TRANSCELLULAR INTESTINAL CALCIUM TRANSPORT IN FRESHWATER AND SEAWATER FISH AND ITS DEPENDENCE ON SODIUM/CALCIUM EXCHANGE

TH. J. M. SCHOENMAKERS, P. M. VERBOST, G. FLIK and S. E. WENDELAAR BONGA

Department of Animal Physiology, Faculty of Science, University of Nijmegen, Toernooiveld, NL-6525 ED Nijmegen, The Netherlands

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Summary

Transepithelial calcium uptake and transcellular calcium uptake mechanisms were compared in the proximal intestine of freshwater- and seawater-adapted tilapia, Oreochromis mossambicus. Stripped intestinal epithelium of seawater fish showed a higher paracellular permeability to calcium in vitro. Net transepithelial calcium uptake was 71% lower, reflecting a physiological response to the increased inward calcium gradient. Na+/K+-ATPase activity was significantly enhanced in enterocytes of seawater-adapted fish, in line with the water transport function of the intestine in seawater fish. The \( V_{\text{max}} \) and the \( K_m \) values for Ca\(^{2+}\) of the ATP-dependent Ca\(^{2+}\) pump in seawater fish enterocytes were 28% and 27%, respectively, lower than in freshwater fish. The \( K_m \) for Ca\(^{2+}\) of the Na\(^+/\)Ca\(^{2+}\) exchanger was 22% lower, and a 57% decrease in the \( V_{\text{max}} \) for Ca\(^{2+}\) of the exchanger was observed. Apparently, the density of exchanger molecules in the basolateral plasma membrane is reduced in seawater fish. From the correlation between the differences in net intestinal calcium uptake and Na\(^+/\)Ca\(^{2+}\) exchange activity we conclude that Na\(^+/\)Ca\(^{2+}\) exchange is the main basolateral effector of transcellular calcium uptake.

Introduction

The Na\(^+/\)Ca\(^{2+}\) exchanger is a plasma membrane protein crucial to calcium homeostasis in, for example, muscles and neurones (DiPolo, 1989). During the last decade, the opinion prevailed that the protein might be typical of excitable cells (Baker, 1986). Non-excitable cells normally do not develop the high intracellular ionic calcium concentrations characteristic of the former. Therefore, it was thought that the contribution of the Na\(^+/\)Ca\(^{2+}\) exchanger, which has a relatively low Ca\(^{2+}\) affinity, to cellular calcium homeostasis of such cells was of minor importance. In recent years, however, evidence has accrued that the exchanger can be found in quite a number of non-excitable cells. Cells in ion-transporting epithelia were repeatedly shown to display Na\(^+/\)Ca\(^{2+}\) exchange activity involved in transcellular ion transport (Flik et al. 1990; Taylor, 1989). The Na\(^+/\)Ca\(^{2+}\) exchanger can serve different purposes in non-excitable cells, as shown by its

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involvement in volume regulation and Na+ extrusion in canine erythrocytes (Parker, 1988; Schoenmakers and Flik, 1992). Basolateral membranes of enterocytes of the freshwater fish Oreochromis mossambicus Peters (tilapia) have been shown to display a weak ATP-dependent Ca2+ pump activity and a vigorous Na+/Ca2+ exchange activity (Flik et al. 1990; Schoenmakers et al. 1992a).

The issue of the importance of the Na+/Ca2+ exchanger in non-excitable cells is interlaced with the topic of its regulation. In vitro the functioning of the Na+/Ca2+ exchange protein has been modulated in many ways: membrane composition, intracellular Ca2+ concentration and cellular energy status are factors known to influence Na+/Ca2+ exchange activity (DiPolo, 1989; Philipson and Ward, 1985). These studies were performed on cells or tissues in a steady state. Few studies have concentrated on the question of how altered physiological requirements are reflected by changes in the activity of the Na+/Ca2+ exchanger (Tibbits et al. 1989).

We provide data on the importance and regulation of the Na+/Ca2+ exchanger in an ion-transporting cell. We used the intestine of the tilapia as a model of an ion-transporting epithelium. The tilapia is a euryhaline fish able to live in fresh water as well as in full-strength sea water. Freshwater fish are hyper-osmoregulators in which the active uptake of ions is needed for metabolism and growth. They drink little and take up most of the monovalent ions they need (such as Na+, K+ and Cl−), as well as most of their calcium, via their gills (Mayer-Gostan et al. 1987; Fenwick, 1989). Seawater fish, however, are hypo-osmoregulators, confronted in particular with osmotic water loss. Therefore, seawater fish drink large amounts of sea water and excrete, via the gills and kidneys, the excess ions taken up in the intestine (Maetz, 1976).

Freshwater fish need extra calcium during growth and ovarian maturation or when the calcium concentration in the water is low, as in soft fresh water (Flik et al. 1986). Under the latter circumstances, fish experience extra calcium loss as a result of an increased epithelial permeability to calcium (Höbe et al. 1984). When faced with such adverse conditions, they supplement branchial calcium uptake with an increase in intestinal uptake (Berg, 1970).

Experiments on tilapia in our laboratory have shown that the net branchial uptake of calcium, sufficient for growth and homeostasis of fish in fresh water containing around 1 mmol l−1 Ca2+, increases when the fish are transferred to sea water: branchial Ca2+ influx is not affected, but branchial Ca2+ efflux is drastically reduced (G. Flik, personal observations). Drinking of sea water containing around 10 mmol l−1 calcium will lead to an excess influx of calcium in seawater fish unless the intestinal uptake of calcium is strictly controlled. Paracellular influx of calcium in the intestine is counteracted by the generation of an inside-positive transepithelial potential (Maetz, 1976). Here, we concentrate on another means of decreasing net calcium uptake, i.e. the reduction of the active transcellular transport of calcium across the intestine.

We measured unidirectional calcium fluxes in stripped intestinal epithelium of freshwater- and seawater-adapted fish. The isolation of basolateral plasma membrane vesicles allowed us to test which of the two extrusion mechanisms for Ca2+ (the ATP-dependent Ca2+ pump or Na+/Ca2+ exchange) is more involved in transcellular calcium uptake under these conditions.
Materials and methods

Holding conditions of fish

Male freshwater tilapia from laboratory stock, weighing around 250 g, were held in 1001 tanks. The aquaria were supplied with running tap water (0.7 mmol l⁻¹ Ca²⁺, 25 °C) under a photoperiod of 12 h of light alternating with 12 h of darkness. Animals were fed Trouvit fish pellets (Trouw and Co., Putten, The Netherlands) at 1.5% body weight per day.

Artificial sea water was prepared by dissolving natural sea salt (Wimex, Krefeld, Germany) to a density of 1.022 g l⁻¹. Fish were first transferred to half-strength sea water. After 1 day, they were transferred to full-strength sea water. Fish were adapted to sea water for at least 8 weeks before experimentation. Food was supplied at 1.5% body weight per day.

Epithelial calcium flux measurements

The intestinal epithelium was stripped of its underlying muscle layers as described previously (Flik et al. 1990; Groot et al. 1979). Briefly, fish were killed by spinal transection and pithed. The peritoneal cavity was opened and the intestinal tract removed. The intestine was flushed with saline (117.5 mmol l⁻¹ NaCl, 5.7 mmol l⁻¹ KCl, 25 mmol l⁻¹ NaHCO₃, 1.2 mmol l⁻¹ NaH₂PO₄, 1.25 mmol l⁻¹ CaCl₂, 1.2 mmol l⁻¹ MgSO₄, 5 mmol l⁻¹ glucose and 28 mmol l⁻¹ mannitol) and attached strands of fat were carefully removed. The intestine was cut open lengthwise and dipped up and down in saline to remove any remaining food residues. Next, the intestine was put on a Parafilm-covered glass plate mucosa-side-up. The mucosa of the proximal 15 cm was stripped free of underlying muscle layers (Groot et al. 1979). The stripped epithelium was mounted on slides (the exposed tissue area was 0.16 cm²) and incubated for approximately 20 min in gassed saline (95% O₂/5% CO₂; pH 7.3±0.1).

The slides were then mounted as the partition between two 4 ml half-chambers filled with saline. At time zero, ⁴⁵CaCl₂ (specific activity: 19 GBq mmol⁻¹) was added as a tracer to either side of the tissue to yield a radioactive concentration of 0.33 MBq ml⁻¹. After 45 min, samples (100 µl) were taken from both half-chambers simultaneously every 15 min, for a total period of 180 min. The samples were instantly replaced by 100 µl of fresh Ringer’s solution. In pilot experiments it was established that unidirectional fluxes are constant over this period.

Using symmetrical conditions (saline on both sides) should keep passive fluxes of ⁴⁵Ca at a minimum, allowing a good assessment of active calcium transport processes (Barry and Diamond, 1984). The transepithelial potential (TEP) of stripped intestinal preparations from freshwater tilapia was 0.93±0.66 mV (N=24). This small TEP indicates that passive calcium flux is low in this Ussing chamber apparatus.

Unidirectional calcium fluxes were calculated as follows. Specific activity (SA) of the radioactive saline (cis-side) was determined from three 10 µl samples distributed over the whole experimental period and expressed in disint min⁻¹ nmol⁻¹. The amount of isotope at the trans-side at a given time [q(t)] in disint min⁻¹ was calculated from the 100 µl samples. Data were corrected for background, and cumulative counts for the whole Ussing hemi-chamber were calculated. Total calcium transported (in nmol cm⁻²) as a
function of time was obtained by calculating \( \frac{q(t)}{SA \times A} \) for each sample, where \( A \) is the exposed tissue area (in cm\(^2\)). Unidirectional steady-state Ca\(^{2+}\) fluxes were determined by linear regression of calcium accumulation over periods of at least 45 min. To calculate net fluxes \( (J_{net}) \), values for unidirectional fluxes from mucosa to serosa \( (J_{ms}) \) and from serosa to mucosa \( (J_{sm}) \) across adjacent segments from the same fish were used in data analysis. Ca\(^{2+}\) fluxes were expressed in nmol h\(^{-1}\) cm\(^{-2}\).

Membrane vesicle preparation and protein activity assays

Membrane vesicles were isolated from the proximal 30 cm of the intestine as described in detail previously (Flik et al. 1990). Vesicles were kept cooled on ice and used on the day of isolation. The protein content of the membrane vesicle preparations was 2.0±0.4 g l\(^{-1}\) (\( N =12 \)), as determined with a commercial reagent kit (Bio-Rad) with bovine serum albumin (BSA) as a reference. Protein recovery was around 1.9% in both freshwater and seawater preparations. Na\(^+/K^+\)-ATPase activity in fish intestinal basolateral plasma membrane vesicles (BLMV) was determined as described earlier (Flik et al. 1990). Na\(^+/K^+\)-ATPase activity was defined as the Na\(^+-\) and K\(^+-\)-dependent, ouabain-sensitive phosphatase activity.

All assay media contained 0.5 mmol l\(^{-1}\) EGTA, 0.5 mmol l\(^{-1}\) N-(2-hydroxyethyl)-ethylenediamine-N,N',N'-triacetic acid (HEEDTA) and 0.5 mmol l\(^{-1}\) nitrilotriacetic acid (NTA). Free calcium and magnesium levels were calculated as described in detail by Schoenmakers et al. (1992a,b). All incubations were performed at 37 °C.

The ATP-driven transport of \(^{45}\)Ca was assayed using a rapid filtration technique (Flik et al. 1990). One-minute incubations of membrane vesicles in the presence of 3 mmol l\(^{-1}\) ATP yielded \(^{45}\)Ca uptakes (representing initial velocities of the pump) and were corrected for uptake in the absence of ATP. Free Ca\(^{2+}\) concentrations were varied from 50 nmol l\(^{-1}\) to 1 \( \mu \)mol l\(^{-1}\). A 14-fold dilution in ice-cold isotonic medium containing 0.1 mmol l\(^{-1}\) LaCl\(_3\) stopped the uptake, and the suspension was filtered (Schleicher & Schüll ME25, pore size 0.45 \( \mu \)m). Filters were rinsed twice with 2 ml of ice-cold medium and transferred to counting vials. 4 ml of Aqualuma was added per vial, filters were allowed to dissolve (30 min at room temperature) and radioactivity was determined in a Pharmacia Wallac 1410 liquid scintillation counter.

Na\(^+/Ca^{2+}\) exchange activity in plasma membrane vesicles from fish enterocytes was assayed as described previously (Flik et al. 1990). Briefly, 5 \( \mu \)l of membrane vesicles equilibrated with 150 mmol l\(^{-1}\) NaCl was added to 120 \( \mu \)l of medium containing \(^{45}\)Ca and either 150 mmol l\(^{-1}\) NaCl (blank) or 150 mmol l\(^{-1}\) KCl. Ionic Ca\(^{2+}\) concentrations ranged from 250 nmol l\(^{-1}\) to 25 \( \mu \)mol l\(^{-1}\). After 5 s at 37 °C, the reaction was stopped by addition of 1 ml of ice-cold isotonic stopping solution containing 1 mmol l\(^{-1}\) LaCl\(_3\) and the solution was filtered. The filter was then rinsed three times with 2 ml of stopping solution and treated as described above. The difference in \(^{45}\)Ca accumulation was taken to represent Na\(^+-\)gradient-driven Ca\(^{2+}\) transport.

Calculations and statistics

The \( K_m \) and \( V_{\text{max}} \) values of the ATP-dependent Ca\(^{2+}\) pump and the Na\(^+/Ca^{2+}\) exchanger were derived by non-linear regression analysis of the mean velocities (\( N =5–6 \)) measured...
Calcium transport in fish intestine

Fig. 1. Unidirectional and net calcium fluxes in stripped intestinal epithelium of freshwater- and seawater-adapted tilapia. Seawater adaptation induces an increased paracellular calcium permeability in vitro. Net uptake of calcium is significantly reduced in seawater-adapted fish. Open bars denote unidirectional calcium fluxes and cross-hatched bars represent net calcium flux. * indicates $P<0.05$ and ** indicates $P<0.001$. Mean values ± standard error of the mean are given for 15 freshwater and 7 seawater fish.

as a function of substrate concentration. The standard deviations of the values given by the computer algorithm indicate the accuracy of the estimated values, but cannot be used for statistical assessment of differences (Press et al. 1986).

Otherwise, statistical significance of differences between mean values was tested using a Mann–Whitney $U$-test. Statistical significance was accepted at $P<0.05$.

Results

**Epithelial calcium flux measurements**

Calcium fluxes in stripped intestinal epithelium of freshwater and seawater tilapia are shown in Fig. 1. The mucosa-to-serosa flux of Ca$^{2+}$ ($J_{ms}$) in seawater epithelium was not significantly different from that through freshwater epithelium. The serosa-to-mucosa ($J_{sm}$) calcium flux in freshwater fish, $19.6±7.5$ nmol Ca$^{2+}$ h$^{-1}$ cm$^{-2}$ (mean ± s.d.; $N=15$), was significantly ($P<0.05$) lower than the flux, $28.6±10.0$ nmol Ca$^{2+}$ h$^{-1}$ cm$^{-2}$ (mean ± s.d.; $N=7$), in seawater fish, indicating an increased permeability to Ca$^{2+}$ of the tight junctions in vitro. The net uptake of Ca$^{2+}$ ($J_{net}=J_{ms}-J_{sm}$) in seawater intestine ($5.0±5.2$ nmol Ca$^{2+}$ h$^{-1}$ cm$^{-2}$; mean ± s.d.; $N=7$) was not significantly different from zero. The net uptake was significantly ($P<0.001$) reduced with respect to the net flux in freshwater fish ($17.1±8.9$ nmol Ca$^{2+}$ h$^{-1}$ cm$^{-2}$; mean ± s.d.; $N=15$).

**Membrane protein activities**

Using Na$^+$/K$^+$-ATPase as a marker to assess basolateral plasma membrane purification
we found no significant ($P \geq 0.15$) difference in purification between freshwater and seawater tilapia membranes: $\text{Na}^+/$$\text{K}^+$-ATPase activity purified 4.8±1.0 ($N=5$) times for seawater tilapia membranes and 6.2±1.7 ($N=6$) times for freshwater tilapia membranes. The activities of the three basolateral plasma membrane proteins we characterized are given in Table 1. $\text{Na}^+/$$\text{K}^+$-ATPase activity in the homogenate of intestinal scrapings from seawater tilapia amounted to 26.9±2.9 $\mu$mol P i h$^{-1}$ mg$^{-1}$ ($N=5$), which is significantly ($P<0.001$) higher than the activity observed in intestinal scrapings from freshwater tilapia (17.3±2.7 $\mu$mol P i h$^{-1}$ mg$^{-1}$; $N=6$). In purified basolateral plasma membranes from seawater fish, its activity was 127.6±14.1 $\mu$mol P i h$^{-1}$ mg$^{-1}$ ($N=5$), differing significantly ($P<0.001$) from that in freshwater fish, which amounted to 102.7±10.5 $\mu$mol P i h$^{-1}$ mg$^{-1}$ ($N=6$).

Seawater fish enterocytes have a greatly decreased $\text{Na}^+/$$\text{Ca}^{2+}$ exchange activity in the purified basolateral membrane fraction. The maximal velocity of the $\text{Na}^+/$$\text{Ca}^{2+}$ exchange activity in basolateral plasma membrane vesicles from freshwater-adapted tilapia [18.2±0.4 nmol Ca$^{2+}$ min$^{-1}$ mg$^{-1}$ ($N=6$)] was reduced by 57% in vesicles from seawater-adapted tilapia [7.85±0.21 nmol Ca$^{2+}$ min$^{-1}$ mg$^{-1}$ ($N=5$)]. The $K_m$ of $\text{Na}^+/$$\text{Ca}^{2+}$ exchange in freshwater tilapia (2.26±0.13 $\mu$mol l$^{-1}$; $N=6$) differs only slightly from that of $\text{Na}^+/$$\text{Ca}^{2+}$ exchange in seawater tilapia (1.76±0.16 $\mu$mol l$^{-1}$; $N=5$).

The ATP-dependent Ca$^{2+}$ pump in the basolateral plasma membrane vesicles did not show such a distinct change in maximal velocity. In vesicles from freshwater and seawater tilapia we measured a slight change in $K_m$, comparable in relative magnitude to the change in $K_m$ of the $\text{Na}^+/$$\text{Ca}^{2+}$ exchanger. $V_{\text{max}}$ decreased in a similar manner by 28% from 0.78±0.06 nmol Ca$^{2+}$ min$^{-1}$ mg$^{-1}$ in freshwater fish to 0.56±0.02 nmol Ca$^{2+}$ min$^{-1}$ mg$^{-1}$ in seawater fish.

**Discussion**

*Epithelial calcium flux measurements*

The net uptake of calcium in the proximal intestine calculated on the basis of unidirectional calcium fluxes approaches zero and is significantly lower in seawater fish than in freshwater fish. Apparently, seawater fish have successfully reduced active calcium transport mechanisms and keep net intestinal transcellular calcium influx low. The decrease in net uptake and the increase in paracellular calcium mobility result in an apparently unchanged unidirectional calcium influx.

The data show a manifest increase in the serosa-to-mucosa flux ($J_{\text{sm}}$) for calcium in the intestine of seawater-adapted fish. It is a well-known phenomenon that the intestine of seawater-adapted fish has a larger osmotic permeability to water (Skadhauge, 1969; Smith et al. 1975). Apparently, the looser tight junctions in seawater intestine have also become more permeable to calcium. The symmetrical conditions we used to minimize the contribution of passive fluxes to the total isotope flux (see above) may not reflect, however, the situation in vivo: the inside-positive transmural potential in the intact fish (around +30 mV; Maetz, 1976) will inhibit passive influx of calcium. An inside-positive transmural potential of 30 mV in seawater fish, when compared with the 0 mV potential
Table 1. Activities of ion-transport mechanisms in freshwater and seawater tilapia enterocytes

<table>
<thead>
<tr>
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<th>Na+/K+-ATPase</th>
<th>ATP-dependent Ca(^{2+}) pump</th>
<th>Na+/Ca(^{2+}) exchange</th>
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<tbody>
<tr>
<td></td>
<td>Homogenate</td>
<td>BLMV</td>
<td></td>
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<td></td>
<td>(V_{\text{spec}})</td>
<td>(V_{\text{spec}})</td>
<td>(K_{\text{m}})</td>
</tr>
<tr>
<td>Freshwater</td>
<td>17.3 (\pm) 2.7</td>
<td>102.7 (\pm) 10.5</td>
<td>193 (\pm) 34</td>
</tr>
<tr>
<td>Seawater</td>
<td>26.9 (\pm) 2.9(*)</td>
<td>127.6 (\pm) 14.1(*)</td>
<td>141 (\pm) 10</td>
</tr>
<tr>
<td>Change (%)</td>
<td>+55</td>
<td>+24</td>
<td>-27</td>
</tr>
</tbody>
</table>

All values are mean \(\pm\) standard deviation for five seawater and six freshwater tilapia.

The given \(K_{\text{m}}\) and \(V_{\text{max}}\) values are calculated from the average values by non-linear regression analysis and cannot be tested for statistically significant differences (Press et al. 1986).

\(*\)Significantly different from the freshwater value, \(P<0.001\).

BLMV, basolateral membrane vesicles; \(V_{\text{spec}}\), specific activity; \(K_{\text{m}}\), Michaelis constant; \(V_{\text{max}}\), maximum activity.
difference seen in freshwater fish, would decrease the unidirectional passive influx of calcium by 75% compared to the value found in freshwater fish according to the formula:

\[ J_{\text{sea}} = J_{\text{fresh}}(\pm zEF/RT)/(1 - e^{\pm zEF/RT}) \]

(Hodgkin and Horowicz, 1959), where \( z \) is valency, \( E \) is the equilibrium potential (for Ca\(^{2+} \)), \( F \) is the Faraday constant, \( R \) is the gas constant and \( T \) is absolute temperature. Therefore, the large inward calcium gradient in seawater fish will not result in the excessive calcium influx that one would predict on the basis of the increased paracellular permeability to calcium.

Whole-body calcium influx and efflux for a 250 g freshwater tilapia can be calculated according to Flik et al. (1985). Influx of calcium will be around 4.3 \( \mu \)mol h\(^{-1} \) while calcium efflux is around 0.7 \( \mu \)mol h\(^{-1} \), resulting in a net whole-body calcium influx of 3.6 \( \mu \)mol h\(^{-1} \). The length of intestine that performs the measured net influx of 17.1 nmol cm\(^{-2} \) h\(^{-1} \) is not known. If one assumes that this transport occurs over a length of 50 cm (on the basis of gut morphology), the calculated net influx (with a width of 1 cm) is 0.86 \( \mu \)mol h\(^{-1} \). Intestinal calcium influx would then contribute significantly to the whole-body influx.

The net uptake of calcium in tilapia intestine under freshwater conditions has been demonstrated by Flik et al. (1990). In that study we also showed that this net uptake depended on the presence of a sodium gradient across the basolateral plasma membrane of the enterocyte. This indicated that Na\(^{+}\)/Ca\(^{2+}\) exchange, shown to be present in these membranes, was important for transcellular calcium uptake (Flik et al. 1990). The lower net intestinal calcium uptake in seawater intestine shown here prompted an investigation into the molecular basis of this change.

**Membrane protein activities**

Seawater adaptation induced significant changes in two of the three plasma membrane ion-transporting mechanisms we studied. The increase in Na\(^{+}\)/K\(^{+}\)-ATPase activity we found is a normal phenomenon for intestine and gills of seawater-adapted fish (Utida et al. 1972; Maetz, 1976; Pagliarani et al. 1991). Around 90% of the cells in the proximal intestine are of the absorptive cell type. Therefore, the observed increase in Na\(^{+}\)/K\(^{+}\)-ATPase activity per milligram membrane protein represents an increase in activity per cell, not an increase in the numbers of a specific cell type. The increase in the ratio of the activities of Na\(^{+}\)/K\(^{+}\)-ATPase to Ca\(^{2+}\)-ATPase in the purified basolateral plasma membrane vesicles, 3.80 \( \times \) 10\(^3 \) in seawater vs 2.19 \( \times \) 10\(^3 \) in freshwater fish [dividing the Na\(^{+}\)/K\(^{+}\)-ATPase activity (\( \mu \)mol P\(_{i}\) h\(^{-1} \) mg\(^{-1} \)) by the Ca\(^{2+}\)-ATPase activity (nmol Ca\(^{2+}\) h\(^{-1} \) mg\(^{-1} \)) and assuming that 1 P\(_{i}\) is formed per Ca\(^{2+}\) transported], shows that the increase in Na\(^{+}\)/K\(^{+}\)-ATPase activity is not due to a purification effect (Flik et al. 1984). The increase is in line with ultrastructural observations on the intestine of seawater tilapia showing more extensive basolateral membrane invaginations and more mitochondria than in freshwater fish and giving the impression of very active cells (G. Flik, personal observations). The elevated Na\(^{+}\)/K\(^{+}\)-ATPase activity is consistent with the water transport function of the intestine of seawater fish (Skadhauge, 1969; Utida et al. 1972), assuming that solvent drag is the motive force for this water transport.
Fig. 2. Activities of basolateral plasma membrane proteins in seawater and freshwater fish as a function of intracellular Ca\(^{2+}\) concentration. Thick curves represent Na\(^{+}/Ca^{2+}\) exchange activity, while thin curves show the activity of the ATP-dependent Ca\(^{2+}\) pump. Activities in freshwater fish are given by solid lines and dashed lines represent activities in seawater fish. Na\(^{+}/Ca^{2+}\) exchange activity exceeds Ca\(^{2+}\) extrusion under both conditions, even when the stimulatory inside-negative cell membrane potential is disregarded.

The ATP-dependent Ca\(^{2+}\) pump activity in plasma membranes from freshwater tilapia is slightly higher than that observed in membranes from seawater tilapia. If we combine these data with the respective Na\(^{+}/K^{+}\)-ATPase purification data, we calculate equal amounts of Ca\(^{2+}\) pump activity per milligram cell protein in the whole-cell homogenate (direct measurements of this activity in such a preparation are complicated) in freshwater (0.13 nmol Ca\(^{2+}\) min\(^{-1}\) mg\(^{-1}\) cell protein) and in seawater enterocytes (0.12 nmol Ca\(^{2+}\) min\(^{-1}\) mg\(^{-1}\) cell protein). Apparently, freshwater- and seawater-adapted enterocytes contain equal amounts of ATP-dependent calcium pump proteins.

A very significant change was found in the Na\(^{+}/Ca^{2+}\) exchange activity. The maximum velocity of this carrier decreased by 57% in seawater tilapia. When we calculate activities in the whole-cell homogenate (as for the ATP-dependent Ca\(^{2+}\) pump above), there is a large difference between freshwater enterocytes (2.9 nmol Ca\(^{2+}\) min\(^{-1}\) mg\(^{-1}\) cell protein) and seawater enterocytes (1.6 nmol Ca\(^{2+}\) min\(^{-1}\) mg\(^{-1}\) cell protein). Seawater enterocytes clearly contain less Na\(^{+}/Ca^{2+}\) exchange activity. The observed 57% reduction in Na\(^{+}/Ca^{2+}\) exchange activity in purified plasma membranes is in line with the 71% decrease in net transepithelial calcium uptake. We take this observation as evidence for the involvement of the Na\(^{+}/Ca^{2+}\) exchanger in the active transcellular uptake of calcium in both freshwater and seawater fish.

This conclusion is further supported when we plot the activities of the two Ca\(^{2+}\)-transporting membrane proteins under both conditions (Fig. 2). This graph does not take the inside-negative cell membrane potential of around \(-60\) mV (Bakker and Groot, 1988) into account. The Na\(^{+}/Ca^{2+}\) exchange is an electrogenic process, swapping 3 Na\(^{+}\) for 1 Ca\(^{2+}\) (Flik et al. 1990), and would be even more active than shown here. In the
physiological intracellular Ca\(^{2+}\) concentration range (around 85 nmol\(1^{-1}\); Schoenmakers et al. 1992a) the Na\(^{+}/Ca^{2+}\) exchanger clearly dominates basolateral Ca\(^{2+}\) extrusion from the enterocytes in freshwater fish. Under seawater conditions, both the absolute calcium transport capacity of the extrusion mechanisms and the contribution of the Na\(^{+}/Ca^{2+}\) exchanger to this transport have decreased.

The distinct decrease in \(V_{\text{max}}\) of the Na\(^{+}/Ca^{2+}\) exchange activity probably reflects a regulatory principle: presumably, the expression rate of the exchanger’s gene has decreased and there are fewer exchanger molecules per cell. Table 1 shows that the percentage decreases in \(K_m\) of the ATP-dependent Ca\(^{2+}\) pump and the Na\(^{+}/Ca^{2+}\) exchanger are similar. This suggests the existence of a mechanism that has a similar effect on both membrane proteins. We suggest that seawater fish develop a more fluid plasma membrane. Increased membrane fluidity has been shown to decrease the \(K_m\) of Na\(^{+}/Ca^{2+}\) exchange (Philipson and Ward, 1985). The lipid composition of gill membranes changes when fish adapt to seawater conditions (Hansen, 1987). The changed endocrine status of seawater fish may well underlie such a phenomenon. Cortisol and prolactin levels change upon adaptation to sea water (Utida et al. 1972). Actions of cortisol on calcium homeostasis appear to involve primarily a stimulation of calcium uptake mechanisms (Utida et al. 1972; Flik and Perry, 1989). Prolactin, however, influences plasma membrane fluidity and enzyme activity in rat tissues in a complex manner (Dave et al. 1981; Dave and Witorsch, 1985). Thus, the plasma membrane fluidity of the enterocytes of seawater fish may have increased as a result of the decreased prolactin levels.

We here show that seawater fish develop more intestinal Na\(^{+}/K^{+}\)-ATPase activity, which is in line with one of the main functions of the intestine in seawater fish, i.e. water uptake by solute-linked water transport, and with the lower prolactin levels in seawater fish, as prolactin is known to exert an inhibitory control over Na\(^{+}/K^{+}\)-ATPase activity (Pickford et al. 1970). Also, this study is the first to give evidence for the regulation of transepithelial calcium flux in the tilapia intestine. Seawater fish drastically reduce active intestinal uptake of calcium. The reduction in Na\(^{+}/Ca^{2+}\) exchange activity in purified basolateral plasma membranes, which parallels the reduction in net transepithelial calcium uptake, supports the notion that the Na\(^{+}/Ca^{2+}\) exchanger is the transport protein chiefly responsible for transepithelial uptake of calcium in fish intestine.

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