Modulation of Rat Chorda Tympani NaCl Responses and Intracellular Na⁺ Activity in Polarized Taste Receptor Cells by pH

Vijay Lyall, Rammy I. Alam, Tam-Hao T. Phan, Oneal F. Russell, Shahbaz A. Malik, Gerard L. Heck, and John A. DeSimone

Department of Physiology, Virginia Commonwealth University, Richmond, VA 23298

Abstract Mixture interactions between sour and salt taste modalities were investigated in rats by direct measurement of intracellular pH (pHi) and Na⁺ activity ([Na⁺]i) in polarized fungiform taste receptor cells (TRCs) and by chorda tympani (CT) nerve recordings. Stimulating the lingual surface with NaCl solutions adjusted to pHs ranging between 2.0 and 10.3 increased the magnitude of NaCl CT responses linearly with increasing external pH (pHₑ). At pH 7.0, the epithelial sodium channel (ENaC) blocker, benzamil, decreased NaCl CT responses and inhibited further changes in CT responses induced by varying pHₑ to 2.0 or 10.3. At constant pHₑ, buffering NaCl solutions with potassium acetate/acetic acid (KA/AA) or HCO₃⁻/CO₂ inhibited NaCl CT responses relative to CT responses obtained with NaCl solutions buffered with HEPEs. The carbonic anhydrase blockers, MK-507 and MK-417, attenuated the inhibition of NaCl CT responses in HCO₃⁻/CO₂ buffer, suggesting a regulatory role for pH. In polarized TRCs step changes in apical pHₑ from 10.3 to 2.0 induced a linear decrease in pHi that remained within the physiological range (slope = 0.035; r² = 0.98). At constant pHₑ, perfusing the apical membrane with Ringer’s solutions buffered with KA/AA or HCO₃⁻/CO₂ decreased resting TRC pHi, and MK-507 or MK-417 attenuated the decrease in pHₑ in TRCs perfused with HCO₃⁻/CO₂ buffer. In parallel experiments, TRC [Na⁺]i decreased with (a) a decrease in apical pHₑ, (b) exposing the apical membrane to amiloride or benzamil, (c) removal of apical Na⁺ salts, and (d) acid loading the cells with NH₄Cl or sodium acetate at constant pHₑ. Diethylpyrocarbostyril and Zn²⁺, modification reagents for histidine residues in proteins, attenuated the CO₂-induced inhibition of NaCl CT responses and the pH₂-induced inhibition of apical Na⁺ influx in TRCs. We conclude that TRC pHₑ regulates Na⁺-influx through amiloride-sensitive apical ENaCs and hence modulates NaCl CT responses in acid/salt mixtures.

Key words: salt taste • sour taste • intracellular pH • taste mixture interaction • epithelial sodium channel

Introduction

During a meal taste receptors cells (TRCs)* are normally stimulated by mixtures of taste stimuli. Since individual TRCs generally respond to more than one class of stimuli (Gilbertson et al., 2001), their outputs reflect the interplay of intracellular processes that link the various transduction mechanisms in complex nonlinear ways. Such interactions are the source of modifications in perceived intensity and quality arising in the peripheral taste organs. Mixture interactions may give rise to either mixture suppression or enhancement. The rat chorda tympani (CT) nerve responses to Na⁺ salts are suppressed when presented together with potassium benzoate (Sato and Beidler, 1979) or potassium gluconate (Stewart et al., 1996). In contrast, CT responses to NaCl are enhanced in mixtures of mannitol or cellobiose (Lyall et al., 1999). In foods and beverages human TRCs are exposed to pHs ranging from 2.3 to 8.6 (Feldman and Barnett, 1995). Protons are not only the primary sour stimulus source (DeSimone et al., 1995, 2001a; Lyall et al., 2001, 2002), but also may play a regulatory role in the transduction of other taste modalities. Beidler (1954) and Ogawa (1969) reported that rat CT nerve responses to NaCl are inhibited at pHs below 3–4, suggesting that taste mixture interactions occur between sour taste and salt taste modalities. However, at present the physiological mechanisms involved in mixture interactions between sour taste and salt taste modalities have not been delineated.

Amiloride inhibits a significant part of the rat CT responses to NaCl, indicating that in fungiform TRCs amiloride-sensitive epithelial sodium channels (ENaCs) contribute most to the NaCl-induced increase in CT response (Lindemann, 1996, 2001; Herness and Gilbertson, 1999; Kretz et al., 1999; Lin et al., 1999; Stewart et al., 1997). Several studies indicate that protons regulate amiloride-sensitive ENaCs in a variety of epithelial cells (Lyall and Biber, 1995; Lyall et al., 1995; Garty and Palmer, 1997; Chalfant et al., 1999; Zeiske et al., 1999; Konstas et al., 2000; Howard et al., 2001). The α, β, and γ subunits of cloned ENaC expressed in Xenopus laevis...
oocytes demonstrated decreased Na\(^+\) current when intracellular pH (pH\(_i\)) was decreased, but not when extracellular pH (pH\(_e\)) was decreased (Chalfant et al., 1999). A reduction in pH\(_e\) reduced the single-channel open probability of ENaC without altering single-channel conductance (Chalfant et al., 1999; Zeiske et al., 1999). We have shown previously that weak organic acids as well as fully dissociated strong acids produce a sustained decrease in TRC pH\(_i\) (DeSimone et al., 2001a; Lyall et al., 2001, 2002). Given that acid stimulation decreases pH\(_e\), it is reasonable to hypothesize that intracellular protons also modulate the activity of TRC ENaC over a wide range of pH. If TRC ENaC is also subject to regulation by H\(^+\) ions, changes in pH could modulate CT responses to NaCl. Intracellular second messengers, cAMP and Ca\(^{2+}\), regulate salt taste (Gilbertson et al., 1993; Lin et al., 1999; Alam et al., 2002; Russell et al., 2002) and sour taste (Gilbertson et al., 1993; Lyall et al., 2002) modalities. It is likely that changes in one or more second messengers (Liu and Simon, 2001) during acid stimulation may also participate in mixture interactions and alter salt responses in bimodal TRCs.

In this paper we investigated mixture interactions between sour taste and salt taste modalities by monitoring CT responses to NaCl. Intracellular second messengers, cAMP and Ca\(^{2+}\), regulate salt taste (Gilbertson et al., 1993; Lin et al., 1999; Alam et al., 2002; Russell et al., 2002) and sour taste (Gilbertson et al., 1993; Lyall et al., 2002) modalities. It is likely that changes in one or more second messengers (Liu and Simon, 2001) during acid stimulation may also participate in mixture interactions and alter salt responses in bimodal TRCs.

In Vivo Studies

CT nerve recordings. Female Sprague-Dawley rats (150–200 g) were anesthetized by intraperitoneal injection of pentobarbital (60 mg/Kg) and supplemental pentobarbital (20 mg/Kg) was administered as necessary to maintain surgical anesthesia. Body temperatures were maintained at 36–37°C with a circulating water heating pad. The left CT nerve was exposed laterally as it exited the tympanic bulla (Ye et al., 1993, 1994; DeSimone et al., 1998) and placed onto a 32G platinum/iridium wire electrode. An indifferent electrode was placed in nearby tissue. Neural responses were differentially amplified with a custom built, optically coupled isolation amplifier. For display, neural responses were full-wave rectified and integrated with a time constant of 1 s. Integrated neural responses and current and voltage records were recorded on a Soltec (model 3314) chart recorder and also captured on disk using Labview software and analyzed off-line (DeSimone et al., 2001b; Lyall et al., 2001, 2002). Stimulus solutions were injected into a Lucite chamber (3 ml; 1 ml/s) affixed by vacuum to a 28 mm\(^2\) patch of anterior dorsal lingual surface. The chamber was fitted with separate Ag-AgCl electrodes for measurement of current and potential. These electrodes served as inputs to a voltage-current clamp amplifier that permitted the recording of neural responses with the chemically stimulated receptive field under zero current-clamp (0CC) or voltage-clamp (Ye et al., 1993, 1994). The clamp-voltages were referenced to the mucosal side of the tongue. The voltage sensitivity index (VSI) was calculated as the difference between the CT response at ~60 and 60 mV (CT~60 mV-CT~60 mV) relative to 0CC voltages (Ye et al., 1993, 1994). The anterior lingual surface was stimulated with a rinse solution containing KC\(_i\) (60 mV) and with a salt stimulus solution containing KC\(_i\) + NaCl (Table I). Amiloride (100 \(\mu\)M) or benzamil (5 \(\mu\)M) was used to block Na\(^+\) ion entry via the apical Na\(^+\) channels (Ye et al., 1993, 1994; Stewart et al., 1998).

Solutions

The composition of various rinse and stimulus solutions used in the CT experiments is given in Table I. The solutions listed in set 1 (Table I) were used to investigate the effect of pH\(_e\) on NaCl CT responses at constant osmolarity. The solution osmo-

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### Table I

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R, rinse solution; S, NaCl stimulus solution; H, HEPES; AA, acetic acid; KA, potassium acetate.

*In some solutions the NaCl was replace with 100 mM KCl or NH\(_4\)Cl.
larity was adjusted with mannitol. Mannitol by itself at these concentrations does not evoke a neural response in the rat CT (Lyall et al., 1999). The solutions listed in Table I (sets 2 and 3) were used to investigate the effect of intracellular acid loading on NaCl CT responses at constant pH and osmolarity. Some experiments were performed at high osmolarity with solutions containing 525 mM KA/H11001/30 mM AA (pH 6.1; Table I, set 2) and others at lower osmolarity with solutions containing 175 mM KA/H11001/10 mM AA (pH 6.1; Table I, set 3). The solutions listed in set 4 (Table I) were used to investigate the effect of CO2 on NaCl CT responses at constant pH and osmolarity. In some experiments both HEPES- and HCO3-/CO2-buffered solutions contained 50 mM MK-507 or MK-417 (Merck), membrane-permeable inhibitors of carbonic anhydrases (Fanous et al., 1999; Lyall et al., 2001) or 20 mM diethylpyrocarbonate (DEPC; Sigma-Aldrich), a modification reagent for histidine residues in proteins (Mankelow and Henderson, 2001; Seebungkert and Lynch, 2001).

Data Analysis

The numerical value of an integrated CT response was obtained in the quasi-steady-state part of the response as the area under the integrated CT response curve for a time interval of 1 min measured from the end of a typical 2 min stimulation period (Lyall et al., 1999, 2001, 2002; DeSimone et al., 2001a). The changes in the area under the integrated NaCl CT response curves under different conditions were normalized to the responses observed in each animal to 300 mM NH4Cl (CTNaCl/CTNH4Cl) and were expressed as the mean ± SEM of N, where N represents the number of animals in each group; M ± SEM (N). Student’s t test was employed to analyze the differences between sets of data.

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R, Ringer’s solution; RC, control Ringer’s solution; NaA, sodium acetate; H, HEPES; CS, pH calibrating solutions.

a In some solutions NaCl was replaced by 150 mM Tris-HCl.

b In some experiments the pHs of RC and R0Na+ were adjusted to 4.4.
**In Vitro Studies**

**pH measurement.** Rats were anesthetized with isoflurane and killed by cervical dislocation. The tongues were rapidly removed and stored in ice-cold Ringer’s solution (R; Table II, set 1). The lingual epithelium was isolated by collagenase treatment (Lyall et al., 1995). A small piece of the anterior lingual epithelium containing a single fungiform papilla was mounted in a special microscopy chamber (Chu et al., 1995) as described before (Lyall et al., 2001, 2002; DeSimone et al., 2001a). The tissue was intermittently perfused with Ringer’s solution (R; Table II, set 1) containing 25 μM of the pH-sensitive fluorophore BCECF-AM (Molecular Probes) at 4°C for 2 h. Before the experiment was started, the tissue was perfused on both sides with control solution for 15 min. The control solution was Ringer’s solution without Na-pyruvate (RC; Table II, set 1). The tissue was continuously perfused at the rate of 1 ml/min and the solution changes in the apical or basolateral compartment were made using three way miniature LFAA solenoid valves (The Lee Company). The TRCs in the taste bud were visualized from the basolateral side through a 40× objective (ZEISS; 0.9 NA) with a dichroic beam splitter (Omega Optical), and a 510 nm emission filter (20 nm band pass; Omega Optical). The cells were alternately excited with a set up consisting of: a cooled CCD camera (Imago, TILL Photonics; Applied Scientific Instrumentation) attached to an image intensifier (VS4–1845; Videoscope), an epifluorescent light source (TILL Photonics Polyévolve IV), a 515 nm dichroic beam splitter (Omega Optical), and a 535 nm emission filter (20 nm band pass; Omega Optical). The cells were alternately excited at 490 and 440 nm and imaged at 10-s intervals. Small regions of interest (ROIs) in the taste bud (diameter 2–3 μm band pass) were chosen in which the changes in FIR (fluorescence intensity ratio; F490/F440) were analyzed using TILLvisION v3.1 imaging software. Each ROI contained 2–3 receptor cells. Thus, the fluorescence intensity recorded for a ROI represents the mean value from 2–3 receptor cells within the ROI. In a typical experiment the FIR measurements were made in an optical plane in the taste bud containing at least six ROIs (~18 cells). The background and autofluorescence at 490 and 440 nm were corrected from images of a taste bud without the dye. The changes in TRC pH, were calibrated by bilateral perfusion of high K⁺ calibrating solutions containing 10 μM nigericin (CS; Table II, set 5) adjusted to pHs between 6.5 and 8.0 (DeSimone et al., 2001b; Lyall et al., 2001, 2002).

\[ [Na⁺] \text{ measurement.} \] We measured relative changes in intracellular sodium activity ([Na⁺]) in polarized TRCs by loading the tissue with the sodium-sensitive fluoroprobes sodium green or SBFI (both from Molecular Probes). Tissue was loaded with sodium green AM (30 μM) at 4°C for 2 h. The tissue was loaded with SBFI-AM (10 μM) in the presence of 0.15% pluronic at room temperature for 4 h. Before the experiment was started, the tissue was perfused on both sides with control solution (RC) for 15 min. In sodium green–loaded cells the changes in [Na⁺] were monitored by exciting the cells at 490 nm and the emitted light was imaged at 535 nm at 10-s intervals. Sodium green is ideal for studying the effects of amiloride, which emits strongly in the long wave length UV light. Since it is a single wavelength dye its emission can be affected by factors such as dye bleaching, dye leakage from the cells, changes in focal plane, and variations in cell volume (Xu et al., 1995). The SBFI-loaded TRCs were alternately excited at 430 and 380 nm and imaged at 10-s intervals. The emitted light was detected with a set up containing a 430 nm dichroic beam splitter (Omega Optical), and a 510 nm emission filter (20 nm band pass; Omega Optical). The changes in FIR are independent of dye bleaching, dye leakage from the cells, changes in focal plane, and variations in cell volume. The fluorescence of SBFI (Diarrá et al., 2001) and sodium green (Xu et al., 1995) is pH independent. All experiments were done at room temperature (~22°C).

**Data analysis.** The changes in TRC pH, were expressed as the mean ± SEM of N; where N represents the number of ROIs within the taste bud; M ± SEM (N). In TRCs loaded with sodium green the changes in [Na⁺], were expressed relative to the fluorescence intensity (F490) under control conditions. The F490 under control conditions for each ROI was taken as 100%. For TRCs loaded with SBFI, the relative changes in FIR (F490/F440) were compared between different ROIs under different conditions. The data were also presented as the mean ± SEM from different tissue preparations. In this case N represented the number of taste buds. Student’s t test was employed to analyze the differences between sets of data.

**Solutions**

The composition of various Ringer’s solutions used in the in vitro experiments is given in Table II. In some experiments the apical or basolateral perfusion solutions contained either MK-417 or MK-597 (Merck), membrane-permeable inhibitors of carbonic anhydrases (Fanous et al., 1999; Lyall et al., 2001). The drugs were used at lower concentrations when applied from the basolateral side.

**Results**

**Effect of external pH (pHₑ) on NaCl CT responses** Under physiological conditions TRCs are exposed to wide variations in pH (Feldman and Barnett, 1995). We investigated if changes in pH alter neural responses to NaCl stimulation. The CT responses were monitored while the tongue was stimulated with 100 mM NaCl solutions adjusted to pH 2.0, 7.0, and 10.3. In Fig. 1 the lingual surface was perfused with a rinse solution R7 (pH 7; Table I, set 1) and the CT activity was taken as baseline. At pH 2.0 (Table I, set 1) increased CT activity (upward deflection in the CT trace; a and b). Replacing S7 with a similar NaCl stimulus solution S2, containing 10 mM HCl (pH 2.0; Table I, set 1) decreased the CT response (upward deflection in the CT trace; a and b). Upon reperfusing the CT activity returned to baseline (d and e). In the next step, replacing R7 with a similar rinse solution R2, containing 10 mM HCl (pH 2.0, Table I, set 1) reversely increased the CT activity (e–g). This increase in CT response is due to the presence of HCl in the rinse solution, R2 (DeSimone et al., 1995; Stewart et al., 1998; Lyall et al., 2001, 2002). The NaCl CT responses were normalized to the response observed in each animal to 300 mM NH₄Cl (CTNaCl/CTNH₄Cl). In five experiments, replacing S7 with S2 decreased the magnitude of the NaCl CT response from 0.71 ± 0.03 to 0.60 ± 0.04 (Δ = -0.11 ± 0.01), a decrease of 16.1 ± 1.9% (P < 0.01) with respect to its activity in S7. In the same experiments replacing R7 with R2 increased CT activity by 0.17 ± 0.01 (n = 5). If there
The tongue was initially perfused with rinse (R7) solution containing 10 mM KCl (i.e., under zero current clamp; 0CC). The tongue was initially grated CT responses were recorded under open-circuit conditions containing 10 mM KCl mannitol and then with the NaCl stimulus solution (S7) containing 10 mM KCl + 100 mM NaCl (a and b). Both R7 and S7 were buffered to pH 7.0 with HEPES. In the second step, S7 was replaced with the NaCl stimulus solution S2 (b and c). In the final step, R7 was replaced with the rinse solution R2 (c and f). Both R2 and S2 were adjusted to pH 2.0 with 10 mM HCl (without HEPES).

Subsequently, perfusing the tongue with the NaCl stimulus solution S2 (pH 2.0; Table I, set 1) produced a further increase in the CT response at 0CC (0.68 ± 0.02; P < 0.01; paired; N = 7; black bar 1). In five animals the CT responses were also recorded under lingual voltage-clamp conditions. The mean normalized CT response at 0CC (0.68 ± 0.03) increased to 0.90 ± 0.04 (black bar 2) at −60 mV (ΔCT = 0.22 ± 0.02; P < 0.01) and decreased to 0.46 ± 0.03 at 60 mV (ΔCT = −0.22 ± 0.02; P < 0.01; paired; N = 5; black bar 3).

At pH 7.0 the VSI (CT−60 mV/CT+60 mV) was 0.44 ± 0.02. Also shown in Fig. 2 (left) are the CT responses when both the rinse and the NaCl stimulus were applied at pH 2.0. Replacing the rinse solution R7 (pH 7.0; Table I, set 1) with the rinse solution R2 (pH 2.0; Table I, set 1) increased the CT response. This increase in CT response is due to the presence of HCl in R2 (DeSimone et al., 1995; Stewart et al., 1998; Lyall et al., 2001, 2002). Subsequently, perfusing the tongue with the NaCl stimulus solution S2 (pH 2.0; Table I, set 1) produced a further increase in CT response under 0CC. If there was no interaction between HCl and NaCl at the level of TRCs, one would predict that the CT responses would be additive. However, the magnitude of the CT response (S2-R2 at 0CC) was decreased by 50% relative to the CT response at pH 7.0 (S7-R7 at 0CC). At pH 2.0, the NaCl CT response was significantly less voltage-sensitive relative to pH 7.0 (compare middle panel). The data from several animals are also summarized in Fig. 3. At pH 2.0 the mean normalized CT response to 100

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**Figure 1.** Effect of pH on the NaCl CT responses. The integrated CT responses were recorded under open-circuit conditions (i.e., under zero current clamp; 0CC). The tongue was initially perfused with rinse (R7) solution containing 10 mM KCl + 300 mM mannitol and then with the NaCl stimulus solution (S7) containing 10 mM KCl + 100 mM NaCl (a and b). Both R7 and S7 were buffered to pH 7.0 with HEPES. In the second step, S7 was replaced with the NaCl stimulus solution S2 (b and c). In the final step, R7 was replaced with the rinse solution R2 (c and f). Both R2 and S2 were adjusted to pH 2.0 with 10 mM HCl (without HEPES).

**Figure 2.** Effect of pH on the voltage sensitivity of the NaCl CT responses. The lingual surface was perfused with rinse (R) solutions containing 10 mM KCl + 200 mM mannitol and stimulus (S) solutions containing 10 mM KCl + 100 mM NaCl adjusted to pH 2.0 (R2 and S2; left), 7.0 (R7 and S7; middle), and 10.3 (R10.3 and S10.3; right). Integrated CT responses were recorded under open-circuit conditions (i.e., under zero current clamp; 0CC), at −60 mV, and at 60 mV lingual voltage-clamp. The NaCl CT responses were voltage-sensitive. The CT responses were enhanced at −60 mV and suppressed at 60 mV voltage-clamp relative to 0CC. Also shown are the CT responses to 0.3 M NH4Cl test pulses before and after the experiment.
mM NaCl at 0CC was 0.35 ± 0.02 (N = 6; gray bar 1). This value is significantly less than the corresponding value (0.68 ± 0.02) at pH 7.0 (P < 0.001; unpaired). In five animals the CT responses were also recorded under lingual voltage-clamp conditions. The mean normalized CT response at 0CC (0.33 ± 0.02) increased to 0.43 ± 0.02 at −60 mV (ΔCT = 0.10 ± 0.01; P < 0.025; gray bar 2) and decreased to 0.19 ± 0.01 at 60 mV (ΔCT = −0.14 ± 0.02; P < 0.025; paired; N = 5; gray bar 3). Thus lowering the NaCl stimulus solution pH from 7.0 to 2.0 decreased mean normalized NaCl CT response by 48.5% and decreased the VSI from 0.44 ± 0.02 to 0.24 ± 0.02, a decrease of 45.4 ± 4.5% (P < 0.001; N = 5).

Also shown in Fig. 2 (right) are the CT responses when both the rinse and the stimulus solutions were applied at pH 10.3. Replacing rinse solution R7 (pH 7.0; Table I, set 1) with rinse solution R10.3 (pH 10.3; Table I, set 1) did not alter the baseline CT response. Subsequently, perfusing the tongue with the NaCl stimulus solution S10.3 (pH 10.3; Table I, set 1) increased the CT response above baseline under 0CC. However, the magnitude of the CT response (S10.3-R10.3 at 0CC) was increased by 50% relative to CT response at pH 7.0 (S7-R7 at 0CC). At pH 10.3, the NaCl CT response demonstrated greater voltage-sensitivity relative to pH 7.0 (compare middle panel). The data from several animals are also summarized in Fig. 3. At pH 10.3 the mean normalized CT response to 100 mM NaCl at 0CC was 0.82 ± 0.06 (N = 5; hatched bar 1) and was significantly greater than the corresponding value at pH 7.0 (0.68 ± 0.02; P < 0.01; unpaired). In four animals the CT responses were also recorded under lingual voltage-clamp conditions. The mean normalized CT response (0.80 ± 0.07) increased to 1.16 ± 0.08 at −60 mV (hatched bar 2) and decreased to 0.51 ± 0.04 at 60 mV (hatched bar 3). Thus increasing the pH from 7.0 to 10.3 increased mean NaCl CT response by 20.6% and increased the VSI from 0.44 ± 0.02 (N = 5) to 0.65 ± 0.05 (N = 4), an increase of 47.7%. When the NaCl CT responses were monitored over the entire range of pH between 2.0 and 10.3, the normalized NaCl CT responses demonstrated a linear relationship with pHo (Fig. 4, filled circles; slope = 0.06; r² = 0.99).

We further investigated if changes in pHo also affect CT responses to KCl and NH4Cl. The CT responses were recorded under 0CC while the tongue was stimulated with 100 mM NaCl, 100 mM KCl, and 100 mM NH4Cl solutions adjusted to pH 2.0, 7.0, and 10.3 (Table I, set 1). In a representative experiment (unpublished data), at pH 2.0, 7.0, and 10.3, the mean normalized CT responses to NaCl increased linearly with increasing pH and were 0.46, 0.62, and 0.77, respectively. The responses to 100 mM KCl at the same pHs were 0.55, 0.34, and 0.34, respectively. And the responses to 100 mM NH4Cl at the same pHs were 0.70, 0.68, and
0.67, respectively. These results indicate that unlike NaCl, the KCl- and NH₄Cl-induced CT responses are pH insensitive.

As described in detail previously (Ye et al., 1993, 1994), we tested the responses to two reference stimuli, namely, 0.3 M NaCl and NH₄Cl before and after the experiment. The data from an experiment were accepted if the CT responses to the above two reference stimuli did not differ by >10% before and after the experiment. In the data shown in Fig. 2, the responses to 0.3 M NH₄Cl before and after stimulating the tongue repeatedly with NaCl solutions buffered to pH 2, 7, and 10.3 did not differ by >3%.

Effect of Benzamil on NaCl CT Responses

Consistent with our previous studies (Stewart et al., 1998), the addition of 5 μM benzamil to R7 (pH 7.0) did not alter the baseline CT activity. Subsequent perfusion of S7 + benzamil produced an increase in NaCl CT response. However, the magnitude of the response in the presence of benzamil was significantly smaller as compared with control. The effect of benzamil on several animals is also summarized in Fig. 3. At pH 7.0, the mean normalized CT response to 100 mM NaCl at 0CC in the presence of benzamil was 0.32 ± 0.03 (N = 4; black bar 1). The CT response increased to 0.37 ± 0.06 at −60 mV (black bar 2) and decreased to 0.22 ± 0.02 at +60 mV (P > 0.05; black bar 3). The VSI was 0.15 ± 0.04. Thus at pH 7.0, benzamil decreased the mean normalized NaCl CT response by 53.4% and decreased the VSI by 67.4% relative to control. These effects of benzamil are consistent with its known role as a blocker of ENaCs (Lyall et al., 1993, 1995; Lyall and Biber, 1995; Stewart et al., 1998).

Data shown in Fig. 5 demonstrate that at pH 7.0, the benzamil-induced inhibition of NaCl CT response (left) are comparable in magnitude to the inhibition observed by decreasing the pH of the NaCl stimulus solution from 7.0 to 2.0 in the absence of benzamil in the same animal (right). The mean normalized CT responses at pH 2.0 under 0CC (0.31 ± 0.02) were not significantly different from CT responses at pH 7.0 in the presence of benzamil (0.32 ± 0.03; P > 0.05; N = 4). Similarly, the mean VSI at pH 2.0 (0.16 ± 0.03) was not significantly different from its corresponding value (0.14 ± 0.04) at pH 7.0 in the presence of benzamil. Data summarized in Fig. 3 also show that in the continuous presence of benzamil, applying the stimulus at pH 2.0 (switching from R2 to S2) did not demonstrate any further suppression of the NaCl CT response. Furthermore, in the absence of benzamil, no significant changes were observed in the VSI at pH 2.0. In additional experiments, 100 μM amiloride inhibited the NaCl CT response at pH 7.0 and in the continuous presence of amiloride, applying the stimulus at pH 2.0, did not produce further suppression in the NaCl CT response (unpublished data). These results indicate that a decrease in pH inhibits most of the amiloride- and benzamil-sensitive component of the NaCl CT response. The data further indicate that the amiloride-insensitive component of the CT response is pH-insensitive.

In three animals, in the presence of benzamil, the mean normalized NaCl CT responses at pH 10.3 under 0CC, −60 mV, and 60 mV were 0.30 ± 0.04, 0.36 ± 0.07, and 0.27 ± 0.01, respectively (Fig. 3). These values are close to those obtained with benzamil at pH 2.0 or 7.0. The data indicate that in the presence of benzamil increasing the pH from 7.0 to 10.3 induced no enhancement in the NaCl CT response. In addition, no enhancement of the VSI was observed at pH 10.3 in the presence of benzamil. Together, these results suggest that the effects of pHo on the NaCl CT responses are due to the modulation of ENaC activity by H⁺ ions.

Effect of Membrane Permeable Weak Acids on NaCl CT Responses

To investigate if changes in NaCl CT responses are due to the changes in TRC pH, further experiments were done in which both the rinse and stimulus solutions were maintained at constant pHo, by buffering the solutions with weak organic acids, acetic acid (AA; Table I, sets 2 and 3) or CO₂ (Table I, set 4) and their corresponding potassium salts, potassium acetate (KA) or KHCO₃ (Lyall et al., 2001).
Studies with Acetic Acid

Data summarized in Fig. 6 A show that switching from the rinse solution HRH6.1 (pH 6.1; Table I, set 2) to the NaCl stimulus solution HSH6.1 (pH 6.1; Table I, set 2) increased the NaCl CT response. For this experiment the area under the CT response curve for a time interval of 1 min measured from the end of the 2-min stimulation period was taken as 100%. In the second step, switching from HRH6.1 to HRAA6.1 (pH 6.1; Table I, set 2), increased the CT response. This increase in CT response is presumably due to the passive influx of membrane-permeable undissociated AA in the rinse solution across the apical membranes of TRCs (Lyall et al., 2001). Subsequently, stimulating with the NaCl stimulus solution HSAA6.1 (pH 6.1; Table I, set 2) increased the CT response further. This increase in CT response is due to the presence of NaCl in HSAA6.1. However, the magnitude of the NaCl CT response in the presence of AA (HSAA6.1-HRAA6.1) was 1/0.40% less than the corresponding NaCl CT response in the presence of HEPES (HS6.1-HRH6.1). Some experiments were also performed at a lower AA concentration. In this case both the rinse and stimulus solutions contained 175 mM KA and the solutions were buffered to pH 6.1 with either 10 mM HEPES (LRH6.1 and LSH6.1) or 10 mM AA (LRAA6.1 and LSAA6.1) (Table I, set 3). The data from several animals are summarized in Fig. 6 B. In the presence of 175 mM KA + 10 mM AA (pH 6.1) the mean normalized NaCl CT responses decreased from 0.71 ± 0.02 (N = 9) to 0.62 ± 0.06 (N = 3), an inhibition of 12.7 ± 4.0% of control. However, in the presence of 525 mM KA + 30 mM AA (pH 6.1) the NaCl CT response decreased to 0.45 ± 0.03, an inhibition of 36.3 ± 3.8% of control (P < 0.005; N = 5; paired). These results indicate that AA induces a dose-dependent inhibition of NaCl CT responses.

Studies with CO₂

Data summarized in Fig. 7 A show that switching from the rinse solution RH7.4 (pH 7.4; Table I, set 4) to the NaCl stimulus solution SH7.4 (pH 7.4; Table I, set 4) increased the NaCl CT response. For this experiment, the area under the NaCl CT response curve for a time interval of 1 min measured from the end of the 2-min stimulation period was taken as 100%. In the second step, switching from the rinse solution RH7.4 to the rinse solution RCO27.4 (pH 7.4; Table I, set 4) increased the CT response. This increase in CT response most probably involves the passive diffusion of dissolved CO₂ across the apical membranes of TRCs and the generation of intracellular H₂CO₃ in a reaction catalyzed by carbonic anhydrases (Lyall et al., 2001). Subsequently, stimulating with the NaCl stimulus solution SCO27.4 (pH 7.4; Table I, set 4) increased the CT response further. This increase in CT response is due to the presence of NaCl in SCO27.4. However, the magnitude of the NaCl CT response in the presence of CO₂ (SCO27.4-RCO27.4) was 1/0.40% less than the corresponding NaCl CT response in the presence of HEPES (SH7.4-RH7.4). The coupling between pH, and the CT responses to NaCl is, therefore, seen to be independent of the acid used, pHo, and osmolarity.

Studies with Carbonic Anhydrase Blockers

We applied 50 mM MK-507 (dissolved in the rinse solution RH7.4; Table I, set 4), a specific blocker of car-
Histidine residues in the cytoplasmic NH₂ terminus of the α-ENaC have been suggested to be potential candidates for its pH-sensitivity (Chalfant et al., 1999). To investigate if changes in pH exert their effects by interacting directly with histidine residues in TRC ENaC, we tested the effect of DEPC and Zn²⁺, modification reagents for histidine residues in proteins (Mankelow and Henderson, 2001; Seebungkert and Lynch, 2001), on NaCl CT responses. Fig. 7 A shows that, similar to the data in Fig. 7 A, stimulating the tongue with 100 mM NaCl solution buffered with HCO₃⁻/CO₂ (pH 7.4) produced NaCl CT response (SCO₂7.4-RCO₂7.4) that was ~40% smaller than the corresponding CT response obtained with stimulating the tongue with NaCl solution buffered with HEPES (SH7.4-RH7.4). After this, we applied 20 mM DEPC (dissolved in the rinse solution RH7.4) topically to the lingual surface for 10 min. DEPC had no effect on the NaCl CT response obtained by stimulating the tongue with NaCl solution buffered with HEPES (SH7.4-RH7.4). However, in the continuous presence of DEPC, stimulating the tongue with NaCl solutions buffered with HCO₃⁻/CO₂ (pH 7.4) did not show any inhibition of NaCl CT response, i.e., the CO₂ response (SCO₂7.4-RCO₂7.4) and the NaCl response (SCO₂7.4-RCO₂7.4) were additive (Fig. 8 B). The effects of DEPC were completely reversible. Perfusing the tongue with RH7.4 without DEPC for 10 min (Fig. 8 C) again produced NaCl CT response in HCO₃⁻/CO₂ buffer (SCO₂7.4-RCO₂7.4) that was ~40% smaller than the corresponding response (SH7.4-RH7.4) in HEPES buffer. Similar results were obtained with 20 mM ZnCl₂ (unpublished data). The data from several animals are also summarized in Fig. 7 C. In three animals the magnitude of the CT responses obtained by stimulating the tongue with NaCl solutions buffered to pH 7.4 with HEPES were not different (P > 0.05) from corresponding CT responses obtained by stimulating with NaCl solutions buffered with HCO₃⁻/CO₂ after DEPC treatment. These results suggest that agents that modify histidine residues in TRC ENaC sub-
units prevent the CO_2-induced decrease in NaCl CT responses.

In the above experiment the tongue was preadapted to HCO_3^-/H_2CO_3/CO_2 buffer (pH 7.4) subsequent to stimulating the tongue with the NaCl solutions also buffered to pH 7.4 with HCO_3^-/H_2CO_3 buffer. However, during a meal rapid changes in pH may occur due to the presence of weak organic acids in food. Thus, under physiological conditions, pH_i variations occur without any intermediate preadaptation steps. Therefore, we further examined if a decrease in the NaCl CT response also occurs if CO_2 and NaCl are coapplied at a fixed pH (7.4) without preadapting the tongue to CO_2 first.

These results are shown in Fig. 9. As shown above, replacing the rinse solution RH7.4 with the NaCl stimulus solution SH7.4 increased the CT response relative to the baseline under open-circuit conditions (i.e., under zero current-clamp; 0CC). Upon perfusing the tongue with SH7.4 the CT response increased to its original steady-state level (c and d). Upon perfusing with RH7.4 the CT response decreased to the original steady-state level (e and f). Upon reperfusing with RH7.4 the CT response began to increase (g). Upon reperfusing with RH7.4 the CT response returned to baseline (h).

In vitro Studies

To correlate pH dependence of the NaCl CT responses with changes in pH_i, we further tested if the above conditions that induce alteration in NaCl CT responses also cause parallel changes in resting TRC pH_i.

Figure 8. Effect of DEPC on CO_2-induced NaCl CT responses. (A) CT responses were recorded while the lingual surface was perfused with rinse (RH) solution containing 72 mM KCl + 200 mM mannitol and with stimulus (SH) solution containing 72 mM KCl + 100 mM NaCl. Both the rinse (RH7.4) and stimulus (SH7.4) solutions contained, in addition, 10 mM HEPES and the pH was adjusted to 7.4 with KOH. In the second part of the experiment, the rinse (RCO_27.4) and the stimulus (SCO_27.4) solutions were buffered to pH 7.4 with 72 mM KHCO_3/10% CO_2. (B) The lingual surface was treated with 20 mM DEPC for 10 min and the CT responses were recorded using the same protocol as in A. (C) The lingual surface was perfused with rinse solution without DEPC (RHT.4) for 10 min and the CT responses were recorded using the same protocol as in A.

Figure 9. Effect of CO_2 on the NaCl CT responses without preadaptation. The integrated CT responses were recorded under open-circuit conditions (i.e., under zero current-clamp; 0CC). The tongue was initially perfused with the rinse solution RH7.4 and then with the NaCl stimulus solution SH7.4 (a-b). Both RH7.4 and SH7.4 were buffered to pH 7.4 with HEPES. In the second step, SH7.4 was replaced with the NaCl stimulus solution SCO_27.4 (b-c). In the final step, RH7.4 was replaced with RCO_27.4 (c and d). Both RCO_27.4 and SCO_27.4 were buffered to pH 7.4 with HCO_3^-/CO_2.

Studies with HCl. Fig. 10 A shows that in polarized TRCs perfused with control Ringer’s solution (RC; pH 7.4; Table II, set 1), decreasing the apical solution pH to 2.0 (RHC1; Table II, set 1) reversibly decreased resting pH_i from 7.46 ± 0.01 to 7.10 ± 0.02 (ΔpH_i = −0.35 ± 0.03; N = 5; P < 0.001, paired) and an increase in the apical solution pH from 7.4 to 10.3 (RTris; Table II, set 1) reversibly increased pH_i from 7.34 ± 0.01 to 8.02 pH Modulates Chorda Tympani Responses to NaCl

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Varying the pH of the rinse solution between 10.3 and 2.0 decreased TRC pHi from 7.35 ± 0.01 to 7.05 ± 0.01 (N = 6), indicating that during acid taste transduction, changes in TRC pHi remain within the physiological range. The mean changes in TRC pHi in several tissues induced by variations in pH of are also plotted in Fig. 4 (slope = 0.035; $r^2 = 0.95$). The data show that the NaCl CT responses are linearly related to changes in TRC pH.

The mean change in TRC pH for a given change in pH of ($\Delta$pH$_i$/$\Delta$pH$_o$) was 0.065 for the data shown in Fig. 10 A and 0.049 for the data shown in Fig. 10 B. The slope of the relationship between pH$_o$ and pH$_i$ was 0.035 (Fig. 4). These results indicate that both apical cell membrane and the paracellular shunt pathway restrict H$^+$ entry such that a large change in apical pH is translated into a relatively small change in TRC pH that remains within the physiological range (Lyall et al., 2001, 2002). In parallel experiments, a step change in the rinse solution pH from 7.0 to 10.3 did not induce changes in CT responses (Fig. 2, right); however, a step change in rinse solution pH from 7.0 to 2.0 induced an increase in CT nerve activity (Fig. 2).

Studies with CO$_2$

Fig. 11 shows that in polarized TRCs initially perfused with Ringer’s solution buffered to pH 7.4 with HEPES, switching to a similar solution buffered with NaHCO$_3$/CO$_2$ (RCO$_2$; pH 7.4; Table II, set 2) in the apical compartment induced a rapid and reversible decrease in TRC pH$_i$ (a and b) from 7.16 ± 0.01 to 6.85 ± 0.01 ($\Delta$pH$_i$ = 0.31 ± 0.01; N = 6; P < 0.001; paired). In three polarized TRC preparations CO$_2$ decreased pH$_i$ by 0.26 ± 0.03 pH unit (P < 0.025; paired). In the experiment shown in Fig. 11, perfusing the basolateral side with 10 mM MK-417, a membrane permeable blocker of carbonic anhydrases, increased TRC pH$_i$ (c and d) from 7.11 ± 0.01 to 7.24 ± 0.01 ($\Delta$pH$_i$ = 0.13 ± 0.03; P < 0.025). However, in the continuous presence of MK-417, switching from HEPES-buffered solution (RC) to the HCO$_3$/CO$_2$-buffered solution (RCO$_2$) decreased pH$_i$ (d and e) from 7.24 ± 0.01 to 7.11 ± 0.01 ($\Delta$pH$_i$ = 0.13 ± 0.01; N = 6; P < 0.001). Thus MK-417 inhibited the dissolved CO$_2$-induced decrease in TRC pH$_i$ by 61.6%. Since in our in vivo studies (compare Fig. 7 B) the drug was applied topically to the lingual surface, we also tested if the apical application of MK-417 also inhibits CO$_2$-induced decreases in TRC pH$_i$. In another tissue, switching from HEPES-buffered solution to the HCO$_3$/CO$_2$-buffered solution in the apical compartment decreased pH$_i$ from 7.17 ± 0.002 to 6.94 ± 0.002 ($\Delta$pH$_i$ = 0.23 ± 0.002; N = 6; P < 0.001). After this, the apical membrane was perfused with...
HEPES-buffered solution (pH 7.4) containing 40 mM MK-417 for 15 min. Upon switching to a similar solution buffered with HCO3-/CO2 (pH 7.4; also containing MK-417) in the apical compartment decreased TRC pHi from 7.07 ± 0.003 to 6.98 ± 0.001 (ΔpHi = 0.09 ± 0.003; N = 6; P < 0.001). Thus, in the presence of apical 40 mM MK-417, the dissolved CO2-induced decrease in TRC pHi was inhibited by 60%. Similar results were obtained with MK-507 (unpublished data).

Studies with Acetic Acid

The polarized TRCs were initially perfused on the apical side with a solution containing 150 mM NaA and buffered to pH 6.3 with MOPS (RNaA1; Table II, set 4) while the basolateral side was perfused with a control Ringer’s solution (pH 7.4; RCM). Replacing the apical solution with a similar solution containing 150 mM NaA buffered to pH 6.3 with AA (RNaA2; Table II, set 4) induced a small but significant decrease in TRC pHi (Fig. 12, a and b). In the second step replacing 150 mM NaA + 600 mM mannitol (Man; RMOPS1; Table II, set 4) with a similar solution (RMOPS2; Table II, set 4) containing 450 mM NaA (both solutions were buffered to pH 6.3 with AA) induced an approximately twofold greater decrease in TRC pHi (d and e). It is interesting to note that increasing the osmolarity of the 150 mM NaA solution with 600 mM mannitol induced a small increase in TRC pHi (c and d). It is likely that this increase in pHi is related to the cell shrinkage-induced activation of the basolateral Na+/H+ exchanger (unpublished data).

In parallel experiments (compare Fig. 6), giving the NaCl stimulus with AA inhibited NaCl CT responses (HSAA6.1-HRAA6.1) relative to control (HSIH6.1-HRH6.1). Both the magnitude of AA-induced inhibition of the NaCl CT response and the magnitude of the AA-induced decrease in TRC pHi were greater at higher AA concentrations. These data are consistent with the hypothesis that at constant pHo, the presence of weak acids in the apical solution induces a decrease in TRC pHi, which then acts as a modifier of cell function. To correlate pH dependence of NaCl CT responses with changes in pHi, we further tested if the above conditions that induce alteration in NaCl CT responses and pHi also cause parallel changes in resting [Na+], in polarized TRCs.

SBFI Loading

Fig. 13 A shows the transmitted image of a fungiform papilla containing a single taste bud mounted in the microscopy chamber. The taste bud was viewed from the basolateral side with a 40× water immersion objective. Fig. 13, B and C, show the image of the same taste bud excited at 340 and 380 nm, respectively. The resulting ratio image (F340/F380) is shown in Fig. 13 D. Fig. 13 shows that SBFI is specifically taken up by the TRCs within the papilla and is excluded from the surrounding epithelial cells. However, squamous epithelial cells on the papillary periphery also absorb the dye. Measurements of F340/F380 changes were made exclusively from the dye-loaded TRCs and reflect relative changes in TRC [Na+]. Similar to SBFI, the single wavelength dye, sodium-green, was also specifically taken up by the TRCs within the papilla (unpublished data). We have demonstrated previously that the pH-sensitive fluoro-probe, BCECF, is also taken up specifically by the TRCs within the fungiform papilla (Lyall et al., 2001, 2002). Therefore, both changes in [Na+] and pHi reflect changes within TRCs.

Effect of Amiloride and Benzamil on TRC [Na+]

We monitored changes in resting [Na+] in polarized TRCs loaded with SBFI. Fig. 14 A shows that in TRCs perfused with Ringer’s solution, decreasing apical Na+ to zero (150 mM NaCl was replaced with an equivalent amount of Tris-HCl; R0Na+; Table II, set 1) reversibly decreased FIR (F340/F380), indicating a reversible decrease in TRC [Na+]. Similar results were obtained when NaCl was replaced with NMDG-Cl (compare Fig. 20). In TRCs loaded with sodium-green (Fig. 14 B), perfusing the apical membrane with control Ringer’s solution (RC; Table II, set 1) containing amiloride decreased fluorescence intensity, F000, indicating a decrease in resting [Na+], (a and b). In the continuous
presence of amiloride, decreasing the apical Na\(^+\) concentration from 150 mM to zero (150 mM NaCl was replaced with an equivalent amount of NMDG-Cl; R0Na\(^+\); Table II, set 1) further decreased \(F_{490}\) (Fig. 14 B, b and c). Returning to 150 mM apical Na\(^+\) in the presence of amiloride restored \([\text{Na}^+]\text{r}\) to its previous value (c and d), and removing amiloride restored \([\text{Na}^+]\text{r}\) to its original value (d and e). Similar results were obtained with apical 5 \(\mu\)M benzamil, another potent blocker of TRC ENaC (Stewart et al., 1998). The amiloride-induced decrease in resting TRC \([\text{Na}^+]\text{r}\) (a and b) reflects the inhibition of Na\(^+\)/H\(^+\) entry via ENaC. A further decrease in TRC \([\text{Na}^+]\text{r}\) by lowering the external Na\(^+\) to zero in the presence of amiloride (b and c) reflects Na\(^+\) efflux via an amiloride-insensitive pathway (Doolin and Gilbertson, 1996; DeSimone et al., 2001b).

Effect of Acid Stimulation on TRC \([\text{Na}^+]\text{r}\)

Fig. 15 shows that in TRCs loaded with sodium green and perfused with control Ringer’s solution (RC), decreasing apical pH from 7.4 to 3.0 (RHC; Table II, set 1) reversibly decreased \(F_{490}\). Similarly, in TRCs loaded with SBFI, increasing the apical pH from 7.4 to 10.3 (RTris; Table II, set 1) increased and decreasing pH from 7.4 to 3.0 decreased FIR (\(F_{340}/F_{380}\); unpublished data). These results indicate that extracellular alkalinization increases and extracellular acidification decreases resting TRC \([\text{Na}^+]\text{r}\).

To further investigate if changes in pH\(_i\) modulate resting TRC \([\text{Na}^+]\), we monitored temporal changes in \([\text{Na}^+]\), after intracellular acid loading with membrane-permeable weak organic acids at constant pH\(_o\).
Effect of Intracellular Acid Loading on TRC [Na⁺]

Studies with basolateral NH₄Cl pulses. Fig. 16 shows the effect of a short basolateral side NH₄Cl pulse on TRC [Na⁺]. In polarized TRCs loaded with SBFI (Fig. 16 A), immediately after the application of basolateral 50 mM NH₄Cl (RNH₄Cl; Table II, set 3) there was a rapid increase in FIR (F₃₄₀/F₃₈₀; a and b) followed by a slow decline toward baseline (b and c). Upon NH₄Cl washout, FIR decreased rapidly and became lower than its resting value (c and d). Qualitatively, similar changes in F₄₉₀ were observed in TRCs loaded with sodium green (Fig. 16 B). Fig. 16 C shows the effect of a similar NH₄Cl pulse on TRC pHᵢ in a parallel experiment in another tissue. Consistent with our previous studies (Lyall et al., 2002), after the application of NH₄Cl TRC pHᵢ rapidly alkalinized (a and b), presumably due to the entry of NH₃ and conversion of free intracellular H⁺ to NH₄⁺ (Roos and Boron, 1981). This was followed by a slow decline of pHᵢ toward baseline (b and c), presumably reflecting NH₄⁺ entry or pH compensation mechanism in TRC membranes (Roos and Boron, 1981). On NH₄Cl washout, TRC pHᵢ acidified and became lower than its resting value (c and d). This is due to the rapid exit of NH₃ from cells and the conversion of NH₄⁺ to H⁺. The spontaneous slow recovery of TRC pHᵢ upon NH₄Cl washout is due to the presence of a basolateral membrane Na⁺/H⁺ exchanger (Lyall et al., 2002). Together, the data presented in Fig. 16 indicate that at constant pHₒ, the intracellular alkalinization phase of the NH₄Cl pulse is associated with an increase and the intracellular acidification phase of the NH₄Cl pulse is associated with a decrease in resting TRC [Na⁺].

Studies with Basolateral Na-acetate Pulses

Fig. 17 A shows the effect of a short basolateral side NaAc pulse on TRC [Na⁺]. In polarized TRCs loaded with sodium green while they were initially perfused on both sides with control Ringer’s solution (pH 7.4) and when the apical membrane was perfused with a Na⁺-free solution (150 mM NaCl was replaced with an equivalent amount of Tris-HCl) (Fig. 17 A). The relative changes in [Na⁺], are presented as mean ± SEM changes in FIR (F₃₄₀/F₃₈₀) of three ROIs within the taste bud. (B) The relative changes in [Na⁺], were monitored in polarized TRCs loaded with sodium green while they were initially perfused on both sides with control Ringer’s solution (pH 7.4) and when the apical membrane was perfused with (i) control Ringer’s solution containing 100 μM amiloride (a and b) and (ii) a Na⁺-free solution (150 mM NaCl was replaced with an equivalent amount of NMDG-HCl) also containing 100 μM amiloride (b and c). The relative changes in [Na⁺], are presented as mean ± SEM of the percentage change in fluorescence intensity (F₄₉₀) of four ROIs within the taste bud.

Figure 14. Effect of apical Na⁺ and amiloride on TRC [Na⁺]. (A) The relative changes in [Na⁺], were monitored in polarized TRCs loaded with SBFI while they were initially perfused on both sides with control Ringer’s solution (pH 7.4) and when the apical membrane was perfused with a Na⁺-free solution (150 mM NaCl was replaced with an equivalent amount of Tris-HCl). The relative changes in [Na⁺], are presented as mean ± SEM changes in FIR (F₃₄₀/F₃₈₀) of three ROIs within the taste bud. (B) The relative changes in [Na⁺], were monitored in polarized TRCs loaded with sodium green while they were initially perfused on both sides with control Ringer’s solution (pH 7.4) and when the apical membrane was perfused with a Na⁺-free solution (150 mM NaCl was replaced with an equivalent amount of Tris-HCl). The relative changes in [Na⁺], are presented as mean ± SEM changes in fluorescence intensity (F₄₉₀) of four ROIs within the taste bud.

Figure 15. Effect of pHᵢ on TRC [Na⁺]. The relative changes in [Na⁺], were monitored in polarized TRCs loaded with sodium green while they were initially perfused on both sides with control Ringer’s solution (pH 7.4) and when the apical membrane was perfused with a similar solution at pH 3.0 (1 mM HCl). The relative changes in [Na⁺], are presented as mean ± SEM of the percentage change in fluorescence intensity (F₄₉₀) of four ROIs within the taste bud.
sion to free intracellular $H^+$ and acetate anion (Roos and Boron, 1981). The intracellular acidification was transient and was followed by a spontaneous recovery of $pH_i$ (b and c) presumably indicating $pH_i$ recovery due to the presence of a basolateral Na$^+$-$H^+$ exchanger (Lyall et al., 2002). Upon NaA washout, TRC $pH_i$ alkalinated and became higher than its resting value (c and d). This is due to the rapid exit of undissociated AA from cells and decrease in intracellular $H^+$. The spontaneous recovery of alkaline $pH_i$ toward baseline (d and e) reflects the presence of an as yet unknown pH recovery mechanism(s) in TRC membranes that allows base ($OH^-$) exit or entry of acid equivalents at alkaline $pH_i$.

Studies with DEPC

Data presented in Fig. 18 show the effect of DEPC on $pH_i$-induced changes in TRC [Na$^+$]. Treating the ba-
solateral membrane of polarized TRCs with 5 mM DEPC (Fig. 18 A) significantly inhibited the decrease in TRC [Na⁺], induced by lowering the apical solution pH from 7.4 to 3.1 relative to control (Fig. 18 B). Data presented in Fig. 19 show that treating the basolateral membrane with 5 mM DEPC significantly attenuated the NH₄Cl-induced changes in TRC [Na⁺], (Fig. 19 B, d–f) relative to control (Fig. 19 A, a–c). In three tissues treated with DEPC there was a 50% decrease in pHo- or NH₄Cl-induced changes in TRC [Na⁺]. Similar results were obtained in polarized TRCs loaded with SBFI (unpublished data).

Effect of pH and DEPC on Na⁺ Influx Across the Apical Membranes of TRCs

We further investigated if the Na⁺ influx across the apical membranes of polarized TRCs was affected by pH and DEPC. The relative changes in [Na⁺], were monitored in TRCs loaded with sodium green during a unilateral step change in apical Na⁺ concentration from 150 mM to 0 (Fig. 20 A). The zero Na⁺ solution contained 150 mM NMDG-Cl (R0Na⁺; Table II, set 1). In this experiment the basolateral membrane was continuously perfused with Ringer’s solution containing 150 mM NaCl (Table II, set 1, RC). At pH 7.4 decreasing the apical Na⁺ concentration from 150 mM to zero produced a reversible decrease in F₄₉₀ (a–c). Decreasing the apical pH from 7.4 to 4.4 (i.e., perfusing RC at pH 4.4) decreased F₄₉₀ and this magnitude (c and d) was smaller than that induced by decreasing apical Na⁺ concentration to zero at pH 7.4 (a and b). However, upon decreasing the apical Na⁺ concentration from 150 mM to 0 at pH 4.4 (i.e., perfusing R0Na⁺ at pH 4.4) induced a further decrease in F₄₉₀ that was completely reversible (d–f). In three animals the magnitude of the decrease in F₄₉₀ produced by lowering apical pH from 7.4 to 4.4 was 74.0 ± 3.4% relative to the decrease in F₄₉₀ induced by reducing apical Na⁺ concentration from 150 mM to 0 at pH 7.4. These data suggest that similar to the case with amiloride and benzamil (compare Fig. 14 B), a decrease in pH blocks only a part of the apical Na⁺ entry that presumably occurs via the AS-ENaCs. However, a significant part of the apical Na⁺ entry is pH insensitive. In the second part of the experiment (Fig. 20 B), the basolateral membrane was perfused with Ringer’s solution containing 5 mM DEPC (pH 7.4) for 10 min and apical Na⁺ influx was monitored again using solutions containing 0 and 150 mM NaCl adjusted to pH 4.4 (g–i). After DEPC treatment, the magnitude of change in F₄₉₀ induced by apical Na⁺ removal was 78% greater than the corresponding changes at pH 4.4 before DEPC treatment (d–f). In four experiments, after DEPC treatment the mag-
DISCUSSION

The data presented in this study demonstrate that the variations in rat NaCl CT responses in vivo under differ-
10.3 (Fig. 3). Second, equivalent inhibition of the NaCl CT responses was observed with benzamil and by decreasing the stimulus solution to pH 2.0 in its absence in the same animal (Fig. 5). Reports of decreased rat responses to NaCl at pHs below 3–4 are consistent with the regulatory pattern of pH on ENaC activity (Beidler, 1954; Ogawa, 1969). However, in these and other studies the expected increase in CT response at higher pHs was not observed (Beidler, 1954; Ogawa, 1969; Elliott and Simon, 1990). This may be due to the narrow range of pH values investigated and the use of a saturating concentration level of NaCl (Elliott and Simon, 1990).

Inside the TRCs dissolved CO₂ is converted to H₂CO₃ in a reaction catalyzed by intracellular carbonic anhydrases and yields free H⁺ and HCO₃⁻ ions (Lyall et al., 2001). This suggests that it is the CO₂-induced decrease in TRC pH that inhibits NaCl CT responses (Fig. 7A) relative to CT responses in HEPES buffer (pH 7.4). This is supported by the observations that the carbonic anhydrase blockers, MK-417 or MK-507, attenuate the CO₂-induced decrease in TRC pH and the CO₂-induced decrease in NaCl CT response (Figs. 7, B and C).

Effect of pH on the Amiloride-insensitive NaCl CT Response
The data further suggest that the amiloride-insensitive part of the CT responses is pH insensitive. DeSimone et al. (2001b) have recently demonstrated that the amiloride-insensitive part of NaCl CT response is cetlypyridinium chloride (CPC) sensitive and probably represents a nonspecific cation channel that is permeable to Na⁺, K⁺, and NH₄⁺ ions. In our preliminary studies, the CT responses to KCl and NH₄Cl stimulation were also insensitive to changes in pH. Both KCl and NH₄Cl CT responses are also amiloride insensitive (Kloub et al., 1997; DeSimone et al., 2001b). Single-unit recordings demonstrate that the amiloride-sensitive response is associated with N fibers that respond specifically to Na salts and can be ascribed to TRCs containing ENaC. In contrast, the amiloride-insensitive responses are associated with the H fiber type and respond to Na⁺, K⁺, NH₄⁺, and other cations (Frank et al., 1983). The generalist characteristics of the H fibers may be ascribed to the amiloride-insensitive CPC-sensitive nonspecific apical cation channel (DeSimone et al., 2001b, 2002). The ENaC pathway represents a high-capacity, low-affinity system and the amiloride-insensitive CPC-sensitive pathway is a low-capacity high-affinity system similar respectively to the N- and H-fiber types (DeSimone et al., 2001b). Thus, at low pH, the H-fibers may still respond to cation stimulation.

Relationship between NaCl CT Responses and TRC [Na⁺]
It is well established for several mammalian species that NaCl CT responses are composed of two parts, an amiloride- and benzamil-sensitive component and an amiloride- and benzamil-insensitive component (Fig. 3) (Lindemann, 1996, 2001; Stewart et al., 1997; Herness and Gilbertson, 1999; Lin et al., 1999; Kretz et al., 1999; DeSimone et al., 2001b, 2002). In our polarized preparations, the resting TRC [Na⁺], concentration was decreased when (a) Na⁺ concentration was decreased in the apical compartment; (b) the apical membrane was treated with either amiloride or benzamil in the presence of Na⁺; and (c) the magnitude of [Na⁺], decrease was significantly attenuated upon decreasing apical Na⁺ concentration in the presence of amiloride. These results suggest that there are also two pathways for Na⁺ influx across the apical membranes of TRCs, an amiloride-sensitive and amiloride-insensitive pathway. It is well established that the apical ENaCs are the transducers for the Na⁺-specific taste in fungi-form TRCs (Stewart et al., 1997; Lindemann, 1996, 2001; Herness and Gilbertson, 1999; Kretz et al., 1999; Lin et al., 1999; DeSimone et al., 2001b, 2002). Our data suggest that the amiloride- and benzamil-insensitive component is also present in the apical membranes of TRCs. In our previous studies (DeSimone et al., 2001b) amiloride + 2 mM CPC completely inhibited the NaCl CT responses to baseline and decreased resting TRC [Na⁺], below its resting level (DeSimone et al., 2002). Our studies indicate that stimulating the tongue with NaCl solutions induces an influx of Na⁺ ions via the above two apical Na⁺ entry pathways and results in an increase in TRC [Na⁺]. Since amiloride or benzamil block ~75% of the NaCl response, it indicates that the Na⁺ flux via apical ENaCs contributes most to the CT response. However, at present the relationship between TRC [Na⁺], and the magnitude of NaCl CT responses has not been established.

Relationship between TRC pH, and [Na⁺]
Our results demonstrate that a decrease in TRC pH inhibits ENaC activity, decreasing apical Na⁺ influx and thus resting TRC [Na⁺]. In contrast, an increase in pH activates ENaC activity, increasing apical Na⁺ influx and thus resting TRC [Na⁺], (Figs. 15–20). This relationship between TRC pH, is observed not only with changes in pH, but is also seen with intracellular acid loading at constant pH, using basolateral NaA and NH₄Cl pulses. Although in our studies the changes in pH, and [Na⁺], were not determined in the same TRCs simultaneously, the data shown in Figs. 16 and 17 show that [Na⁺], changes are temporally related to changes in pH. The changes in TRC [Na⁺], are sensitive to even small changes in pH since spontaneous recovery in TRC pH, following basolateral NaA pulses were reflected in changes in F₁₀₀ in cells loaded with sodium-green (Fig. 17A). These results are consistent with the effects of apical or basolateral NH₄Cl pulses in cultured A6 cells (Zeiske et al., 1999) in which an intracellular
alkalization increased and intracellular acidification decreased short-circuit current (Isc, a measure of amiloride-sensitive apical Na+ influx). The changes in pH and Isc demonstrated very similar time course, indicating a probable causal relationship between pH and the magnitude of Isc.

In other studies, intracellular alkalization increased and acidification decreased TRC volume (unpublished data). During intracellular alkalization, e.g., immediately after an NH4Cl pulse (Fig. 16) or after basolateral NaA washout (Fig. 17), an increase in cell volume is expected to dilute the dye resulting in a decrease in F490. Similarly, upon intracellular acidification, a decrease in cell volume would be expected to increase dye concentration and hence an increase in F490. The data clearly show that F490 changes do not reflect changes in cell volume, but follow changes in TRC pH. The data further suggest that the actual changes in F490 must be significantly greater under these conditions but are attenuated due to changes in cell volume.

Our data demonstrate that changes in TRC pH are linearly related to NaCl CT responses (Fig. 4) and to [Na+], (Figs. 16 and 17). A linear relationship between pH and Isc and apical membrane potential was also reported in the principal cells of frog skin (Lyall et al., 1993, 1995; Lyall and Biber, 1995), in A6 cells exposed to apical or basolateral NH4Cl pulses (Zeiske et al., 1999), and in cultured M-1 mouse cortical collecting duct cells during changes in PCO2 (Howard et al., 2001). The cloned ENaC expressed in oocytes also demonstrated steep pH-dependence of amiloride-sensitive currents between pH of 7.0 and 6.4 (Konstas et al., 2000).

**Temporal Relationship between NaCl CT Responses, TRC pH, and [Na+]**

As discussed previously (Lyall et al., 2001, 2002), it is important to note that in our studies CT nerve activity in anesthetized rats was monitored at normal physiological temperatures, and the stimuli were applied to the tongue at the rate of 1 ml/s at room temperature. In contrast, our pH and [Na+] measurements were made in a small microscopy chamber in which the maximum flow rate was limited to 1 ml/min, and the measurements were made at room temperature (see MATERIALS AND METHODS). However, we made some CT recordings with stimulus and rinse applied at 1 ml/min (Lyall et al., 2001). For acids, the phasic part of the CT response was strongly influenced by the flow rate, however, the magnitude of the pseudo-steady-state of the CT response was unaffected by the flow rate. At the flow rate of 1 ml/min the HCl or the CO2-induced CT response profiles, i.e., the rising phase of the response following stimulation and the rate of decline of the response after washout were similar to the TRC pH changes observed in vitro (Lyall et al., 2001).

In the in vivo studies the tongue was perfused with the rinse and stimulus solutions also at room temperature. Lundy and Contreras (1997) compared the relative CT responses to mineral salts at 25°C and 35°C 30 s after the stimulus on-set and reported that taste nerve responses varied with adaptation/stimulus temperature. However, only the response magnitudes to Na-acetate and the NH4+ salts were found to be statistically smaller at 25°C than at 35°C. Their studies further showed that the amiloride-suppression of CT nerve responses to NaCl was greater at 25°C than at 35°C by ~15%. These data indicate that only quantitative differences in the neural responses to mineral salts are observed when stimulus solutions are presented at room temperature. Therefore, under our experimental conditions the in vitro measurements conducted at room temperature can be directly related to the neural responses. In our recent studies (Lyall et al., 1999, 2001, 2002), the in vitro measurements of pH, cell volume, Na+-H+ exchange activity, effect of ion substitution, and the effect of second messengers (cAMP and Ca2+) on polarized TRCs have demonstrated remarkably good correlation with the CT responses measured under similar experimental conditions.

These data suggest that under our experimental conditions changes in TRC pH are correlated with the pseudo-steady-state of the NaCT responses in vivo when stimuli are applied at low flow rate or with the time-average CT responses when stimuli are applied at high flow rate at room temperature. In our present studies, the changes in pH were also temporally related to changes in TRC [Na+], (Figs. 16 and 17). Therefore, it follows that under our experimental conditions the pH-induced changes in the relative concentration of TRC [Na+] can also be related to pH-induced alterations in NaCl CT responses observed in vivo.

**Possible Mechanisms for H+ Effects on ENaC**

Protons modulate the activity of amiloride-sensitive ENaCs in a variety of epithelial cells (Lyall and Biber, 1995; Lyall et al., 1995; Garty and Palmer, 1997; Chalfant et al., 1999; Zeiske et al., 1999; Awayda et al., 2000; Konstas et al., 2000; Nakhoul et al., 2001). The cloned α, β, and γ subunits of ENaC expressed in *Xenopus* oocytes demonstrated decreased Na+ currents when pH was decreased but not when pH was increased (Chalfant et al., 1999). Acidification reduced and alkalization increased channel activity by a voltage-independent mechanism. A reduction in pH reduced single-channel open probability, reducing single-channel open time, and increased single-channel closed time without altering single-channel conductance. By expressing various combinations of α, β, and γ subunits of ENaC it was further demonstrated that the α-ENaC subunit is regulated directly by pH (Chalfant et al., 1999). In *Xenopus*...
laevis oocytes expressing either wild-type αβγ-ENaC or Liddle αβ(R564Istop)γ-ENaC cytosolic, but not extracellular acidification, substantially reduced the amiloride-sensitive inward currents (Konstas et al., 2000). The ENaC currents demonstrated a steep pH dependence between pH 7.2 and 6.4. The inhibition of wild-type ENaC and Liddle ENaC by cytosolic acidification was independent of so-called sodium-feedback inhibition, since it was not associated with a concomitant increase in intracellular Na+ concentration. This is also the case in TRCs, since a decrease in pH is consistently associated with a decrease in \([\text{Na}^+]_i\) (Figs. 15–17).

The specific amino acid residues within the ENaC that interact with H+ ions have not been identified as yet. However, COOH-terminal deletions in the α or γ subunit or in all three subunits of ENaC did not abolish the inhibitory effect of cytosolic acidification, indicating that ENaC’s pH-sensitivity is not mediated by its cytoplasmic COOH terminus (Konstas et al., 2000). Histidine residues are potential pH-sensitive residues. Since COOH-terminal deletions preserve pH-sensitivity in Liddle’s syndrome, histidine 568 in the β-subunit and histidine 648 in the α-subunit are most likely not involved in pH-sensing. The lack of sensitivity of ENaC to pH suggests that histidine residues at positions 6, 7, and 8 in the extracellular loops of the α, β, and γ-subunits, respectively, also do not contribute to the pH-sensitivity of ENaC. However, it is suggested that histidine residues in the cytoplasmic NH2 terminus of α-ENaC may serve as potential candidates for its pH sensitivity (Chalfant et al., 1999). Our data (Figs. 7 and 18–20) suggest that possible modification of histidine residues with DEPC or Zn2+ makes the ENaC activity unresponsive to changes in TRC pH. It is likely that similar to the case of the ROMK channel other amino acids such as lysine and/or arginine residues may also be involved in pH sensitivity (Choe et al., 1997). However, in another study (Awaya et al., 2000) the cloned ENaC expressed in oocytes was not appreciably affected by changes in pH. The reason for the lack of pH sensitivity of ENaC in that study is not clear.

In 100 mM NaCl solutions buffered at pH 7.0 with HEPES, both DEPC and Zn2+ had no effect on NaCl CT responses (compare Fig. 7), which is consistent with the presumed action of these agents on the pH regulatory site of ENaC. However, in other studies (unpublished data) at the lower NaCl concentration of 30 mM, topical lingual application of Zn2+ enhanced NaCl CT responses relative to control. These effects of Zn2+ are consistent with its role in relaxing the sodium-feedback inhibition of ENaC (Lyall et al., 1995; Garty and Palmer, 1997; Gilbertson and Zhang, 1998; Konstas et al., 2000). The sulfhydryl reagent, p-hydroxymercuribenzoate, reversibly removed sodium feedback inhibition (Gilbertson and Zhang, 1998). Since Zn2+ has a high affinity for sulfhydryl groups (Lyall et al., 1995), it is likely that Zn2+ also enhances NaCl responses at low NaCl concentrations by modification of cysteine residues in TRC ENaCs. In frog skin epithelial cells Cd2+ and Zn2+ increased pH, and increased \(I_{\text{Na}}\) (Lyall et al., 1995). However, in our studies, apical application of ZnCl2 did not produce significant changes in TRC pH (unpublished data).

In A6 cells changes in pH were positively correlated with Na+ current through the native ENaC and the apically dominated transepithelial conductance (Zeiske et al., 1999). The pH affected the open Na+ channel density by altering the open probability of the channel, and/or the total channel number. In contrast, Awaya et al. (2000) reported that in A6 cells, decreasing the apical pH from 7.4 to 6.4 or to 5.4 over a period of minutes caused a slow stimulation of the amiloride-sensitive \(I_{\text{Na}}\). The effects on \(I_{\text{Na}}\) were blocked by buffering intracellular Ca2+ with BAPTA. The observed variations in the sensitivity of ENaC to pH suggest that the role of pH in regulating ENaCs may differ among tissues and may depend on additional Na+ transport pathways, such as, Na+-K+-ATPase, Na+-H+ exchangers, NaCl cotransport, and Na+-K+-2Cl− cotransport. The overall changes in \([\text{Na}^+]_i\) may reflect a combined effect of pH on these pathways (Nakhoul et al., 2001). Similar to the case in other epithelial cells (Lyall et al., 1995; Garty and Palmer, 1997; Howard et al., 2001), in TRCs, the activation of ENaC was only observed at alkaline pH, (Figs. 2 and 3).

It is likely that other factors may also come into play during mixture interactions. In a recent study by Liu and Simon (2001), stimulation of rat fungiform TRCs with acid revealed two distinct responses. Type I cells responded with an increase in intracellular Ca2+ ([Ca2+]), and type II cells responded with a decrease in [Ca2+]. In our preliminary studies an increase in [Ca2+], in ionomycin-treated fungiform TRCs inhibited rat NaCl CT responses (Alam et al., 2002). Therefore, it is likely that in a subset of TRCs, changes in other intracellular second messengers during acid stimulation can further modify CT responses to NaCl. The CT responses to Na+ salts are also affected by the anion. The CT responses to Na+ salts such as, gluconate and acetate, which are less permeable than Cl− ions, gave lower CT responses relative to NaCl (Elliott and Simon, 1990; Ye et al., 1994; Kloub et al., 1997). These data suggest that transepithelial potentials generated by the less permeable anions across tight junctions also affect CT responses to Na+ salts. However, at present it is not clear if changes in pH, or pH also affect anion permeability across the paracellular shunt pathway.

The main conclusions of the paper and the proposed mechanisms for mixture interaction between sour taste and salt taste modalities are summarized in a schematic.
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**Figure 22.** Proposed mechanism for taste mixture interactions between sour taste and salt taste modalities. The apical membrane of fungiform TRCs contains pathways for the entry of Na\(^+\) and H\(^+\) ions. The Na\(^+\) influx occurs, in part, via the amiloride- and benzamil-sensitive ENaCs (Am(+) red circle) and also through an amiloride-insensitive (Am(−)) CPC-modulated (CPC(+)) cation channel that is permeable to Na\(^+\), K\(^+\), and NH\(_4\)\(^+\) ions (green circle). The Na\(^+\) exits from the TRCs across the basolateral membrane via the ouabain-sensitive Na\(^+\)-K\(^+\)-ATPase (−). Weak organic acids enter TRCs across the apical cell membrane as neutral molecules and strong acids gain access into TRCs via an H\(^+\) entry pathway that is amiloride- and Ca\(^2+\)-insensitive, but is activated by cAMP (cAMP(+) Am(−); blue circle). Acid entry decreases TRC pH\(_i\), TRC pH\(_i\) recovery occurs in part due to the activation of basolateral Na\(^+\)-H\(^+\) exchanger. However, both ASIC and hyperpolarization-activated (HCN) channels in the basolateral membranes of TRCs could also be activated if H\(^+\) ions can cross the tight junctions and decrease pH\(_i\) in the basolateral compartment. When both acid stimulants and NaCl stimuli are presented together, the acid-induced decrease in TRC pH\(_i\) inhibits apical Na\(^+\) influx via amiloride- and benzamil-sensitive ENaCs (dotted line) and subsequently inhibits CT responses to NaCl. On the other hand, an increase in pH\(_i\) enhances apical Na\(^+\) influx via ENaCs and enhances CT responses to NaCl. Since Zn\(^{2+}\) and DEPC inhibit pH\(_i\)-induced effects on NaCl CT responses, the data suggest that protons act directly on histidine residues in ENaC subunits and modify its activity.

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