

**The role of H⁺/OH⁻ channels in salt stress response of
*Chara australis***

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ABSTRACT

We investigate electrophysiological salt stress response of salt-sensitive charophyte *Chara australis* as function of time in saline artificial pond water (Saline APW), containing 50 mM NaCl and 0.1 mM CaCl₂. The effects are due to increase of Na⁺ concentration, rather than increase in Cl⁻ concentration or medium osmolarity. Previous paper (Shepherd et al. 2008) described the rise in the background conductance and inhibition of proton pumping in first 60 min of Saline APW. Here we investigate shift of membrane potential difference (PD) to levels above -100 mV and change of shape of the current-voltage (I/V) profiles to upwardly concave. Arguing from thermodynamics, the I/V characteristics can be modeled by channels that conduct H⁺ or OH⁻. OH⁻ was chosen, as H⁺ required unrealistic increase in number/permeability of the channels at higher pH. Prolonged exposure to Saline APW stimulated opening of more OH⁻ channels. Recovery was still possible even at PD near -50 mV, with partial return of proton pumping and decrease in OH⁻ current following APW wash. Upon change of pH from 7 to 9, the response was consistent with previously observed I/V characteristics of OH⁻ channels. For pH change to 6, the response was transient before channel closure, but could still be modeled. The consequences of opening of H⁺ or OH⁻ channels while the cell is under salt stress are discussed.

Key words: salt stress, charophytes, H⁺/OH⁻ channels, current-voltage analysis

INTRODUCTION

The experiments described in this paper are a part of a larger investigation that compares the electrophysiology of salt-sensitive and salt-tolerant charophytes challenged by saline stress.

To gain full understanding into the ability of salt tolerant plants to survive in saline media, it is also necessary to study the pathology of salt stress in their salt-sensitive relatives.

The salt-tolerant charophyte *Lamprothamnium* thrives in brackish coastal lakes where salinity can be higher than that of seawater at the time of drought (Shepherd et al 1999). The salt-sensitive *Chara australis* dies within 6 days in media with 50 mM NaCl and 0.1 mM Ca²⁺. Thus comparing the electrophysiological responses to salinity of these closely related plants of ancient lineage is likely to identify a minimal ensemble of factors that influence salt tolerance (Tester and Davenport 2003).

In plant cells proton ATPase at the plasma membrane pumps protons out of the cytoplasm. The resulting negative membrane potential difference (PD) energizes the import of nutrients and export of undesirable ions, such as Na⁺. The proton pump in *Lamprothamnium* is stimulated by both decrease in internal pressure (increase in medium osmolarity) and increase in medium salinity (Al Khazaaly and Beilby 2007). The proton pump in *Chara australis*, on the other hand, is insensitive to decrease in internal pressure and becomes inhibited by salinity, especially if the calcium ion in the medium is low. In previous paper we modeled the decline of the proton pump towards the passive background state with resting PD near -100 mV, documented increase of the background conductance and onset of repetitive spontaneous action potentials (APs) in first 60 min of salinity stress (Shepherd et al 2008).

In this paper we follow further development of electrical characteristics of *Chara* cells after longer exposure to salinity stress. The cells were pre-treated with Sorbitol APW (artificial pond water). The I/V characteristics were pump current-dominated (see Fig. 1a, empty squares and Fig. 1c and d, heavy continuous lines). After exposure to Saline APW of same osmolarity the membrane PD moved towards -100 mV and the shape of the I/V profile transformed close to linear – the background state (Fig. 1a, triangles, Fig. 1c and d, short dashed lines). In this case there is still a small pump current component present. With further exposure to Saline APW the I/V characteristics became upwardly concave (Fig. 1a, diamonds, Fig. 1c and d, long dashed lines). Such I/V characteristics suggest contribution of a negative

current (outflow of negative charge or inflow of positive charge) with reversal PD at 0 or positive PDs. The ions with the appropriate inside and outside concentrations are Cl^- , Ca^{2+} and proton (H^+) or hydroxyl (OH^-). Large currents of Ca^{2+} are unlikely and would result in stoppage of cytoplasmic streaming (Kamiya 1959), which was not observed. Cl^- was eliminated, as replacement of NaCl by Na_2SO_4 in the saline APW did not shift the reversal PD or change the shape of the I/V characteristics. The change of medium pH shifted the membrane PD in the right direction and affected the shape of the I/V characteristics. Consequently, we modeled the negative current as inflow of H^+ or outflow of OH^- , employing the Goldman-Hodgkin-Katz (GHK) equation.

The H^+/OH^- channels are well documented in charophytes. The discovery of acid and alkaline bands along the surface of charophyte cells (Spear et al 1969; Lucas and Smith 1973) was one of the starting points for the research into the localized transporter operation and external currents flowing between these specialized cell zones (Walker and Smith 1977; Lucas and Nuccitelli 1980). The transporter active in the acid zone is the proton pump creating the H^+ efflux, while the alkaline zones facilitate opening of channels conducting H^+ or OH^- (Bisson and Walker 1980; Lucas 1982). While it is clear that the banding system helps the cells assimilate carbon, different schemes have been proposed involving CO_2 or HCO_3^- transport (Walker et al 1980; Lucas 1982).

The speculation whether the channels conduct H^+ or OH^- remains unresolved for almost 40 years. OH^- is the favored ion, as concentration of H^+ is very low in the alkaline bands, where pH rises up to 10.5. Bisson and Walker (1980), Smith and Walker (1983) and Beilby and Bisson (1992) measured conductances of up to 10 S/m^2 , which would be difficult to sustain with so few H^+ in the vicinity of the membrane, unless there is water splitting in the membrane due to high electric fields (Simons 1979). Lucas (1979) also argued for OH^- to be the transported ion. However, the definitive experiment is yet to be designed and so we will continue to refer to the channels as H^+/OH^- .

Under normal non-saline conditions the *Chara* H^+/OH^- channels are activated at high external pH of 9.0 and above (Bisson & Walker 1980). It is not yet known, why the saline APW opens the H^+/OH^- channels at neutral medium pH. However, this new aspect of salinity stress contributes to the cell deterioration, as the proton electrochemical gradient is dissipated and the cytoplasm becomes more acid.

Extant Charales are a sister group to the ancestors of all land plants (Karol *et al.* 2001) and their cellular responses to salinity are likely to reveal fundamental mechanisms with wider applications. Acid and alkaline zones were found in aquatic angiosperms (Prins *et al.*, 1980). Raven (1991) surveyed rhizophytes from many habitats, exhibiting H⁺ (or OH⁻) currents in root tips that assist with nutrient acquisition. The similarity between salt sensitive charophytes and roots of crops will be discussed.

MATERIALS AND METHODS

Cell culture

Chara australis Brown (Garcia and Chivas 2006) was collected from a golf course lake at Little Bay, Sydney, and planted in round containers on a bed of autoclaved garden soil, covered with rainwater with a handful of rotting leaves added. *C. australis* was cultured under equal numbers of Sylvania Gro-Lux fluorescent tubes (Sylvania Australasia, Pty. Ltd.) and cool white fluorescent tubes, providing photosynthetically active radiation of 80 $\mu\text{mol m}^{-2} \text{s}^{-1}$, on a cycle of 10 hours light and 14 hours darkness. Young sub-apical internodal cells, 7 - 15 mm in length and between 0.6 and 0.7 mm in diameter, were trimmed from healthy plants, and left to recover in artificial pond water (APW) for at least 3 d. Experiments were conducted at room temperature (25 °C).

Electrophysiology

The internal microelectrode was placed in the large vacuolar compartment. Thus the PD was measured across both plasma membrane and the tonoplast. However, the plasma membrane I/V characteristics dominate under most conditions because of the high tonoplast conductance (Beilby 1990). The cells were placed in a three-compartment holder, with each compartment insulated by grease. The voltage-clamp was achieved by passing current between Ag/AgCl wire electrodes in the outside and middle compartments (Beilby 1989, Beilby and Shepherd 1996). We measured current-voltage (I/V) characteristics using a bipolar staircase voltage command, with pulses of width between 60 and 100 ms, separated by 120 - 250 ms, at the resting PD. The data-logging rate was one measurement /ms (Beilby and Beilby, 1983). The resting PD was data-logged separately at a rate of one PD measurement every 10 s in early experiments and at 10 points/s in later experiments.

Experimental protocol and media

In the experimental protocol the cells were inserted into the apparatus and left to recover in the APW for about one hour. The Sorbitol APW was then introduced into the chamber for another hour. The I/V characteristics were monitored in both APW and Sorbitol APW. Finally the Sorbitol APW was exchanged for the Saline APW and series of I/V characteristics were recorded. Thus the effects measured were due to salinity stress as distinct from turgor decrease. Some cells were returned into APW and the electrophysiology of the recovery recorded. **To maintain the composition constant the bathing medium was often refreshed by hand.** The pH changes of the Saline APW were performed quickly, as the electrophysiology of the cells was changing slowly as function of time in Saline APW.

Artificial Pond Water (APW) consisted of (in mM): 0.1 KCl, 1.0 NaCl, 0.1 CaCl₂, 2.0 HEPES [4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid], pH 7. Sorbitol APW was made from APW by adding 90 mM sorbitol to match the osmolarity of Saline APW. Saline APW was made from APW by adding 50 mM NaCl. For Saline APW of pH 9, HEPES was replaced by AMPSO [N-(1,1-Dimethyl-2-hydroxyethyl)-3-amino-2-hydroxypropanesulfonic acid] at same concentration. For Saline APW of pH 6, the buffer was MES [2-(N-Morpholino) ethanesulfonic acid]. The buffer concentration was increased to 5.0 mM in Saline APW.

Modeling

The total clamp current was resolved into contributions made by parallel populations of ion transporters. The proton pump current I_p was modeled by the two state Hansen, Gradmann, Sanders and Slayman model (HGSS, Hansen *et al.* 1981). **This model has been used extensively to model chloride or proton ATPases in *Acetabularia*, charophytes, guard cells and wheat root protoplasts (Gradmann 1989; Beilby 1984; Blatt 1987; Tyerman et al 2001).**

$$I_p = z_p F N \frac{k_{io} \kappa_{oi} - k_{oi} \kappa_{io}}{k_{io} + k_{oi} + \kappa_{io} + \kappa_{oi}} \quad (1)$$

$$k_{io} = k_{io}^0 e^{\frac{zFV}{2RT}} \quad (1a)$$

$$k_{oi} = k_{oi}^0 e^{-\frac{zFV}{2RT}} \quad (1b)$$

where F , R , T symbols have their usual meanings; z_p is the pump stoichiometry, which has been set to 1. N is a scaling factor (2×10^8) and V is the PD across the membrane or membranes. The number of carrier states was reduced to two with a pair of PD-dependent constants, k_{io} and k_{oi} , with a symmetric Eyring barrier and two PD-independent rate constants, κ_{io} and κ_{oi} . **These constants are fitted to the data.**

The background current was fitted by an empirical equation

$$I_{\text{bkg}} = g_{\text{bkg}} (V - V_{\text{bkg}}) \quad (2)$$

The channels passing I_{bkg} are thought to be the equivalent of non-selective cation permeable channels (NCCs) found in land plants (Shepherd et al. 2002; Demidchik & Maathuis 2007; Demidchik et al. 2002). The reasons for choosing this form of the background current are explained in the Discussion.

The inward and outward rectifiers (with K^+ as the permeant ion) and H^+/OH^- channels were fitted by the Goldman, Hodgkin and Katz model (GHK) with the channel number/permeability as single parameter (equation 3). **The moderate PD dependence of the GHK model was supplemented by multiplying by Boltzmann distribution of open probabilities P_{o-} (equation 4) for the inward rectifier, I_{irc} , P_{o+} (equation 5) for the outward rectifier, I_{orc} , and both probabilities for OH^- current, I_{OH} .**

$$I_X = P_{o+} P_{o-} \left[\frac{N_X P_X (zF)^2 V ([X]_i - [X]_o e^{-\frac{zFV}{RT}})}{RT (1 - e^{-\frac{zFV}{RT}})} \right] \quad (3)$$

$$P_{o-} = 1 - \frac{1}{1 + e^{-\frac{z_g F (V - V_{50})}{RT}}} \quad (4)$$

$$P_{o+} = \frac{1}{1 + e^{-\frac{z_g F (V - V_{50})}{RT}}} \quad (5)$$

where z is the valence of the transported ion, $[X]_o$ and $[X]_i$ are the ion concentrations in the medium, and in the cytoplasm, respectively. $N_X P_X$ stands for the number of X ion channels and their permeability treated as a single parameter; z_g is the number of gating charges, V_{50} .

and V_{50+} are the half activation potentials, V_{50} , at the negative and positive PDs of channel closure (Amtmann and Sanders 1999; Beilby and Shepherd, 2001).

The I/V profiles were fitted by eye. Due to large number of parameters, good fit could be achieved with several parameter combinations. Some parameters were constrained by additional information, as outlined in the discussion. Families of I/V profiles were fitted with minimal parameter changes. The main goal was to visualize the components of the total clamp current and their evolution as function of exposure to salinity. The conductance-voltage (G/V) characteristics were calculated by differentiating the modeled I/V profiles. The G/V profiles sometimes aid interpretation, as parallel conductances of channel and pump populations are directly additive.

RESULTS

Membrane PD and the I/V characteristics as function of time in Saline APW

More than 50 cells were exposed to APW, Sorbitol APW and then to Saline APW at neutral pH. The membrane PD depolarized in all cells in saline APW, whether they were subjected to repeated voltage-clamping protocol to obtain I/V characteristics or the membrane PD was allowed to vary spontaneously while the salinity noise was measured (Al Khazaaly et al 2009). However, the time course of the depolarization varied from cell to cell. This effect manifested as large scatter in the statistics from four voltage-clamped cells after one hour in Saline APW (Shepherd et al 2008). The complexity of the response to low Ca^{2+} Saline APW is due to several mechanisms activated (or inactivated) by salinity: (i) increase in background conductance, (ii) salinity induced noise, (iii) pump inhibition, (iv) activation of negative currents, (v) spontaneous and prolonged action potentials and (vi) activation of the outward rectifier current. In this paper we investigate mechanism (iv) in more detail.

Twelve cells were subjected to the I/V analysis as function of time in Saline APW. All exhibited depolarization of the membrane PD to levels above -100 mV and upwardly concave I/V characteristics. The pH of the medium was changed in four of these cells. Another four cells were tested for changes of NaCl to Na_2SO_4 : neither membrane PD nor I/V characteristics were affected by this change (results not shown). Thus we could eliminate chloride as possible carrier of the depolarizing negative currents.

A typical change from the pump-dominated I/V characteristics (empty rectangles) in the Sorbitol APW to background current-dominated I/V profile after 67 min of Saline APW (filled triangles) and to upwardly concave I/V characteristics after 117 min of Saline APW (diamonds) is shown in Fig. 1a. The pump-dominated I/V characteristics are curved and the resting PD can be more negative than -200 mV. The G/V profile exhibits a maximum near -200 mV attributed to the proton pump. In the background current-dominated state, the I/V profile is close to linear. Note also the increase in the background conductance in Saline APW (Fig. 1d). After 117 min of saline APW the membrane PD depolarized further and the profile exhibited an upward bend (filled diamonds). The modeled components of each I/V profile and the fit parameters are listed in the figure caption. The total conductance-voltage profiles are shown in Fig. 1b. The resting conductance (shown in part b by symbols on each curve) increased with time in Saline APW.

The development of the H^+/OH^- state with time in Saline APW is documented in Fig. 2. At the beginning of this experiment the cell was left to recover from handling and microelectrode insertion for more than an hour in APW and then exposed to Sorbitol APW for more than an hour (not shown). The I/V characteristics were measured several times. An I/V profile in Sorbitol APW, which is typical for this cell, is shown as black points in Fig. 2b. Fig. 2a shows the membrane PD response after the cell was exposed to Saline APW (thin vertical line). The membrane PD exhibited fast shift to -120 mV followed by a slower trend to levels more positive than -100 mV. The I/V scans were performed at 21 min (violet line), 60 min (light green line), 66 min (blue line) and 74 min (pink line) after the Saline APW challenge. The membrane PD moved to -50 mV after the last I/V scan. In a preliminary recovery experiment the Saline APW was replaced by APW. The Sorbitol APW step was omitted to save time and to return the cell to full turgor. To our surprise, the membrane PD returned rapidly to -100 mV and gradually became more negative. The I/V characteristics after 33 min of APW (orange line) were recorded.

The I/V characteristics in Sorbitol APW were fitted by the pump model (Fig. 2d), the background current and the inward rectifier models (Fig. 2e). The I/V characteristics in Saline APW were modeled by the background current, the inward rectifier (Fig. 2e) and the OH^- channels (Fig. 2d). The recovery I/V characteristics in APW required both the OH^- channel and pump model (Fig. 2d) and the background current and inward rectifier models (Fig. 2e). The fit parameters are listed in Table 1.

The response to pH change of the saline APW

To test if H^+/OH^- channels indeed participate in salinity stress, we exposed four cells (cell 5 – 8) to the same sequence of APW, Sorbitol APW and Saline APW. When the cells exhibited the upwardly concave I/V characteristics, **that we consider typical** of the H^+/OH^- channels, (see Figs. 1a and 2b), the pH of the Saline APW was changed to either more alkaline or more acidic values.

Fig. 3a shows the membrane PD of cell 5, which has been exposed to Saline APW (pH 7) for 106 min. The medium pH was increased to 9. The cell responded with two action potentials (AP) and a prompt negative shift of the membrane PD of about 20 mV. Better fits of the data were obtained when the pH_i was increased, especially for the second I/V curve after about 5 min in alkaline Saline APW (see Table 2). For the hydroxyl to flow into the cell, E_{OH} has to be negative of V_{bkg} . In this case both reversal PDs were close. As the resting PD settled close to -90 mV, we set V_{bkg} as -90 mV in alkaline Saline APW. To fit the hydroxyl current at pH 9, the $N_{OH}P_{OH}$ parameter decreased slightly. The current started to inactivate at PDs positive of E_{OH} , but no inactivation was seen at negative PDs (see Table 2 for parameters). To obtain an equivalent fit of the data at pH 9 using H^+ channels, the parameter $N_H P_H$ had to be increased to 1400 m/s. Such a large increase seemed unrealistic and all the data were modeled with OH^- channels. **The cells were excitable at this stage of saline stress (Shepherd et al. 2008) and thus APs are often observed upon change of media or after I/V protocol. The I/V data were discarded, if AP occurred at the time of the I/V scan.**

The change from neutral to low pH elicited a positive going transient in the resting PD. Fig. 4a shows the resting PD of cell 7 upon change from pH 9 to 6. This larger change in pH caused a larger transient and I/V scans could be performed before the membrane PD re-polarized. The cell was exposed to neutral pH Saline APW for 191 min. Upon exposure to pH 9, the membrane PD shifted in negative direction in a similar fashion to cell 5 (Fig. 3a). The shape of the I/V curves was also similar (Fig. 4b). A change to pH 6 resulted in positive going transient of about 76 mV. The I/V scan was run 100 s after the pH decrease. The membrane was left clamped and another I/V scan was run over a greater PD range (see Fig. 4b). Once the membrane PD was free, it continued to move back to negative levels. Another I/V scan was performed. The modeling confirmed that the low pH was closing the hydroxyl channels

and the last I/V curve at pH 6 was fitted by background current and the rectifiers only. The closure of hydroxyl channels caused the membrane PD to tend to V_{bkg} . The PD level at pH 6 approached -88 mV.

Fig. 5 shows statistics of the response to pH change from cells 5 – 8. The I/V scans at low pH were done as soon as possible after medium change. The average immediate negative step upon increase of pH from 7 to 9 was 27 mV (5 changes in 4 cells) with a large range from 8 to 53 mV. A repeated increase in cell 4 produced negative going change of 27 mV upon the first exposure, but only 8 mV upon the second exposure. The change from pH 9 to 6 produced average positive going transient of 59 mV (three changes in three cells), with range of 43 to 76 mV.

DISCUSSION

Modeling strategies and insights

The Background state

Figs. 1 and 2 show that salinity stress is yet another condition that induces *Chara* cells to enter, in this case transiently, the “background state”. This state is characterized by near linear I/V characteristics in the PD window delimited by inward and outward rectifiers, I_{irc} and I_{orc} , which are modeled as separate transporter populations mainly permeable to K^+ . The reversal PD for background current, V_{bkg} , is -100 mV (± 30 mV). There is abundance of experimental data indicating that the background state underpins all the other PD states. The proton pump inhibition by different types of inhibitors (DES, Azide, Vanadate) and withdrawal of ATP in perfused cells yields very similar background state in *Chara australis* and *longifolia* (Beilby 1984; Yao et al 1992; Beilby and Walker 1996). Closure of the high conductance K^+ channels by blockers such as TEA, Ba^{2+} , Na^+ or Cs^+ , high concentration of Ca^{2+} or low concentration of K^+ again reveals similar background state (Beilby 1985, 1986a,b, Tester 1988a,b). The cells of salt tolerant charophyte *Lamprothamnium* are often found in background state (Beilby and Shepherd 1996). Comparison of I/V characteristics from *Lamprothamnium* cells acclimated to range of salinities revealed that the background conductance increases with salinity, but the reversal PD remains near -100 mV (Beilby and Shepherd 2001). Similar increase in conductance is found in *Chara* (Beilby and Shepherd 2006; Shepherd et al 2008 and Figs. 1 and 2). We are assuming that the background current flows through nonselective channels (Demidchik and Mathuis 2007) and that these channels are the main pathways for

Na^+ into the cell. While the non-zero reversal PD, which seems relatively insensitive to changes of most ionic concentrations, is yet to be explained, the background currents are well documented not only in charophytes but also in many land plant cells. For instance, a bimodal distribution of membrane PDs and I/V characteristics is observed in guard cells (Thiel et al 1992). In wheat root protoplasts, linear background currents with non-zero reversal PDs had to be included to match the measured proton fluxes with the measured total currents (Tyerman et al 2001).

Modeling H^+/OH^- channels

The early I/V characteristics in Saline APW (violet and green I/V curves, Fig. 2b) exhibit reversal PDs only slightly positive with respect to -100 mV (reversal PD for the background current). The profiles are nearly linear, with only a hint of curvature, as the contribution of the negative current is small. However, with time in Saline APW, the membrane PD becomes less negative and the upwardly concave shape more pronounced (blue and pink I/V curves, Fig. 2b). We model this development by increasing the combined parameter for hydroxyl channel number and permeability, $N_{\text{OH}^-\text{P}_{\text{OH}}}$ (see Fig. 2d and Table 1). The upwardly concave shape arises from the PD-dependence of the hydroxyl current. The current decreases in amplitude as membrane PD becomes more negative (See Fig. 1d). Similar PD dependence of H^+/OH^- channels was calculated from flux measurements in wheat root protoplasts (Tyerman et al 2001). The half activation potential, V_{50} , (see Table 1) becomes progressively more negative with time in saline APW. This tendency of the H^+/OH^- channels to close at PDs more negative than -100 mV in the early exposure to Saline APW is a probable cause of the membrane PD noise (Al Khazaaly et al 2009): we postulate that groups of H^+/OH^- channels open and close spontaneously as the proton pump still maintains negative membrane PD. The PD noise is no longer observed once the I/V characteristics indicate that the H^+/OH^- state has become dominant. The gating charge z_g remains constant with time in Saline APW. The fractional value is taken to indicate partial movement of the charged structural elements of the channel. The low value indicates relatively weak PD-dependence.

The resting PD is determined by the balance between the hydroxyl current (Fig. 2d) and the background current (Fig. 2e). Consequently, as the hydroxyl current increases, the membrane PD tends towards E_{OH} (see Table 2). The cytoplasmic pH, pH_i , for *Chara*, *Nitella* and *Nitellopsis* was found to be in the range 7.2 - 7.8 in their native media (Walker and Smith 1975; Smith and Raven 1979, Katsuhara et al 1989), providing a starting value for pH_i in the

modeling. However, better fits of our data were obtained with pH_i becoming more acidic with time in Saline APW (see Table 1). This finding is reasonable, as the presence of the background state maintains the membrane PD negative of E_{OH} , causing outflow of OH^- out of or inflow of H^+ into the cytoplasm. This trend is supported by NMR measurement of Katsuhara et al. (1989) who found that cytoplasmic pH in *Nitellopsis obtusa* decreased to pH 6.9 in 2 hours of exposure to Saline APW.

The inward rectifier channels open at more positive PDs in Saline APW (Fig. 2e). Positive shift in half activation PD was found in salt-tolerant charophyte *Lamprothamnium* (Al Khazaaly and Beilby, 2007). However, in *Chara* the resting PD is located too far in the positive direction to allow any K^+ inflow. The $[\text{K}^+]_i$ was set to 40 or 30 mM for when modeling I/V characteristics of cells exposed to Saline APW for more than 60 min. These values are supported by measurements by Katsuhara and Tazawa (1986).

The background conductance, which increased by up to an order of magnitude in Saline APW, was reduced by the APW wash. The smaller background current can be seen as the orange line in Fig. 2e (see also Table 1 for fit parameters). The half activation potential for the inward rectifier returned to more negative PD. The I/V curve displayed unusual shape with both upward and downward curvature. Such shape can be obtained by a simultaneous fit of both proton pump and hydroxyl channels. The recovery of the proton pumping and gradual closure of the H^+/OH^- channels (see Fig. 2d) suggests that the cell can make a full recovery in APW. Such recovery can be slow, as documented in pump recovery from the K^+ state (Beilby 1985).

The pH change experiments support our hypothesis that the H^+/OH^- channels are involved in salinity stress. The membrane PD moved in the right direction in each case. In medium of pH 7, E_{OH} is in the range from +30 to 0 mV, depending on internal pH. In medium of pH 9 the E_{OH} is near -100 mV. In the medium of pH 6 the E_{OH} moves to between +50 and +80 mV. The membrane PD settled between E_{OH} and V_{bkg} at pH 9 or 7. At pH 6 there was a positive going transient and then H^+/OH^- channels closed. The shape of the I/V profiles at pH 9 in Fig. 3 is similar to that observed by Beilby and Bisson (1992). In APW the H^+/OH^- channels close at pH levels below 9 (Beilby and Bisson, 1992), while in saline APW this threshold pH is lowered to values between pH 7 and 6. It will be interesting to investigate if the lowering of

the pH threshold for the channel opening depends on the Na^+ concentration of the Saline APW.

The role of H^+/OH^- channels in salt stress in *Chara australis*

Bisson and Walker (1980) found that if external pH of the APW is increased to a threshold value (near pH 9), the surface of the whole cell becomes an alkaline band. Beilby and Bisson (1992) measured the I/V profiles of this high pH state and found that both the conductance and the reversal PD were rather variable. However, the membrane has always reverted to proton pump-dominated state below pH 9. Thus, finding activation of these channels at pH 7 in Saline APW is rather surprising. While the opening of the H^+/OH^- channels in the alkaline band is beneficial for the cell in native pond water, the circumstances are very different under salinity stress. The negative H^+/OH^- current implies outflow of OH^- or inflow of H^+ , acidifying the cytoplasm. The proton pump is inactivated (Shepherd et al 2008) and the buffering capacity of cytoplasm is finite. The membrane PD continues to move to more positive levels, reaching the activation threshold for the outward rectifier (about -50 mV), where the cell will lose more K^+ . The balance of K^+ to Na^+ , important for normal metabolism (Maathuis & Amtmann 1999), will be further disrupted. Finally, the increased permeability to H^+/OH^- dissipates some of the proton electrochemical gradient that is needed for $2\text{H}^+/\text{Cl}^-$ symport and H^+/Na^+ antiport. And, of course, the cell cannot band without the pump to provide the acid regions. The mechanism that increases carbon assimilation is sabotaged. The cell is doomed if it remains in the saline medium. The high Na^+ concentration and $\text{Na}^+/\text{Ca}^{2+}$ ratio of the medium is clearly the cause of the proton pump inactivation, large background conductance and H^+/OH^- channel activation, as once the cell is returned to APW all these effects are gradually reversed (orange curve in Fig. 2b – e).

What happens in salt tolerant charophytes? Yao and Bisson (1993) found that the alkaline bands in salt tolerant *Chara buckellii* (*longifolia*) cover more surface area in Saline APW than in APW. They observed an increase in membrane conductance and assumed that it is due to activation of H^+/OH^- channels. The key difference to salt-sensitive *Chara australis*, is the salinity-activated increase in proton pumping. Thus *Chara longifolia* is able to maintain negative membrane PD and the banding system. Another salt-tolerant charophyte *Lamprothamnium*, also exhibits progressively greater membrane conductance as the medium

salinity is increased (Beilby and Shepherd 2001). However, modeling of the I/V characteristics suggests that it is the background conductance that increases (Beilby and Shepherd 2001, Al Khazaaly and Beilby 2007). *Lamprothamnium* has not been observed to band in saline media, but does exhibit the high pH state in alkaline media (Bisson and Kirst 1983). Neither *Chara longifolia* nor *Lamprothamnium* exhibits the sodium-induced noise observed in *Chara australis* (Al Khazaaly et al 2009).

H⁺/OH⁻ channels in roots

Roots of land plants have a similar system to charophyte banding, with proton (or hydroxyl) channels activated at the root tip and proton pumping in the sub-apical zone of the root (Raven 1991). Wheat root protoplasts were observed to oscillate from pump dominated state with H⁺ efflux, to a state with channel-mediated H⁺ influx (Tyerman et al 2001). If salinity inactivates the pump and opens the proton (or hydroxyl) channels in the sub-apical zone of roots, this will lead to major disruption of the normal root function (Raven 1991). Tyerman et al (1997) observed inward currents at membrane PDs more positive than E_K and E_{Cl}, as well as salinity-induced noise, in salt stressed wheat root protoplasts. Consequently, the role of H⁺/OH⁻ channels in salinity stress may extend to many salt-sensitive land plants.

Conclusions

While pH changes can affect various transporters and more experiments are necessary for final identification, we present strong evidence that H⁺/OH⁻ channels open in latter stages of salinity stress in *Chara australis*. In native pond water these channels are part of the banding mechanism that enhances the cell's carbon assimilation in non-saline pond media and are closed at pH levels below 9. The activation at neutral pH in saline APW is thus rather unexpected. Under salinity stress the opening of these channels causes positive going shift of the membrane PD and possible acidification of the cytoplasm. The electrochemical gradient for H⁺ is progressively dissipated, so there is less motive force for the H⁺/Na⁺ antiport and 2H⁺/Cl⁻ symport. The membrane PD becomes more positive and outward K⁺ rectifier channels are activated, depleting the cell of more K⁺.

FIGURE LEGENDS

Figure 1 (a) shows a typical trend in the I/V characteristics from the pump-dominated profile (empty rectangles) in the Sorbitol APW to background current-dominated profile after 67 min of Saline APW (filled triangles). After 117 min of saline APW the membrane PD depolarized further and the profile exhibited an upward bend (filled diamonds). The experimental data are simulated by background current and pump (continuous line, model parameters: **background current:** $g_{\text{bkg}} = 0.2 \text{ Sm}^{-2}$, $V_{\text{bkg}} = -110 \text{ mV}$, **pump parameters:** $k_{\text{io}}^0 = 7200 \text{ s}^{-1}$, $k_{\text{oi}}^0 = 2.9 \text{ s}^{-1}$, $\kappa_{\text{io}} = 0.5 \text{ s}^{-1}$, $\kappa_{\text{oi}} = 138 \text{ s}^{-1}$), by background current, declining pump and inward rectifier current (short-dashed line, model parameters: **background current:** $g_{\text{bkg}} = 1.36 \text{ Sm}^{-2}$, $V_{\text{bkg}} = -110 \text{ mV}$, **pump parameters:** $k_{\text{io}}^0 = 100 \text{ s}^{-1}$, $k_{\text{oi}}^0 = 0.1 \text{ s}^{-1}$, $\kappa_{\text{io}} = 0.5 \text{ s}^{-1}$, $\kappa_{\text{oi}} = 55 \text{ s}^{-1}$, **inward rectifier parameters:** $N_{\text{KPK}} = 40 \times 10^{-7} \text{ ms}^{-1}$, $V_{50} = -258 \text{ mV}$, $z_{\text{g}} = 3.5$) and background current, OH⁻ channels and inward rectifier current (long-dashed line, model parameters: **background current:** $g_{\text{bkg}} = 1.3 \text{ Sm}^{-2}$, $V_{\text{bkg}} = -110 \text{ mV}$, **OH⁻ channel parameters:** $N_{\text{OHPOH}} = 35 \times 10^{-4} \text{ ms}^{-1}$, $V_{50-} = -130 \text{ mV}$, $z_{\text{g-}} = 0.6$, **inward rectifier parameters:** $N_{\text{KPK}} = 40 \times 10^{-7} \text{ ms}^{-1}$, $V_{50} = -174 \text{ mV}$, $z_{\text{g}} = 4$, $\text{pH}_i = 6.98$). The pump currents and the OH⁻ current are shown in part (c), the background currents and inward rectifier currents are displayed in part (d). The total conductance-voltage profiles are shown in part (b), with the resting PD indicated on each curve by a point of the same type as in part (a). The thin continuous lines in parts (b), (c) and (d) show the extrapolation of the models beyond the PD window delimited by the data.

Figure 2 (a) The response of the membrane PD to salinity. Cell 2 was pretreated in APW for 90 min and in Sorbitol APW for 118 min (not shown). The exposure to Saline APW is indicated by a vertical line extending across the whole PD range. The membrane shifted to PD levels more positive than -100 mV and the I/V profiles were measured at 21 min (violet), 60 min (light green), 66 min (turquoise) and 74 min (pink) in Saline APW. The cell was then returned to APW and I/V profile was measured at 33 min (orange). The membrane PD was data-logged at 1 point/10 s. (b) The I/V profile in Sorbitol APW is depicted by black points and the I/V profiles in Saline APW are in colours corresponding to part (a). The lines represent the total fitted current. (c) The total conductance was calculated by differentiating the current with respect to membrane PD. The modeled pump and OH⁻ currents are shown in part (d). In this figure only the modeled OH⁻ currents were extrapolated beyond the PD window delimited by the data and this is depicted by dashed lines. The fitted background and

inward rectifier currents (dashed lines) are depicted in part (e). The background current was fitted as remaining constant in Saline APW, thus only the last (pink) line is visible. The parameters of the fit are given in Table 1.

Figure 3 (a) The response of the membrane PD in Saline APW to change of pH from 7 to 9 (cell 5). The membrane PD was data-logged at faster rate of 10 points/sec. The horizontal axis shows the time from the start of the experiment, with the cell exposed to Saline APW at 9120 s. At this data-logging speed and the scale of the time axis the I/V staircases appear as thick vertical bars. These are designated by different symbols (empty square, full triangle and full diamond). The change to pH 9 is indicated by an arrow. Action potentials can be seen after the first and third I/V data collection and upon change of Saline APW. (b) The I/V profiles are shown as points using same symbols as in part (a). The data are modeled (continuous line for pH 7, short-dashed line for the first I/V curve at pH 9, long-dashed line for the second I/V curve at pH 9. The modeling parameters are given in Table 2. (c) G/V profiles are obtained by differentiation of the I/V profiles. The OH^- currents are shown in part (d). **The thin continuous lines show the extrapolation of the model beyond the PD window delimited by the data.** The background and rectifier currents are displayed in part (e). **The background current was fitted as remaining constant at pH 9.** Same types of lines are employed in parts (b) – (e).

Figure 4 (a) The response of the membrane PD in Saline APW to change of pH from 7 to 9 and to 6. The membrane PD was data-logged at faster rate of 10 points/sec. The horizontal axis shows the time from the start of the experiment with the cell exposed to Saline APW at 8160 s. The I/V curves appear as vertical lines and were designated by different symbols (empty square, empty triangle, full triangle, full diamond and a star). The changes to pH 9 and pH 6 are indicated by arrows. **The membrane PD drift seen before the change to pH 9 is typical of fluctuations observed at this stage of exposure to saline.** (b) The I/V profiles are shown as points using same symbols as in part (a). **The modeled currents are shown by continuous lines for pH 9, short-dashed line for the first I/V curve at pH 6, long-dashed line for the second I/V curve at pH 6 and alternate dash and dot line for the third I/V curve at pH 6.** The membrane PD was clamped at -45 mV between the first two I/Vs at pH 6. The modeling parameters are given in Table 3. (c) G/V profiles are obtained by differentiation of the I/V profiles. The OH^- currents are shown in part (d). **The thin continuous lines show the extrapolation of the model beyond the PD window delimited by the data.** The background and rectifier **currents** are displayed in part (e). Same types of lines are employed in parts (b) – (e).

Figure 5 (a) Statistics of the response of the I/V characteristics in Saline APW to pH change. At pH 7: cells 4 – 8, (four I/V profiles), filled rectangles, continuous line; at pH 9 cells 7 and 8 (four I/V profiles), empty triangles, long-dashed line; at pH 6 cell 7 and 8 (four I/V profiles), stars, short-dashed line. The data were sorted into 15 mV slots (horizontal error bars), with standard error for each slot as vertical error bar. The fitted parameters are given in Table 4. **(b)** The G/V profiles, **(c)** fitted OH⁻ currents and **(d)** background and rectifier currents. The line types are the same for parts **(a)** – **(d)**. **The thin continuous lines in part (d) show the extrapolation of the model beyond the PD window delimited by the data.**

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