CFTR Functions as a Bicarbonate Channel in Pancreatic Duct Cells

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Pancreatic duct epithelium secretes a HCO$_3^-$-rich fluid by a mechanism dependent on cystic fibrosis transmembrane conductance regulator (CFTR) in the apical membrane. However, the exact role of CFTR remains unclear. One possibility is that the HCO$_3^-$ permeability of CFTR provides a pathway for apical HCO$_3^-$ efflux during maximal secretion. We have therefore attempted to measure electrodiffusive fluxes of HCO$_3^-$ induced by changes in membrane potential across the apical membrane of interlobular ducts isolated from the guinea pig pancreas. This was done by recording the changes in intracellular pH (pH$_i$) that occurred in luminally perfused ducts when membrane potential was altered by manipulation of bath K$^+$ concentration. Apical HCO$_3^-$ fluxes activated by cyclic AMP were independent of Cl$^-$ and luminal Na$^+$, and substantially inhibited by the CFTR blocker, CFTRinh-172. Furthermore, comparable HCO$_3^-$ fluxes observed in ducts isolated from wild-type mice were absent in ducts from cystic fibrosis (ΔF) mice. To estimate the HCO$_3^-$ permeability of the apical membrane under physiological conditions, guinea pig ducts were luminally perfused with a solution containing 125 mM HCO$_3^-$ and 24 mM Cl$^-$ in the presence of 5% CO$_2$. From the changes in pH$_i$, membrane potential, and buffering capacity, the flux and electrochemical gradient of HCO$_3^-$ across the apical membrane were determined and used to calculate the HCO$_3^-$ permeability. Our estimate of ~0.1 μm sec$^{-1}$ for the apical HCO$_3^-$ permeability of guinea pig duct cells under these conditions is close to the value required to account for observed rates of HCO$_3^-$ secretion. This suggests that CFTR functions as a HCO$_3^-$ channel in pancreatic duct cells, and that it provides a significant pathway for HCO$_3^-$ transport across the apical membrane.

INTRODUCTION

Pancreatic duct epithelium secretes a HCO$_3^-$-rich ionic fluid that acts as a vehicle for the protein-rich secretion from the acinar cells and serves to raise the pH of the duodenal contents. The ductal system of the human pancreas produces ~2.5 liters of juice per day, the HCO$_3^-$ concentration of which reaches 140 mM at maximal stimulation (Argent et al., 2006). The CFTR, which is located in the apical membrane of the pancreatic duct cells (Crawford et al., 1991; Marino et al., 1991), is thought to play a key role in ductal HCO$_3^-$ secretion. Severe loss of CFTR function due to mutation causes impaired ductal HCO$_3^-$ secretion in cystic fibrosis (Ahmed et al., 2003). Mild dysfunction due to less severe mutations and/or polymorphisms may be responsible for certain cases of idiopathic chronic pancreatitis (Fujiki et al., 2004; Cohn, 2005).

The molecular mechanisms responsible for HCO$_3^-$ uptake across the basolateral membrane of pancreatic duct cells are now well understood. HCO$_3^-$ uptake is mediated both by Na$^+$-HCO$_3^-$ cotransporter (pNBCe1) and, indirectly, by Na$^+$-H$^+$ exchange (NHE1) and H$^+$-ATPase activity, although the relative contributions of these pathways may vary between species (Steward et al., 2005). In the guinea pig, pNBCe1 accounts for ~75% of basolateral HCO$_3^-$ uptake (Ishiguro et al., 1996, 1998). Furthermore, the hyperpolarizing effect of this transporter is important in maintaining the membrane potential required to drive HCO$_3^-$ efflux across the apical membrane.

The mechanism by which HCO$_3^-$ crosses the apical membrane is not so clearly defined. The key transporters are CFTR and a Cl$^-$/HCO$_3^-$ exchanger that is now thought to be a member of the SLC26 family, most probably SLC26A6 (Lohi et al., 2000). The classical view is that CFTR mainly secretes Cl$^-$, having a relatively low permeability to HCO$_3^-$, and HCO$_3^-$ subsequently enters the duct lumen by exchange with Cl$^-$.

This is little doubt that this is the predominant mechanism in species such as the rat and mouse, where the pancreatic duct secretes relatively low concentrations of HCO$_3^-$. However, isolated interlobular ducts from the guinea pig pancreas, like the human pancreas, can secrete HCO$_3^-$ at maximal rates, even when the luminal fluid contains 140 mM HCO$_3^-$. This would be impossible to achieve by 1:1 exchange of...
HCO$_3^-$ for Cl$^-$ because the ionic gradients would favor HCO$_3^-$ reabsorption rather than secretion (Sohma et al., 2000; Steward et al., 2005). Even if the stoichiometry of SLC26A6 was 2HCO$_3^-$:1Cl$^-$, as has been suggested (Ko et al., 2002; Shcheynikov et al., 2006), the exchanger would be operating very close to equilibrium (Steward et al., 2005; Ishiguro et al., 2007b). Given that CFTR appears to develop an increased HCO$_3^-$ permeability under conditions of low extracellular Cl$^-$ (Shcheynikov et al., 2004), it has been suggested that CFTR might become the main pathway for HCO$_3^-$ efflux across the apical membrane during maximal secretion (Steward et al., 2005; Ishiguro et al., 2007b).

Our previous work has shown that the electrochemical driving force for HCO$_3^-$ secretion across the apical membrane remains strong during maximal secretion mainly because of the tight regulation of intracellular pH (pH$_i$) and the hyperpolarizing effect of the basolateral pNBCe1 activity (Ishiguro et al., 2000, 2002b). So it is quite possible that HCO$_3^-$ is secreted largely via a conductive pathway rather than by exchange. Furthermore, the driving force for Cl$^-$, at least in the guinea pig, dwindles to very little because of the cells’ limited capacity for basolateral Cl$^-$ uptake (Ishiguro et al., 2002a; Fernandez-Salazar et al., 2004). It is therefore feasible that CFTR secretes more HCO$_3^-$ than Cl$^-$ under these conditions, even if it remains preferentially permeable to Cl$^-$. Although the electrochemical gradient favors HCO$_3^-$ secretion via a conductive pathway, the plausibility of this model also depends upon the HCO$_3^-$ permeability of the apical membrane being sufficiently large. Measurement of the latter was therefore the principal aim of this study. Interlobular ducts were isolated from the guinea pig pancreas, stimulated with dibutylryl cAMP (dbcAMP), and lumina perfused with 125 mM HCO$_3^-$ and 24 mM Cl$^-$ to replicate the conditions that exist during maximal secretion. Taking advantage of the basolateral localization of K$^+$ channels (Novak and Greger, 1988) and the low paracellular resistance of the ductal epithelium (Novak and Greger, 1991), we have used changes in bath K$^+$ concentration to induce changes in the membrane potential at the apical membrane. From the resulting changes in pH$_i$ we have been able to (1) demonstrate electrodiffusive fluxes of HCO$_3^-$ across the apical membrane, (2) to estimate the HCO$_3^-$ permeability of the apical membrane, and (3) to evaluate the direct contribution of CFTR to HCO$_3^-$ secretion. We conclude that a substantial fraction of the secreted HCO$_3^-$ crosses the apical membrane through CFTR channels rather than by exchange with luminal Cl$^-$. 

**MATERIALS AND METHODS**

This study was approved by the Ethical Committee on Animal Use for Experiment and the Recombinant DNA Experiment Safety Committee of Nagoya University.

**Animals**

Female Hartley guinea pigs (350–450 g) were purchased from Japan SLC. A cystic fibrosis mouse model in which the ΔF508 mutation was introduced into the CFTR gene (ΔF mouse; Zeiher et al., 1995) was purchased from The Jackson Laboratory. The mice were maintained on a standard diet, and genotyping was performed on day 14 postpartum as described previously (Zeng et al., 1997).

**Isolation of Interlobular Ducts**

Animals were killed by cervical dislocation. As described previously (Ishiguro et al., 1996), the pancreas was removed and interlobular ducts (100–150 μm in diameter) were isolated and cultured overnight.

**Microperefusion of the Isolated Interlobular Ducts**

The lumen of each interlobular duct segment was microperefused (Ishiguro et al., 2000). Both ends of the duct were cut open using sharpened needles, and one end was cannulated with concentric holding and perfusion pipettes (Fig. 1 B). The bath and lumen were perfused separately, and the bath was maintained at 37°C.

**Solutions**

The standard (normal-K$^+$) HCO$_3^-$-buffered solution contained (in mM) 35 NaCl, 80 NMDG-Cl, 5 KCl, 1 CaCl$_2$, 1 MgCl$_2$, 10 D-glucose, and 25 NaHCO$_3$, and was equilibrated with 95% O$_2$ plus 5% CO$_2$. The standard (normal-K$^+$) HEPES-buffered solution contained (in mM) 60 NaCl, 80 NMDG-Cl, 5 KCl, 1 CaCl$_2$, 1 MgCl$_2$, 10 D-glucose, and 10 HEPES, and was equilibrated with 100% O$_2$. High-K$^+$ (70 mM) solutions were made by replacing NMDG with K$^+$ so that the Na$^+$ concentration remained constant at 60 mM. Low-K$^+$ (1 mM) solutions were made by replacing K$^+$ with NMDG. The high-HCO$_3^-$ solutions contained 125 mM HCO$_3^-$ and were equilibrated with 95% O$_2$ plus 5% CO$_2$. pH ~8.2. The Na$^+$-free high-HCO$_3^-$ solution was made by replacing Na$^+$ with NMDG. Cl$^-$-free solutions were made by replacing Cl$^-$ with glucuronate. All solutions, apart from the high-HCO$_3^-$ solution, were adjusted to pH 7.4 at 37°C.

**Measurement of pH$_i$**

pH$_i$ in the duct cells was estimated by microfluorometry (Ishiguro et al., 2000) using the pH-sensitive fluorochrome 2’7’-bis(2-carboxyethyl)-5(6)-carboxyfluorescein (BCECF). After cannulating the duct for luminal perfusion, the duct cells were loaded with BCECF by advancing the electrode into the lumen under identical conditions. Apical membrane potential V$_a$ was calculated from the bathing solution. Small regions of the duct epithelium (10–20 cells; Fig. 1 B) were illuminated alternately at excitation wavelengths of 430 and 480 nm. Values of pH$_i$ were calculated (10–20 cells; Fig. 1 B) were illuminated alternately at excitation wavelengths of 430 and 480 nm. Values of pH$_i$ were calculated (10–20 cells; Day 14 postpartum as described previously (Zeng et al., 1997).

**Measurement of Intracellular Potential**

Basolateral membrane potential V$_b$ was measured with respect to the bath by impaling the duct cells with glass microelectrodes (Ishiguro et al., 2002b). Transepithelial potential difference (V$_t$) was measured by advancing the electrode into the lumen under identical conditions. Apical membrane potential V$_a$ was calculated by subtraction (V$_b$–V$_a$).

**Materials**

BCECF-AM and dihydro-4,4’-disothioctyanostilbene-2,2’-disulfonic acid (H$_2$DIDS) were obtained from Invitrogen. dbcAMP was from Sigma-Aldrich. CFTR inh-172 was from EMD.

**Statistics**

Data are presented as the means ± SEM. Tests for statistically significant differences were made with Student’s t test or the Mann-Whitney U test as appropriate.
RESULTS

Electrodiffusive HCO\textsubscript{3}\textsuperscript{-} Fluxes across the Apical Membrane of Guinea Pig Ducts

Initial experiments established whether electrodiffusive transport of HCO\textsubscript{3}\textsuperscript{-} could be detected across the apical membrane of guinea pig interlobular duct cells. The approach was to alter the membrane potential of the cells and record the changes in pH, that resulted from HCO\textsubscript{3}\textsuperscript{-} movements into or out of the cells across the apical membrane. Because the ductal epithelium is categorized as “leaky” (i.e., the paracellular pathway has a low electrical resistance), it was assumed that changes in basolateral membrane potential, induced by varying the bath K\textsuperscript{+} concentration ([K\textsuperscript{+}]\textsubscript{b}), would be replicated at the apical membrane and that the absolute values would differ by no more than a few millivolts (Novak and Greger, 1991).

The conditions used in these experiments are summarized in Fig. 1 A. To minimize the movements of HCO\textsubscript{3}\textsuperscript{-} across the basolateral membrane, the bath was perfused with a HCO\textsubscript{3}\textsuperscript{-}-free, HEPES-buffered solution. This also contained 0.5 mM H\textsubscript{2}DIDS to inhibit HCO\textsubscript{3}\textsuperscript{-} efflux via the basolateral Na\textsuperscript{+}-HCO\textsubscript{3}\textsuperscript{-} cotransporter and Cl\textsuperscript{-}-HCO\textsubscript{3}\textsuperscript{-} exchanger (Ishiguro et al., 2000, 2002a). The concentrations of Na\textsuperscript{+} in the bath and luminal solutions were kept constant at 60 mM throughout these experiments, and [K\textsuperscript{+}]\textsubscript{b} was varied (1, 5, or 70 mM) by substitution with the impermeant organic cation NMDG. Only the luminal solution contained HCO\textsubscript{3}\textsuperscript{-}; therefore, any changes that occurred in pH\textsubscript{i} should largely reflect HCO\textsubscript{3}\textsuperscript{-} movements across the apical membrane.

Representative traces from these experiments are shown in Fig. 1 (C and D). Initially, both bath and lumen were perfused with the standard (normal-K\textsuperscript{+}) HEPES-buffered solution. To simulate the high luminal HCO\textsubscript{3}\textsuperscript{-} and low luminal Cl\textsuperscript{-} concentrations that exist in the ducts under physiological conditions, the luminal solution was switched after 3 min to one containing 125 mM HCO\textsubscript{3}\textsuperscript{-} and 24 mM Cl\textsuperscript{-} and equilibrated with 5% CO\textsubscript{2}.

As described previously (Ishiguro et al., 2000), pH\textsubscript{i} fell by almost 1 pH unit (Fig. 1 C) due to CO\textsubscript{2} diffusion into the cells, and it showed no sign of recovery, despite the presence of 125 mM HCO\textsubscript{3}\textsuperscript{-} in the lumen. When [K\textsuperscript{+}]\textsubscript{b} was raised from 5 to 70 mM to depolarize the cells, a maneuver that would be expected to favor HCO\textsubscript{3}\textsuperscript{-} entry
from the lumen, pH increased only slightly (0.10 ± 0.02; n = 4) in these unstimulated ducts. However, when the membrane permeant cAMP analogue dbcAMP (0.5 mM) was added to the bath perfusate to stimulate secretion, the increase in pH accelerated dramatically (Fig. 1 C). When [K']b was subsequently restored to 5 mM, pH also fell rapidly.

In experiments of the type shown in Fig. 1 D, the ducts were stimulated continuously with dbcAMP. When [K']b was switched from 5 to 1 mM to hyperpolarize the cells, pH quickly decreased from 6.83 ± 0.11 (n = 4) to 6.72 ± 0.09 (P < 0.05; paired Student’s t test). It then increased steadily when [K']b was raised to 70 mM, reaching 7.32 ± 0.09 (P < 0.01) after 7 min. Thus, depolarization and hyperpolarization caused increases and decreases in pH, respectively. These changes are consistent with HCO₃⁻ moving across the apical membrane according to its electrochemical gradient via a HCO₃⁻ conductance activated by intracellular cAMP.

Cl⁻ and Na⁺ Dependence of Apical HCO₃⁻ Fluxes in Guinea Pig Ducts

Electrodiffusion through an anion channel such as CFTR provides one possible explanation for these results. However, alternative pathways might account for membrane potential–induced HCO₃⁻ movements across the apical membrane. These include electrogenic Na⁺-nHCO₃⁻ cotransporters and electrogenic SLC26 transporters that mediate Cl⁻-nHCO₃⁻ exchange, such as SLC26A6 (Ko et al., 2002; Shcheynikov et al., 2006). To evaluate their contribution, we next examined whether the apical fluxes of HCO₃⁻ induced by membrane potential changes were dependent on the presence of Cl⁻ (Fig. 2 A) or luminal Na⁺ (Fig. 2 B).

In the Cl⁻-free experiments, such as the one shown in Fig. 2 A, the bath and lumen of ducts stimulated with dbcAMP were initially perfused for 30 min with Cl⁻-free, HEPES-buffered solution (normal-K'). The expectation was that Cl⁻ would leave the cells via activated CFTR channels, and that the intracellular Cl⁻ concentration ([Cl⁻]i) would be close to zero by the time the experiment was begun. As before, switching the luminal solution to the high-HCO₃⁻, Cl⁻-free solution (0 mM Cl⁻, 125 mM HCO₃⁻, 5% CO₂) caused pH to fall rapidly as a result of CO₂ entry into the cells (Fig. 2 A). When [K']b was reduced from 5 to 1 mM and then raised to 70 mM, with dbcAMP present throughout, pH decreased from 7.15 ± 0.06 (n = 4) to 7.06 ± 0.07 and then increased steadily, reaching 7.54 ± 0.16 after 8 min. These results are very similar to those observed in the presence of Cl⁻ (Fig. 1 D), which suggests that electrogenic Cl⁻-nHCO₃⁻ exchange does not contribute significantly to the observed fluxes of HCO₃⁻ across the apical membrane under these conditions.

To examine the Na⁺ dependence of the apical HCO₃⁻ fluxes, all of the Na⁺ in the luminal solution was replaced with NMDG, while the bath Na⁺ concentration remained at 60 mM. In all other respects the protocol was the same as in Figs. 1 D and 2 A, with 125 mM HCO₃⁻ in the lumen and continuous stimulation applied with dbcAMP. When [K']b was raised from 1 to 70 mM, pH rose steadily as before, increasing from 6.96 ± 0.08 (n = 4) to 7.36 ± 0.07 after 8 min. Because the rate of increase in pH was unaffected by the presence or absence of luminal Na⁺, we conclude that electrogenic Na⁺-nHCO₃⁻ cotransport does not contribute significantly to the depolarization-evoked influx of HCO₃⁻ across the apical membrane.

Collectively, these data suggest that the movements of HCO₃⁻ that result from manipulation of the membrane...

Figure 2. Cl⁻ and Na⁺ dependence of HCO₃⁻ fluxes across the apical membrane of guinea pig pancreatic ducts. (A) Membrane potential–evoked changes in pH in the absence of Cl⁻. To deplete intracellular Cl⁻, the bath and lumen were perfused with the Cl⁻-free, HEPES-buffered solution in the presence of dbcAMP for 30 min before the measurements. Experimental conditions were similar to those in Fig. 1 D, but with Cl⁻ replaced by glucuronate in both the bath and luminal perfusates. Representative of four experiments. (B) Membrane potential–evoked changes in pH in the absence of luminal Na⁺. Experiments were similar to those shown in Fig. 1, but with Na⁺ replaced by NMDG in the luminal perfusate. Representative of four experiments.
potential are mediated by a cAMP-activated HCO₃⁻ conductance in the apical membrane.

**Effect of CFTRinh-172 on Apical HCO₃⁻ Fluxes in Guinea Pig Ducts**

To explore the possibility that the apical HCO₃⁻ conductance in stimulated guinea pig ducts is due to the presence of CFTR, we next tested the effect of adding the selective blocker CFTRinh-172 to the luminal perfusate (Fig. 3). The experimental conditions and protocol were otherwise similar to those used in the experiments shown in Fig. 1. 2 min after applying 5 μM CFTRinh-172 to the apical membrane, the rise in pH, evoked by switching [K⁺]ᵢ from 1 to 70 mM (Fig. 3 A) was significantly slower than in the absence of the blocker. The rate of increase in pH was reduced from 0.158 ± 0.030 pH units min⁻¹ (n = 6) to 0.066 ± 0.023 pH units min⁻¹ (n = 6; P < 0.05), representing a mean inhibition of 61 ± 7% in the presence of CFTRinh-172.

Furthermore, when CFTRinh-172 was removed from the luminal perfusate during basolateral exposure to 70 mM K⁺ (Fig. 3 B), the increase in pH accelerated as the block was reversed. These results support the idea that much of the apical membrane HCO₃⁻ conductance is carried by CFTR.

**Apical HCO₃⁻ Fluxes in Ducts Isolated from Normal and Cystic Fibrosis Mice**

As a further test of this hypothesis, we performed a small number of similar experiments on interlobular ducts isolated from a cystic fibrosis mouse model (ΔF) in which the ΔF508 mutation has been introduced into the CFTR gene. Experiments were performed in the absence of Cl⁻ to eliminate any possible contribution from apical anion exchangers, and the protocol was similar to that used in Fig. 2 A. The bath was perfused with a Cl⁻- and HCO₃⁻-free, HEPES-buffered solution containing H₂DIDS and dbcAMP, and the lumen was perfused with a high-HCO₃⁻, Cl⁻-free solution (0 mM Cl⁻, 125 mM HCO₃⁻, 5% CO₂).

In ducts isolated from wild-type mice, membrane hyperpolarization and depolarization evoked by lowering and raising [K⁺]ᵢ caused decreases and increases in pHᵢ (Fig. 4 A), which were similar to those observed in the guinea pig ducts. In ducts isolated from the ΔF mice (Fig. 4 B), however, these changes in pHᵢ were almost entirely abolished. This result strongly supports the conclusion that, in mice at least, the electrodiffusive fluxes of HCO₃⁻ that we have observed across the apical membrane are carried largely by CFTR.

**Estimation of the Apical HCO₃⁻ Permeability of Guinea Pig Ducts**

Our next task was to determine whether the apical HCO₃⁻ permeability would be sufficient to account for the rates of HCO₃⁻ secretion that are observed in isolated guinea pig ducts. For these experiments, the bath perfusate contained 25 mM HCO₃⁻ so that, like the luminal perfusate, it could be equilibrated with 5% CO₂. It was important that the luminal and bath pCO₂ values, and therefore the intracellular pCO₂, were the same because a value for the latter is required (1) to calculate [HCO₃⁻]ᵢ from pHᵢ and (2) to determine the intracellular buffering capacity. Including 25 mM HCO₃⁻ in the bath perfusate required the additional, but justifiable, assumption that HCO₃⁻ entry across the basolateral membrane would be adequately blocked by the H₂DIDS in the bath perfusate.

As before, the lumen was perfused with the high-HCO₃⁻ solution (24 mM Cl⁻, 125 mM HCO₃⁻, 5% CO₂),...
Pancreatic duct epithelium is believed to be a low-resistance epithelium (Novak and Greger, 1991), so the apical membrane potential $V_a$, the critical value required for the calculation of apical $\text{HCO}_3^-$ permeability, would be expected to lie close to $V_b$. However, measurements of the transepithelial potential difference $V_t$, under the conditions of these experiments, revealed that there was a small difference and that it varied with $[\text{K}^+]_B$ (Fig. 5 C). Mean values of $V_t$ (lumen relative to bath) were $1.7\pm0.1\ (n=8)$, $3.5\pm0.1\ (n=12)$, and $4.1\pm0.2\ \text{mV}\ (n=6)$ in 70, 5, and 1 mM K$^+$, respectively. These, together with the corresponding mean values for $V_b$, were used to calculate best estimates of $V_a$, which were $37$, $46$, and $55\ \text{mV}$, respectively.

Changes in $\text{pH}_i$ were measured under exactly the same experimental conditions. As $V_a$ became depolarized or hyperpolarized as a result of the step changes in $[\text{K}^+]_B$, $\text{pH}_i$ increased or decreased accordingly (Fig. 5 D). The steady-state $\text{pH}_i$ values that were approached when $[\text{K}^+]_B$ was stepped between 70, 5, and 1 mM were $7.34\pm0.05\ (n=8)$, $7.18\pm0.02\ (n=5)$, and $7.07\pm0.03\ (n=7)$, respectively. These lie reasonably close to the values that would be predicted (7.45, 7.30, and 7.15) if $\text{HCO}_3^-$ was distributed at electrochemical equilibrium with measured membrane potential values.

The rate of change of $\text{pH}_i$ ($\frac{dpH_i}{dt}$) during these transitions was calculated by linear regression at 1-min intervals (Fig. 6 A). At each time point, the $\text{HCO}_3^-$ flux across the apical membrane, $J_{\text{HCO}_3^-}$, was calculated from $\frac{dpH_i}{dt}$ using the following expression:

$$J_{\text{HCO}_3^-} = \frac{dpH_i}{dt} \cdot \beta \cdot h,$$

where $\beta$ is the total intracellular buffering capacity (values from Szalmay et al., 2001), and $h$ is the volume of the epithelium per unit area. Assuming that the volume of the lateral intercellular spaces is negligible, the epithelial volume per unit area is equivalent to the cell height, which was estimated to be 10 $\mu$m (Argent et al., 1986; Arkle et al., 1986).

The apical $\text{HCO}_3^-$ permeability $P_{\text{HCO}_3^-}$ was then calculated from each value of $J_{\text{HCO}_3^-}$ on the assumption that the apical $\text{HCO}_3^-$ flux obeys the Goldman-Hodgkin-Katz equation:

$$J_{\text{HCO}_3^-} = -P_{\text{HCO}_3^-} \frac{zF}{RT} \left[ \frac{[\text{HCO}_3^-]_l - [\text{HCO}_3^-]_i \exp \left( \frac{zFV_a}{RT} \right)}{1 - \exp \left( \frac{zFV_a}{RT} \right)} \right],$$

where $z$, $F$, $R$, and $T$ have their usual meaning. The intracellular $\text{HCO}_3^-$ concentration ([$\text{HCO}_3^-$]) was calculated from $\text{pH}_i$, assuming that the intracellular pCO$_2$ was 38 mmHg, the intracellular CO$_2$ solubility was 0.0316 mM mmHg$^{-1}$, and the effective $pK_a$ for $\text{HCO}_3^-$/CO$_2$ was 6.03 (Edsall and Wyman, 1958). The luminal $\text{HCO}_3^-$...
microelectrode recordings (e.g., Fig. 5 B). In the bottom of Fig. 6 C, the apical fluxes of HCO$_3^-$ and the consequent changes in pH$_i$ have been calculated in 1-s steps for pHCO$_3^-$ values of 0.05, 0.1, and 0.2 μm sec$^{-1}$. Comparing the experimental data with the predicted changes, it is clear that the initial rise in pH$_i$, due to HCO$_3^-$ influx when V$_a$ depolarizes, is consistent with a pHCO$_3^-$ value of 0.1 μm sec$^{-1}$. Thereafter, pH$_i$ increases more slowly than predicted. The initial fall in pH$_i$, due to HCO$_3^-$ efflux when V$_a$ repolarizes to 55 mV (1 mM K$^+$), is also fitted well by assuming a pHCO$_3^-$ value of 0.1 μm sec$^{-1}$, but pH$_i$ appears to approach a slightly lower value than predicted.

**DISCUSSION**

The aim of this study was to measure voltage-driven fluxes of HCO$_3^-$ through conductive pathways in the apical membrane of guinea pig duct cells. Using these data to estimate the HCO$_3^-$ permeability of the apical membrane, we hoped to find out how much of the HCO$_3^-$ secretion that occurs under physiological conditions is
mediated directly by CFTR rather than by an associated anion exchanger.

To eliminate HCO₃⁻ movements via other pathways, the HCO₃⁻ transporters present in the basolateral membrane (pNBCe1 and AE2) were blocked throughout these experiments with H₂DIDS. Membrane potential was altered by manipulation of basolateral K⁺ concentration, and care was taken to keep extracellular Na⁺ constant at 60 mM. What we believe to be electrodiffusive fluxes of HCO₃⁻ across the apical membrane were detected as increases and decreases in pH₁ after depolarization and hyperpolarization. As [K⁺]₀ was stepped between 1, 5, and 70 mM, the apical membrane potential of the duct cells moved swiftly between −55, −46, and −37 mV, respectively. The corresponding changes in pH₁ were slower, but in each case pH₁ moved toward the steady-state value (7.15, 7.30, or 7.45) that would be expected if HCO₃⁻ redistributed itself passively across the apical membrane according to the new membrane potential. Furthermore, we observed that the changes in pH₁ (1) were stimulated by cAMP, (2) were not dependent on the presence of Cl⁻, (3) were not dependent on luminal Na⁺, (4) were significantly blocked by luminal CFTRinh-172, and (5) were absent in ducts isolated from ΔF mice that lacked functional CFTR.

The most plausible explanation for these results is that raising or lowering membrane potential leads to electrodiffusive movements of HCO₃⁻ across the apical membrane via a conductive pathway, most probably CFTR. Because the high luminal HCO₃⁻ and low luminal Cl⁻ concentrations chosen for these experiments closely resemble those that exist during maximal stimulation in vivo, we believe that CFTR, acting as a HCO₃⁻ channel, makes a significant direct contribution to the secretion of HCO₃⁻ by the pancreatic duct epithelium.

**Estimation of Apical HCO₃⁻ Permeability**

To estimate the direct contribution of CFTR to HCO₃⁻ secretion, we attempted to measure the HCO₃⁻ permeability of the apical membrane under conditions as close as possible to physiological. Our previous work had shown that there is a substantial driving force for electrodiffusive HCO₃⁻ efflux from the cells during maximal stimulation. The aim here was to determine whether the HCO₃⁻ permeability of the apical CFTR channels was sufficient to make a significant contribution to the total secretory flux of HCO₃⁻.

In these experiments, apical HCO₃⁻ permeability was estimated from the measured HCO₃⁻ fluxes and the corresponding driving forces when the membrane...
potential was stepped between different values. In each experiment, the HCO₃⁻ flux was estimated at a series of time points from the rate of change of pHᵢ and the buffering capacity of the cytoplasm. The electrochemical gradient was calculated at each time point from the current pHᵢ value and the membrane potential, which was measured in a parallel series of experiments.

Most of our individual estimates of P_{HCO₃} lie between 0.02 and 0.2 μm s⁻¹, with mean values of around 0.1 μm s⁻¹ for both influx and efflux (Fig. 6 B). An alternative, curve-fitting approach also suggests that the value is most likely to be around 0.1 μm s⁻¹. Before drawing any conclusions from these values, it is important to consider some of the possible sources of error and some of the assumptions that have been made in performing the calculations.

1. Other Acid/Base Transporters. In our calculations, we have assumed that the changes in pHᵢ evoked by alterations in membrane potential were due solely to electro-diffusive HCO₃⁻ movements across the apical membrane via a conductive pathway. In other words, we believe that the chosen experimental conditions eliminated any significant contributions from other H⁺ or HCO₃⁻ transporters. Certainly the H₂DIDS in the bath solution would have adequately blocked HCO₃⁻ influx or efflux via the basolateral pNBCe1 and anion exchanger (Ishiguro et al., 2000, 2002a), but the basolateral NHE1 would still have been active in these experiments. This would not have had much effect on pHᵢ changes at or above normal values, but it would have become increasingly active when pHᵢ dropped to lower values. Thus, in the case where Vₛ was hyperpolarized by switching [K⁺]ₒ to 1 mM, the pHᵢ drop due to HCO₃⁻ efflux could have been partially offset by increased H⁺ extrusion via NHE1. This in turn would have led to underestimation of P_{HCO₃}.

However, we have noted previously that NHE1 activity is quite low in stimulated guinea pig duct cells (Ishiguro et al., 1996), and the fact that pHᵢ readily approached the equilibrium value for HCO₃⁻ (7.15) at −55 mV suggests that the contribution of NHE1 was minimal in these experiments.

The apical Cl⁻/HCO₃⁻ exchanger would have also remained active in these experiments, although the high luminal HCO₃⁻ and low luminal Cl⁻ concentrations would have ensured that it was very close to equilibrium. Furthermore, an electrically neutral exchanger would not contribute directly to pHᵢ changes induced by hyper- or depolarization. However, there is strong evidence to suggest that the apical anion exchanger in pancreatic duct cells is SLC26A6 (Lohi et al., 2000; Ishiguro et al., 2007b), and there are some indications to suggest that it may be electrogenic, mediating a 2:1 exchange of intracellular HCO₃⁻ for extracellular Cl⁻ (Ko et al., 2002; Shcheynikov et al., 2006). On the other hand, there may be species differences in stoichiometry, and there are undoubtedly some discrepancies in the literature (Chernova et al., 2005). It is also not clear whether a 2HCO₃⁻:1Cl⁻ stoichiometry would remain the same when the transporter reverses. Nonetheless, we have to consider the possibility that an electrogenic exchanger responded to the changes in membrane potential that were used in these experiments.

If HCO₃⁻ and Cl⁻ were individually at equilibrium in the steady states approached in these experiments, it can be shown that a 2HCO₃⁻:1Cl⁻ exchanger would also be at equilibrium, as would a 1:1 neutral exchanger. However, suddenly changing Vₛ would immediately affect the 2:1 exchanger, but not the 1:1 exchanger. Depolarization would favor HCO₃⁻ influx via a 2:1 exchanger, thus adding to the HCO₃⁻ influx via CFTR, and hyperpolarization would favor HCO₃⁻ efflux. Significant fluxes of this kind could have led to overestimation of P_{HCO₃} in our experiments.

Our reasons for concluding that the contribution of a 2:1 exchanger is small are (1) the minimal change in voltage-driven HCO₃⁻ fluxes that we observed in Cl⁻ free conditions (Fig. 2 A) and (2) the 60% inhibition of HCO₃⁻ entry observed in the presence of CFTR inh-172 (Fig. 3). Given that CFTR inh-172 may not achieve a complete block of CFTR after 2 min of exposure at this concentration (Wang et al., 2006; Tang et al., 2008), the figure of 60% must be viewed as a minimum estimate of the fraction of the electrodiffusive HCO₃⁻ flux that was mediated by CFTR.

2. Cell Volume. To extract HCO₃⁻ flux data from changes in pHᵢ, one needs to know both the volume of the cells and the buffering capacity of the cytoplasm. Because our fluxes were calculated per unit area of epithelium, the cell volume per unit area is sufficient, and this is well approximated by the cell height if the lateral intercellular spaces are small. This tends to be the case in secretory epithelia, and the assumption is supported by electron micrographs of interlobular ducts from several species (Egerbacher and Bock, 1997). However, to our knowledge, there are no published values for cell height in any species, and our assumed value of 10 μm is based on visual inspection of published light micrographs of rat ducts (Argent et al., 1986; Arkle et al., 1986) and our own light microscope images of isolated guinea pig ducts. There could therefore be a significant error in this parameter value. If cell height is actually >10 μm, P_{HCO₃} will have been underestimated and, if <10 μm, it will have been overestimated.

We are also assuming that this is the correct value for cell volume under the slightly artificial conditions of these experiments. Cell volume in secretory epithelia is tightly linked to intracellular Cl⁻ content (e.g., Foskett, 1990), so the combination of a high apical Cl⁻ conductance (due to activated CFTR) and low luminal Cl⁻ concentration (24 mM) could have resulted in significant...
Cl− loss and cell shrinkage even in the baseline condition for these experiments, particularly with the basolateral transporters disabled. More significantly, the hyperpolarization induced by lowering [K+]b could have resulted in a further loss of K+ and Cl− from the cell and therefore further cell shrinkage. Conversely, there could have been a net gain of K+ and Cl−, and cell swelling when [K+]b was raised.

3. Buffering Capacity. Calculation of the apical HCO3− fluxes also requires knowledge of the buffering capacity of the cytoplasm and its dependence on pH. The values used here were based on a quadratic function fitted to individual estimates of intrinsic buffering capacity that were obtained under slightly different experimental conditions and which showed a significant degree of scatter (Szalmay et al., 2001). The level of uncertainty in βi could be as large as ±50%, which would have had a comparable effect on our estimates of P[HCO3].

The situation is complicated further by the fact that the buffering capacity would have changed as a result of any osmotic swelling or shrinkage of the cells that occurred when [K+]b was altered. For example, cell shrinkage would cause the concentration of macromolecular buffering sites and impermeant buffers to increase, thereby raising the intrinsic component of βi. P[HCO3] might therefore be underestimated; however, the increase in buffering capacity would be offset by the corresponding decrease in cell volume. In other words, the product βi · h in Eq. 1 would remain largely unchanged, and this would not introduce any additional error into the calculation of P[HCO3].

4. pH Calibration. Conversion of BCECF fluorescence ratios to pH values was based here on calibration data obtained using nigericin (a K+/H+ antiporter) and pH calibration solutions with high K+ concentrations to clamp pHt to known values. Numerous studies have shown that other calibration methods can yield slightly differing results (e.g., Eisner et al., 1989; Hegyi et al., 2004; Taylor et al., 2006). Consequently, there is the possibility that pHt may have been systematically over- or underestimated by as much as 0.1 pH units in these experiments, which could also have led to sizeable errors in estimating P[HCO3]. On the other hand, the fact that the steady-state pHt values approached at the three different Vt values were close to those predicted for HCO3− equilibrium argues against there being a systematic calibration error of this kind.

Contribution of CFTR to Apical HCO3− Secretion

Clearly, there is a considerable margin of uncertainty in our estimate of P[HCO3]. However, it is probably safe to say that P[HCO3] lies between 0.05 and 0.2 μm s−1. Because this may be the first study to estimate absolute, rather than relative, HCO3− permeability in native epithelium, it is difficult to make comparisons with previous work. A P[HCO3] value of 0.1 μm s−1 under the conditions of these experiments would be equivalent to a HCO3− conductance of around 2 mS cm−2 (assuming a Goldman-Hodgkin-Katz model for channel permeation), which is similar to estimates of apical HCO3− conductance in the CFTR-expressing Calu-3 cell line (1.1 mS cm−2; Illek et al., 1999). Others have estimated apical HCO3− permeability in bovine corneal endothelium (Bonanno et al., 1999) and guinea pig colon (Endeward and Gros, 2005), but unfortunately without taking into account the effects of membrane potential and/or the contribution of anion exchangers.

To put our estimate of P[HCO3] into context with regard to ductal secretion in the pancreas, we return to a calculation that we published previously (Ishiguro et al., 2002b). Stimulated interlobular ducts from guinea pig have been shown to secrete HCO3− at a rate of ~0.5 nmol sec−1 cm−2 (Ishiguro et al., 1998) under conditions similar to those used in the present study. (Because the duct lumen was not perfused in those experiments, we have to bear in mind the possibility that perfusion may influence secretory rate.) We also know the electrochemical gradient for HCO3− from measurements of intracellular HCO3− concentration (20 mM) and membrane potential (−60 mV). It is therefore possible to calculate the apical HCO3− permeability that would be required for all of the secreted HCO3− to cross the apical membrane via a conductive pathway. The figure we obtained was 0.25 μm sec−1 (Ishiguro et al., 2002b), so our estimate of 0.05–0.2 μm sec−1 for P[HCO3] in the present study is clearly of the right order of magnitude. Given the degree of uncertainty in this value, it would be dangerous to put a precise figure on the fraction of the secreted HCO3− that crosses the apical membrane via a conductive pathway. However, there are good reasons for supposing that it is at least one half of the total HCO3− flux, and it may be considerably more. Moreover, there is strong evidence to suggest that it is mediated directly by CFTR.

CFTR has not previously been thought to provide a major route for HCO3− secretion in the pancreatic duct. This is because estimates of the P[HCO3]/P[G3] ratio (0.2–0.5; Poulsen et al., 1994; Linsdell et al., 1997; Illek et al., 1999; O’Reilly et al., 2000) were considered to be too low, and it was expected that the secretion of Cl− would greatly exceed that of HCO3−. The problem with the alternative hypothesis, namely that HCO3− would be secreted predominantly by exchange with luminal Cl−, was that a neutral HCO3−:Cl− exchanger would reverse and reabsorb HCO3− during maximal secretion when the luminal HCO3− concentration is ~140 mM. The discovery that the apical anion exchanger is SLC26A6 and that it probably operates electrogenically with a 2HCO3−:1Cl− stoichiometry may prove to be very important. With a
2:1 stoichiometry, the exchanger would be very close to equilibrium when the luminal HCO$_3^-$ concentration reaches 140 mM, but it could nonetheless play a significant role, particularly if the majority of the HCO$_3^-$ is secreted via a conductive pathway (Steward et al., 2005; Ishiguro et al., 2007b). Studies of ductal function in slc26a6-null mice (a species which unfortunately secretes rather little HCO$_3^-$) have so far yielded conflicting and inconclusive results (Wang et al., 2006; Ishiguro et al., 2007a).

The idea that CFTR provides a significant conductive pathway for HCO$_3^-$ secretion is supported by several observations. It is now known that the anion selectivity of CFTR is regulated by both intracellular and extracellular factors (O’Reilly et al., 2000; Reddy and Quinton, 2005). In particular, low extracellular Cl$^-$ concentrations, as are found in the duct lumen during maximal secretion, have been shown to increase the permeability of CFTR to HCO$_3^-$ relative to Cl$^-$ (Scheynikov et al., 2004; Wright et al., 2004), although this interpretation has recently been challenged (Tang et al., 2008). This effect, combined with a fall in the driving force for Cl$^-$ secretion (owing to the limited capacity of the basolateral Cl$^-$ uptake pathways; Fernandez-Salazar et al., 2004) would tend to favor HCO$_3^-$ rather than Cl$^-$ efflux via CFTR during maximal secretion. A similar conclusion has been drawn previously both in experimental studies of Calu-3 airway epithelial cells (Devor et al., 1999) and in computational modeling studies of the pancreatic duct (Sohma et al., 2000; Whitcomb and Ermentrout, 2004).

In summary, we have demonstrated voltage-driven fluxes of HCO$_3^-$ across the apical membrane of pancreatic duct cells that are not dependent on the presence of Cl$^-$ or luminal Na$^+$, are largely blocked by CFTR$_{ab}$, and are absent in ducts isolated from ΔF mice. Our estimate of $\sim$0.1 μm sec$^{-1}$ for the apical HCO$_3^-$ permeability of guinea pig duct cells under physiological conditions is close to the value required to account for the observed rate of HCO$_3^-$ secretion. We therefore conclude that a significant fraction of the secreted HCO$_3^-$ enters the ductal lumen via CFTR. It seems likely that the remainder is secreted by a 2HCO$_3^-$:1Cl$^-$ exchanger (SLC26A6) operating close to equilibrium.

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