Evidence for P$_2$-purinoceptor-mediated uptake of Ca$^{2+}$ across a fish (Oreochromis mossambicus) intestinal brush border membrane

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INTRODUCTION
Extracellular ATP-stimulated Ca$^{2+}$ influx has been demonstrated in many different cell types, including ovarian tumour cells, smooth-muscle cells, cells from HL-60, HeLa and NG108-15 lines, J774 mouse macrophages, rat thyroid cells and atrial myocytes [1–8]. The literature on ATP-stimulated Ca$^{2+}$ uptake in intestinal cells is scarce; stimulatory effects of ATP in isolated enterocytes from human colon and from rat and chicken intestine have been reported [9–11]. A P$_2$ purinoceptor [10], an ATP-activated, protein kinase-regulated ion channel [11] and a Ca$^{2+}$ uptake system sensitive to prenylamine (an antagonist for calmodulin) [9] have been advanced to explain the stimulation by ATP of Ca$^{2+}$ uptake in these cells. Unfortunately, observations on isolated cells do not allow discrimination between the apical and basolateral membrane domains as the site where ATP interacts with the Ca$^{2+}$ transport system. Proceeding from the stimulatory effect of extracellular ATP on Ca$^{2+}$ uptake in isolated enterocytes [9–11], and from the observation that millimolar concentrations of a nucleoside triphosphate occur in tilapia intestinal mucosal fluid, we here focus on the hypothesis that ATP regulates Ca$^{2+}$ entry across the apical membrane of the enterocyte. Purified brush border membrane vesicles (BBMVs) were used as a tool. We provide evidence for an ATPase-independent, ATP-stimulated Ca$^{2+}$ uptake in intestinal BBMVs and conclude from pharmacological studies that a subtype of a P$_2$ purinoceptor is present in the apical membrane of the enterocyte and is involved in Ca$^{2+}$ uptake.

MATERIALS AND METHODS

Animals
Sexually mature tilapia (Oreochromis mossambicus) of both sexes, weighing 250–450 g, were obtained from laboratory stock. Fish were kept in 100-litre aquariums, supplied with running Nijmegen water ([Ca$^{2+}$] 0.8 mM, at 25 °C) under a photoperiod of 16 h of light alternating with 8 h of darkness. The animals were fed with Trouvit® commercial fish food (Trouw, Putten, The Netherlands), at a ration of 1.5% (w/w) of their body weight per day.

Materials
45CaCl$_2$ was purchased from Amersham International (Aylesbury, Bucks., U.K.). Scintillator 299® was from Packard Instrument Co. (Meriden, CT, U.S.A.). ATP (Tris salt), adenosine 5'-(x,β-methylene)triphosphate (pp[CH$_2$]pA) and ADP [di(monocyclohexylammonium) salt] were from Boehringer (Mannheim, Germany). Reactive Blue-2 and the tetrasodium salt of 2-methylthioadenosine 5'-triphosphate (2-MeSATP) were from Research Biochemicals International (Natick, MA, U.S.A.). SK&F 96365 (dissolved in DMSO) was kindly provided by Dr. R. J. M. Bindels (Department of Physiology, Faculty of Medicine, University of Nijmegen, Nijmegen, The Netherlands). Suramin was a gift from Bayer AG (Leverkusen, Germany). Solutions of suramin were made in ultrapure water and were prepared freshly before experimentation. All chemicals were of analytical grade and obtained from commercial suppliers. Membrane protein was determined with a Coomassie Brilliant Blue kit (Bio-Rad, München, Germany), with BSA as a reference.

Isolation of intestinal brush border membranes
Fish were killed by spinal transection, and intestinal brush border membranes were isolated by using a magnesium aggregation technique and differential centrifugation as described in detail previously [12]. Brush border membranes were collected in 150 mM KCl/0.8 mM MgCl$_2$/20 mM Hepes/Tris (pH 7.4). The final membrane preparation was enriched 17-fold in alkaline phosphatase (EC 3.1.3.1). We previously determined that almost 100% of the vesicles are oriented right-side-out [12].

Abbreviations used: BBMV, brush border membrane vesicle; pp[CH$_2$]pA, adenosine 5'-[x,β-methylene]triphosphate; ATP[S], adenosine 5'-[y-thio]triphosphate; 2-MeSATP, 2-methylthioadenosine 5'-triphosphate.
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**Ca^{2+} transport assays**

**Zero trans Ca^{2+} uptake**

The assay medium was identical with the buffer in which the membranes were suspended and contained calculated free concentrations of 5 mM Ca^{2+} and 0.8 mM Mg^{2+}, and graded amounts of total nucleotide. The Ca^{2+} concentration used in our assays was in the range of the ambient intestinal luminal concentration, which we measured to range from 2 to 27 mM. Ca^{2+} uptake in the presence of a fixed nucleotide concentration was measured at 1 mM nucleotide. This concentration represents $V_{max}$ conditions with respect to ATP, as measured by ATP hydrolysis in a 5 min assay. The $^{45}$CaCl₂ radioactive concentration was 2.5 MBq/ml. Assays were performed at 37 °C; membranes and assay media were prewarmed before incubation. The incubation temperature chosen was the optimum for another important Ca^{2+} transporting protein in fish, namely the high-affinity Ca^{2+}-ATPase [13]. We calculate that in the presence of 1 mM total ATP, 96 % of the ATP is complexed with Ca (0.72 mM CaATP₂⁻) or Mg (0.24 mM MgATP₂⁻), leaving a free ATP⁴⁻ concentration of 35 μM. Incubation was initiated by mixing 10 μl of a preparation of BBMVs with 70 μl of the assay medium. Zero trans Ca^{2+} uptake was measured as the difference between uptake for 5 min at 37 °C and at 0 °C. SK & F 96365 was tested at a concentration of 15 μM, which is in the range of the IC₅₀ values reported for different preparations [7,14,15]. Suramin is generally employed at concentrations equal to or higher than the agonist concentration [2,16,17]. We added suramin at 0.1 and 1.0 mM to the assay medium. Reactive Blue-2 was added at concentrations ranging from 30 to 500 μM. All antagonists were tested with 1 mM ATP present in the incubation medium. The reaction was quenched by the addition of 1 ml of ice-cold isotonic stop buffer containing 150 mM KCl, 20 mM Trizma-7.0® (pH 7.4 at 0 °C) and 10 mM LaCl₃. The quenched sample was immediately filtered over a 80 kPa vacuum, using MES25 nitrocellulose filters with a pore size of 0.45 μm (Schleicher & Schuell, Dassel, Germany). Filters were rinsed three times with 2 ml of the ice-cold stop buffer and dissolved in 4 ml Scintillator 298® scintillation cocktail. The radioactivity retained on the filters was measured in a Wallac 1410 (Pharmacia, Turku, Finland) liquid-scintillation counter. Uptake values are expressed as nmol of Ca^{2+} per 5 min per mg of protein.

**Isotope equilibrium exchange**

In isotope equilibrium exchange experiments $^{45}$Ca^{2+} movements were measured in the absence of an electrochemical driving force for Ca^{2+}. Membrane vesicles were effectively loaded with Ca^{2+} as described earlier [12]. Incubations were performed in the same assay buffer and at the same temperature as was used in zero trans experiments. Intravesicular (trans) and extravesicular (cis) free Ca^{2+} concentrations were 5 mM. Quenching and filtering were done as described for the zero trans experiments. Blank values were determined in quadruplicate. The tracer content of the BBMVs was divided by the specific activity of the assay medium to obtain the amount of Ca^{2+} exchanged across the membrane.

**Enzyme assays**

Adenine nucleotidase activity was measured by incubating 10 μl of membrane suspension (protein concentration 0.3–0.7 mg/ml) for 5 min at 37 °C in 500 μl of medium including 150 mM KCl, a calculated 5 mM free Ca^{2+} (added as CaCl₂), 0.8 mM free Mg^{2+} (added as MgCl₂), 20 mM Hepes/Tris (pH 7.4) and graded amounts of ATP or ADP. Ouabain, theophylline and oligomycin-B were added at concentrations of 1 mg/ml, 2 mM and 5 μg/ml respectively. The reaction was quenched by the addition of 1 ml ice-cold 8.6% (w/v) trichloroacetic acid to the mixture. Liberated Pi was colorimetrically measured at a wavelength of 700 nm with the iron molybdate reagent described by Fiske and SubbaRow [18]. An inorganic phosphate solution (Sigma Chemical Co.) served as a Pi standard.

**ATP detection in intestinal luminal contents**

An ATP diagnostic kit (Sigma Chemical Co.) was used. Luminal contents were sampled immediately after the fish was killed. To 1 vol. of a sample (approx. 10 μl) was added 1 vol. of 8.6%, trichloroacetic acid. Samples were mixed and left on ice for 5 min, and then centrifuged at 4500 g for 10 min in a Microfuge Centaur centrifuge to obtain a clear supernatant on which the reaction mixture was performed. The assay is based on the phosphorylation of 3-phosphoglycerate by ATP and the subsequent conversion of 1,3-diphosphoglycerate to glyceraldehyde 3-phosphate, during which reaction NADH is oxidized to NAD⁺. The decrease in NADH content of the reaction mixture is then a measure of the initial ATP content of the sample. A solution containing 1 mM ATP was run in parallel with the intestinal samples and served as a standard. According to the manufacturer’s information, the ATP-diagnostic kit is equally sensitive to the nucleoside triphosphates GTP, ITP and UTP. We therefore refer to the results of this assay as nucleotide triphosphate levels. A method in which a firefly luciferase–luciferin reagent was employed proved unsuitable for the detection of ATP in luminal samples because of the turbidity of the samples, luminescence could not be detected even after the addition of an internal ATP standard.

**Calculations and statistics**

To calculate free and complexed Ca, Mg and ATP concentrations in our assay media we used the computer program Chelator [19]. Stability constants were from Sillen and Martell [20]. Data points were obtained by in vivo studies were fitted to the equation:

$$v = v_o(1 - [(I)/(K_i)])$$

where $v_o$ is the uptake rate in the absence of the inhibitor, [I] is the inhibitor concentration and $K_i$ is the value of [I] at which inhibition is half-maximal under the specific incubation conditions. Data were analysed with a nonlinear regression data analysis program [21]. Results are presented as means ± S.E.M. unless stated otherwise. Student’s t test for unpaired data and Welch’s approximate, and Kruskal-Wallis’ non-parametric, analysis of variance followed by Dunn’s multiple comparison test were used for statistical evaluation as appropriate. Significance was accepted at $P < 0.05$. Asterisks indicate a significant difference with respect to the control (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$).

**RESULTS**

The average nucleoside triphosphate concentration in the luminal fluid of tilapia was $0.9 ± 0.3$ mM ($n = 9$). Figure 1 shows a linear time course of the ATP-stimulated zero trans Ca^{2+} uptake. A slope of 55 nmol/min per mg is calculated. The tracer content of the BBMVs was not affected by the addition of 10 μM ionomycin/1% Triton X-100, indicating the binding of Ca^{2+} to membrane components. In contrast, in control incubations (i.e. in the absence of extracellular ATP) the addition of ionomycin resulted in a 2-fold increase in the
Involvement of a P₂ receptor in Ca²⁺ uptake in fish intestine

**Figure 1** Time course of ATP-stimulated zero trans Ca²⁺ uptake in tilapia intestinal BBMVs (means ± S.E.M., n = 5)

Effects of 10 μM ionomycin and 1% Triton X-100 in the extravesicular medium are shown. The final Ca²⁺ concentration was 5 mM. Symbols: ○ △ □ ▪, controls (i.e. uptake in the absence of ATP). Arrows indicate the addition of ionomycin (▲ △ ) and Triton X-100 (□ ▪) respectively. ○ ●. Controls (untreated membranes). The slope of the straight line indicates an uptake rate of 55 nmol/min per mg protein.

**Figure 2** ATP-stimulated ⁴⁵Ca²⁺ uptake, measured in a 5 min incubation interval, plotted as a function of protein concentration in the membrane vesicle preparation.

The ⁴⁵Ca in the BBMVs is expressed as a fraction of the specific radioactivity of the tracer. The straight line is described by the function \( y = 4.3 \times 10^{-2} x - 3 \times 10^{-3} \) (\( r = 0.69 \), \( n = 23 \), \( P = 0.0003 \)). A runs test did not indicate a significant departure from linearity (\( P = 0.36 \)).

**Figure 3** Effect of 1 mM ATP cis on isotope equilibrium exchange rate (n = 4)

Means ± S.E.M. are shown. Isotope exchange rate in the presence of 1 mM ATP cis can be described by a straight line with a slope of 68 nmol/mg. Symbols: ○, uptake in the presence of 1 mM ATP cis; ●, controls.

**Table 1** Effect of ATP, ADP, AMP, ATP[S], pp[CH₂]pA and 2-MeSATP (all 1 mM), 10 μM vanadate, 15 μM SK&F 96365 or 0.1 or 1 μM suramin in the extravesicular medium on zero trans Ca²⁺ uptake (f) in tilapia intestinal BBMV

<table>
<thead>
<tr>
<th>Addition</th>
<th>f (nmol per 5 min per mg)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>25.2±1.4</td>
<td>5</td>
</tr>
<tr>
<td>ATP</td>
<td>372.4±150.1**</td>
<td>5</td>
</tr>
<tr>
<td>ADP</td>
<td>157.9±26.5</td>
<td>5</td>
</tr>
<tr>
<td>AMP</td>
<td>38.9±4.1</td>
<td>5</td>
</tr>
<tr>
<td>Adenosine</td>
<td>26.4±3.3</td>
<td>5</td>
</tr>
<tr>
<td>ATP +10 μM vanadate</td>
<td>333.3±101.2**</td>
<td>5</td>
</tr>
<tr>
<td>ATP, no SK&amp;F 96365</td>
<td>291.7±71.1</td>
<td>3</td>
</tr>
<tr>
<td>ATP +15 μM SK&amp;F 96365</td>
<td>278.7±54.5</td>
<td>3</td>
</tr>
<tr>
<td>Control</td>
<td>24.5±9.5</td>
<td>4</td>
</tr>
<tr>
<td>ATP</td>
<td>112.7±26.4*</td>
<td>4</td>
</tr>
<tr>
<td>ATP +0.1 mM suramin</td>
<td>80.1±23.1</td>
<td>4</td>
</tr>
<tr>
<td>ATP +1 mM suramin</td>
<td>37.9±11.0†</td>
<td>4</td>
</tr>
<tr>
<td>Control</td>
<td>35.5±5.2</td>
<td>13</td>
</tr>
<tr>
<td>ATP</td>
<td>423.5±65.5***</td>
<td>14</td>
</tr>
<tr>
<td>ATP[S]</td>
<td>83.6±12.6</td>
<td>4</td>
</tr>
<tr>
<td>pp[CH₂]pA</td>
<td>43.2±12.3</td>
<td>5</td>
</tr>
<tr>
<td>2-MeSATP</td>
<td>352.1±72.5**</td>
<td>5</td>
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</table>
† Suramin (1 mM) significantly inhibits ATP-stimulated Ca²⁺ uptake (\( P = 0.04 \)).

In our experimental set-up the ATP-stimulated Ca²⁺ uptake is measured as a temperature-sensitive uptake. This approach is common in many membrane transport studies and is used to distinguish non-specific binding of tracer to extravesicular sites from transmembrane translocation. Ca²⁺ uptake at 0 °C and in the presence of 1 mM ATP was 31 ± 3% (n = 23) of the total uptake measured at 37 °C; 70% of the ATP-stimulated Ca²⁺ uptake is thus temperature-dependent. Compared with control BBMVs, at 0 °C 1 mM ATP increased the Ca²⁺ content in BBMVs by a factor of 1.9±0.2 (n = 21). At 37 °C this increase was a factor of 11.8 ± 1.7 (n = 23), again showing temperature dependence. We further investigated extravesicular Ca²⁺ binding by using an isotope equilibrium exchange protocol. During the loading procedure, vesicles are not only loaded intravesicularly (as validated in a previous paper [12]), but it can also be assumed that extravesicular binding sites will be masked by Ca²⁺. Figure 3 shows that 1 mM ATP in the extravesicular medium produces a linear rate of tracer equilibrium exchange, compared with control incubations. From the knowledge that the specific vesicular volume of the BBMVs is 6.0 μl/mg it can be calculated that from a vesicular Ca²⁺ content of 30 nmol/mg intravesicular loading takes place. These results are best explained by assuming
the exposure of intravesicular Ca^{2+}-binding sites on incubation with ATP. ATP, ADP and AMP (1 mM) stimulated Ca^{2+} uptake in BBMVs, albeit with a decreasing amplitude (Table 1). Adenosine was without effect. Vanadate (10 {\mu}M), an inhibitor of P-type ATPases, and SK&F 96365 (15 {\mu}M), an antagonist of receptor-mediated Ca^{2+} entry [15], did not inhibit ATP-stimulated Ca^{2+} uptake in BBMVs.

From the results obtained so far it seems that an adenosine phosphoesterase is important in the uptake of Ca^{2+} in BBMVs. Because ATPase activity has been localized to the apical membrane mammalian intestinal cells [22-27], an investigation of the involvement of an ATPase in the uptake of Ca^{2+} was warranted.

In the presence of inhibitors of (Na^{+}+K^{+})-ATPase and alkaline phosphatase activity, BBMVs showed a nucleotidase activity, hydrolysing ATP and ADP (Figure 4). Apparent affinity coefficients (K_{app}) were 88 {\mu}M ATP and 230 {\mu}M ADP respectively. Because AMP did not affect transport (Table 1) we did not assay AMP hydrolysis by BBMVs. When BBMVs were incubated at pH 10.2 and with a zinc supplementation, i.e. under optimal conditions for alkaline phosphatase, the potency rank order was reversed: AMP ADP ATP (results not shown). Because all of the BBMVs preparation is oriented right-side-out [12], the nucleotidase activity must be an ectoenzymic activity in the enterocyte. These results could indicate that hydrolysis of a phosphate ester is necessary to cause the stimulatory effect of ATP. We therefore examined the kinetics of ATP hydrolysis and the ATP concentration dependence of Ca^{2+} uptake in BBMVs. Both experiments were performed under conditions that yielded initial velocities. Figures 5(A) and 5(B) show that the kinetics of these processes, measured in paired preparations, differed significantly.

ATP hydrolysis was well described by single Michaelis-Menten kinetics (Hill coefficient 1.0). The kinetic parameters V_{max} and K_{m} were calculated to be 82 nmol of P_{i}/h per mg and 64 {\mu}M ATP respectively. In the same substrate range, the ATP-stimulated Ca^{2+} uptake was linear, having a slope of 60 {\mu}l/min per mg and an offset representing ATP-independent uptake (as described previously [12]). These results show that ATP hydrolysis is not responsible for the ATP-stimulated Ca^{2+} uptake in BBMVs. The free ATP^{4-} concentration in our assay medium can be calculated from the total ATP concentration. The inset in Figure 5(B) shows that, up to 180 {\mu}M free ATP^{4-} (which is equivalent to 5 mM total ATP in our assay medium), Ca^{2+} uptake is also a linear function of the ATP^{4-} concentration.

We finally tested the involvement of an ATP receptor. Incubations of BBMVs with 1 mM suramin, a P_{2y} purinoceptor antagonist, resulted in a significant decrease in the ATP-stimulated Ca^{2+} uptake (Table 1). From Table 1 a K_{i} of 0.17 mM suramin was calculated. An ATP analogue of which the adenine base is modified (2-MeSATP, a P_{2y} agonist) mimicked the stimulatory effect of ATP (Table 1). Analogues with modifications in the triphosphate chain (ATP[S] and pp(CH_{3})pA) were unable to stimulate Ca^{2+} uptake in BBMVs (Figure 6). The P_{2y} antagonist Reactive Blue-2 dose-dependently inhibited the ATP-stimulated Ca^{2+} uptake (Figure 6). A K_{i} of 58 {\mu}M was calculated.

The inset shows an Eadie-Hofstee transformation of the data. Kinetic parameters are: V_{max} = 82 nmol of P_{i}/h per mg, K_{m} = 64 {\mu}M ATP, Hill coefficient 1.0. (B) ATP-dependent Ca^{2+} uptake in tilapia intestinal BBMVs. Means± S.E.M. (n = 3). Slope and intercept of the straight line are 60 {\mu}l/min per mg and 19 nmol of Ca^{2+}/min per mg respectively. The inset shows Ca^{2+} uptake as a function of the calculated free ATP^{4-} concentration. Slope and intercept of the straight line in the inset are 2 {\mu}l/min per mg and 19 nmol of Ca^{2+}/min per mg respectively.

Figure 5 A comparison of the ATP concentration-dependence of ATPase activity and ATP-dependent Ca^{2+} uptake in resealed tilapia BBMVs

(A) ATPase activity in resealed tilapia intestinal BBMVs as a function of the extravesicular ATP concentration. Means± S.E.M. (n = 3). The curve is described by a single Michaelis—Menten equation. The inset shows an Eadie—Hofstee transformation of the data. Kinetic parameters are: V_{max} = 82 nmol of P_{i}/h per mg, K_{m} = 64 {\mu}M ATP, Hill coefficient 1.0. (B) ATP-dependent Ca^{2+} uptake in tilapia intestinal BBMVs. Means± S.E.M. (n = 3). Slope and intercept of the straight line are 60 {\mu}l/min per mg and 19 nmol of Ca^{2+}/min per mg respectively. The inset shows Ca^{2+} uptake as a function of the calculated free ATP^{4-} concentration. Slope and intercept of the straight line in the inset are 2 {\mu}l/min per mg and 19 nmol of Ca^{2+}/min per mg respectively.

Figure 4 Initial rates of a nucleotidase activity in resealed tilapia intestinal BBMVs

Means± S.E.M. are shown. Data points were fitted to a Michaelis—Menten equation. Symbols: – ATP (n = 5), V_{max} = 265 nmol/h per mg, K_{app} = 88 {\mu}M ATP; ○, ADP (n = 4), V_{max} = 233 nmol/h per mg, K_{app} = 230 {\mu}M ADP.
Apical membranes of the enterocytes of several teleost species are involved in the absorption of nutrients. Our results show that purinoceptors are involved in regulating muscular contractions in teleosts. The entrance of Ca\(^{2+}\) ions into cells is mediated by ATP-stimulated uptake and by ATP hydrolysis. The involvement of ATP-stimulated Ca\(^{2+}\) uptake in fish intestine has been observed, particularly in tilapia. For 2 mM ATP, increased Ca\(^{2+}\) uptake 2-6-fold was measured in isolated rat intestinal epithelial cells. In cell lines of human ovarian cancer cell origin, an ATP-stimulated Ca\(^{2+}\) uptake was also observed by Popper and Batra [3] in a human ovarian cancer cell line. The inhibition by prenylamine is congruent with observations on chlorpromazine inhibition [11]. Richards et al. [9] suggest that hydrolysis of a terminal phosphate of ATP is required for the stimulated Ca\(^{2+}\) uptake, but they do not rule out the involvement of a nucleotide-specific receptor.

A prerequisite for a functional purinergic receptor in the enterocyte’s brush border membrane is the presence of the proper ligand, i.e., ATP, in the intestinal lumen. One point that needs to be addressed is the source of the ligand. A possible source for luminal ATP would be sloughed-off epithelial cells. In isolated enterocytes from rat and human, cellular values of ATP were measured to range from 5 to 6 nmol of ATP/mg of protein [38]. If we assume cellular ATP levels in tilapia enterocytes to be in the same range, we calculate that a luminal concentration of 0.9 mM ATP is equivalent to 150–180 mg of protein/ml of luminal fluid. Assuming a cytoplasmatic ATP concentration of 5 mM [31], cellular dimensions of 5 \(\mu\)m \(\times\) 5 \(\mu\)m \(\times\) 20 \(\mu\)m, and a cellular volume of 5 \(\times\) 10\(^{-14}\) litre for an enterocyte, we calculate that a luminal ATP concentration of 0.9 mM is equivalent to 4 \(\times\) 10\(^{14}\) cells per ml of luminal fluid. We therefore do not think that sloughed-off enterocytes are a plausible source for ATP. Ingested food could be another source for luminal ATP, but the industrially processed fish feed we provide our fish contains no detectable amounts of ATP.

**REFERENCES**

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