Immunocytochemical localization of Na\(^{+}\)-HCO\(_{3}^{-}\) cotransporters and carbonic anhydrase dependence of fluid transport in corneal endothelial cells

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Immunocytochemical localization of Na\(^{+}\)-HCO\(_{3}^{-}\) cotransporters and carbonic anhydrase dependence of fluid transport in corneal endothelial cells. Am J Physiol Cell Physiol 286: C1434–C1442, 2004. First published February 11, 2004; 10.1152/ajpcell.00539.2003.—In corneal endothelium, there is evidence for basolateral entry of HCO\(_{3}^{-}\) into corneal endothelial cells via Na\(^{+}\)-HCO\(_{3}^{-}\) cotransporter (NBC) proteins and for net HCO\(_{3}^{-}\) flux from the basolateral to the apical side. However, how HCO\(_{3}^{-}\) exits the cells through the apical membrane is unclear. We determined that cultured corneal endothelial cells transport HCO\(_{3}^{-}\) similarly to fresh tissue. In addition, Cl\(^{-}\) channel inhibitors decreased fluid transport by at most 16%, and inhibition of membrane-bound carbonic anhydrase IV by benzolamid or dextran-bound sulfonamide decreased fluid transport by at most 29%. Therefore, more than half of the fluid transport cannot be accounted for by anion transport through apical Cl\(^{-}\) channels, CO\(_{2}\) diffusion across the apical membrane, or a combination of these two mechanisms. However, immunocytochemistry using confocal microscopy and cryosections revealed the presence of NBC transporters in both the basolateral and apical cell membranes of cultured bovine corneal endothelial cells and freshly isolated rabbit endothelia. This newly detected presence of an apical NBC transporter is consistent with its being the missing mechanism sought. We discuss discrepancies with other reports and provide a model that accounts for the experimental observations by assuming different stoichiometries of the NBC transport proteins at the basolateral and apical sides of the cells. Such functional differences might arise either from the expression of different isoforms or from regulatory factors affecting the stoichiometry of a single isoform.

confocal microscopy; cryosections; stoichiometry; pH titration; chloride channels

THE BICARBONATE ION (HCO\(_{3}^{-}\)) appears to be central to fluid transport across corneal endothelium; the fact that its presence in the medium is required has been well documented (12, 18, 22). Net HCO\(_{3}^{-}\) flux from the stromal to the aqueous side across rabbit corneal endothelium has been reported (18, 19). In addition, that flux is in all likelihood transcellular, given that it takes place across a small but significant voltage gradient across the endothelium (∼500 μV; aqueous negative; Refs. 4, 11, 12, 17). For transcellular flux, HCO\(_{3}^{-}\) would have to enter the cell via the basolateral membrane against a voltage gradient (intracellular potential −45 mV; Ref. 24) and exit via the apical membrane. There is evidence that the entry step involves secondary active transport across a Na\(^{+}\)-HCO\(_{3}^{-}\) cotransporter (NBC) in that removal of external Na\(^{+}\) led to acidification (7, 37) and a NBC has been located by immunocytochemistry in the basolateral membrane (but not in the apical membrane) by Sun et al. (37) and Bok et al. (5). On the other hand, the mechanism by which HCO\(_{3}^{-}\) exits the cell is less clear. Jentsch and colleagues (20) proposed a Na\(^{+}\)-HCO\(_{3}^{-}\}-coupled exit. Bonanno and Giasson (7) gave arguments for an alternative mechanism based on a role of an apical Cl\(^{-}\)/HCO\(_{3}^{-}\} exchanger. Recently, however, the same laboratory (6) demonstrated that the anion exchanger is actually located in the lateral membrane and thus cannot mediate HCO\(_{3}^{-}\} exit through the apical membrane. These authors propose currently that HCO\(_{3}^{-}\} exits the cell via the cystic fibrosis transmembrane conductance regulator (CFTR) (36) and calcium-activated chloride channels (CaCC) (43). In addition, they postulate that CO\(_{2}\) diffuses across the apical membrane, because of a CO\(_{2}\) gradient established by the combined action of a cytoplasmic carbonic anhydrase (CA) II catalyzing dehydration of HCO\(_{3}^{-}\} and an extracellular membrane-bound CA IV (31) catalyzing hydration of CO\(_{2}\} into HCO\(_{3}^{-}\} (6, 8).

We recently reexamined the question of apical exit of HCO\(_{3}^{-}\} and, from theoretical considerations (unpublished observations), determined that for proper balance of electrical and chemical fluxes across these cells, coupled Na\(^{+}\)-HCO\(_{3}^{-}\} apical exit [as postulated by Jentsch et al. (20)] could not be disregarded. Moreover, we report here that inhibition of Cl\(^{-}\} channels as well as selective inhibition of the membrane-bound CA IV with impermeant CA inhibitors result in only small changes in corneal endothelial fluid transport and thus do not appear to be the major driving forces for it. In the search for other mechanisms for fluid transport, we therefore set out to examine the distribution of NBC proteins in cultured and fresh corneal endothelial cells. Here we present evidence that both basolateral and apical membranes express an NBC protein, and we discuss how different stoichiometries (2:1 entry, 3:1 exit) might underlie transcellular HCO\(_{3}^{-}\} flux.

MATERIALS AND METHODS

Cell culture. Corneal endothelial cells were cultured and subcultured as described previously (9). Cells reached confluence in 5–7 days after which they were subcultured. For immunochemistry experiments cells were subcultured into two-well chamber slide systems (Nunc, Naperville, IL), and for the HCO\(_{3}^{-}\} flux measurements cells were subcultured on 25-mm Costar permeable inserts until 2–3 days after confluence. Confluence was checked visually under a microscope 200) and by 10.220.33.4 on August 14, 2017 http://ajpcell.physiology.org/ Downloaded from http://ajpcell.physiology.org/ by 10.220.33.4 on August 14, 2017
Resistance measurement chamber (WPI, Sarasota, FL) in conjunction with an EVOM epithelial voltmeter (WPI).

**Corneal tissue preparation.** Bovine eyes were obtained from an abattoir as previously described (9). Before dissection, the ocular globes were washed with PBS. The globes were placed in a petri dish, and the corneas were dissected off. Corneas were then washed twice with a HEPEs-buffered Hanks’ balanced salt solution (medium 199; catalog no. 12350, Gibco-BRL) and were cut in rectangular pieces of \( -1 \times 0.5 \) cm. These pieces were then washed three times with medium 199 at 4°C and 90 min as described in Immunochemistry.

**Immunocytochemistry.** Cultured bovine corneal endothelial cells (CBCEC) subcultured as described in Cell culture were washed twice with medium 199 at 37°C, fixed for 30 min in PLP fixative (2% formaldehyde, 75 mM lysine, 10 mM sodium periodate, 45 mM sodium phosphate, pH 7.4; Ref. 28), washed in Dulbecco’s PBS (Gibco-BRL) three times, permeabilized with 0.075% saponin in PBS for 20 min, and washed again in PBS three times. The cells were then incubated for 1 min in a 1% solution of sodium dodecyl sulfate (SDS) in PBS. The cell monolayers were then incubated in blocking solution (15% goat serum, 0.3% Triton X-100, 20 mM sodium phosphate, 0.9 mM sodium chloride; Ref. 25) for 30 min. After the blocking solution was removed by aspiration, the monolayers were exposed to a rabbit anti-NBC polyclonal antibody (catalog no. AB3204, Chemicon International, Temecula, CA), which recognizes the rat kidney NBC-1 COOH terminus amino acids 990–1035 segment, or to another rabbit anti-NBC polyclonal antibody (also from Chemicon, catalog no. AB3212), which recognizes the rat kidney NBC-1 NH2 terminus amino acids 338–391 segment. The antibodies were diluted in PBS plus 15% goat serum and 0.2% bovine serum albumin (Sigma, St. Louis, MO) in PBS. After trying a range of concentrations, we settled on a dilution of 1:500 for the primary antibody (final concentration 2 \( \mu \)g/ml). As a control, in given experiments, we preabsorbed with the immunogenic NBC COOH-terminal peptide (amino acids 990–1035; synthesized for us by Alpha Diagnostics International, San Antonio, TX). The final concentration of the peptide was 2 \( \mu \)g/ml (in PBS). The incubations were done for 60 min in a humid chamber at room temperature. Subsequently, the cell layers were washed three times in PBS and twice in PBS plus 5% goat serum (5–10 min each time). The cell layers were then incubated in rhodamine red-X-conjugated goat anti-rabbit IgG (Jackson ImmunoResearch Laboratories, West Grove, PA) at a dilution of 1:200 (in PBS) for 90 min in the same humid chamber at room temperature. Samples were prepared and kept in the dark to prevent light-induced damage to rhodamine red-X.

**Tissue preparation.** Corneal tissue samples were fixed in PLP medium for 1 h and were washed in PBS three times. They were then immersed in 30% sucrose and kept overnight at 4°C. Subsequently the excess solution was absorbed away, and the pieces were embedded in optimal cutting temperature (OCT) compound (Tissue-Tek; Sakura Finetek, Torrance, CA). The pieces were kept in a freezer at \(-20°C\) and were subsequently sectioned in a cryostat (CM 1850, Leica Microsystems, Bannockburn, IL; 4-μm-thick specimens). Specimens were collected on Silane-Prep slides (Sigma). The rest of the procedure was the same as described for the cultured cells, including permeabilization, denaturation, and blocking. For control experiments once more we used the antigen peptide.

**Nuclear counterstaining and mounting.** Samples were equilibrated briefly in 2× SSC solution (300 mM sodium chloride, 30 mM sodium citrate, pH 7.0 titrated with HCl) and then incubated for 20 min in 2× SSC solution containing 5 \( \mu \)g/ml DNase-free RNase (Boehringer Mannheim, Indianapolis, IN). Incubation was terminated with three washes in 2× SSC solution (1 min each), after which samples were incubated for 5 min in Sytox green (Molecular Probes, Eugene, OR) diluted 1:1 (v/v) in 2× SSC solution and then rinsed five times (1 min each) in 2× SSC solution. The upper part of the channel slide system was then quickly removed, leaving only the cells on the slides. Finally, coverslips were applied to the samples with 1 drop per well of H-1000 Vectashield Mounting Medium (Vector Laboratories, Burlingame, CA). The excess mounting medium was aspirated, and the coverslips were secured with clear nail polish.

The preparations were screened for fluorescence with an Axiovert S100 microscope (Carl Zeiss, Thornwood, NY) using excitation wavelengths of 480 and 545 nm to detect emission by nuclear staining (Sytox green) or antibody staining (rhodamine red-X), respectively. Preparations showing staining were then examined with a scanning confocal microscope (LSM 410, Carl Zeiss). Excitation came from its argon-krypton laser, producing lines at 488 or 568 nm. Fluorescence in the x-y plane was recorded at different depths, and fluorescence in the x-z and y-z planes was obtained from the combined x-y images with Zeiss LSM-PC software. The images were enhanced with Adobe Photoshop software (San Jose, CA).

**Transendothelial HCO3- flux measurements.** The HCO3- flux across cultured bovine endothelial cell monolayers was measured with a pH-stat method adapted and modified from van Adelsberg et al. (42). Permeable tissue culture inserts with confluent monolayers were mounted in a modified Ussing chamber (Fig. 1) consisting of two compartments separated by the insert membrane and the cell monolayer. Each compartment was connected to a reservoir, and solutions from the reservoirs circulated continuously through the compartments with the aid of an airlift system so that the chamber volume was exchanged once every 15 s. One compartment of the Ussing chamber was perfused with a HCO3- buffer solution aerated with a mixture of 5% CO2 and 95% air, whereas the other compartment was perfused with a solution nominally free of HCO3- and CO2, which was vigorously bubbled with CO2-free air and buffer with a low concentration (0.1 mM) phosphate buffer. Except where noted, the detailed composition of the HCO3- buffer solution (solution II) was (in mM) 126.5 NaCl, 4.8 KCl, 1.7 CaCl2, 1.0 MgSO4, 1.0 NaH2PO4, 26.2 NaHCO3, and 5.5 glucose; pH was 7.4. The HCO3- CO2-free solution (solution I) contained (in mM) 154 NaCl, 4.8 KCl, 1.7 CaCl2, 1.0 MgSO4, 0.066 NaH2PO4, 0.033 Na2HPO4, and 5.5 glucose (pH 7.4). With this arrangement, CO2 and HCO3- diffused from solution II to solution I in parallel with any active transendothelial transport. In the phosphate-buffered compartment (solution I), the CO2 was driven off by the CO2-free air and the pH change resulting from the accumulating HCO3- was detected by a pH electrode and a pH meter. Because the pH of the compartment became more alkaline than the control pH (7.4, unless specified), the voltage...
output from the pH meter differed from a set level, triggering a stepping motor that in turn drove a microsyringe injecting 1 M HCl into the solution I compartment until its pH returned to the control value. Each step of the motor injected 1 nmol of HCl into solution I; the amount of steps accumulated was displayed on a LED display reset every 30 min. This automatic titration system maintained the pH of solution I constant within 0.08 pH units.

The HCO₃⁻ unidirectional fluxes were calculated as

\[ \text{HCO}_3^- \text{flux} = \frac{n \text{ (injection steps)} \times 1 \text{ nmol \ step} \times 60 \text{ min}}{\text{area of monolayer} \times 30 \text{ min}} \]  \hspace{1cm} (1)

The HCO₃⁻ flux was measured in the basolateral-to-apical and apical-to-basolateral directions alternatively during a same experiment, by placing solution I in the target compartment and solution II in the contralateral compartment. The difference of fluxes in these two directions was assumed to be the transendothelial HCO₃⁻ flux resulting from membrane transport mechanisms.

A possible error of this method is due to the reversible reaction of CO₂ diffusing from solution II to solution I to yield carbonic acid followed by subsequent dissociation of carbonic acid to H⁺ and HCO₃⁻. This error was kept low by bubbling the solution I vigorously with CO₂-free air so as to maintain PCO₂ as close to zero as possible. Moreover, because the hydration reaction is much slower than the dehydration reaction, the probability that some HCO₃⁻ is converted to CO₂ and removed in the CO₂-free atmosphere is higher than for the reverse reaction. This would then lead to an underestimate of the unidirectional HCO₃⁻ fluxes. However, because the transendothelial HCO₃⁻ transport is calculated as the difference of the unidirectional fluxes in the basolateral-to-apical and apical-to-basolateral directions, the errors would tend to cancel out.

Transendothelial fluid transport measurements. The putative role of the Cl⁻ channels and CO₂ diffusion in the generation of fluid transport was investigated by the Maurice-Dikstein method (10), a method that determines fluid transport by monitoring corneal thickness. Corneal thickness is a function of the imbibition pressure and is converted to CO₂ and removed in the CO₂-free atmosphere is higher than for the reverse reaction. This would then lead to an underestimate of the unidirectional HCO₃⁻ fluxes. However, because the transendothelial HCO₃⁻ transport is calculated as the difference of the unidirectional fluxes in the basolateral-to-apical and apical-to-basolateral directions, the errors would tend to cancel out.

In a typical experiment, HCO₃⁻ flux from the apical to the basolateral side (presumed direction of the leak) was measured for a period of 30 min. The solutions were then replaced on both sides of the preparation so as to determine HCO₃⁻ flux in the opposite direction (from basolateral to apical, with the expectation of determining active transport plus leak) again for 30 min. This was then followed by yet another solution exchange and a determination of apical-to-basolateral flux for 30 min. Thus there were two measurements of the presumed leak bracketing the measurement of active transport plus leak. We took the average of the two leak measurements and subtracted it from the basolateral-to-apical flux, which gave us the putative transcellular net HCO₃⁻ flux for that experiment. Figure 2 shows the values for the unidirectional fluxes (basolateral to apical and apical to basolateral) and the net fluxes. The HCO₃⁻ flux from the basolateral to the apical side was consistently greater than the reverse flux, resulting in a statistically significant net flux of 0.53 ± 0.07 μeq·h⁻¹·cm⁻² (Fig. 2). In addition, from the passive unidirectional flux values for the cell monolayer on its insert and the insert alone and the HCO₃⁻ concentration ([HCO₃⁻]I) gradient, we calculated the permeability of the cell monolayer to HCO₃⁻ to be 4.8 ± 0.2 × 10⁻⁵ cm/s.

RESULTS

HCO₃⁻ fluxes. Rabbit corneal endothelial preparations exhibit net translayer transport of HCO₃⁻ (18, 19). As for the cultured endothelial cells used extensively by other laboratories and ourselves, because there is evidence that they transport fluid [bovine (29), human (1)], they would also be expected to transport HCO₃⁻. However, because this has not been documented, we set out to determine it. The pH-stat method we chose appears convenient in that it does not require isotopes or a closed system.

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To further characterize these fluxes, we investigated the effect of the CA inhibitor ethoxyzolamide on them. For this purpose, with conditions similar to those described above, it was not possible to detect a statistically significant inhibition because of the variability of the two large unidirectional fluxes (cf. Fig. 2). To obviate this, we sought to reduce the unidirectional fluxes by decreasing the [HCO$_3^-$]/[H$_2$CO$_3$] to 9.2 mM in solution II while keeping the P$_{CO_2}$ constant in that solution by bubbling with 5% CO$_2$. As a result, the pH of solution II became 7.0, and this meant that the phosphate buffer in solution I had to be adjusted to 7.0, which was the set point pH for this series. A representative experiment is shown in Fig. 3; as can be seen in that figure, the inhibitor at a high concentration (0.1 mM) results in a large but reversible inhibition of the unidirectional flux. These experiments suggest that cellular CA is capable of contributing to HCO$_3^-$ flux under those particular conditions, namely, low ambient [HCO$_3^-$] and normal P$_{CO_2}$. Because CO$_2$ + OH$^-$ $\leftrightarrow$ HCO$_3^-$, the intracellular CA II-driven reaction from left to right would gain importance at lower [HCO$_3^-$], in agreement with our observation. This issue may be further illuminated by our consideration of the roles of the intracellular and extracellular CAs as described for the alternate model for the anion pathway in DISCUSSION.

Cl$^-$ channel inhibition. It has been postulated that one of the two pathways for the passage of HCO$_3^-$ across the apical membrane of corneal endothelial cells is via Cl$^-$ channels. Two types of these channels have been identified in corneal endothelial cells, calcium-activated Cl$^-$ channels (CaCC; Ref. 43), and CFTRs (36). We have examined the role of Cl$^-$ channels in fluid transport by using a number of Cl$^-$ channel inhibitors and the Dikstein-Maurice technique. Figure 4 compares the effects of several of these inhibitors on corneal thickness, NPPB, pBPB, a specific CFTR inhibitor, and niflumic acid, with the rates of swelling obtained in ouabain (1 mM) and the spontaneous swelling in control solution. Ouabain affected a rapid equilibration of all intracellular electrolyte concentrations, abolished the membrane and transendothelial potential differences, and thus inhibited the transendothelial fluid transport completely. The rate of swelling (32.3 $\mu$m/h) observed in ouabain solutions reflects a fluid leak of 3.23 $\mu$l/h from the aqueous side to the stromal side due to the imbibition pressure of the stroma. This fluid leak was not completely compensated in control solution, and there remained a spontaneous rate of swelling of 3.2 $\mu$m/h. The transendothelial fluid transport under in vitro conditions was therefore 2.91 $\mu$l/h. In solutions containing the Cl$^-$ channel inhibitors NPPB or pBPB (Fig. 5) at maximally effective concentrations (100 $\mu$M), the
rate of swelling increased at an average of 6.2 \( \mu \)m/h, corresponding to a reduction of transendothelial fluid transport to 2.61 \( \mu \)l/h, a 10.3\% decrease from control. The CFTR inhibitor had no significant effect compared with spontaneous swelling, whereas niflumic acid, a compound used to inhibit the CaCC (43), reduced the transendothelial fluid transport by \( \sim 16\% \).

**Inhibition of apical extracellular CA IV.** The apical membrane of corneal endothelial cells possesses a membrane-bound extracellular CA IV (31). It has been proposed that this CA establishes a transcellular CO\(_2\) gradient by catalyzing the conversion of CO\(_2\) to HCO\(_3^-\) and thus effectively generating a HCO\(_3^-\) flux across the endothelial cells. We have examined the possible role of CA IV in transendothelial fluid transport by inhibiting the enzyme with the relatively impermeant CA inhibitor benzolamide and an impermeant dextran-bound sulfonamide. The results are summarized in Fig. 5. Benzolamide, at the supramaximal concentration of 10 \( \mu \)M, produced a rate of swelling of 11.3 \( \mu \)m/h. This corresponds to a reduction of transendothelial fluid transport by 0.81 \( \mu \)l/h, or 27.8\%. Increasing the benzolamide concentration to 30 \( \mu \)M reduced fluid transport by the same amount. When the swelling initiated by benzolamide was interrupted by switching to a solution containing CA, to absorb any residual inhibitor and restore CA activity, the swelling stopped immediately. This indicates that benzolamide indeed inhibits an extracellular CA. The results obtained with benzolamide were confirmed with an impermeant dextran-bound CA inhibitor of mol wt 7,000, which at the concentrations of 0.1 and 1 mM produced a rate of swelling corresponding to a reduction of fluid transport by 0.67 \( \mu \)l/h, or 22.8\%.

**Localization of NBC: cultured cells.** We investigated the localization of NBC both in cultured cells and in fresh corneal tissue slices. Figure 6 depicts selected images of a gallery of optical sections of CBCEC obtained by confocal microscopy. Evidence for the presence of NBC is seen at the level of the apical membrane (Fig. 6, a and b), lateral membrane (Fig. 6c), and lateral and basal membrane (Fig. 6d). The three-dimensional reconstruction shown in Fig. 7 reinforces this view. Figure 7b, the x–z reconstruction, is especially noteworthy in that the stained membrane envelope all around a cell is clearly noticeable. There is also some diffuse staining of the cytoplasm. This gallery is representative of 11 galleries obtained in cells from two different batches of bovine eyeballs.

**Localization of NBC: tissue slices.** Because it is conceivable that expression of given proteins and/or their isoforms could be different in proliferating cultured cells from that in fresh tissue cells, we investigated the localization of NBC in bovine corneal cryosections. The results in Fig. 8 once more show evidence for the localization of NBC in both apical and basolateral endothelial cell membranes. The staining in the apical membrane region is significantly lower than that in the basolateral membrane, indicating a lower density of transport proteins. These data are representative of 23 cryosections obtained from 10 corneas.

Finally, for control purposes, we preabsorbed the antigenic peptide and subjected sections to the same procedures as above.
and 4.5 (13)]. Larger HCO₃⁻ (not shown). No staining for NBC was evident, whereas all corneal structures were clearly visible (3 sections in a cornea that evidenced clear NBC staining without preabsorption).

**DISCUSSION**

HCO₃⁻ fluxes. As mentioned above, the net HCO₃⁻ flux we determined was 0.53 ± 0.07 μeq·h⁻¹·cm⁻². This value is comparable to that (0.67 ± 0.11 μeq·h⁻¹·cm⁻²) reported by Hodson and Miller (18). It should be noted that they used rabbit corneal endothelial preparations and we used cultured bovine cells. In addition, their ambient [HCO₃⁻] was much larger (2.5 ± 0.2 μeq·h⁻¹·cm⁻²). Assuming tight isotonic coupling between electrolyte net fluxes and water flows, fluxes of the order of 0.53–0.67 μeq·h⁻¹·cm⁻² would correspond to flows of ~3.5–4.5 μl·h⁻¹·cm⁻². These values agree with the order of the values experimentally determined for isolated rabbit corneal preparations in Ussing chambers modified for flow measurements [in μl·h⁻¹·cm⁻²: ~6.0 (27) and 4.5 (13)]. Larger HCO₃⁻ flux values (19) would entail either looser coupling or much larger fluid flows than those determined so far. The value of the permeability of the cell monolayer to HCO₃⁻ was 4.8 ± 0.2 × 10⁻⁵ cm/s. This is of the same order of magnitude as a value of 2.1 ± 0.2 × 10⁻⁵ cm/s reported by Hodson and Miller (18) for the deep epithelialized rabbit cornea.

These observations justify the conclusion that the cultured cells are polarized and exhibit net HCO₃⁻ transport that would correspond to a distribution and a density of expression of HCO₃⁻ transporters similar or identical to those of fresh tissue. This net HCO₃⁻ transport would then form part of the fluid transport machinery in this layer; a recent model (33) includes a role for electrogenic transcellular HCO₃⁻ transport in electroosmosis-driven transendothelial fluid transport.

**Inhibition of Cl⁻ channels.** Several types of anion channels have been described for corneal endothelial cells. These channels include a large-conductance nonspecific anion channel identified by patch-clamp studies (30), which is inoperative at resting membrane potential. In addition, RT-PCR screening has revealed the presence and activation of CFTR (38) and CaCC (43) channels in the bovine corneal endothelium.

Inhibition of Cl⁻ channels with a range of different Cl⁻-channel inhibitors (Fig. 4) consistently showed only relatively small effects on transendothelial fluid transport, ranging from insignificant to a maximum of 16%. The contribution of apical Cl⁻ channels to transendothelial fluid transport is of the same order of magnitude as that of the basolateral Na⁺-K⁺-2Cl⁻ cotransporter (NKCC) (21), suggesting the existence of a small vectorial Cl⁻ transport from the basolateral to the apical side.

**Inhibition of CA IV.** The corneal endothelium possesses a membrane-bound extracellular CA IV (31), which is confined to the apical membrane (6). It has been hypothesized that this
CA IV catalyzes the hydration of CO$_2$ to HCO$_3^-$ in the unstirred layer adjacent to the apical membrane and thus creates a stromal-to-aqueous CO$_2$ gradient; it has been postulated that this is one of the pathways that contribute to transcellular HCO$_3^-$ flux and fluid transport (8). We have examined this hypothesis by determining the effect of selective inhibition of the extracellular CA IV, and the consequent deletion of the putative CO$_2$ gradient, on fluid transport. Benzolamide, a slowly permeant CA inhibitor, and a dextran-bound acetazolamide (mol wt 7,000) inhibit fluid transport by 28.8% and 22.8%, respectively (Fig. 5). Benzolamide has been reported to equilibrate slowly in human red blood cells at a rate of ~7%/h (39) and thus might also act on intracellular CA. We therefore ran a series of experiments in which we initiated the inhibition of fluid transport and stromal swelling with benzolamide and then followed with a solution containing CA. This should lead to an immediate reduction of benzolamide to nanomolar levels and thus should return fluid transport to control levels. The swelling ceased immediately (Fig. 5), indicating that the action of benzolamide was extracellular, although corneal thickness did not return completely to control levels. Consistently, the effect of inhibition of CA IV on fluid transport shown here (~20–30%) is significantly less than the known effect of inhibiting both CA IV and CA II, which was ~40–60% (12). In summary, slowly permeant or impermeant inhibitors of CA indeed reduce transendothelial fluid transport, but the inhibition is <30% of control (Fig. 5). In addition, as mentioned above, inhibition of Cl$^-$ channels resulted in at most a 16% decrease of fluid transport (Fig. 4). It is interesting that the effects of impermeant and permeant CA inhibitors are additive. This is consistent with separate effects on an intracellular CA II and an extracellular CA IV, as discussed below.

In conclusion from the two segments above, from our evidence, inhibition of the two apical pathways previously proposed for anion efflux by Bonanno and colleagues, Cl$^-$ channels (36, 43) and CO$_2$ flux (6, 8), even if combined together, cannot account for more than 40–45% of the baseline rate of transendothelial fluid transport. In the CO$_2$ gradient hypothesis above (6, 8), the intracellular CA II would mediate HCO$_3^-$ dehydration and the extracellular CA IV HCO$_3^-$ hydration. However, the function of luminal and interstitial CA IV described for kidney proximal tubule (40) and for gastric parietal cells (39) is dehydration of HCO$_3^-$, whereas the function of intracellular anhydrase is postulated to be hydration. In the scheme we propose below for the tandem of CAs in corneal endothelium, the enzymes function as proposed for the kidney and stomach.

Localization of NBC. We have demonstrated with confocal microscopy that in both cultured corneal endothelial cells and endothelial cells of freshly dissected cornea NBC proteins are located at the basolateral membrane and the apical membrane. As shown in Fig. 8, the density of staining at the apical membrane is significantly less than that at the basolateral membrane. This difference in the density of transport proteins is consistent with the HCO$_3^-$ permeability of the apical membrane, which reportedly is four to three times lower than that of the basolateral membrane (8). If, in addition, the apical NBC transporter moves three molecules of HCO$_3^-$ per turnover compared with two molecules per turnover of the basolateral NBC, then an apical protein density of 17–22% of that in the basolateral membrane may be expected.

The distribution of NBC isoform(s) to both the basolateral and apical cell membranes reported here poses the question of whether the cell can be polarized so as to generate vectorial HCO$_3^-$ flux under such conditions. In this connection, NBC is distributed throughout the basolateral and apical membrane domains in cultured bovine endothelial cells and freshly dissected rabbit corneal preparations. Such distribution has also been observed recently in the ducts of the submandibular glands of the rat (32). However, in those duct cells there appears to be a gradient of distribution that changes from a purely basolateral localization in the proximal sections of the submandibular ducts to localization in both basolateral and apical membrane domains and then to apical localization only in the distal parts of the duct. In the corneal endothelium and in cultured bovine endothelial cells simultaneous basolateral and apical fluorescence is seen consistently in all cells, as shown in Figs. 6–8. Our finding is in contrast prima facie to the observation by Sun et al. (37) and Bok (5), who report that indirect fluorescence, due to antibody binding, is confined to the basolateral membrane. However, the analysis of the data was somewhat different. We used three-dimensional reconstruction of the confocal images to show the antibody distribution in cross sections of the cultured bovine endothelial cells, whereas Sun et al. (37) examined optical slices in the x-y plane only. In addition, we obtained cryosections of the freshly dissected corneal endothelium, again to visualize the antibody distribution in cell cross sections. Finally, there is a large difference in protein density between the apical and basolateral membrane domains, which might have led other investigators to consider the apical staining insignificant. For this and other reasons, it will be relevant to attempt to explore the putative function of the newly described apical NBC.

Thermodynamics of net transcellular HCO$_3^-$ flux. From the preceding arguments, our results suggest that NBCs are expressed in both apical and basolateral membrane domains. Under these conditions, vectorial HCO$_3^-$ transport across the endothelium via NBCs can occur either if different NBC isoforms are located on the apical and basolateral membranes or if the same isoform exists but functions differently. One of these isoforms would require a stoichiometry of 2 HCO$_3^-$:1 Na$^+$ or less for HCO$_3^-$ influx across the basolateral membrane, whereas the other would require a stoichiometry of 3 HCO$_3^-$:1 Na$^+$ or greater for HCO$_3^-$ efflux across the apical membrane. There is a conceivable alternative in which the NBC would function with the same 2:1 stoichiometry on both cell sides. In that case, HCO$_3^-$ would be transported into the cell from both sides and high cell HCO$_3^-$ could drive the reaction HCO$_3^-$ + H$^+$ > CO$_2$ + H$_2$O, with CO$_2$ rapidly diffusing across the apical membrane. However, as mentioned above, for such vectorial diffusion of CO$_2$ (Bonanno’s hypothesis), there would have to be an apical extracellular CA IV reducing the extracellular CO$_2$ by hydration; only thus could there be a basolateral-to-apical CO$_2$ gradient and a net flow of CO$_2$. Our results this far do not support that view; inhibition of an apical extracellular CA IV (Fig. 5) with the consequent removal of the hypothetical CO$_2$ gradient reduces fluid transport by at most 29%. From the 16% inhibition of fluid transport (Fig. 4) seen in blocking apical anion channels, the expected inhibition of fluid transport, if due to CO$_2$ flow, would be some 84% instead.

Figure 9 describes the thermodynamic limits of the operating range for a system consisting of NBCs with 2:1 and 3:1 stoichiometry.
endothelial cells. The antibody used in our studies does not et al. (23) were unable to identify either isoform in cultured cells and freshly dissected corneal endothelia. Curiously, Lane to identify only the presence of pNBC in cultured endothelial group of investigators (41). However, Sun et al. (37) were able isoforms, a pancreatic (pNBC-1) and a kidney (kNBC-1) logically expected range for an endothelial layer.

mV membrane potential. These values fall within the physiologically expected range for an endothelial layer.

Identity of NBC isoforms. The expression of two different isoforms, a pancreatic (pNBC-1) and a kidney (kNBC-1) isoform, in corneal endothelium has been described by one group of investigators (41). However, Sun et al. (37) were able to identify only the presence of pNBC in cultured endothelial cells and freshly dissected corneal endothelia. Curiously, Lane et al. (23) were unable to identify either isoform in cultured endothelial cells. The antibody used in our studies does not distinguish between the pancreatic and kidney isoforms and therefore does not provide any information about the specific isoform(s) in our preparation. Still, there is another possibility. Recently it was reported that the kNBC-1 isoform, which excludes HCO$_3^-$ from proximal tubule cells at a 3:1 stoichiometry, exhibits 2:1 stoichiometry when expressed in Xenopus oocytes (16, 34). It has been suggested as a possible explanation for these observations that the stoichiometry of rat kNBC is determined by the absence or presence of an accessory protein (34). Another report (14) demonstrated that phosphorylation of a specific serine residue of the kNBC of murine tubule cells can shift its stoichiometry from 2:1 to 3:1. Therefore, it seems conceivable that tissue-dependent expression and translocation to specific membrane domains might thus allow the same NBC isoform to be used for HCO$_3^-$ influx across the basolateral membrane and efflux across the apical membrane of the same cell.

An alternate transcellular anion transport model for corneal endothelial cells. On the basis of the data presented here, we propose a new model of transcellular anion transport across corneal endothelial cells (Fig. 10). In this model HCO$_3^-$ enters the cell across the basolateral membrane via a NBC with a stoichiometry of 2 HCO$_3^-$:1 Na$^+$ (7). In parallel to this influx is a significantly smaller entry of Cl$^-$ ions via the NKCC (9) and the anion exchanger. We propose that the anion efflux through the apical membrane is predominantly due to a NBC with a ratio of 1 Na$^+$:3 HCO$_3^-$ and a smaller Cl$^-$ efflux through Cl$^-$ channels. An apical NBC mediating HCO$_3^-$ efflux is in line with evidence for Na$^+$-HCO$_3^-$ coupled exit cited above for cultured corneal endothelial cells (20). As Fig. 9 shows, a 3:1 NBC would operate relatively close to the thermodynamic limit. However, as hypothesized in Fig. 10, the combined action of the intracellular CA II and extracellular CA IV working in tandem would create/enhance a local [HCO$_3^-$] gradient across the apical membrane to facilitate efflux across the NBC. The intracellular CA II would catalyze the conversion of CO$_2$ to HCO$_3^-$, whereas the membrane-bound extracellular CA IV would catalyze the reverse reaction. This is consistent with recent proposals that CA II is bound to the COOH terminal of NBC-1 in kidney proximal tubule (35); such binding apparently takes place only when the NBC is dephosphorylated and hence working in the 3:1 mode (15). There is also evidence that CA II and CA IV are tethered in...
close proximity to NBC extracellular and intracellular sites, respectively, in NBC1-transfected HEK293 cells (3).

GRANTS

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REFERENCES


