Dual effects of n-alcohols on fluid secretion from guinea pig pancreatic ducts


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ALCOHOL IS THE LEADING CAUSE of acute and chronic pancreatitis, but few studies have succeeded in demonstrating cellular effects of ethanol that directly cause pancreatitis. Most studies have been conducted with acinar cells and the significant effect, such as a sustained increase in intracellular Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]) (6), was observed at a concentration (850 mM) that far exceeded lethal concentrations (>80 mM) of ethanol in humans (16). Furthermore, these effects appear to be mediated by ethanol’s nonoxidative metabolites rather than by ethanol itself (6, 28). Recently, we found that 0.3–30 mM ethanol, relevant to usual levels of alcohol drinking (21), strongly augmented secretin-stimulated fluid secretion from interlobular ducts isolated from the guinea pig pancreas (31). The pancreatic duct system produces a HCO\(_3\)-rich fluid secretion in response to secretin and acetylcholine (ACh) via elevation of intracellular cAMP and [Ca\(^{2+}\)], respectively (3). HCO\(_3\) is secreted into the lumen via apical Cl\(^{-}/\)HCO\(_3\) exchange and the cystic fibrosis transmembrane conductance regulator (CFTR) (3, 15). Water transport via the basolateral and apical water channel (aquaporin-1, AQP1) follows a small osmotic gradient caused by apical HCO\(_3\) transport (11, 18, 31). The augmentation of fluid secretion by ethanol appears to be mediated by the activation of the intracellular cAMP pathway and a transient increase in [Ca\(^{2+}\)]. Because very low concentrations of ethanol quickly and reversibly induced the augmentation, we speculate that ethanol directly affects some ion channels and/or transporters, such as the plasma membrane Ca\(^{2+}\) channel and the CFTR Cl\(^{-}\) channel, rather than altering cellular metabolism (24).

Ethanol produces profound alterations in brain function. There has been a longstanding debate concerning whether alcohols produce their effects by acting on the membrane lipids or proteins of the central nervous system (CNS) neurons (20, 25). The “lipid theory” postulates that alcohols affect primarily membrane fluidity and thereby modify the function of membrane ion channels, receptors, and other proteins. The “protein theory,” on the other hand, proposes that alcohols interact directly with these membrane proteins. Accumulating evidence suggests that proteins are the primary sites of action (25). Although the primary site of action differs between the two theories, both theories attribute the effects of alcohol to alterations in protein function. The CNS effects of alcohols are notably characterized by the cutoff effect: the potency of an alcohol increases with increasing alkyl chain length until a point is reached at which the potency attains a maximum and then decreases or disappears with further increases in chain length (20). In this article, we report a distinct cutoff effect of a series of short-chain n-alcohols on fluid secretion and [Ca\(^{2+}\)], in interlobular ducts isolated from the guinea pig pancreas. Our observations suggest that alcohols strongly affect the function of not only CNS neurons but also nonexcitable epithelial cells.

METHODS

The present study was approved by the Ethical Committee of Nagoya University on Animal Use for Experiments.

Materials and Solutions

Methanol, ethanol, 1-propanol, 1-butanol, ACh, dibutyryl adenosine 3‘,5‘-cyclic monophosphate (DBcAMP), thapsigargin, ethylene glycol.
glycol-bis(β-aminoethyl ether)-N,N',N'-'N'-tetraacetic acid (EGTA), and all other standard laboratory chemicals were of the highest grade available from Sigma (St. Louis, MO). The purities of alcohols were >99.5%. Fura-2 AM (Dojindo Laboratories, Kumamoto, Japan) was dissolved in dimethyl sulfoxide (DMSO), and its loading solution contained 0.01% DMSO. Secretin (Peptide Institute, Minoh, Japan) was dissolved in standard HCO₃⁻-buffered solution containing 0.5% bovine serum albumin (Sigma), and the final concentration of albumin in the bathing solution was 0.01%. The HEPES-buffered solution contained 0.1% DMSO. Secretin (Peptide Institute, Minoh, Japan) was dissolved in standard HCO₃⁻-buffered solution containing 0.5% bovine serum albumin (Sigma), and the final concentration of albumin in the bathing solution was 0.01%. The HEPES-buffered solution contained (in mM) 140 NaCl, 5 KCl, 1 CaCl₂, 1 MgCl₂, 10 d-glucose, and 10 HEPES (~280 mosmol/l) and was equilibrated with 100% O₂.

The standard HCO₃⁻-buffered solution contained (in mM) 115 NaCl, 5 KCl, 1 CaCl₂, 1 MgCl₂, 10 d-glucose, and 25 NaHCO₃ (~280 mosmol/l). The HCO₃⁻-buffered solution with lower [Ca²⁺] (expected to be <1 μM) contained 1 mM CaCl₂ and 3 mM EGTA (17). The Ca²⁺-free, HCO₃⁻-buffered solution contained 5 mM EGTA but no CaCl₂. In these solutions, aliquots of 50 mM Na₂H₂-EGTA solution were added and NaCl concentrations were reduced to maintain the same osmolarity as the standard solution. HCO₃⁻-buffered solutions were equilibrated with 95% O₂-5% CO₂. All solutions were adjusted to pH 7.4 at 37°C with 1 N HCl.

**Isolation and Culture of Interlobular Ducts**

Female Hartley guinea pigs (~350 g) were killed by cervical dislocation. The pancreas was removed, and interlobular ducts (diameter, 100–150 μm) were isolated as described previously (14). The duct segments were cultured at 37°C in 5% CO₂ in air for 3 h, during which time both ends of the interlobular duct segments sealed spontaneously, thus isolating the luminal space from the bathing medium.

**Measurement of the Fluid Secretory Rate**

The fluid secretory rate into the closed luminal space was measured as we described previously (27, 31). The sealed ducts were superfused at 37°C on the stage of an inverted microscope, and the bright-field images were obtained at 1-min intervals using a charge-coupled device camera. The initial values for the length (L₀), diameter (2R₀), and image area (A₀) of the duct lumen were measured in the first image of the series. The initial volume (V₀) of the duct lumen was calculated as πR₀²L₀ assuming cylindrical geometry. The L₀, R₀, and V₀ values of all ducts used for experiments were 315 ± 12 μm, 75 ± 3 μm, and 6.0 ± 0.4 nl, respectively (n = 87; means ± SE). The luminal surface area of the epithelium was assumed to be 2πR₀L₀. In subsequent images of the series, the luminal image area (A) was expressed as relative area (A/A₀). Relative volume (V/V₀) was estimated from relative area using the equation V/V₀ = (A/A₀)²/2. The rate of fluid secretion was calculated at 1-min intervals from the increment in volume and expressed as the secretory rate per unit of luminal area of epithelium (nl·min⁻¹·mm⁻²).

**Measurement of [Ca²⁺].**

[Ca²⁺], was estimated using microfluorometry in duct cells loaded with fura-2 as we described previously (19). The cultured duct segments were incubated for 90 min at room temperature with the fura-2 AM (3 μM). Microfluorometry was performed on a small area of the ductal epithelium containing from three to five cells illuminated alternately at 340 and 380 nm. The fluorescence intensities (F₃₄₀ and F₃₈₀) were measured at 510 nm. Changes in [Ca²⁺], are presented as changes in the F₃₄₀-to-F₃₈₀ fluorescence ratio.

**Statistics**

Data are presented as means ± SE, with n representing the number of ducts. Statistical analysis was performed using Student’s t-test for paired data or ANOVA followed by Tukey’s procedure for multiple comparisons, with P < 0.05 used as the level of significance.

**RESULTS**

**Effects of n-Alcohols on Fluid Secretion**

**Spontaneous (HCO₃⁻ dependent) fluid secretion.** The isolated interlobular ducts secreted little fluid in the absence of HCO₃⁻, i.e., in a HEPES-buffered solution (13). When the ducts were superfused with the standard HCO₃⁻-buffered solution, the fluid secretory rate was 1.01 ± 0.07 nl·min⁻¹·mm⁻² (n = 18; Fig. 1). When 1 mM methanol or ethanol was added to the bath, fluid secretion transiently stopped for a 1-min period but quickly recovered to steady-state levels in the next 1-min period (P < 0.01). Bath application of 1 mM propanol or butanol significantly (P < 0.05) and reversely reduced the spontaneous fluid secretion. A transient cessation in secretion was not observed.

**Secretin (cAMP)-stimulated fluid secretion.** To avoid rupture of the ducts that was sometimes caused by the increased...
luminal pressure due to accumulated fluid secretion within the closed lumen, the total experimental period needed to be <25 min. Therefore, in the following experiments (Figs. 2 and 3), the perfusate was switched from HEPES- to HCO₃⁻-buffered solution when the stimulants were applied. Secretin (0.3 nM) increased the fluid secretory rate from 0 to 1.67 ± 0.01 nl·min⁻¹·mm⁻² (n = 20) within ~5 min, and this rate remained constant for >15 min (Fig. 2). Methanol and ethanol at 1 mM significantly (P < 0.01) and reversibly increased the secretin-stimulated fluid secretion by 41 ± 7% and 85 ± 6%, respectively (n = 5). The augmentation by ethanol was significantly (P < 0.01) greater than that by methanol. Propanol and butanol (1 mM), on the other hand, significantly (P < 0.01) and reversibly reduced the secretin-stimulated fluid secretion by 44 ± 13% and 44 ± 9%, respectively (n = 5). Similarly, DBcAMP (0.5 mM), a membrane-permeable analog of cAMP, increased the fluid secretory rate to 1.49 ± 0.11 nl·min⁻¹·mm⁻² (n = 18). Methanol and ethanol significantly (P < 0.01) increased DBcAMP-stimulated fluid secretion by 40 ± 16% (n = 4) and 57 ± 15% (n = 5), respectively. Propanol and butanol significantly (P < 0.01) reduced secretion by 34 ± 8% (n = 5) and 33 ± 14% (n = 4), respectively.

Fig. 2. Effects of n-alcohols on fluid secretion (means ± SE; n = 5) in secretin-stimulated ducts. Methanol (A), ethanol (B), propanol (C), or butanol (D) at 1 mM was added to the bath during stimulation with 0.3 nM secretin. Note that the perfusate was switched from HEPES- to HCO₃⁻-buffered solution at time 0. *P < 0.05, significant difference from secretory rate before application of n-alcohols.

Fig. 3. Effects of n-alcohols on fluid secretion (means ± SE) in acetylcholine (ACh)-stimulated ducts. Methanol (A; n = 4), ethanol (B; n = 5), propanol (C; n = 5), or butanol (D; n = 4) at 1 mM was added to the bath during stimulation with 1 μM ACh. Note that the perfusate was switched from HEPES- to HCO₃⁻-buffered solution at time 0. *P < 0.05, significant difference from secretory rate before application of n-alcohols.
**ACh-stimulated fluid secretion.** ACh (1 μM) increased the fluid secretory rate to 1.29 ± 0.09 nl·min⁻¹·mm⁻² (n = 18) (Fig. 3). Methanol and ethanol failed to affect ACh-stimulated fluid secretion, but propanol and butanol significantly (P < 0.01) reduced secretion by 46 ± 16% (n = 5) and 48 ± 11% (n = 4), respectively.

**Effects of n-Alcohols on [Ca²⁺]i.**

In the following studies, we used higher concentrations of secretin (1 nM) and ACh (10 μM) than in the above secretory studies to demonstrate their clear effects on [Ca²⁺]i and shorter application periods of alcohols to avoid photobleaching and/or leakage of fura-2. Some of the experiments were repeated under the same protocol used to study fluid secretion (see Fig. 5, E and F, and Fig. 6, E and F).

**Unstimulated ducts.** Methanol and ethanol at 1 mM failed to affect [Ca²⁺]i, while the application of 1 mM propanol or butanol induced a sustained decrease in [Ca²⁺]i (Fig. 4).

**Secretin (cAMP)-stimulated ducts.** When methanol or ethanol was applied during stimulation with 1 nM secretin, [Ca²⁺]i showed a transient increase without a plateau phase (Fig. 5, A and B). To the contrary, propanol and butanol induced a sustained decrease in [Ca²⁺]i that gradually recovered after they were removed from the perfusate phase (Fig. 5, C and D).

In ducts stimulated with 0.3 nM secretin (Fig. 5, E and F), both the stimulatory (ethanol) and inhibitory (propanol) effects were smaller than those in ducts stimulated with 1 nM secretin. After reaching the nadir, [Ca²⁺]i showed a tendency to increase during a 7-min application of propanol and returned to control levels after the removal of propanol (Fig. 5F). During stimulation with DBcAMP (0.5 mM), methanol and ethanol induced a transient increase in [Ca²⁺]i, while propanol and butanol induced a sustained decrease (data not shown).

**ACh-stimulated ducts.** When alcohols were applied during the sustained elevation of [Ca²⁺]i induced by ACh (1 or 10 μM), ethanol and methanol failed to affect [Ca²⁺]i (Fig. 6, A, B, and E). Propanol and butanol induced a reversible decrease in [Ca²⁺]i, which showed a tendency to increase before their removal (Fig. 6, C and D). When propanol was applied during stimulation with 1 μM ACh, [Ca²⁺]i exhibited a more stable decrease and returned to the plateau levels after removal of propanol (Fig. 6F).

**Concentration-Response Relationship**

At 0.01 and 0.1 mM, n-alcohols failed to affect fluid secretion and [Ca²⁺]i in secretin (1 nM)-stimulated ducts (Tables 1 and 2). Both stimulatory (methanol and ethanol) and inhibitory (propanol and butanol) effects on fluid secretion and [Ca²⁺]i appeared at 0.3 mM and peaked at 1 mM. Their effects were either reduced or unchanged at 10 mM.

**Inhibition of Ca²⁺ Entry Pathway**

Under stimulation with secretin, ACh induced a typical peak and plateau response of [Ca²⁺]i (Fig. 7A). The addition of 1 mM propanol induced a sustained decrease in [Ca²⁺]i (Fig. 7B). Propanol completely abolished the [Ca²⁺]i plateau response to ACh, and only the initial transient response remained. The application of 1 μM thapsigargin, an inhibitor of the Ca²⁺-ATPase of the endoplasmic reticulum, caused a sustained elevation in [Ca²⁺]i (Fig. 7C). Propanol inhibited thapsigargin-induced elevation in [Ca²⁺]i. Under stimulation with secretin, propanol inhibited a transient [Ca²⁺]i response to ethanol (Fig. 7D); the peak increase in F₃₄₀/F₃₈₀ ratio was significantly (P < 0.05) decreased from the control of 0.99 ± 0.030 (Fig. 2B) to 0.029 ± 0.015 and decreased the integrated response by 94%.

**Effects of Extracellular Ca²⁺ on Fluid Secretion and [Ca²⁺]i in Secretin-Stimulated Ducts**

When the superfusate was switched from the standard HCO₃⁻-buffered solution to the low-Ca²⁺ solution (1 mM CaCl₂ + 3 mM EGTA) during stimulation with secretin (1 nM), the fluid secretory rate reversibly decreased by 45 ± 11% (n = 5; P < 0.05) (Fig. 8A). When the superfusate was switched to the Ca²⁺-free solution (0 CaCl₂ + 5 mM EGTA), fluid secretion was almost abolished (n = 4; P < 0.01) (Fig. 8B). The inhibition was partially reversible. In the same experimental conditions, [Ca²⁺]i decreased by 0.068 ± 0.028 (Δ ratio) with low Ca²⁺ in the bath (Fig. 8C) and decreased by 0.090 ± 0.024 without Ca²⁺ in the bath (Fig. 8D), respectively (n = 4).

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**Fig. 4.** Effects of n-alcohols on intracellular Ca²⁺ concentration ([Ca²⁺]i) in unstimulated ducts. The closed ducts were superfused with the standard HCO₃⁻-CO₂-buffered solution. Methanol (A), ethanol (B), propanol (C), or butanol (D) at 1 mM was added to the bath as indicated. Changes in fura-2 fluorescence (F₃₄₀ to F₃₈₀) ratio indicate changes in [Ca²⁺]i in pancreatic duct cells. Each trace is representative of four experiments.
DISCUSSION

Dual Actions of n-Alcohols on Pancreatic Duct Cells

In this study, we tested a series of short-chain n-alcohols and found a distinct cutoff point between ethanol (C2) and propa-
nol (C3) in their effects on fluid secretion and [Ca\(^{2+}\)]\(_i\), in guinea pig pancreatic duct cells. This cutoff point for n-alcohols is the shortest that has been reported (20). The actions of methanol on duct cell functions were very similar to those of ethanol (31); both augmented cAMP-mediated fluid secretion and induced a transient increase of [Ca\(^{2+}\)]\(_i\), but failed to affect spontaneous or ACh-stimulated secretion and [Ca\(^{2+}\)]\(_i\). Unexpectedly, propanol (C3) and butanol (C4) showed the opposite effects; both reduced fluid secretion as well as [Ca\(^{2+}\)]\(_i\), regardless of the stimuli used. Both stimulatory and inhibitory effects of n-alcohols were rapid in onset time and disappeared quickly and completely upon removal from the perfusate. The effective concentration ranges (0.3–10 mM) were also very similar among alcohols (Tables 1 and 2). Because appreciable changes in the fluidity of cell membranes occur at 11–44 mM ethanol (4), the observed effects in this study probably were not induced by perturbation of membrane lipids. In addition, the membrane disordering potency of n-alcohol increases logarithmically with the number of methylene groups. Hence the disordering potency of propanol is 3.6 times that of ethanol, and the disordering potency of butanol is 11.9 times that of ethanol (23). If propanol and butanol act via membrane disordering, their effective concentration ranges should be different, i.e., lower for butanol than for methanol, which we never observed. Therefore, it is very likely that they act directly on proteins, but at different sites.

Transient Cessation of Spontaneous Fluid Secretion

The transient cessation of spontaneous fluid secretion by methanol and ethanol (Fig. 1) is most likely due to their osmotic effects until they reach equilibrium with the luminal

Fig. 5. Effects of n-alcohols on [Ca\(^{2+}\)]\(_i\), in secretin-stimu-
lated ducts. Methanol (A), ethanol (B and E), propanol (C and F), or butanol (D) at 1 mM was added to the bath during stimulation with 1 nM (A–D) or 0.3 nM (E and F) of secretin. Each trace is representative of four experiments.
As low as 1 mosmol/l gradient between the lumen and the perfusate was sufficient to completely stop spontaneous fluid secretion from the ducts. The absence of such effects of propanol and butanol is probably because their diffusion rates through the cell membranes are much faster than those of methanol and ethanol; the membrane-buffer partition coefficients are 0.036 for methanol, 0.096 for ethanol, 0.438 for propanol, and 1.52 for butanol (23).

**Augmentation by Methanol and Ethanol**

Because the augmentation of fluid secretion and the [Ca$^{2+}$]$_i$ increase by methanol and ethanol were observed only under cAMP stimulation, both alcohols should act at a point distal to the production of cAMP. Transient elevation of [Ca$^{2+}$]$_i$ by ethanol is probably caused by the activation of plasma membrane Ca$^{2+}$ channels, because the [Ca$^{2+}$]$_i$ increase was abolished by the removal of extracellular Ca$^{2+}$ but not by the depletion of intracellular Ca$^{2+}$ stores with thapsigargin (31). The activation of Ca$^{2+}$ influx is necessary for augmentation because it was completely abolished when changes in [Ca$^{2+}$]$_i$ were buffered with BAPTA (31). Methanol acted on ductal fluid secretion and [Ca$^{2+}$]$_i$ in the same manner (Figs. 1–6), as well as the same concentration range (Tables 1 and 2), as methanol and ethanol; the membrane-buffer partition coefficients are 0.036 for methanol, 0.096 for ethanol, 0.438 for propanol, and 1.52 for butanol (23).

**Table 1. Relationship of n-alcohol concentrations and responses in fluid secretion stimulated with 0.3 nM secretin in isolated pancreatic ducts**

<table>
<thead>
<tr>
<th>n-Alcohol</th>
<th>0.01 mM</th>
<th>0.1 mM</th>
<th>0.3 mM</th>
<th>1 mM</th>
<th>10 mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>0.3±4.0</td>
<td>1.2±5.0</td>
<td>31.0±9.6*</td>
<td>40.9±6.9*</td>
<td>28.4±9.4*</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.5±3.2</td>
<td>1.9±6.0</td>
<td>49.7±9.6*</td>
<td>85.2±6.3*</td>
<td>40.2±11.4*</td>
</tr>
<tr>
<td>Propanol</td>
<td>−2.8±5.9</td>
<td>−3.6±6.2</td>
<td>−19.8±8.2</td>
<td>−44.3±12.7*</td>
<td>−50.0±8.9*</td>
</tr>
<tr>
<td>Butanol</td>
<td>−2.4±5.9</td>
<td>−3.5±6.0</td>
<td>−18.8±8.3</td>
<td>−44.0±9.0*</td>
<td>−49.2±8.9*</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 4 experiments. Data are % increase from secretory rate without alcohol. *P < 0.05, significant difference from control (0 mM).
ethanol. Because they differed only in their potency (methanol < ethanol), they probably acted on the same sites. Possible sites for their actions are a regulatory site for cAMP/protein kinase A of the plasma membrane Ca\textsuperscript{2+} channel and a cAMP-regulated anion channel and/or transporter such as CFTR on the basolateral membrane.

**Inhibition by Propanol and Butanol**

The inhibition of ductal fluid secretion and the reduction of [Ca\textsuperscript{2+}]\textsubscript{i} caused by propanol and butanol under resting conditions were also observed after stimulation with secretin, cAMP, or ACh (Figs. 1–6). The [Ca\textsuperscript{2+}]\textsubscript{i} decrease started immediately after the application of propanol or butanol and reached the nadir within ~3 min. The secretory rate started to decrease after a delay of 2 min but reached the nadir within 2–3 min. Both [Ca\textsuperscript{2+}]\textsubscript{i} and secretion returned to preapplication control levels within ~5 min. The minimal effective concentration of propanol and butanol was 0.3 mM for both fluid secretion and [Ca\textsuperscript{2+}]\textsubscript{i}, and no further reductions were observed at 1–10 mM (Tables 1 and 2). Furthermore, the magnitudes of inhibition were similar with all stimulants tested. These data strongly suggest that reductions of [Ca\textsuperscript{2+}]\textsubscript{i} induced by propanol and butanol are closely related to their inhibitory effects on ductal fluid secretion.

### Table 2. Relationship of n-alcohol concentrations and responses in [Ca\textsuperscript{2+}]\textsubscript{i} stimulated with 1 nM secretin in isolated pancreatic ducts

<table>
<thead>
<tr>
<th>n-Alcohol</th>
<th>0.01 mM</th>
<th>0.1 mM</th>
<th>0.3 mM</th>
<th>1 mM</th>
<th>10 mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>0.001±0.004</td>
<td>0.003±0.003</td>
<td>0.052±0.015</td>
<td>0.122±0.038*</td>
<td>0.041±0.022</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.002±0.003</td>
<td>0.003±0.002</td>
<td>0.045±0.011*</td>
<td>0.096±0.030*</td>
<td>0.038±0.009*</td>
</tr>
<tr>
<td>Propanol</td>
<td>-0.003±0.006</td>
<td>-0.008±0.009</td>
<td>-0.041±0.011*</td>
<td>-0.082±0.022*</td>
<td>-0.088±0.019*</td>
</tr>
<tr>
<td>Butanol</td>
<td>-0.003±0.008</td>
<td>-0.007±0.010</td>
<td>-0.039±0.023</td>
<td>-0.064±0.020*</td>
<td>-0.078±0.025*</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 4 experiments. Data are Δratio compared with data without alcohol. *P < 0.05, significant difference from control (0 mM).

**Propanol and Butanol Inhibit Ca\textsuperscript{2+} Influx**

As in acinar cells (30), ACh induced a biphasic elevation of [Ca\textsuperscript{2+}]\textsubscript{i} in pancreatic duct cells; the initial peak by Ca\textsuperscript{2+} release from intracellular stores was followed by a plateau phase caused by influx of extracellular Ca\textsuperscript{2+} via plasma membrane Ca\textsuperscript{2+} channels (2). The application of propanol or butanol caused a reversible inhibition of the plateau phase (Fig. 6). The prior application of propanol completely abolished the plateau phase Ca\textsuperscript{2+} response to ACh, but not the initial peak response (Fig. 7B), indicating that propanol inhibits Ca\textsuperscript{2+} influx via plasma membrane Ca\textsuperscript{2+} channels. Furthermore, propanol inhibited the elevation of [Ca\textsuperscript{2+}]\textsubscript{i} due to the increased Ca\textsuperscript{2+} influx by thapsigargin (Fig. 7C) as well as ethanol-induced Ca\textsuperscript{2+} entry (Fig. 7D). These inhibitory effects of propanol and butanol are very similar to those of lanthanum, an inhibitor of the plasma membrane Ca\textsuperscript{2+} channels (12). The molecule responsible for Ca\textsuperscript{2+} influx in duct cells, however, has not been identified yet (7), and the exact sites of action of propanol and butanol remain to be studied.

**Ca\textsuperscript{2+} Influx Is Necessary for Ductal Fluid Secretion**

ACh evokes fluid secretion via elevation of [Ca\textsuperscript{2+}]\textsubscript{i} in isolated pancreatic ducts (2); hence propanol and butanol probably inhibited ACh-stimulated fluid secretion by their...
inhibitory effects on the Ca\textsuperscript{2+} influx pathway. The inhibition of secretin- and cAMP-stimulated fluid secretion by these alcohols is rather surprising because cAMP and Ca\textsuperscript{2+} pathways have been considered to be independent of each other in pancreatic duct cells (3). A simultaneous application of secretin and ACh elicits an additive effect of each stimulant alone in guinea pigs (31) but an inhibitory interaction in rats (8). In agreement with previous studies (26), removal of extracellular Ca\textsuperscript{2+} quickly reduced [Ca\textsuperscript{2+}]i (Fig. 8, C and D). Removal of extracellular Ca\textsuperscript{2+} reduced secretin-stimulated fluid secretion by 26% in rat pancreatic ducts (1). In guinea pigs, however, fluid secretion completely ceased in the absence of extracellular Ca\textsuperscript{2+} (Fig. 8B), which indicates that continuous Ca\textsuperscript{2+} influx or a certain level of [Ca\textsuperscript{2+}]i is necessary to maintain secretin-stimulated fluid secretion and [Ca\textsuperscript{2+}]i.

Hypothetical Mechanism for Dual Actions of n-Alcohols

Ligand-gated ion channels and voltage-gated Ca\textsuperscript{2+} channels have been found to be sensitive to alcohols (5, 22). Alcohols exhibit a cutoff effect that is dependent on their alkyl chain length (20), which varies widely (4–13 carbons) among the ion channels. In the present study, the cutoff point was between two and three carbons. The most attractive hypothesis to account for the different cutoff points of alcohols is that their target sites are amphiphilic pockets in the protein structure (9, 10, 29). The binding of alcohols to preformed pockets, one for methanol and ethanol and the other for propanol and butanol, might cause slight rearrangements of certain amino acids that affect the gating of Ca\textsuperscript{2+} channels; the former induces the opening, and the latter induces the closure.

In summary, we have shown that n-alcohols have dual effects on pancreatic ductal fluid secretion, depending on the length of their alkyl chain; methanol and ethanol cause the augmentation, while propanol and butanol cause inhibition. Both stimulatory and inhibitory effects are probably caused by their direct actions on ion channel or transporter proteins rather than by their indirect actions on membrane fluidity. Although the exact molecule remains to be identified, the inhibition of membrane Ca\textsuperscript{2+} channels by propanol and butanol unveils the importance of Ca\textsuperscript{2+} influx in cAMP-mediated fluid secretion. The diverse effects of aliphatic alcohols have been attributed to their CNS-depressant actions or to toxic effects of their metabolites. Our study suggests that these alcohols may also exert their actions on any cell by interacting with preformed pockets on a variety of ion channel or transporter proteins.

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REFERENCES


