Electrogenic Sodium-dependent Bicarbonate Secretion by Glial Cells of the Leech Central Nervous System

JOACHIM W. DEITMER
From the Abteilung für Allgemeine Zoologie, FB Biologie, Universität Kaiserslautern, D-6750 Kaiserslautern, Germany

ABSTRACT The ability to move acid/base equivalents across the membrane of identified glial cells was investigated in isolated segmental ganglia of the leech Hirudo medicinalis. The intracellular pH (pHi) of the glial cells was measured with double-barreled, neutral-ligand, ion-sensitive microelectrodes during step changes of the external pH (pH o 7.4-7.0). The rate of intracellular acidification after the decrease in extracellular pH (pH o) was taken as a measure of the rate of acid/base transport across the glial membrane. Taking into account the total intracellular buffering power, the maximum rate of acid/base flux was 0.4 mM/min in CO2/HCO3-free saline, and 3.92 mM/min in the presence of 5% CO2/10 mM HCO3, suggesting that the acid/base flux was dependent upon HCO3. The rate of acid influx/base efflux increased both with the external HCO3 concentration and with increasing pH o (and hence HCO3). This suggested that the decrease in pH i was due to HCO3 efflux. The rapid decrease of pH i was accompanied by a HCO3-dependent depolarization of the glial membrane from -74 ± 5 mV (n = 20) to -54 ± 7 mV (n = 13). Both this depolarization and the rate of intracellular acidification were greatly reduced by the anion exchange inhibitor 4,4-diisothiocy- anostilbene-2,2'-disulfonic acid (DIDS; 0.3-0.5 mM), but were not affected by the removal of external Cl-. Reduction of the external Na+ concentration to one-tenth normal affected the rate of intracellular acidification only in the presence of CO2/HCO3: the rate increased within the first 3-5 min after lowering external Na+; after longer exposures in low external Na+ the rate decreased, presumably due to depletion of intracellular Na+. Amiloride (1 mM), which inhibits the Na+-H+ exchange in these cells, had no effect on the rate of intracellular acidification. The intracellular Na activity (aNa) of the glial cells was measured to be 5.2 ± 1.0 mM (n = 8) in CO2/HCO3-free saline; aNa increased to 7.3 ± 2.2 mM (n = 8) after the addition of 5% CO2/24 mM HCO3. Upon a change in pH o to 7.0 in the presence of CO2/HCO3, aNa decreased by an average of 2 ± 1.1 mM (n = 5); in CO2/HCO3-free saline external acidification produced a transient increase in aNa. It is concluded that, in the presence of CO2/HCO3, the rate of intracellular acidification in glial cells is dominated by an outwardly directed, electogenic...
Na\(^+-\)HCO\(_3\) cotransport. Neurons, which do not possess this cotransporter, acidify at much lower rates under similar conditions. Since the Na\(^+-\)HCO\(_3\) cotransporter is reversible, glial cells might play a crucial role in dampening ("muffling") acid and base transients in the extracellular spaces of the nervous system by active, Na\(^+-\)dependent secretion and uptake of HCO\(_3\)\(^-\).

**INTRODUCTION**

Living cells usually maintain an alkaline intracellular pH (pH\(_i\)) with respect to the H\(^+\) electrochemical equilibrium by actively removing acid equivalents across the cell membrane. This has been extensively studied in neurons (for references see Roos and Boron, 1981; Thomas, 1984; Chesler, 1990). The main mechanisms involved are coupled ion transport processes across the membrane, such as Na\(^+-\)H\(^+\) and Na\(^+-\)dependent Cl\(^-\)-HCO\(_3\) exchange.

In glial cells, similar mechanisms of pH regulation have recently been reported, as well as a DIDS-sensitive electrogenic Na\(^+-\)HCO\(_3\) cotransporter (Deitmer and Schlue, 1987, 1989; Astion and Orkand, 1988; Kettenmann and Schlue, 1988). Upon introduction of CO\(_2\)/HCO\(_3\), this Na\(^+-\)HCO\(_3\) cotransport is inwardly directed and hence alkalinizes the glial cytoplasm. Since more than one HCO\(_3\) ion is transported per Na\(^+\) ion, the intracellular alkalinization is accompanied by a DIDS-sensitive membrane hyperpolarization. In leech neuropile glial cells, the stoichiometry of this cotransporter was determined to be 1 Na\(^+\):2 HCO\(_3\) (Deitmer and Schlue, 1989), and it was shown to be sensitive to membrane potential changes (Deitmer and Szatkowski, 1990).

Much less is known, however, about the transport of acid equivalents down the H\(^+\) electrochemical gradient. With respect to the Na\(^+-\)HCO\(_3\) cotransporter in glial cells, this might be achieved by the reversal of the cotransporter. Indeed, in many epithelial cells electrogenic Na\(^+-\)HCO\(_3\) cotransport is outwardly directed in its normal mode (cf. Boron and Boulpaep, 1989). In the proximal tubule of the salamander kidney, where Na\(^+-\)HCO\(_3\) cotransport was first described at the basolateral membrane (Boron and Boulpaep, 1983), this produces an intracellular acidification of the epithelial cells and serves to reabsorb HCO\(_3\) into the blood.

Acid uptake into, or base secretion from cells might be of importance in the nervous system, where considerable extracellular acid transients may occur during neuronal activity (Kraig, Ferreira-Filho, and Nicholson, 1983; Mutch and Hansen, 1984; Somjen, 1984; Krishtal, Osipchuk, Shelest, and Smirnoff, 1987; Chesler and Chan, 1988; Chvátal, Jendelová, Kríz, and Syková, 1988; Rice and Nicholson, 1988; Walz, 1989). This, in turn, may affect the activity of nerve cells (Fukuda and Loreschke, 1977; Jarolimek, Misgeld, and Lux, 1990) and glial cells (Walz and Hinks, 1987) by influencing channels, carriers, and synaptic receptors of these cells.

Glial cells, which play an important role in the regulation of the K\(^+\) microenvironment in the nervous system (Hertz, 1965, 1990; Nicholson, 1983; Walz, 1989), may also be good candidates to help control the pH of the extracellular (interstitial) spaces. This would require a mechanism of rapid acid/base influx or efflux across the glial membrane. In previous studies, effective HCO\(_3\) uptake by glial cells was shown to be due to inwardly directed Na\(^+-\)HCO\(_3\) cotransport; this may produce acid transients or counteract alkaline transients in the extracellular spaces. On the other
hand, a reversed mode of the cotransporter might be activated by an extracellular acidification, and hence be able to remove acid from the interstitial spaces. In this study I have tried to test this possibility by measuring the pH and the intracellular Na activity (aNa) of identified glial cells in the neuropile of the leech central nervous system. The results suggest that under appropriate thermodynamic conditions, the electrogenic Na\(^+\)-HCO\(_3\)\(^-\) cotransport in the glial membrane can be directed outwardly. This effective secretion of base equivalents into the extracellular spaces might be significant for acid/base homeostasis in the brain.

**METHODS**

The experiments were performed on the anterior or posterior glial cell in the neuropile of segmental ganglia of the leech *Hirudo medicinalis*. The preparations and dissection procedures used to isolate single ganglia have been described before (Schlue and Deitmer, 1980; Deitmer and Schlue, 1981). Isolated ganglia were pinned by their connectives, ventral side upward, to the silicone rubber base of a small experimental chamber (volume, 0.1 ml). The ganglia were superfused with saline at a rate of ~2 ml/min. The selection and identification of the glial cells and neurons followed criteria described previously (Deitmer and Schlue, 1981, 1987). All experiments were performed 3–12 times, each type with essentially similar protocols, at room temperature (22–25°C).

**Physiological Solutions**

The CO\(_2\)/HCO\(_3\)-free saline had the following composition (in mM): 85 NaCl, 4 KCl, 2 CaCl\(_2\), 1 MgCl\(_2\), and 10 HEPES (N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid), adjusted to pH 7.4 with 4.5–5 mM NaOH. When the pH was changed to 7.0, 10 mM MOPS (3-(N-morpholino)propanesulfonic acid) instead of HEPES was used as a buffer. Solutions containing CO\(_2\)/HCO\(_3\) had the same amount of HEPES or MOPS, and were bubbled with either 1% or 5% CO\(_2\); 2 and 5 mM HCO\(_3\) or 10 and 24 mM HCO\(_3\) were added to make a pH of 7.0 and 7.4, respectively. Equivalent amounts of NaCl were replaced by NaHCO\(_3\) to maintain isotonicity. Reduction of external Na\(^+\) was achieved by replacing NaCl by N-methyl-d-glucamine (NMDG) neutralized with HCl and/or CO\(_2\) as appropriate. In some experiments the stilbene DIDS (4,4-diisothiocyanatostilbene-2,2'-disulfonic acid, 0.3–0.5 mM) or the diuretic amiloride (1 mM) was applied directly to the saline shortly before use.

**Microelectrodes**

"Side-by-side" double-barreled borosilicate microelectrodes were used for recording pH or Na\(^+\) and the reference (membrane) potential. The electrodes were pulled in two stages and were silanized essentially as described by Borelli, Carlini, Dewey, and Ransom (1985): a drop of a 5% tri-N-butylchlorosilane in 99.9% pure carbon tetrachloride solution was filled into the prospective ion-selective barrel. The pipette was then baked on a hot plate at 460–475°C for 4.5–5 min.

For the pH-sensitive electrodes, H\(^+\) cocktail (Fluka 95291) was backfilled into the tip of the silanized barrel, and then filled up with 0.1 M Na-citrate, pH 6.0. The reference barrel was filled with 3 M KCl. The electrodes were calibrated in leech saline buffered to 7.4 with HEPES, 7.0 with MOPS, and 6.4 with PIPES (piperazine-N,N\(^+\)bis(2-ethanesulfonic acid) (Fig. 1A). They responded on average with a 52-mV unit change in pH. The sensitivity to CO\(_2\)/HCO\(_3\) was tested for each electrode, and a response of up to 5 mV (i.e., <0.1 pH unit) was accepted. Most electrodes used responded with <3 mV to 5% or 1% CO\(_2\) (Fig. 1A).

For Na\(^+\)-sensitive electrodes, Na\(^+\) cocktail was produced by mixing the Na\(^+\) ionophore VI (Fluka 71739), 2-N-phenyl-octyl-ether (o-NPOE; Fluka 73732) and Na-tetraphenylborate.
(Fluka 72018) in wt % at a ratio 10:89.5:0.5. This mixture was backfilled into the silanized barrel, and then filled up with 0.1 M NaCl + 10 mM MOPS, pH 7.0. The reference barrel was filled with 3 M KCl. The electrode was calibrated in salines with different Na⁺ concentrations at constant ionic background with NMDG or K⁺ as the Na⁺ substitute (Fig. 1 B). The electrodes responded on average with 55 mV between 90 and 9 mM Na⁺ concentration, corresponding to 67.5 and 6.75 mM Na activity, using an activity coefficient of 0.75 for Na⁺. At lower Na⁺ concentrations the electrode response was nearly linear down to 4.5 mM (3.4 mM activity), but 3–5 mV less when Na⁺ was replaced by K⁺ instead of NMDG (Fig. 1 B). All measurements of Na⁺ are presented as Na activity.

**FIGURE 1.** Calibration of a pH-sensitive (A) and a Na⁺-sensitive (B) microelectrode. The pH-sensitive microelectrode was tested in leech salines at pH 7.4, 6.4, and 7.0, and back to 7.4 in CO₂/HCO₃⁻-free saline and in saline containing 5% CO₂ at pH 7.4 (24 mM HCO₃⁻) and pH 7.0 (10 mM HCO₃⁻). The Na⁺-sensitive microelectrode was tested in leech saline containing different Na⁺ concentrations (here converted to Na activities), when Na⁺ was replaced by N-methyl-D-glucamine (NMDG; left part, when the Na⁺ concentration was lowered) or by K⁺ (right part, when the Na⁺ concentration was restored).

**Recording**

The electrical arrangements were the same as described previously (Deitmer and Schlue, 1981, 1987). Each channel of the double-barreled microelectrode was connected to one input of a differential electrometer (FD-223; World Precision Instruments, Inc., New Haven, CT). The electrometer outputs were displayed on an oscilloscope and recorded on tape and/or on chart paper for direct display.
RESULTS

The standard protocol used in the present study was to change the pH of the saline from 7.4 to 7.0 for 5–15 min, either in nominal CO₂/HCO₃⁻-free saline or in a CO₂-gassed saline containing different HCO₃⁻ concentrations. An experiment of this type with a pH-sensitive microelectrode in a neuropile glial cell is shown in Fig. 2. The external HCO₃⁻ concentration was first reduced from 24 to 10 mM at constant pressure of 5% CO₂ with a concomitant decrease of the pH to 7.0, and then from 24 mM HCO₃⁻ (5% CO₂) to nominal CO₂/HCO₃⁻-free saline with a pH of 7.0. The maximum rates of intracellular acidification were determined as the initial ΔpH/min; they were 0.052 and 0.065 pH units/min, respectively. A similar rate of intracellular acidification occurred after the removal of CO₂/HCO₃⁻ at constant pH (7.4). This suggests that it was the decrease of the external HCO₃⁻ concentration which induced the rapid intracellular acidification in these glial cells.

The steady-state values of pHᵢ were 7.25 ± 0.12 (n = 12) in 5% CO₂/24 mM HCO₃⁻ (pHₑ 7.4), and 7.05 ± 0.1 (n = 9) in 5% CO₂/10 mM HCO₃⁻ (pHₑ 7.0). The glial membrane reversibly depolarized after the reduction of the external HCO₃⁻ concentration, on average by 20 mV; i.e., from −74 ± 5 mV (n = 20) to −54 ± 7 mV (n = 13; Table I).

After restoring the external pH and/or the HCO₃⁻ concentration, the pHᵢ increased rapidly to its initial value. The maximum rates of this pHᵢ recovery were 0.08 and 0.17 mM/min, and were accompanied by a membrane hyperpolarization. It was shown previously that addition of HCO₃⁻ to the external solution stimulates an inwardly directed, electrogenic Na⁺-HCO₃⁻ cotransport (Deitmer and Schlue, 1989).

The equilibrium potential of H⁺ and HCO₃⁻ in CO₂/HCO₃⁻-containing salines changed from −9 mV at pHₑ 7.4 to +2 mV at pHₑ 7.0 (Table I). With the different membrane potentials in the high and low HCO₃⁻ salines, the electrochemical gradients for H⁺ and HCO₃⁻ were 56 and 65 mV, respectively. In CO₂/HCO₃⁻-free
saline the $\text{H}^+/\text{HCO}_3^-$ equilibrium potential was $-25$ mV, resulting in an electrochemical gradient for $\text{H}^+/\text{HCO}_3^-$ of $40$ mV.

**Acid/Base Fluxes across the Membrane**

To convert the rate of pH$_i$ change into fluxes of acid or base equivalents across the membrane, the intracellular buffer capacity has to be taken into account. The mean intrinsic buffer capacity, $\beta_i$, of the glial cells had been determined previously by the ammonium pulse technique to be $25$ mM in CO$_2$/HCO$_3^-$-free, HEPES-buffered saline (Deitmer and Schlue, 1987). A similar value was found using the weak acid (propionic acid) method (after Szatkowski and Thomas, 1989). In the presence of CO$_2$/HCO$_3^-$, a CO$_2$-induced buffer capacity, $\beta_{co_{2}}$, is added, which is given in first approximation by

$$\beta_{co_{2}} = 2.3[HCO_3^-]$$

The intracellular HCO$_3^-$ concentration was calculated with the Henderson-Hasselbalch equation, using the value of pH$_i$ measured with the ion-sensitive electrode. The total buffer capacity, $\beta_i$, is the sum of $\beta_i$ and $\beta_{co_{2}}$. At a mean pH$_i$ of 7.25 in the presence of 5% CO$_2$/24 mM HCO$_3^-$, the intracellular HCO$_3^-$ concentration was 17 mM (Table I). This resulted in a $\beta_{co_{2}}$ of 39 mM and a $\beta_i$ of 64 mM. With the rate of pH$_i$ change and $\beta_i$ known, the acid flux, $J_H$, or the base flux in opposite direction, $J_{HCO_3^-}$, are given by

$$J_H = -J_{HCO_3^-} = \Delta \text{pH}_i / \min \times \beta_i$$

The acid/base flux ($J_{acid}$; Table II) was determined using the initial maximum rate of pH$_i$ change at the first 1–2 min of the change to a saline with different pH. The maximum rates of pH$_i$ change upon reduction of the external HCO$_3^-$ concentration, as shown in Fig. 2, would indicate an acid influx of 4.0 mM/min (10 mM HCO$_3^-$, pH 7.0) and 5.0 mM/min (HCO$_3^-$-free, pH 7.0), or a base efflux of the same values. In comparison, the change from a saline containing 5% CO$_2$/24 mM HCO$_3^-$ (pH 7.4) to CO$_2$/HCO$_3^-$-free saline (pH 7.4) induced a maximum acid influx/base efflux of 3.98 mM/min in the same experiment (not shown).

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**Table I**

<table>
<thead>
<tr>
<th>Saline</th>
<th>pH$_i$</th>
<th>HCO$_3^-$</th>
<th>aNa$_i$</th>
<th>$E_{n}$</th>
<th>$E_{m}$</th>
<th>$E_{cy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$-free</td>
<td>6.97 ± 0.1</td>
<td>&lt;0.1</td>
<td>5.2 ± 1.0</td>
<td>-65 ± 1</td>
<td>-25</td>
<td>+65</td>
</tr>
<tr>
<td>(n = 13)</td>
<td>(n = 8)</td>
<td>(n = 21)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% CO$_2$, pH 7.4</td>
<td>7.25 ± 0.12</td>
<td>17</td>
<td>7.35 ± 2.2</td>
<td>-74 ± 1</td>
<td>-9</td>
<td>+56</td>
</tr>
<tr>
<td>(n = 12)</td>
<td>(n = 8)</td>
<td>(n = 20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% CO$_2$, pH 7.0</td>
<td>7.05 ± 0.1</td>
<td>11</td>
<td>5.3 ± 2.0</td>
<td>-54 ± 1</td>
<td>+2</td>
<td>+65</td>
</tr>
<tr>
<td>(n = 9)</td>
<td>(n = 5)</td>
<td>(n = 13)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE I
Rate of Intracellular Acidification (ΔpH/min) and Acid/Base Flux (Jw,b) in Neurophil Glial Cells and Retzius Neurones after a Change of External pH from 7.4 to 7.0 in the Presence of Different HCO3- Concentrations, and in the Presence of the Stilbene DIDS (0.3–0.5 mM)

<table>
<thead>
<tr>
<th>Saline</th>
<th>Glia</th>
<th>Jw,b</th>
<th>Neurone</th>
<th>Jw,b</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2-free</td>
<td>0.015 ± 0.004</td>
<td>0.38 ± 0.1</td>
<td>0.01 ± 0.004</td>
<td>0.2 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>(n = 8)</td>
<td>(n = 8)</td>
<td>(n = 12)</td>
<td>(n = 12)</td>
</tr>
<tr>
<td>5% CO2</td>
<td>0.07 ± 0.02</td>
<td>3.92 ± 1.1</td>
<td>0.022 ± 0.009</td>
<td>1.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>(n = 20)</td>
<td>(n = 20)</td>
<td>(n = 14)</td>
<td>(n = 14)</td>
</tr>
<tr>
<td>5% CO2 + DIDS</td>
<td>0.022 ± 0.008</td>
<td>0.55 ± 0.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>(n = 8)</td>
<td>(n = 8)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HCO3- Dependence of Acid/Base Fluxes

Fig. 3 shows an experiment where the external pH was repeatedly reduced to 7.0 at different HCO3- concentrations. The rate of intracellular acidification decreased with lower HCO3- concentrations, and it was greatly reduced in nominally CO2/HCO3- free saline. In the experiments shown, the maximum (initial) rate of pH change was 0.055 pH units/min in the presence of 5% CO2/10 mM HCO3-, which corresponds to an acid influx of 3.8 mM/min (or a base efflux of 3.8 mM/min). In the presence of 1% CO2/2 mM HCO3- the maximum rate of pH change was 0.047 pH units/min, which was calculated to be equivalent to an acid/base flux of (-) 2.3 mM/min. In the nominal absence of CO2/HCO3- (where the HCO3- concentration of the saline amounts to ~60 μM at pHo 7.0 due to the equilibration of air-CO2 in the solutions), the rate of maximum pH change was 0.018 pH units/min, corresponding to an acid/base flux of (-) 0.45 mM/min across the glial membrane. This is a flux rate about five times lower than in the presence of 1% CO2/2 mM HCO3-, and more than eight times lower than in the presence of 5% CO2/10 mM HCO3-.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Changes in pH, and membrane potential after the reduction of external pH at different external concentrations of CO2/HCO3 (5, 1, and 0% CO2). Note the different initial rates of the intracellular acidifications.
This suggests that the rates of intracellular acidification were HCO₃⁻ dependent, and reflect HCO₃⁻ efflux rather than H⁺ influx. Accordingly, they were expected to vary with pHᵢ and hence with the intracellular HCO₃⁻ concentration, too. This is evident when the acid/base fluxes as calculated from the experiment shown in Fig. 3 were plotted against pHᵢ (Fig. 4). There was a strong dependence of the transmembrane transport of acid/base equivalents on both the external HCO₃⁻ concentration and pHᵢ. The plot also shows that the different rates of acid/base flux were not simply due to the different values of the initial pHᵢ in the various salines before changing to pHₒ 7.0, when the rates of intracellular acidification were measured.

The mean maximum acid/base flux calculated from the initial pHᵢ changes was 3.92 ± 1.1 mM/min (n = 20) in the presence of 5% CO₂/10 mM HCO₃⁻, as compared with 0.38 ± 0.1 mM/min (n = 8) in the nominal absence of CO₂/HCO₃⁻ (Table II). This indicated that in the presence of CO₂/HCO₃⁻ the rate of intracellular acidification was dominated by > 90% by HCO₃⁻ efflux.

![Figure 4](https://example.com/figure4.png)

**FIGURE 4.** Dependence on pHᵢ of the rate of acid equivalent influx plotted as HCO₃⁻ efflux at different external CO₂/HCO₃⁻ concentrations as indicated.

Removal of external Cl⁻ (exchanged by glucuronate) did not affect the rate of intracellular acidification. Thus, the HCO₃⁻ efflux was not coupled to a Cl⁻ influx, as would be expected during stimulation of a Cl⁻-HCO₃⁻ exchanger.

**Effect of Ethoxzolamide**

An intracellular acidification produced by a HCO₃⁻ efflux might be dependent on the rate of HCO₃⁻ production in the cell due to carbonic anhydrase activity. This enzyme can be inhibited (irreversibly) by the membrane permeable ethoxzolamide (EZA) in leech glial cells and neurons (unpublished observations). Addition of 2 μM EZA tended to reduce the rate of intracellular acidification after lowering pHᵢ from 7.4 to 7.0 and the HCO₃⁻ concentration from 24 to 10 mM. The mean rate was decreased to 72 ± 20% (n = 7) in the presence of EZA. It should be emphasized, however, that while in some experiments the reduction of the rate of intracellular acidification, indicative of HCO₃⁻ efflux, was reduced by > 50%, in three experiments the effect of EZA on this rate was < 10%. In addition, the buffering power would be expected to change if the HCO₃⁻ production was slowed by EZA, which itself would enhance the
rate of intracellular acidification. Furthermore, the activity of carbonic anhydrase in other compartments (neurons and extracellular space) would also be inhibited by EZA, which makes it difficult to interpret the relatively small EZA effect. This is especially true since EZA also decreases the apparent buffer capacity of the extracellular spaces surrounding neurons and glial cells (Thomas, Coles, and Deitmer, 1991).

**Effect of DIDS**

In another type of experiment I tested whether the anion exchange inhibitor DIDS had an effect on the rate of intracellular acidification in the presence of CO$_2$/HCO$_3^-$ (Fig. 5). After two exposures to pH$_e$ 7.0 (Fig. 5 A), 0.5 mM DIDS was added to the saline for 10 min. This is sufficient to block the Na$^+$-HCO$_3^-$ cotransporter in these glial cells (Deitmer and Schlue, 1989; Deitmer and Szatkowski, 1990). The subsequent exposure to pH$_e$ 7.0 induced a much smaller and slower intracellular acidification (Fig. 5 B).

The mean rate of intracellular acidification in the presence of DIDS was reduced to $0.022 \pm 0.008$ pH units/min ($n = 8$). Since the buffer capacity of the glial cytoplasm was also reduced by DIDS to values found in CO$_2$/HCO$_3^-$-free salines (Deitmer, 1990, 1991), this rate of acidification indicated a maximum flux of acid/base across the glial membrane of $0.55 \pm 0.2$ mM/min. This value is close to the flux found in CO$_2$/HCO$_3^-$-free saline. Thus, DIDS completely blocked the HCO$_3^-$-dependent rate of
acidification; in other words, the $\text{HCO}_3^-$ efflux from glial cells, induced by the reduction of external pH and $\text{HCO}_3^-$ concentration, was largely DIDS sensitive. The membrane depolarization observed during the induced $\text{HCO}_3^-$ efflux was also reduced by DIDS from 16 mV to 2-5 mV. This is in line with a DIDS-sensitive electrogenic efflux of $\text{HCO}_3^-$.

Since under all experimental conditions the gradient for $\text{HCO}_3^-$ is directed outwardly, this $\text{HCO}_3^-$ efflux might be due to a high $\text{HCO}_3^-$ conductance of the glial membrane. The positive shift of the $\text{HCO}_3^-$ electrochemical potential upon reducing the external $\text{HCO}_3^-$ concentration from 24 to 10 mM briefly increases the $\text{HCO}_3^-$ outward gradient further. The membrane depolarization observed during the intracellular acidification would be in line with a high $\text{HCO}_3^-$ permeability.

Previous studies, however, did not indicate a high $\text{HCO}_3^-$ permeability of the glial membrane (Deitmer and Schlue, 1989), although a high Cl$^-$ conductance has been reported for leech glial cells (Ballanyi and Schlue, 1990; Munsch and Deitmer, 1990). Measurement of the input resistance indicated only a small change of membrane conductance (<10%) when replacing a CO$_2$/HCO$_3^-$-free saline with one containing 5% CO$_2$/24 mM HCO$_3^-$ (Munsch, T., and J. W. Deitmer, unpublished observations). This suggests that the HCO$_3^-$ conductance of the glial membrane would be rather low.

Alternatively, the high rate of HCO$_3^-$ efflux might be due to coupled ion transport via a carrier such as the electrogenic Na$^+$-HCO$_3^-$ cotransport in the glial membrane (Deitmer and Schlue, 1987, 1989), which was suggested to reverse from an inwardly directed mode to an outwardly directed mode under appropriate conditions (Deitmer and Szatkowski, 1990). If the outwardly directed cotransport was also electrogenic as was shown for the inwardly directed mode, its stimulation would cause a membrane depolarization, which indeed was observed in the present experiments. Therefore, the importance of the Na$^+$ gradient across the membrane for the rate of intracellular acidification was studied.

**Dependence of the Acid/Base Flux on the Na$^+$ Gradient**

If the efflux of HCO$_3^-$ was coupled to Na$^+$, reduction of the external Na$^+$ concentration should alter the rate of intracellular acidification in the presence of CO$_2$/HCO$_3^-$. This was tested in two types of experiments.

First, the change of the external pH to 7.0 was briefly preceded by the reduction of the external Na$^+$ concentration. Since immediately after the reduction of the external Na$^+$ concentration Na$^+$ movement out of the cell is facilitated, any Na$^+$-coupled efflux should be accelerated. This was indeed the case, as shown in Fig. 6 A. The rate of intracellular acidification was 0.053 pH units/min in normal Na$^+$ (90 mM), indicating a HCO$_3^-$ efflux rate of 2.5 mM/min, and 0.159 pH units/min 3 min after the reduction of external Na$^+$ to 1/10 (9 mM), from which a maximum HCO$_3^-$ efflux rate of 7.6 mM/min was calculated. In three other experiments of this kind similar accelerations of the initial intracellular acidification were measured 2-4 min after reducing the external Na$^+$ concentration.

Second, when the external Na$^+$ concentration was reduced for 10 min or longer, time enough for the intracellular Na$^+$ to decrease to 1-2 mM (not shown), the rate of intracellular acidification upon lowering the external pH was not altered or even
reduced in the presence of CO$_2$/HCO$_3^-$ (Fig. 6 B). Indeed, the mean maximum rate of intracellular acidification was similar in CO$_2$/HCO$_3^-$-free saline and in low external Na$^+$ with or without CO$_2$/HCO$_3^-$. The rates of intracellular acidification in pH$_0$ 7.0 were 0.02, 0.017, and 0.016 pH units/min, respectively. This type of experiment indicated that the HCO$_3^-$-independent intracellular acidification was unaffected by changing the Na$^+$ gradient.

At a very low intracellular Na$^+$, the HCO$_3^-$-dependent rate of acidification was greatly reduced. When the intracellular Na$^+$ was depleted, the presence of CO$_2$/HCO$_3^-$ did not alter the rate of intracellular acidification, suggesting that the HCO$_3^-$ efflux as such was inhibited.

This experiment was repeated with slightly different protocols; they all indicated a much reduced intracellular acidification, when the external Na$^+$ concentration had been lowered for 10–30 min.

The reduction of the external Na$^+$ concentration caused a membrane depolarization which was amplified by reducing the external pH within a few min of the Na$^+$ reduction. After a longer exposure to low external Na$^+$, however, lowering external pH not only produced a greatly slowed intracellular acidification, but also a much reduced membrane depolarization. This is in line with the suggestion that the membrane depolarization accompanying the rapid intracellular acidification was due to Na$^+$-dependent electrogenic HCO$_3^-$ efflux.

Effect of Amiloride

The experiments described above showed that the rate of intracellular acidification was dependent on the Na$^+$ gradient. To exclude that the effects might be produced by changing the activity of the Na$^+$-H$^+$ exchanger, which also runs on the Na$^+$
gradient and which was shown to exist in the glial cell membrane (Deitmer and Schlue, 1987), amiloride was applied before and during the change in external pH (Fig. 7). There was no effect of amiloride on the rate of intracellular acidification in the presence of CO$_2$/HCO$_3^-$ in these experiments ($n = 4$).

**Measurements of the Intracellular Na Activity**

The aNa$_i$ of the neuropile glial cells was $5.2 \pm 1.0$ mM ($n = 8$) in CO$_2$/HCO$_3^-$-free saline. After introduction of CO$_2$/HCO$_3^-$, aNa$_i$ increased by several millimoles/liter (Fig. 8). Often there was a transient peak before aNa$_i$ settled near 7 mM; on average, aNa$_i$ was $7.4 \pm 2.2$ mM ($n = 8$) in a saline containing 5% CO$_2$/24 mM HCO$_3^-$. The equilibrium potentials for Na$^+$ were +65 mV in the absence and +56 mV in the presence of 5% CO$_2$/24 mM HCO$_3^-$. With the membrane potentials of $-65$ and $-74$ mV in these two salines, the electrochemical gradient for Na$^+$ remained virtually constant, being 131 and 130 mV, respectively.

Reducing the pH$_o$ from 7.4 to 7.0 produced a small increase of aNa$_i$ in the CO$_2$/HCO$_3^-$-free saline (Fig. 8), which could be due to some stimulation of Na$^+$-H$^+$ exchange during the induced intracellular acidification. In the presence of CO$_2$/HCO$_3^-$, however, aNa$_i$ decreased significantly in the lowered external HCO$_3^-$ concentration (pH$_o$, 7.0), on average by $2.0 \pm 1.1$ mM ($n = 5$). Thus, the aNa$_i$ at lowered external pH (7.0) was comparable to the value measured in the absence of CO$_2$/HCO$_3^-$ at pH$_o$, 7.4 (Table I). After restoring pH$_o$ to 7.4, aNa$_i$ increased rapidly to its initial value.

*Figure 7*. The effect of amiloride on the rate of intracellular acidification after the reduction of external pH.

*Figure 8*. Changes in the aNa$_i$ (lower trace) and the membrane potential (upper trace) after the reduction of external pH from 7.4 to 7.0 in the absence and in the presence of 5% CO$_2$/HCO$_3^-$. 

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These experiments indicate that the HCO₃⁻ efflux was accompanied by a reduction of intracellular Na⁺. On the other hand, restoration of the external pH, which led to a rapid intracellular HCO₃⁻-dependent alkalinization, was accompanied by an increase in aNa⁺. The pH₂O-dependent changes in aNa⁺ strongly suggest that the fluxes of HCO₃⁻ across the cell membrane were coupled to Na⁺ movements in the same direction.

**Acid/Base Flux across the Neuronal Cell Membrane**

For comparison, some of the experiments described above were also performed while measuring pHᵢ and membrane potential from identified neurons in intact leech ganglia, such as P(ressure) cells and Retzius cells. The intracellular acidification in these neurons after a step change of external pH from 7.4 to 7.0 was also faster in the presence than in the absence of CO₂/HCO₃⁻ (Fig. 9). The mean maximum rate of intracellular acidification in Retzius neurons was 0.01 ± 0.004 pH units/min (n = 12) in CO₂/HCO₃⁻-free saline, and 0.022 ± 0.01 pH units/min (n = 14) in the presence of

![Figure 9. pHᵢ and membrane potential measurement in a Retzius neuron. The external pH was repeatedly lowered from 7.4 to 7.0 in the absence and presence of 5% CO₂/HCO₃⁻ and after the addition of 0.3 mM DIDS.](image)

5% CO₂/10 mM HCO₃⁻. This indicated acid/base fluxes of 0.2 and 1.3 mM/min, respectively (Table II). The rate of acidification in the presence of CO₂/HCO₃⁻ was somewhat reduced by DIDS (Fig. 9), but was unaffected by amiloride (not shown). This suggested that the transport of acid/base equivalents was due in part to HCO₃⁻ fluxes across the neuronal membrane.

The aNa⁺ of Retzius neurons increased upon lowering the external pH both in the absence and in the presence of CO₂/HCO₃⁻. Lowering the external Na⁺ concentration had little or no effect on the rate of intracellular acidification. It is therefore concluded that the Na⁺ gradient was not involved in driving acid equivalents across the neuronal membrane into the cells.

In Retzius neurons the membrane rapidly hyperpolarized by 7–10 mV upon lowering pH to 7.0, both in the presence and absence of CO₂/HCO₃⁻. This membrane hyperpolarization occurred even before any change in pH was observed (Fig. 9). The spontaneously firing neurons became silent and only resumed their electrical activity after restoring the external pH to 7.4. It seems that Retzius neurons are very sensitive to extracellular pH changes, a phenomenon reported for a variety of neurons.
This indicates the importance of extracellular pH changes for neuronal activity, and the demand for active regulation also of the extracellular pH.

**DISCUSSION**

This study shows that, when pH$_o$ is decreased, the rate of intracellular acidification in leech neuropile glial cells is dependent on the presence of CO$_2$/HCO$_3^-$. It is suggested that this acidification is produced by a Na$^+$-coupled HCO$_3^-$ efflux, due to an outwardly directed electrogenic Na$^+$-HCO$_3^-$ cotransport. The main evidence is the following: (a) The rate of intracellular acidification and the membrane depolarization were dependent on the external HCO$_3^-$ concentration and pH$_i$ (and hence on the intracellular HCO$_3^-$ concentration). (b) The stilbene DIDS blocked the HCO$_3^-$-dependent rate of intracellular acidification. (c) Reduction of the external Na$^+$ concentration changed the acid/base flux across the membrane in a time-dependent fashion as expected for a transport process coupled to Na$^+$ efflux. (d) The aNa$_i$ decreased during the intracellular acidification in the presence, but increased in the absence of CO$_2$/HCO$_3^-$. (e) The rate of intracellular acidification was unaffected by the removal of external Cl$^-$, or by the addition of amiloride, an inhibitor of the Na$^+$-H$^+$ exchange. The results are consistent with the conclusion that the electrogenic Na$^+$-HCO$_3^-$ cotransport, which was previously described as an inwardly directed carrier in leech glial cells (Deitmer and Schlue, 1989; Deitmer and Szatkowski, 1990) can be reversed under appropriate thermodynamic conditions.

**Factors Determining the Mode of Na$^+$-HCO$_3^-$ Cotransport**

The reversibility of this acid/base transport system appears to be a key characteristic with respect to the role of glial cells in pH regulation. The direction of acid/base transport across the glial membrane depends on the thermodynamic conditions. These are given by the gradients of H$^+$/HCO$_3^-$ and Na$^+$, the stoichiometry of the Na$^+$-HCO$_3^-$ cotransporter, and the membrane potential. For the inwardly directed Na$^+$-HCO$_3^-$ cotransport, a stoichiometry of 1 Na$^+$:2 HCO$_3^-$ was determined (Deitmer and Schlue, 1989). At steady-state values of intra- and extracellular Na$^+$ and HCO$_3^-$, this gave an equilibrium potential for Na$^+$-HCO$_3^-$ cotransport of $-90$ mV. In the present study with the somewhat modified salines (lower NaCl and higher CO$_2$/HCO$_3^-$ concentration than in our previous studies; see Deitmer and Schlue, 1987, 1989; Deitmer and Szatkowski, 1990) a stoichiometry of 1:2 would indicate an equilibrium potential of $-74$ mV, a value identical to the mean resting potential of the glial cells in the presence of 5% CO$_2$/24 mM HCO$_3^-$. This suggests that at steady state, the Na$^+$-HCO$_3^-$ cotransport is at equilibrium, where no net transport of acid/base equivalents occurs across the glial membrane.

It should be mentioned that in this preparation no distinction has been defined between a transport of two HCO$_3^-$ or one CO$_3^{2-}$ coupled to one Na$^+$ in the cotransporter. This may depend on the stoichiometry of the cotransporter, 1:2 or 1:3, as recently discussed by Boron and Boullapae (1989).

When the external pH is reduced from 7.4 to 7.0, which corresponds to a decrease in the external HCO$_3^-$ concentration from 24 to 10 mM, the Na$^+$-HCO$_3^-$ cotrans-
porter is far from equilibrium; its equilibrium potential, assuming a constant stoichiometry of 1:2, would shift from $-74$ to $-30$ mV. This would activate Na$^+$-HCO$_3^-$ cotransport in the outwardly directed mode to approach a new equilibrium. The glial membrane depolarized during this change in external pH by a mean of 20 mV from $-74$ to $-54$ mV, and pH$_i$ decreased by ~0.2 pH units.

At pH$_o$ 7.0, the pH$_i$ approached a value near 7.05, from which an equilibrium potential of the Na$^+$-HCO$_3^-$ cotransporter of $-60$ mV was calculated. This is fairly close to the mean membrane potential value in this saline ($-54$ mV). It appears, therefore, that the membrane potential and the equilibrium potential of the Na$^+$-HCO$_3^-$cotransporter come close to each other in salines of various pH and HCO$_3^-$ concentrations.

Assuming a stoichiometry of 1 Na$^+$:3 HCO$_3^-$, the equilibrium of the Na$^+$-HCO$_3^-$ cotransporter would be $-41$ mV at steady-state conditions in 5% CO$_2$/24 mM HCO$_3^-$ (pH$_o$ 7.4). This would drive Na$^+$ and HCO$_3^-$ out of the cell at the resting potential of $-74$ mV. Since there is no apparent mechanism other than the Na$^+$-HCO$_3^-$ cotransporter to maintain the glial cytoplasm alkaline (7.25) with respect to the H$^+$ equilibrium (which would be 6.13 at these conditions) a stoichiometry of 1:3 or more seems unlikely. Furthermore, returning from pH$_o$ 7.0 to 7.4 would not hyperpolarize the glial membrane and alkalinize the glial cytoplasm as much as it actually does if the stoichiometry was more than 1:2. The present experiments therefore suggest a stoichiometry of 1 Na$^+$:2 HCO$_3^-$ for both directions of the cotransporter.

It is also interesting to compare the equilibrium potentials and electrochemical gradients of the ions involved, Na$^+$ and HCO$_3^-$, in the different salines (Table I). While the Na$^+$ gradient remains virtually the same with and without CO$_2$/HCO$_3^-$, the H$^+$/HCO$_3^-$ gradient increased from 40 to 65 mV in the presence of 5% CO$_2$/24 mM HCO$_3^-$. This was suggested to be due to the activity of the Na$^+$-HCO$_3^-$ cotransporter, which is responsible for the alkaline pH$_i$ in this saline (Deitmer and Schlue, 1987, 1989).

**Occurrence of Electrogenic Na$^+$-HCO$_3^-$ Cotransport in Glial Cells**

Evidence for a DIDS-sensitive Na$^+$-HCO$_3^-$ cotransport has been presented from a variety of different types of glial cells, such as glial cells from amphibian optic nerve (Aston and Orkand, 1988) and cultured mouse oligodendrocytes (Kettenmann and Schlue, 1988), as well as in frog retinal pigment epithelium, which is part of the blood–retinal barrier and may be regarded as glial-like tissue (Hughes, Adorante, Miller, and Lin, 1989; LaCour, 1989). The stoichiometry in all these glial cells was reported to be greater than 1. In frog retinal pigment epithelium (Hughes et al., 1989) and in leech neuropile glial cells (Deitmer and Schlue, 1989) a stoichiometry of 1:2 was suggested. In kidney epithelia, a stoichiometry of 1:2 (Alpern, 1985; Jentsch, Schwartz, Schill, Langner, Lepple, Keller, and Wiederholt, 1986) and of 1:3 (Yoshitomi, Burckhardt, and Frömter, 1985; Lopes, Siebens, Giebish, and Boron, 1987; Soleimani, Grassl, and Aronson, 1987) has been reported. It is unclear whether this cotransporter occurs with different stoichiometries or different binding sites for CO$_2^-$ and/or HCO$_3^-$ (Boron and Boulpaep, 1989).

In frog retinal pigment epithelium, a reversal of the membrane response, pre-
sumed to be due to electrogenic \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransport, occurred at \(-114 \text{ mV} \) (Hughes et al., 1989). While the normal direction of the cotransport is carrying \( \text{Na}^+ \), \( \text{HCO}_3^- \), and negative charge into the cells, this direction can be reversed by strong membrane hyperpolarization or by the removal of \( \text{Na}^+ \) and/or \( \text{HCO}_3^- \). Although the equilibrium potential of the \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransporter appears more negative in frog pigment epithelium than in leech neuropile glial cells, there seems to be a remarkable similarity in the properties of the electrogenic \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransport in these two types of cells.

Functional Significance of Base Secretion from Glial Cells

If glial cells were to play a role in the regulation of extracellular (interstitial) pH, they should be able to transport acid/base equivalents across their membranes in both directions. Their ability to remove base equivalents effectively, and thereby to damp extracellular alkalosis, has been suggested to occur mainly by an inwardly directed, electrogenic \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransporter (Deitmer and Schlue, 1987, 1989). This process alkalizes the glial cell and, due to accumulation of \( \text{HCO}_3^- \), would increase their intracellular buffering power.

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Schematic diagram of the inwardly and outwardly directed (\( n = 2 \)) \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransport across the glial cell membrane, stimulated by raising or lowering external pH (\( \text{pH}_{i+} \), \( \text{pH}_{i-} \)). The outwardly directed cotransport would provide the base equivalents to neutralize protons extruded by the neurons via \( \text{Na}^+\)-\( \text{H}^+ \) exchange into the extracellular space (ecs). Thus, extracellular alkalosis and acidosis could be counteracted by uptake and secretion of \( \text{HCO}_3^- \) by glial cells. See text for further description.

The diagram in Fig. 10 summarizes the impact of inwardly and outwardly directed electrogenic \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransport across the glial membrane for the regulation of intraglial and extracellular pH. We have shown that the inward movement of \( \text{HCO}_3^- \) is stimulated not only by increasing the external \( \text{HCO}_3^- \) concentration (and/or decreasing external pH), but also by membrane depolarization, caused, for example, by a rise in extracellular \( \text{K}^+ \) or by other substances that depolarize the membrane (Deitmer and Szatkowski, 1990).

In this paper it is shown that after extracellular acidosis the electrogenic \( \text{Na}^+\)-\( \text{HCO}_3^- \) cotransporter in the glial membrane can be reversed. Base equivalents are secreted due to \( \text{HCO}_3^- \) efflux into the extracellular space. This would tend to reduce a given extracellular acid load, as may occur during neuronal activity (cf. Syková, Svoboda, Chvátal, and Jendelová, 1988; Chesler, 1990). Due to the efflux of \( \text{HCO}_3^- \) into the extracellular spaces, the buffering power in these spaces increases (Deitmer, 1991). Ammonium-induced extracellular pH transients were significantly

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reduced in the presence of $\text{CO}_2/\text{HCO}_3^-$, indicating an increased interstitial buffer capacity.

The pH regulation by leech neurons mainly involves $\text{Na}^+\cdot\text{H}^+$ exchange (Schlue and Thomas, 1985; Deitmer and Schlue, 1987). The extruded H ions from neurons would then be neutralized in the extracellular space by HCO$_3^-$ ions secreted by the glial cells (Fig. 10). Neurons take up acid or secrete base much less rapidly than glial cells, as indicated by the relatively slow intracellular acidification of Retzius neurons. Although the rate of this acidification was also higher in the presence of $\text{CO}_2/\text{HCO}_3^-$, it was still about three times lower than that in glial cells. The rate of intracellular acidification in neurons, in contrast to glial cells, was not affected by the $\text{Na}^+$ gradient. This is in accordance with the finding that neurons do not possess a $\text{Na}^+\cdot\text{HCO}_3^-$ cotransport (Deitmer and Schlue, 1987, 1989). On the other hand, Cl$^-$–HCO$_3^-$ exchange may be involved in transporting acid/base equivalents across the neuronal membrane under these conditions.

In conclusion, the electrogenic $\text{Na}^+\cdot\text{HCO}_3^-$ cotransporter of glial cells can operate in both directions, and may, depending on the thermodynamic conditions, effectively secrete or take up acid/base equivalents. Due to the membrane potential dependence of the $\text{Na}^+\cdot\text{HCO}_3^-$ cotransport (Deitmer and Szatkowski, 1990), modulators of the glial membrane potential, such as extracellular K$^+$ or neurotransmitters, could stimulate or inhibit this cotransport, and/or determine the direction of acid/base transport into or out of glial cells. This may be a key mechanism to damp ("muffle") extracellular pH changes and to contribute to the overall H$^+$ homeostasis in the nervous system.

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