0.84 ± 0.08 \( \mu \)A, \( n = 20, N = 2; p < 0.001 \)). In addition, we introduced a cysteine residue in the neighboring position (δβN522Cγ-ENaC). The mutant δβN522Cγ-ENaC behaved like the wild-type channel in response to CDCA (Figs. 7, F and I, and 8B), supporting the specific functional importance of the position βAsn521 for the interaction of bile acids with the channel in the δβγ-configuration. This interaction may be only partially prevented by mutating βAsn521 to cysteine or alanine, which may explain the incomplete inhibition of the CDCA effect by these mutations. Alternatively, the incomplete inhibition may be due to an interaction of CDCA with additional sites. Candidate sites in the δ- and γ-subunits are δAla527 and γAsn530, respectively, which correspond to βAsn521 in the β-subunit. As stated above, no channel function was observed when δAla527 or γAsn530 were mutated to cysteine. In contrast, functional channel expression was preserved when mutating δAla527 and γAsn530 to asparagine and alanine, respectively. However, in oocytes expressing δA527Nβγ- or δβγN530Sα-ENaC, the stimulatory effect of CDCA was similar to that observed in oocytes expressing wild-type δβγ-ENaC, and an additional stimulation by chymotrypsin was also absent (Figs. 7, G–I, and 8B). These findings do not support the hypothesis that δAla527 or γAsn530 contribute to the functional interaction of bile acids with the channel. However, this possibility and the existence of additional interaction sites cannot be ruled out.

Substitution of Asparagine Residue βAsn521 by Alanine Decreases the Relative Stimulatory Effect of t-DCA on αβγENaC—We wondered whether βAsn521 also plays a role in bile acid-mediated activation of αβγENaC. Co-expression of the βN521A and βN521S with wild-type α- and γ-subunits resulted in measurable ENaC currents, whereas in this configuration, no functional channels were detected with the βN521C subunit. At first inspection, the stimulatory effect of t-DCA on αβN521AγENaC appeared to be similar to that on wild-type αβγENaC (Fig. 9). However, subsequent application of chymotrypsin in the presence of t-DCA revealed a larger additional increase of αβN521AγENaC currents when compared with that of wild-type αβγENaC currents (Fig. 9, B and C). Thus, the increased stimulatory effect of chymotrypsin on αβN521AγENaC after pre-stimulation with t-DCA may be interpreted as a reduced relative stimulatory effect of t-DCA on the mutant channel when compared with its effect on the wild-type
In summary, these findings support the concept that the \(\beta\text{Asn}^{521}\) residue in the degenerin region is involved in mediating the stimulatory effect of bile acids on \(\alpha\beta\gamma\text{ENaC}\) as well as on \(\delta\beta\gamma\text{ENaC}\).

**Discussion**

In this study, we demonstrated that physiologically relevant bile acids activate human ENaC in the \(\alpha\beta\gamma\) and \(\delta\beta\gamma\) configuration. Moreover, we found that substitution of a single amino acid residue within the degenerin region of \(\beta\text{ENaC}\) (Asn\(^{521}\)) significantly reduced this stimulatory effect. This indicates that the degenerin region is critical for the functional interaction of bile acids with ENaC.

To study the mechanism by which bile acids stimulate human ENaC activity, we used outside-out patch clamp recordings. We could demonstrate that t-DCA stimulated human \(\alpha\beta\gamma\text{ENaC}\) by increasing single-channel \(P_o\) without recruiting additional near-silent channels in the patch. Our findings confirm recent results reported for rat \(\alpha\beta\gamma\text{ENaC}\) (34). In outside-out patches, baseline \(P_o\) of \(\delta\beta\gamma\text{ENaC}\) was close to 1 and therefore could not be further stimulated by CDCA. The reason for this high baseline \(P_o\) of \(\delta\beta\gamma\text{ENaC}\) in our patch clamp recordings is presently unknown but is in good agreement with previous findings (22). Importantly, our whole-cell recordings demonstrated that \(\delta\beta\gamma\text{ENaC}\) was activated by bile acids to a similar extent as by chymotrypsin, which is known to increase \(P_o\) of \(\delta\beta\gamma\text{ENaC}\) to about 1 (22). Thus, our findings suggest that the stimulatory effect of bile acids on ENaC in the \(\delta\beta\gamma\) configuration is also mediated by an increase in single-channel \(P_o\).

The increase of ENaC \(P_o\) may be caused by direct interaction of bile acids with a specific binding site of the channel or by changing the plasma membrane properties, thereby modifying the interaction of the channel protein with membrane lipids. Changes in physical properties of the plasma membrane, such as plasma membrane thickness, intrinsic monolayer curvature, or elastic properties of the lipid bilayer, are known to regulate various membrane proteins including ion channels (46). Indeed, it has been proposed that activation of rat bile acid-sensitive ion channel by bile acids is likely to be caused by an alteration of the membrane environment (47).

Interestingly, a significant portion of ENaC has been reported to be associated with lipid rafts, which are thought to be important for channel function and regulation (48–51). In model lipid systems such as liposomes (68) or giant plasma membrane vesicles (52), bile acids bind more efficiently to non-raft (lipid-disordered) than to raft (ordered) membrane fractions. Thus, the ability of bile acids to modify the lipid environment of ENaC localized in lipid rafts may be limited. However, at present, the possibility that bile acids modulate ENaC activity indirectly by modifying the properties of the plasma membrane in the vicinity of the channel cannot be ruled out.

Alternatively, bile acids may interact directly with the channel protein through specific binding sites. Modification of protein function by bile acid binding to specific sites is a known phenomenon. The list of examples includes the specific nuclear receptor farnesoid X receptor (FXR), G protein-coupled receptor TGR5, bile salt export pump (BSEP), and Na\(^+\)/taurocholate co-transporting polypeptide (NTCP) (53). We demonstrated...
that ENaC in the αβγ-configuration is activated by tauro-conjugated bile acids, whereas application of non-conjugated CA and DCA only moderately stimulated αβγENaC and CDCA even had an inhibitory effect. Thus, slight differences in the chemical structure of bile acids are sufficient to modulate the effect of bile acids on αβγENaC. This favors the interpretation that bile acids interact with specific binding sites of the channel protein, which may have a preference for certain types of bile acids. Based on the reported co-crystallization of the detergent maltoside within the degenerin region of ASIC1 (3), we hypothesized that bile acids may interact with the degenerin region of ENaC. Our findings, that maltoside mimicked the effect of bile acids on ENaC and that mutations in the degenerin region (βN521C and βN521A) significantly reduced the stimulatory effect of bile acids on ENaC, strongly support this hypothesis.

The discovery of the functional importance of the degenerin site for channel gating was initially made in the context of identifying MEC-4 and DEG-1 mutations, which cause neurodegeneration in Caenorhabditis elegans (12, 14, 15). The introduction of bulky amino acid residues to homologous sites in other ENaC-degenerin channels mimics the gain-of-function effect of naturally occurring mutations and results in hyperactivity of the mutant channels (13, 37, 38, 54, 55). The gain-of-function effect of degenerin mutations on ENaC can be reproduced by introducing a cysteine residue at the degenerin site of the β-subunit. Subsequent covalent modification of this cysteine residue by sulfhydryl reagents, e.g. MTSET, activates the mutant channel and has been used as a tool to experimentally increase ENaC Popen to close to 1 (1, 10, 13, 41). Under these conditions, MTSET increases Popen of active αβγENaC without recruiting additional near-silent channels (41). Moreover, the stimulatory effect of MTSET on Popen is accompanied by a small reduction in the single-channel current amplitude (1, 10, 13). Interestingly, these effects of MTSET are similar to the bile acid effects on ENaC observed in the present study. In the light of these findings, it is tempting to speculate that MTSET and bile acids share a similar mechanism of action. Thus, binding of bile acids to the degenerin site may stabilize the open state of the ENaC and CDCA can affect δβγENaC in the brain. Our finding that bile acids and the detergent maltoside have similar effects on ENaC raises the possibility that other endogenous amphiphilic substances may modulate ENaC activity in a similar way. Such endogenous substances, capable of binding to the degenerin region of the channel, may act as local modulators of ENaC function in a tissue-specific manner, but they remain to be identified. In conclusion, our results highlight the potential role of the degenerin region as a regulatory site involved in the functional interaction of bile acids and possibly other naturally occurring amphiphilic substances with ENaC.

Experimental Procedures

Materials—The sulfhydryl reagent MTSET was obtained from Biotium (Hayward, CA). Amiloride hydrochloride, sodium chenodeoxycholate and tauro-chenodeoxycholate, sodium deoxycholate and tauro-deoxycholate, sodium taurocholate and tauro-cholate, and α-chymotrypsin type II from bovine pancreas were purchased from Sigma-Aldrich (Taufkirchen, Germany). n-Dodecyl-β-D-maltoside was obtained from Thermo Fisher.

Plasmids—Full-length cDNAs for human α-, β-, and γENaC and for the short isoform of δENaC were kindly provided by H. Cuppens (Leuven, Belgium) and by R. Waldmann (Valbonne, France), respectively. They were subcloned into the pTLN vector (59). Linearized plasmids were used as templates for cRNA synthesis using T7 RNA polymerases (mMESSAGE mACHINE, Ambion, Austin, TX). Mutants in which critical residues in the degenerin region of α-, β-, γ-, and δENaC were individually replaced by cysteine, alanine, serine, aspartate, or asparagine were generated by site-directed mutagenesis (QuikChange II site-directed mutagenesis kit (Stratagene, La Jolla, CA)). Sequences were confirmed by sequence analysis (LGC Genomics, Berlin, Germany).

Isolation of Oocytes and Two-electrode Voltage Clamp Experiments—Defolliculated stage V-VI oocytes were obtained from ovarian lobes of adult female X. laevis in accordance with the principles of German legislation, with approval by the animal welfare officer for the University of Erlangen-Nürnberg, and under the governance of the state veterinary health inspectorate. Animals were anesthetized in 0.2% ethyl 3-aminobenzoate methanesulfonate (MS-222) (Sigma), and ovarian lobes were obtained by a small abdominal incision. Isolation of oocytes and two-electrode voltage clamp experiments were performed essentially as described previously (22, 45, 60–63). Oocytes were injected with cRNA using the same amount of cRNA per ENaC subunit per oocyte in the range of 0.1 to 5 ng. Injected oocytes were incubated in ND96 solution (in mM: 96 NaCl, 2 KCl, 1.8 CaCl2, 1 MgCl2, 5 HEPES, pH 7.4, with Tris) supplemented with 100 units/ml sodium penicillin and 100 μg/ml streptomycin sulfate. Unless stated otherwise, oocytes were studied 48 h after cRNA injection. Ion currents were determined by subtracting the current values recorded in the presence of amiloride (2 and 100 μM for αβγENaC- and δβγENaC-expressing oocytes, respectively) from those recorded in the absence of amiloride.

Single-channel Recordings in Outside-out Patches—Oocytes injected with αβγENaC or δβγENaC cRNA were stored in...
ND96 solution. Single-channel recordings in outside-out membrane patches of ENaC-expressing oocytes were performed 48 h after cRNA injection essentially as described previously (35, 41, 45) using conventional patch clamp technique. Patch pipettes were pulled from borosilicate glass capillaries and had a tip diameter of about 1–1.5 μm after fire polishing. Pipettes were filled with potassium gluconate pipette solution (in mM: 90 potassium gluconate, 5 NaCl, 2 Mg-ATP, 2 EGTA, and 10 HEPES, pH 7.2, with Tris). Seals were routinely formed in a low sodium NMDG-Cl bath solution (in mM: 95 NMDG-Cl, 1 NaCl, 4 KCl, 1 MgCl₂, 1 CaCl₂, 10 HEPES, 7.4 pH, with Tris). In this bath solution, the pipette resistance averaged about 7 megaohms. After seal formation, the NMDG-Cl solution was switched to a NaCl bath solution in which NMDG-Cl (95 mM) was replaced by NaCl (95 mM). For continuous current recordings, the holding potential was set to −70 mV. Using a 3 M KCl flowing boundary electrode, the liquid junction potential occurring at the pipette/NaCl bath junction was measured to be 12 mV (bath-positive) (35). Thus, at a holding potential of −70 mV, the effective trans-patch potential was −82 mV. This value is close to the calculated equilibrium potential of Cl⁻ (E_Cl = −77.4 mV) and K⁺ (E_K = −79.4 mV) under our experimental conditions. Experiments were performed at room temperature (−23 °C). Single-channel current data were initially filtered at 1.25 kHz and sampled at 5 kHz. The current traces were re-filtered at 250 Hz to resolve the single-channel current amplitude (i) and channel activity. The latter was derived from binned amplitude histograms as the product N_π_i (35, 41, 45, 64). The current level at which all channels are closed was determined in the presence of 2 μM amiloride for αβγENaC and of 10 μM amiloride for δβγENaC. The apparent number of active channels (apparent N) in a patch was determined by visual inspection of the current traces. Single-channel data were analyzed using the program Nest-o-Patch written by Dr. V. Nesterov (Institut für Zelluläre und Molekulare Physiologie, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany).

Statistical Methods—Data are presented as mean ± S.E., individual data points, and bar diagrams as appropriate. Statistical significance was assessed by the appropriate version of ANOVA (with Bonferroni post hoc test) or Student’s t test. N indicates the number of different batches of oocytes, and n indicates the number of individual oocytes studied. Statistical and regression analysis was performed using GraphPad Prism 5.04.

Author Contributions—A. I. and A. D. performed the experiments, analyzed the data, and prepared the figures. A. I., A. D., C. K., and S. H. designed the study, interpreted the data and wrote the paper. All authors approved the final version of the manuscript.

Acknowledgments—We thank Prof. Dr. Heinrich Sticht (Division of Bioinformatics, Institute of Biochemistry, Friedrich-Alexander-University Erlangen-Nürnberg, Erlangen, Germany) for helpful discussions and valuable comments. The expert technical assistance of Ralf Rinke is gratefully acknowledged.

References
Activation of Human ENaC by Bile Acids


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