Actions of Cadmium on Basolateral Plasma Membrane Proteins Involved in Calcium Uptake by Fish Intestine

Theo J.M. Schoenmakers, Peter H.M. Klaren, Gert Flik, Robert A.C. Lock, Peter K.T. Pang†, and Sjoerd E. Wendelaar Bonga

Department of Animal Physiology, Faculty of Science, University of Nijmegen, Toernooiveld, NL-6525 ED Nijmegen, The Netherlands, and †Department of Physiology, School of Medicine, University of Alberta, Edmonton, Alberta T6G 2H7, Canada

Summary. The inhibition of Ca2+-ATPase, (Na+ + K+)-ATPase and Na+/Ca2+ exchange by Cd2+ was studied in fish intestinal basolateral plasma membrane preparations. ATP driven 4Ca2+ uptake into inside-out membrane vesicles displayed a $K_m$ for Ca2+ of 88 ± 17 nm, and was extremely sensitive to Cd2+ with an IC50 of 8.2 ± 3.0 μM Cd2+, indicating an inhibition via the Ca2+ site. (Na+ + K+)-ATPase activity was half-maximally inhibited by micromolar amounts of Cd2+, displaying an IC50 of 2.6 ± 0.6 μM Cd2+. Cd2+ ions apparently compete for the Mg2+ site of the (Na+ + K+)-ATPase. The Na+/Ca2+ exchanger was inhibited by Cd2+ with an IC50 of 73 ± 11 nM. Cd2+ is a competitive inhibitor of the exchanger via an interaction with the Ca2+ site ($K_i = 11$ nM). Bepridil, a Na+ site specific inhibitor of Na+/Ca2+ exchange, induced an additional inhibition, but did not change the $K_i$ of Cd2+. Also, Cd2+ is exchanged against Ca2+, albeit to a lesser extent than Ca2+. The exchanger is partly blocked by the binding of Cd2+. In vivo cadmium that has entered the enterocyte may be shuttled across the basolateral plasma membrane by the Na+/Ca2+ exchanger. We conclude that intracellular Cd2+ ions will inhibit plasma membrane proteins predominantly via a specific interaction with divalent metal ion sites.

Key Words cadmium · Ca2+-ATPase · (Na+ + K+)-ATPase · Na+/Ca2+ exchange · competitive inhibition · teleost fish

Introduction

Living cells need to extrude calcium continuously: the large inward electrochemical gradient for calcium results in "leakage" of this ion into the cell and, as high Ca2+ levels are toxic, it has to be eliminated in order for the cell to function properly. The intracellular Ca2+ concentration plays a key role in the regulation of many cellular processes, acting as an intracellular second messenger. Cellular calcium homeostasis is often safeguarded by the ATP-dependent Ca2+ pump, a high affinity Ca2+-ATPase [27]. This enzyme belongs to the family of E1-E2 type ion pumps [23], of which the ubiquitous sodium/potassium-dependent ATPase ((Na+ + K+)-ATPase) is the most widely studied member. (Na+ + K+)-ATPase is considered a pivotal transport ATPase for cellular ion homeostasis. It uses intracellular ATP to extrude Na+ ions, and to import K+ ions into the cell. Thereby it maintains the electrochemical gradients for Na+ and K+, which in turn are used by other membrane proteins that are essential for vital processes as cell volume regulation, ion extrusion and nutrient uptake [35]. We have demonstrated both these plasma membrane ion pumps in the intestine of the teleost Oreochromis mossambicus (tilapia) [13].

In this freshwater fish intestinal calcium uptake not only depends on the action of the ATP-dependent Ca2+ pump, but also on sodium/calcium exchange activity, which is abundantly present in the basolateral membrane. Na+/Ca2+ exchange may well be the dominant Ca2+ extrusion mechanism, in contrast to higher vertebrates where the ATP-dependent Ca2+ pump is most important [21]. Sodium/calcium exchange requires the action of (Na+ + K+)-ATPase for the creation of the electrochemical gradient for Na+, which is its main driving force. The apparent maximum exchange velocity is 16 times higher than that reported for a comparable membrane preparation from rat small intestine [13, 17]. The maximum velocity of the fish Na+/Ca2+ exchanger exceeded that of the fish ATP-dependent Ca2+ pump 34 times. Also, net intestinal calcium uptake was dependent on the existence of a Na+ gradient across the basolateral cell membrane. These data indicate the involvement of Na+/Ca2+ exchange in cell Ca2+ homeostasis as well as transcellular Ca2+ transport in tilapia intestinal epithelium [13]. With its array of Ca2+ transport mechanisms in the basolateral membrane the fish intestine...
may provide a suitable model for analyzing toxicological effects of Cd\(^{2+}\) on ion transport mechanisms.

In freshwater tilapia the major part of Ca\(^{2+}\) uptake takes place via the gills [15]. Uptake of calcium via the gastrointestinal tract may present a significant route of calcium influx, viz. in water containing low levels of calcium ("soft water") or when the fish are in need of extra calcium, e.g. during sexual maturation [3, 13]. Branchial Ca\(^{2+}\) uptake is readily inhibited by submicromolar amounts of waterborne Cd\(^{2+}\) [30, 46, 48]. Cadmium from the water as well as from the food accumulates in the gastrointestinal tract [9, 10]. The latter pathway appears to be important for uptake of cadmium [7]. In tilapia adapted to soft water dietary cadmium is known to cause hypocalcemia [29]. However, the mechanisms whereby cadmium interferes with calcium uptake in fish intestine have not yet been studied.

For tilapia gills it has been shown that Cd\(^{2+}\) is able to pass the apical membrane of the calcium-transporting epithelial cell via the same route as Ca\(^{2+}\) [48]. The inhibition of transcellular calcium transport takes place at the basolaterally located Ca\(^{2+}\) pumps [46]. In analogy then, our understanding of the interactions of Cd\(^{2+}\) with the cytoplasmic substrate and cation sites of proteins in the basolateral plasma membrane will be of primary importance to evaluate the mechanism of inhibition of intestinal Ca\(^{2+}\) uptake by Cd\(^{2+}\). The basolateral membrane proteins involved in Ca\(^{2+}\) transport are the Na\(^+\)/Ca\(^{2+}\) exchanger, which is dependent on the correct operation of the (Na\(^+\) + K\(^+\))-ATPase, and the Ca\(^{2+}\)-ATPase. We report here on the effects of Cd\(^{2+}\) on these three mechanisms, which appear to result from an interaction with divergent metal cation sites of the proteins. The Na\(^+\)/Ca\(^{2+}\) exchanger appeared to be able to shuttle Cd\(^{2+}\) into the blood.

**Materials and Methods**

Male tilapia, *Oreochromis mossambicus*, weighing around 250 g were obtained from the electricity plant Bergheim/Niederhausen (Germany). The fish were kept in 100 liter aquaria supplied with running tap water (0.7 mM Ca, 25°C) under a photoperiod of 12 hr of light alternating with 12 hr of darkness, during at least one month before experimentation. Cadmium was not detectable in running tap water (detection limit 1 nM). Animals were fed Trouvit\(^{®}\) fish pellets (Trouw & Co., Putten, The Netherlands). 4 to 5\% body weight per day. Trace amounts of cadmium in the food resulted in a total cadmium content of mucosal tissue of 6.0 ± 2.4 nmol g\(^{-1}\) dry weight \((n = 6)\). The possible consequences of this amount will be discussed below.

Fish were killed by spinal transection. The peritoneal cavity was opened and the intestinal tract removed. The intestine was rapidly flushed with ice-cold saline and processed as described below. Enterocyte basolateral plasma membrane vesicles were prepared as described in detail recently [13].

Briefly, the intestine was cut lengthwise and intestinal mucosa was collected by scraping off the epithelium onto an ice-cooled glass plate. The cells were homogenized in an isotonic sucrose buffer, and nuclei and cellular debris were pelleted by centrifugation at 1,400 \(\times g\), for 10 min. The supernatant containing 75% of the (Na\(^+\) + K\(^+\))-ATPase activity of the homogenate) was collected and centrifuged for 25 min at 150,000 \(\times g\). The resulting pellet consists of two parts: a firm brown part which contains mostly mitochondrial membranes, and a white and fluffy part on top which consists of plasma membranes. The fluffy layer was resuspended in a 250 mmol/liter \(^{-1}\) sucrose buffer and subsequently brought to 37% (wt/wt) sucrose by addition of 1.25 volumes of a 60% (wt/wt) sucrose solution. On top of 8 ml of this suspension 4 ml of sucrose buffer was layered, and the assembly was centrifuged isopycnically for 90 min at 200,000 \(\times g\). Using a syringe fitted with a 23-gauge needle the membranes at the interface were collected and mixed with 30 volumes of the final isotonic assay buffer (150 mmol KCl, 0.8 mM MgCl\(_2\); and 20 mmol HepES/Tris, pH 7.4). After centrifugation at 180,000 \(\times g\) for 35 min, the pellet was rinsed twice with assay buffer and resuspended by 25 passes through a 23-G needle. This final fraction contained 18% of the (Na\(^+\) + K\(^+\))-ATPase activity present in the homogenate.

The configuration of the tilapia enterocyte plasma membrane vesicle preparation is 29% IOV, 24% ROV and 47% leaky fragments [13]. Protein content of membrane or enzyme preparations was estimated with a commercial reagent kit (Bio-Rad), using bovine serum albumin (BSA) as a reference. Protein recovery with respect to the homogenate was 1.6 ± 0.5%. The membrane preparation was enriched 7.1 times in Na\(^+\) and K\(^+\)-ATPase activity with respect to the homogenate. Contamination with mitochondrial and apical membrane fragments was minimal, as indicated by the purification factors of 1.1 and 1.2 for succinate dehydrogenase and alkaline phosphatase, respectively.

**Buffering of Ca\(^{2+}\), Mg\(^{2+}\) and Cd\(^{2+}\) Concentrations**

All assay media contained (in mm): 0.5 [ethylenedistioxyethyl-enentriol]tetraacetic acid (EGTA), 0.5 N-2-hydroxyethyl-ethylenediamine-N,N',N'-tetraacetic acid (HEEDTA), and 0.5 nitritotriacetic acid (NTA). Free calcium, magnesium and cadmium levels were calculated as outlined below. All incubations were performed at 37°C.

We have written a computer program (implemented in Turbo Pascal 5.5\(^{®}\) for IBM PC and compatibles; available upon request) that incorporates multiple metal-chelator equilibria to calculate free metal ion concentrations when using metal-chelating substrates. The program also corrects for several experimental conditions, known to affect the apparent stability constants used in the calculations. Tsien and Rink [43] noted that textbook stability constants for H\(^{+}\) are based on [H\(^{+}\)]\(^{\text{aq}}\). At non-zero ionic strength [H\(^{+}\)]\(^{\text{aq}}\) is not equal to H\(^{+}\) activity, of which pH is the negative logarithm. Unfamiliarity with this fact has lead to important errors in free metal calculation routines. Several authors have continued to overlook this point. Users of the algorithm of Fabiato and Fabiato [12] should use the correction published by Fabiato [11]. Also, the method of van Heeswijk, Geertsen and van Os [21], which we used previously, does not contain this correction. Furthermore, textbook stability constants are obtained at standard experimental conditions, viz. ionic strength and temperature, which are different from those used in most biological in vitro
systems. They therefore have to be corrected for these differences.

We converted $H^+$ activity to $[H^+]$ in all our calculations by the use of a semi-empirical form of the Guggenheim-Davis extension of the Debye-Hückel limiting law [20]. This was also used to correct the stability constants $K$ for the effects of ionic strength:

$$\log K' = \log K + F \cdot (\log f - \log f')$$

where $K'$ is the constant after and $K$ the constant before correction, $f_j$ the activity coefficient of ion $j$ at the tabulated ionic strength and $f'_j$ that for the desired conditions. $F$ is a factor dependent on the electrical charges of the cationic and anionic species relevant to a specific stability constant and is calculated according to different formulae, depending on which stability constant is being corrected for effects of ionic strength. The activity coefficient $f_j$ is calculated by:

$$\log f_j = (1.8246 \times 10^3/((eT)^{1/2}) \times \left( \sqrt{T}/(1 + \sqrt{T}) \right) - 0.25 \times I)$$

where $e$ is the relative dielectric constant of water (we corrected this constant for the temperature used), $T$ the absolute temperature and $I$ the ionic strength in ionic equivalents [20].

The effect of temperature is calculated by using Van’t Hoff’s Isochoric [20]:

$$\log K' = \log K - (\Delta H/\ln(10) \cdot R) \cdot (T^{-1} - T'^{-1})$$

where $R$ is the universal gas constant ($8.314 \times 10^{-3}$ kJ·mol$^{-1}$·K$^{-1}$) and $\Delta H$ is expressed in kJ·mol$^{-1}$. Van’t Hoff’s Isochoric was also used to correct $K_s$ (water constant; used in some equilibria) for temperature effects.

The contributions of all charged species of metal ions, chelators, complexes and pH buffers to ionic strength were included in the calculation. The pK$x_n$ of the pH buffers was adjusted for effects of ionic strength. Table 1 lists the corrected stability constants used in our calculations. Calculated Ca$^{2+}$ concentrations were counterchecked using a Ca$^{2+}$-selective electrode (above 1 $\mu$M Ca$^{2+}$) and found to be correct (see Note Added in Proof).
60 mM imidazole, adjusted to pH 7.4 with HEPES. The final protein concentration was 42 mg·ml⁻¹. (Na⁺ + K⁺)-ATPase activity of this preparation was determined using 5 μl of preparation on 500 μl assay medium.

**Na⁺/Ca²⁺ Exchange**

Na⁺/Ca²⁺ exchange activity in plasma membrane vesicles was assayed as described earlier [13]. Briefly, 5 μl membrane vesicles equilibrated with 150 mM NaCl were added to 120 μl of 6Ca⁺-containing media with either 150 mM NaCl (blank) or 150 mM KCl as main salt constituents. The media also contained O.5 mM MgCl₂ mimicking intracellular conditions. Earlier experiments had shown that addition of valinomycin did not further increase exchange velocities in media containing equal amounts of intracellular and extravesicular K⁺, indicating that no build-up of membrane potential occurred during the assay period. We therefore did not use valinomycin in the present studies on Na⁺/Ca²⁺ exchange. After 5 sec at 37°C (this represents initial velocities), the reaction was stopped by addition of 1 ml ice-cold isotonic stopping solution containing 1 mM LaCl₃. A 1-ml sample was filtered (Schleicher & Schuell 0.45 μm), and the filter was rinsed three times with 2 ml stopping solution. The difference in ⁶Ca⁺ accumulated was taken to represent Na⁺-gradient driven Ca²⁺ transport.

**Ca²⁺/Ca²⁺ Exchange**

Ca²⁺/Ca²⁺ exchange was tested according to Philipson and Nishimoto [20] with minor modifications. Briefly, 5 μl membrane vesicles equilibrated with 150 mM NaCl were added to 70 μl medium with 150 mM KCl and 25 μM ⁶Ca⁺. No calcium-chelating substances were used in these assays. The vesicle Na⁺ gradient will have dissipated 3 min after the primary dilution (see also Fig. 2 in ref. 13; Na⁺-gradient driven Ca²⁺ uptake reaches a maximum at t = 2 min). Then, the vesicle suspension was diluted 14-fold by addition of 975 μl 150 mM KCl medium containing neither calcium and cadmium, or 25 μM calcium, or 25 μM cadmium. KCl-equilibrated vesicles were used as blanks to correct for ⁶Ca⁺ bound to the exterior of vesicles. Efflux of ⁶Ca⁺ was stopped by filtration immediately followed by a threefold wash with ice-cold 150 mM KCl medium containing 1 mM LaCl₃.

**Isolation of Fish Enterocytes and Loading with Fura-2**

After having obtained the intestine as described above, the intestinal mucosal cells were scraped off the submucosa onto an ice-cold glass plate using a glass slide. Cells were resuspended in 4 ml bicarbonate-Ringer containing NaCl 140 mM, KCl 2.4 mM, CaCl₂ 1.2 mM, MgSO₄ 1.4 mM, KH₂PO₄ 1.3 mM, NaHCO₃ 25 mM, glucose 500 mg/liter, glutathione 290 mg/liter, and Eagle’s Minimal Essential Medium amino acids (50×) 20 ml/liter. The cell suspension was distributed in aliquots of 0.4 ml over plastic petri dishes containing one round cover slip (d = 25 mm) each, and put in an incubation chamber at 28°C that was flushed with humidified gas (5% CO₂ and 95% O₂). After 60 min, the cells attached to the cover slips were washed twice with 1 ml medium. Finally, 0.5 ml medium, containing 5 μM fura-2-acetoxyethyl ester (Fura-2/AM: Molecular Probes, Junction City, OR), was added. Cells were incubated for 30 min. The cover slips were subsequently washed twice with 1 ml medium without fura-2/AM and used in the experiments described below.

**Intracellular Free Ca²⁺ Measurements**

Fura-2 fluorescence was determined using a Tracor Fluoroprobe III system (TN 6500 Rapid Scan Spectrometer; TN 6075 Photon Counter; IBM AT-compatible computer) coupled to a Nikon Diaphot microscope equipped with UV-optics. The excitation wavelength was alternated every 200 msec between 340 and 380 nm. Emitted fluorescence was filtered through a barrier filter (BA520) and measured through the front port of the microscope using a photomultiplier tube (FP 1400 Photon Counting Detector). Intracellular free Ca²⁺ concentrations were calculated according to Grynkiewicz, Poenie and Tsien [18], using a Kₛ of 162 nm [24]. Since the Kₛ for Mg²⁺ is 9.8 mM [18] and intracellular Mg²⁺ levels are unknown (but predicted to be around 1 mM), no correction for competitive binding of Mg²⁺ to fura-2 was applied.

Calibration of fura-2 was performed inside the cells on which an experiment had been performed. Ionomycin was added to the observation chamber (final concentration: 10 mM) to obtain influx of calcium and to assess the maximum fluorescence ratio (Rₘₐₓ). Next, EGTA (final concentration: 1.25 mM) was added to determine the minimum fluorescence ratio (Rₘᵦₙ). Typical values were 0.5 for Rₘₐₓ, 0.7 for Rₘᵦₙ and 9 for Rₘₐₓ.

**Calculations and Statistics**

Kinetic parameters and their standard deviations were derived by nonlinear regression analysis of the data. Statistical significance of differences between mean values was tested using the Mann-Whitney U-test.

**Results**

**Ca²⁺-ATPase**

Figure 1 shows the Ca²⁺ dependency of ATP-driven ⁴⁵Ca uptake into inside-out basolateral plasma membrane vesicles. The calculated Kₘₐₓ is 88 ± 17 nm Ca²⁺ and the Vₘₐₓ is 0.81 ± 0.05 nmol Ca²⁺·min⁻¹·mg⁻¹ protein.

Figure 2 shows the dose-dependent inhibition of the Ca²⁺-pump by Cd²⁺. Non-linear regression analysis yielded a half-maximal inhibition constant of 8.2 ± 3.0 pm Cd²⁺ ([Ca²⁺] = 200 nm). We were unable to evaluate the kinetics of the inhibition by Cd²⁺, as a result of the low maximal velocity of the pump. Assuming that Cd²⁺ competes with Ca²⁺ for the Ca²⁺ binding site of the pump, as shown for other preparations before [46, 47, 49], the Kᵢ (Kᵢ = [Ca²⁺])
Fig. 1. Double reciprocal plot of the Ca$^{2+}$ dependency of the ATP-dependent Ca-pump in basolateral plasma membrane vesicles from fish intestine. Mean values (± SEM) of five experiments are given. Initial rates of ATP-dependent Ca$^{2+}$ uptake were corrected for ATP-independent uptake. The calculated $K_{m}$ is 88 ± 17 nM, while the computed $V_{max}$ is 0.81 ± 0.05 nmol · min$^{-1}$ · mg$^{-1}$.

Fig. 2. Cd$^{2+}$ inhibition of the ATP-dependent Ca pump in basolateral plasma membrane vesicles from fish intestine. Mean values (± SEM) of nine experiments are given. The free [Ca$^{2+}$] was kept constant at 200 nM. Initial rates of ATP-dependent Ca$^{2+}$ uptake were corrected for ATP-independent uptake. Asterisks indicate values significantly different from the control value ($P < 0.001$). The calculated IC$_{50}$ is 8.2 ± 3.0 pm Cd$^{2+}$.

IC$_{50}$ · ($K_{m}/(K_{m} + S)$) for cadmium-inhibition of the ATP-dependent Ca$^{2+}$ transporter in basolateral plasma membranes of fish enterocytes is approximately 3.0 pm.

(Na$^{+}$ + K$^{+}$)-ATPase

Cadmium inhibits the (Na$^{+}$ + K$^{+}$)-ATPase activity in the basolateral plasma membranes isolated from fish intestinal epithelium half-maximally at a concentration of 2.6 ± 0.6 µM Cd$^{2+}$ (Fig. 3). In the dog kidney enzyme preparation the IC$_{50}$ for cadmium inhibition was 6.3 ± 1.4 µM Cd$^{2+}$.

To test whether Cd$^{2+}$ specifically interferes with activation of the enzyme by intracellular substrates, we investigated the effects of a fixed concentration of Cd$^{2+}$ on the ATP- and Mg$^{2+}$-dependent activities of (Na$^{+}$ + K$^{+}$)-ATPase. ATP exerts both a high-affinity phosphorylation of the (Na$^{+}$ + K$^{+}$)-ATPase and a low-affinity allosteric stimulation. The ATP concentrations used are aimed specifically at discriminating the low-affinity stimulatory action of ATP on the E$_{2}$-form of the (Na$^{+}$ + K$^{+}$)-ATPase, since this action is most important for overall reaction velocity [32]. At 2.5 µM free Cd$^{2+}$ the $V_{max}$ of (Na$^{+}$ + K$^{+}$)-ATPase for activation by ATP decreased to 62 ± 10% of the control value, while the $K_{m}$ for ATP had not changed significantly ($P > 0.5; n = 3$) from 0.85 ± 0.11 to 0.97 ± 0.16 mM (Fig. 4). Apparently, Cd$^{2+}$'s inhibition of the (Na$^{+}$ + K$^{+}$)-ATPase does not take place via the low-affinity site of ATP.

Figure 5 shows the Mg$^{2+}$ dependency of the (Na$^{+}$ + K$^{+}$)-ATPase and the effect of the presence of 2.5 µM Cd$^{2+}$. Control kinetics were complex, apparently involving more than one action of Mg$^{2+}$. At low Mg$^{2+}$ concentrations, the high affinity component of the Mg$^{2+}$ dependency of (Na$^{+}$ + K$^{+}$)-ATPase displayed a half-maximal activation constant of around 4 µM. With 2.5 µM free Cd$^{2+}$ present,
the activation of the (Na\(^+\) + K\(^+\))-ATPase by Mg\(^2+\) could be described by a single Michaelis-Menten relationship. The \(K_m\) of the (Na\(^+\) + K\(^+\))-ATPase for Mg\(^2+\) increased to 243 ± 13 \(\mu\)M, and the \(V_{max}\) was reduced to 69 ± 3% of the control value.

In isolated fish enterocytes the resting intracellular Ca\(^{2+}\) concentration was 85 ± 21 \(nM\) (\(n = 25\)). When the outside medium was supplied with 1 mM ouabain (blocking the (Na\(^+\) + K\(^+\))-ATPase of the cells), the intracellular Ca\(^{2+}\) concentration rose. Cells exposed to a ouabain-containing solution without calcium did not exhibit a rise in intracellular Ca\(^{2+}\), indicating that the extracellular Ca\(^{2+}\) is necessary for this response to be observed (Fig. 6).

Figure 7 shows the Cd\(^{2+}\) concentration dependence of the inhibition by Cd\(^{2+}\) of Na\(^+/Ca\(^{2+}\) exchange (\(n = 5\)) at a fixed free Ca\(^{2+}\) concentration of 7 \(\mu\)M. Nonlinear regression analysis yields an IC\(_{50}\) of 73 ± 11 \(nM\) Cd\(^{2+}\). Given that Cd\(^{2+}\) is a competitive inhibitor of the Ca\(^{2+}\) site of the antiporter (see below), we calculated a \(K_i = IC_{50} \cdot K_m \cdot (K_m + S)^{-1}\) of 11 \(nM\).

The Ca\(^{2+}\) kinetics of the Na\(^+/Ca\(^{2+}\) exchanger were determined at 0, 5 and 65 \(nM\) Cd\(^{2+}\). Substrate dependence of initial velocities obeyed a Michaelis-Menten relationship. In the absence of Cd\(^{2+}\) a \(K_m\) of 1.21 ± 0.06 \(\mu\)M and a maximal velocity of 18.1 ± 0.6 nmol \cdot min\(^{-1}\) \cdot mg\(^{-1}\) protein (\(n = 5\)) were calculated. Cd\(^{2+}\) (5 and 65 \(nM\)) had a competitive inhibitory effect on Ca\(^{2+}\) kinetics (Fig. 8). The \(K_m\) for Ca\(^{2+}\) increased significantly to 8.1 ± 0.5 \(\mu\)M at 5 \(nM\) Cd\(^{2+}\), and to 16.6 ± 0.7 \(\mu\)M at 65 \(nM\) Cd\(^{2+}\) (\(P < 0.001\)). Maximal velocities had not changed significantly (\(P > 0.1\)).
Fig. 7. Inhibition of initial velocities of Na⁺/Ca²⁺ exchange in tilapia basolateral plasma membrane vesicles by Cd²⁺. Free Ca²⁺ concentration was kept constant at 5 µM. An IC₅₀ of 73 ± 11 nM Cd²⁺ was observed. Mean ± SEM of six experiments are shown. Asterisks indicate a significant difference from the control value (P < 0.01).

Fig. 8. Lineweaver-Burk plot of the Ca²⁺ dependence of initial velocities of Na⁺/Ca²⁺ exchange. The two fixed Cd²⁺ concentrations (5 and 65 nM Cd²⁺) induce a competitive inhibition for Ca²⁺, increasing Ca²⁺’s K₅ but not significantly increasing V₉ MAX (P > 0.1). The K₅ for Ca²⁺ activation of the Na⁺/Ca²⁺ exchanger changed from 1.21 ± 0.06 µM to 8.1 ± 0.5 µM in the presence of 5 nM Cd²⁺, and to 16.6 ± 0.7 µM when 65 nM Cd²⁺ was present. Controls (n = 5) are shown as filled circles, 5 nM Cd²⁺ values (n = 3) as filled squares and 65 nM Cd²⁺ values (n = 3) as filled triangles. Means ± SEM are shown. Error bars were not drawn when smaller than the symbols.

Bepridil (80 µM), known to specifically interfere with the exchanger’s activation by Na⁺ [16], induced an additional inhibition of the Na⁺/Ca²⁺ exchanger apart from that caused by Cd²⁺ (Fig. 9). Furthermore, the abscissa intercept of the regression line in the Dixon plot (where [Cd²⁺] = -Kᵣ + Kᵣ × K₅⁻¹ × [Ca²⁺]) remained unchanged, indicating that the Kᵣ of the inhibition by Cd²⁺ remained unchanged. Thus, bepridil does not compete for the site by which Cd²⁺ inhibits Na⁺/Ca²⁺ exchange.

To test whether Cd²⁺ substitutes for Ca²⁺ in the activation of the antiporter we followed an approach originally suggested by Philipson and Nishimoto [28]. Using a differential assay to determine the stimulation of efflux of ⁴⁴Ca accumulated intravesicularly through the action of the exchanger, it was demonstrated that 25 µM extravesicular calcium induces a significant efflux of ⁴⁴Ca (statistically tested as the effect of the treatment on the fractional loss that had occurred after 1 min of efflux; P < 0.01). Cd²⁺ also induced a significant (P < 0.05) release of ⁴⁴Ca from the vesicles, indicating a functional Ca²⁺/Cd²⁺ exchange (Table 2). Cd²⁺ was less readily exchanged than Ca²⁺ itself.

Table 2. ⁴⁴Ca efflux from basolateral plasma membrane vesicles

<table>
<thead>
<tr>
<th>Fractional loss of ⁴⁴Ca at t = 60 sec</th>
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<tr>
<td>Control</td>
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<td>25 µM calcium</td>
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<td>25 µM cadmium</td>
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<sup>a</sup> P < 0.01, significantly different from control values; <sup>b</sup> P < 0.05. Efflux of ⁴⁴Ca is expressed as the fractional loss of ⁴⁴Ca associated with the vesicles between t = 0 and t = 60 sec. ⁴⁴Ca was introduced into the vesicles by Na⁺/Ca²⁺ exchange activity during 3 min of preincubation. K⁺-loaded vesicles served as blanks, for which all figures above were corrected. Means ± SD for six experiments are given.
Discussion

Cadmium Content of Intestinal Tissue

Trace amounts of cadmium in the fish food led to a total cadmium content of the mucosal scrapings of 6.0 nmol·g⁻¹ dry weight. We calculate a total [Cd] of 1.4 μM if this amount were to be homogeneously distributed in the epithelial water, i.e. 4.2 ml·g⁻¹ dry weight. However, sequestration of Cd²⁺ by intracellular calcium stores and binding to calcium binding proteins will minimize the amount of available ionic Cd²⁺. Ca²⁺ buffering mechanisms (stores and binding proteins) reduce the total [Ca] of 2.9 nm [45] to a free concentration of 85 nM (this study). Assuming that their affinity for cadmium is (at least) 100-fold higher than for calcium (see e.g. this study and [46, 47]), they will buffer free Cd²⁺ levels to 0.4 pm (or less). We therefore conclude that the trace amounts of cadmium originating from the food do not interfere with the calcium transport mechanisms in tilapia intestinal cells. Moreover, the assays reported on here will not be perturbed by any cadmium possibly associated with the enterocyte plasma membrane vesicles after their isolation, since the use of millimolar amounts of metal chelating substances warrants stable free metal ion concentrations.

Ca²⁺-ATPase

The half-maximal activation concentration of the pump for Ca²⁺ (88 ± 17 nM) appears to be at variance with the value previously published, i.e. 27 ± 4 nM [13]. However, the calculated free calcium concentrations of the latter experiment were not corrected for effects of experimental conditions on the stability constants of chelator-cation complexes, as described above. Recalculation of the previous data yielded a similar Kₘ value (65 ± 8 nM Ca²⁺).

The Kₘ found is near the measured [Ca²⁺] of around 85 nM, and is comparable to those previously published for ATP-dependent ⁴⁵Ca uptake in plasma membrane vesicles from rat duodenum [49], trout gill [46], rat kidney cortex [21], and rat enterocyte endoplasmic reticulum [5].

The observed sensitivity to inhibition by Cd²⁺ is unlikely to be caused by a competition for the Mg²⁺ site, but rather for the Ca²⁺ site of the enzyme, since ATP-dependent uptake of ⁴⁵Ca into inside-out membrane vesicles typically requires millimolar amounts of Mg²⁺ for activation, but submicromolar amounts of Ca²⁺ [4]. Moreover, it is well known that Cd²⁺ interacts with the Ca²⁺ site of the enzyme in trout gills [46], rat enterocytes [49] and human erythrocytes [47].

Although the Ca²⁺ affinity of the pump is comparable in the preparations mentioned above, its affinity for Cd²⁺ is remarkably different: the Ca²⁺ pump in trout gill basolateral plasma membranes was half-maximally inhibited at 3 nm Cd²⁺ ([Ca²⁺] = 250 nM) and the rat duodenal Ca²⁺ pump displayed an IC₅₀ of 1.6 nm Cd²⁺ at 1 μM Ca²⁺. Fish intestinal Ca²⁺ pump, however, showed an IC₅₀ of 8.2 ± 3.0 pm at 200 nM Ca²⁺. These differences cannot be explained by the different Ca²⁺ concentrations used. We suggest species differences or membrane environment of the pump as possible causes. Whatever the cause of these differences, the very low IC₅₀ value indicates an extreme sensitivity to Cd²⁺ for the Ca²⁺ pump of tilapia enterocytes. In vivo, this pump will become impaired once free Cd²⁺ ions are present in intestinal mucosal cells.

(Na⁺ + K⁺)-ATPase

A purified preparation of (Na⁺ + K⁺)-ATPase from dog kidney displayed a somewhat lower affinity for cadmium, i.e. 6.3 ± 1.4 μM, than (Na⁺ + K⁺)-ATPase in fish intestinal basolateral plasma membrane vesicles (2.6 μM Cd²⁺). Other preparations have displayed similar IC₅₀ values for Cd²⁺ inhibition of (Na⁺ + K⁺)-ATPase activity: in rat brain synaptosomes half-maximal inhibition occurred at 5.4 μM [25], in disrupted vascular smooth muscle cells at 10 μM [40], and in microsomes obtained from frog skin at 30 μM [37].

The 5 orders of magnitude difference in IC₅₀ values observed for Cd²⁺ inhibition of the (Na⁺ + K⁺)-ATPase and the Ca²⁺-ATPase leads us to conclude that the affinity for Cd²⁺ is not dictated by the homologous regions of these E₁ - E₂ class ion pumps. The reduction in Vₘₐₓ and the unchanged apparent Kₘ for ATP caused by 2.5 μM Cd²⁺ also shows that Cd²⁺ does not exert its inhibitory action on the (Na⁺ + K⁺)-ATPase through occupation of the low-affinity ATP site.

(Na⁺ + K⁺)-ATPase displayed non-Michaelis-Menten behavior with respect to Mg²⁺. Rossi and Garrahan [33] have taken this to be an indication for the presence of a contaminant amount of Mg²⁺ in the assay media. Analyzing our data along these lines, we calculate a contaminant Mg²⁺ concentration of 1.2 ± 0.4 μM. The half-maximal activation constant found in this way, i.e. 12.2 ± 1.7 μM, equals that previously published by Rossi and Garrahan [33], i.e. 11.8 ± 1.7 μM. However, our use of chelating compounds will prevent errors caused by small contaminations. Therefore, we tend to favor an alternative explanation advanced by Covarrubias and de Weer [6]: the non-Michaelis-Menten behavior ob-
served is the direct consequence of a dual action of Mg\textsuperscript{2+} on a single site of the (Na\textsuperscript{+} + K\textsuperscript{+})-ATPase. The presence of Cd\textsuperscript{2+} changed this behavior drastically: the \(K_m\) for Mg\textsuperscript{2+} increased from around 4 \(\mu\)M to 243 ± 13 \(\mu\)M and the kinetics could be adequately described by a normal Michaelis-Menten function. Cd\textsuperscript{2+} apparently competes for the Mg\textsuperscript{2+} site on the (Na\textsuperscript{+} + K\textsuperscript{+})-ATPase.

**Na\textsuperscript{+}/Ca\textsuperscript{2+} Exchange**

The mean intracellular Ca\textsuperscript{2+} concentration of around 85 nm in isolated tilapia enterocytes is in good agreement with literature values of other types of epithelial cells [38]. We used two treatments that greatly decreased net intestinal calcium uptake [13] to test whether the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger is also involved in intracellular Ca\textsuperscript{2+} homeostasis. Changing the extracellular medium to a medium containing N-methyl-d-glucamine instead of sodium yielded similar results as seen in Fig. 6: the intracellular Ca\textsuperscript{2+} concentration rose rapidly to values slightly above 100 nm (data not shown). This is most probably caused by Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange working in a “reverse” mode as a result of the change in electrochemical gradient for Na\textsuperscript{+}. The relatively rapid onset of the response implies that the exchanger operated near its zero-flux equilibrium, so that a small change in Na\textsuperscript{+} driving force resulted in a reversal of net flux. Indeed, the measured resting free Ca\textsuperscript{2+} concentration is close to the estimated equilibrium value of 67 nm for the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger (with [Ca\textsuperscript{2+}], = 1.25 mm [19], [Na\textsuperscript{+}], = 125 mm [14], [Na\textsuperscript{+}], = 9 mm [38], a membrane potential of −50 mV [2], a stoichiometry of 3 Na\textsuperscript{+} to 1 Ca\textsuperscript{2+}, and [Ca\textsuperscript{2+}], = [Ca\textsuperscript{2+}], × [Na\textsuperscript{+}]\textsuperscript{3} × [Na\textsuperscript{+}]	extsuperscript{−3} × exp(V\textsubscript{m}F/(RT)).

A potential pitfall in the fura-2 experiments is that intracellular Ca-chelating substances inhibit “reverse-mode” Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange in certain cell types [1, 8, 34]. The inhibitory action is not caused by the chelation of intracellular Ca\textsuperscript{2+} ions, since even an excess amount of intracellular Ca\textsuperscript{2+} cannot reverse the inhibition of Ca\textsuperscript{2+} influx [34]. The “reverse-mode” Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange activity that we attempted to use in these experiments might be severely inhibited by the presence of intracellular fura-2 [38]. In fact, the modest response of intracellular [Ca\textsuperscript{2+}] observed (when viewed against the drastic effects of the same treatments on transcellular Ca\textsuperscript{2+} transport [13]) suggests that such an inhibition did indeed occur: in experiments using fura-2, the role of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange in intracellular Ca\textsuperscript{2+} homeostasis may well be underestimated.

Cd\textsuperscript{2+} was previously shown to inhibit the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange in mammalian sarcolemmal vesicles with an IC\(_{50}\) of approximately 30 \(\mu\)M in the presence of 20 \(\mu\)M calcium (Fig. 2 in ref. 41). In cultured arterial smooth muscle cells the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger apparently was more sensitive to Cd\textsuperscript{2+} inhibition, since an IC\(_{50}\) of 2.4 \(\mu\)M was observed at a calcium concentration of 100 \(\mu\)M (with a \(K_m\) for Ca\textsuperscript{2+} of 100 \(\mu\)M) [36]. No metal chelating substances were used in these studies. Proceeding from these published data and the present study we calculate apparent \(K_m\)'s of 11 nm Cd\textsuperscript{2+} for the tilapia Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger. 1.2 \(\mu\)M for the arterial smooth muscle exchanger and 15 \(\mu\)M for the antiporter in mammalian sarcolemma. The tilapia Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger is by far the most sensitive of the antiport systems studied, with respect to both Ca\textsuperscript{2+} and Cd\textsuperscript{2+}. The Cd\textsuperscript{2+} sensitivity of the exchanger falls midway between the Cd\textsuperscript{2+} sensitivities of the ATP-dependent calcium pump and the (Na\textsuperscript{+} + K\textsuperscript{+})-ATPase in these membranes. The order of sensitivity suggests a correlation between the IC\(_{50}\) for inhibition by Cd\textsuperscript{2+} and the affinity of the divalent metal ion site for which Cd\textsuperscript{2+} competes.

The Ca\textsuperscript{2+} dependence of the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger obeyed single Michaelis-Menten kinetics (improvements in the procedure to calculate free Ca\textsuperscript{2+}, Mg\textsuperscript{2+} and Cd\textsuperscript{2+} concentrations allowed us to reject the previously reported double Michaelis-Menten relationship [13]). The \(K_m\) for Ca\textsuperscript{2+} of 1.21 ± 0.06 \(\mu\)M is low compared to values published for Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange in mammalian sarcolemmal vesicles (around 27 \(\mu\)M) or in synaptosomal membranes (around 34 \(\mu\)M) [31]. The higher Ca\textsuperscript{2+} affinity may reflect a species-specific difference. Alternatively, it may arise from the use of calcium chelating substances: Troper and Philipson [42] state that the apparent \(K_m\) of the sarcolemmal Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger falls midway between the Ca\textsuperscript{2+} levels are around 85 nm, a Ca\textsuperscript{2+} extrusion mechanism should respond to changes in submicromolar Ca\textsuperscript{2+} concentrations. The use of calcium chelators is not a prerequisite for the determination of the Ca\textsuperscript{2+} dependence of the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange per se, but it is indispensable to accurately establish free Ca\textsuperscript{2+}, Mg\textsuperscript{2+} and Cd\textsuperscript{2+} concentrations in the kinetic
assessment of Cd\textsuperscript{2+} inhibition of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange. If no metal ion buffering is used, Cd\textsuperscript{2+} ions become bound to membrane structures and reaction vessel walls to a very significant degree. This leads to an overestimation of the IC\textsubscript{50} of Cd\textsuperscript{2+}. We therefore used calcium chelators in our system to circumvent problems related to this topic.

The kinetic study thus performed showed an exclusive effect of Cd\textsuperscript{2+} on Ca\textsuperscript{2+} affinity, which indicates that Cd\textsuperscript{2+} exerts an inhibition via a competition for the Ca\textsuperscript{2+} site of the exchanger. Pharmacological studies using bepridil supported this hypothesis: a change in the K\textsubscript{s} for inhibition by Cd\textsuperscript{2+} was not observed. We conclude that Cd\textsuperscript{2+} inhibits the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger solely via a competition for the Ca\textsuperscript{2+} site on the molecule.

It is well known that intracellular Ca\textsuperscript{2+} ions activate Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange (usually measured in its "reversed-mode," i.e. Na\textsuperscript{+} efflux/Ca\textsuperscript{2+} influx) in excitable tissues [1, 8, 34]. The Ca\textsuperscript{2+} affinity of the regulatory site can be much higher than that of the Ca\textsuperscript{2+} transport site, although excised-patch clamp studies on guinea pig sarcolemma showed that binding of Na\textsuperscript{+} to the exchanger molecule induces a drop in Ca\textsuperscript{2+} affinity of the regulatory site to around 1 \mu M [22]. If such a regulatory site exists on the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger found in fish intestinal epithelium, binding of Cd\textsuperscript{2+} to it could either mimic Ca\textsuperscript{2+}’s action and stimulate Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange, or exchange could be inhibited by prohibiting Ca\textsuperscript{2+} to bind to the activatory site. The first possibility implies that the observed inhibition by Cd\textsuperscript{2+} stems only from its competition for the Ca\textsuperscript{2+} transport site. The second would result in Cd\textsuperscript{2+} acting on two sites simultaneously, since both sites appear to have similar affinities (for Ca\textsuperscript{2+}, and thus probably for Cd\textsuperscript{2+}, too). The dose-dependent inhibition by Cd\textsuperscript{2+} did not, however, show any signs of cooperativity, which argues against the latter possibility.

The competition of Cd\textsuperscript{2+} for the Ca\textsuperscript{2+} site of the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger raises the question whether Cd\textsuperscript{2+} might also be translocated across the cell membrane. We did not observe a Na\textsuperscript{+}/Cd\textsuperscript{2+} exchange activity in this plasma membrane preparation. However, when we tested for \textsuperscript{45}Ca\textsuperscript{2+}/Cd\textsuperscript{2+} exchange according to the procedure of Philipson and Nishimoto [28], we found that 25 \mu M cadmium elicited a significant \textsuperscript{45}Ca efflux. Troser and Philipson [41] showed that, in canine cardiac sarcolemmal vesicles, 20 \mu M cadmium was exchanged against calcium even more effectively than calcium itself. In our experiments calcium was more effective in inducing \textsuperscript{45}Ca efflux than cadmium.

Does Ca\textsuperscript{2+}/Cd\textsuperscript{2+} exchange occur in vivo? The high Cd\textsuperscript{2+} affinity displayed by the exchanger in vitro suggests that intracellular Cd\textsuperscript{2+} ions will compete successfully with Ca\textsuperscript{2+} ions for the Ca\textsuperscript{2+} site of the exchanger. The putative 1:1 stoichiometry of an electroneutral Ca\textsuperscript{2+}/Cd\textsuperscript{2+} exchange would dictate that the equilibrium ratio for Cd\textsuperscript{2+} ([Cd\textsuperscript{2+}]/[Ca\textsuperscript{2+}]) equals that for Ca\textsuperscript{2+} ([Ca\textsuperscript{2+}]/[Cd\textsuperscript{2+}]). Hence, an operational Ca\textsuperscript{2+}/Cd\textsuperscript{2+} exchange would attempt to create a steady-state [Cd\textsuperscript{2+}] in the extracellular serosal compartment that exceeds the intracellular [Cd\textsuperscript{2+}] more than 10,000-fold. Intracellular Cd\textsuperscript{2+} will be exchanged for extracellular Ca\textsuperscript{2+}, leading to a Cd\textsuperscript{2+} efflux through the basolateral membrane of the epithelial cell.

Taken together, our data show that the inhibition by Cd\textsuperscript{2+} of the three membrane proteins studied occurs predominantly through an interaction with divalent metal ions sites. Ca\textsuperscript{2+} extrusion via the calcium pump will become inhibited to a significant degree when intracellular Cd\textsuperscript{2+} concentrations reach the level of 100 \mu M, whereas the activity of the other E\textsubscript{2}-E\textsubscript{4} type ion pump, the (Na\textsuperscript{+} + K\textsuperscript{+})-ATPase, will only be inhibited significantly by micromolar amounts of Cd\textsuperscript{2+}. Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange activity will decrease when intracellular Cd\textsuperscript{2+} concentrations are in the nanomolar range. Since transcellular calcium uptake in the tilapia intestine mainly depends on Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange activity [13], the inhibition of the ATP-dependent Ca\textsuperscript{2+} pump will result in a minor decrease of intestinal Ca\textsuperscript{2+} uptake. Therefore we conclude that inhibition of the Ca\textsuperscript{2+}- and (Na\textsuperscript{+} + K\textsuperscript{+})-ATPase is not the main mechanism by which Cd\textsuperscript{2+} suppresses intestinal calcium uptake and disturbs fish calcium homeostasis. Rather, intestinal calcium uptake will become hampered once Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange is inhibited by nanomolar amounts of Cd\textsuperscript{2+} ions. Furthermore, the ability to exchange Ca\textsuperscript{2+} for Cd\textsuperscript{2+} suggests the exchanger as the prime candidate for a mechanism of Cd\textsuperscript{2+} extrusion across the basolateral plasma membrane of the enterocyte. Dietary cadmium will not only accumulate in the tissue, but will be transported into the blood.

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Note Added in Proof

A paper on the calculation of free metal ion concentrations with our computer program (CHELATOR) is currently in press in Biotechniques. This article and the computer program will become available on Biotechnet.