Ca\(^{2+}\)-ATPase-driven calcium accumulation in *Ustilago maydis* plasma membrane vesicles

A. Hernández, D. T. Cooke and D. T. Clarkson

Ca\(^{2+}\) transport has been measured across plasma membrane vesicles isolated from cells of *Ustilago maydis*. This transport was found to be ATP- (or to a lesser extent GTP) and Mg\(^{2+}\)-dependent. Inconsistent release of Ca\(^{2+}\) from intact vesicles was obtained using the calcium ionophore A23187. However, Ca\(^{2+}\) was released by Triton X-100 in a concentration-dependent manner. Transport was inhibited by vanadate (> 50%) and erythrosin B (about 50%), I\(_{50}\) being about 10 \(\mu\)M for both inhibitors. In the presence of the protonophores CCCP or gramicidin, partial inhibition of Ca\(^{2+}\) transport (about 20%) was observed, but the Ca\(^{2+}\)-channel blockers, nifedipine, diltiazem and verapamil had no effect, although the latter inhibited proton transport. The results indicate that Ca\(^{2+}\) transport in *U. maydis* is regulated by a P-type ATPase with similar properties to that found in higher plants.

**Keywords**: *Ustilago maydis*, calcium transport, calcium-ATPase, plasma membrane

**INTRODUCTION**

Calcium is well known as a second messenger in eukaryotic cells. Responses to various signals result in its release into the cytoplasm from either intracellular stores (e.g. sarcoplasmic/endoplasmic reticulum) or via Ca\(^{2+}\) channels at the plasma membrane (Berridge, 1993). However, in resting cells it is necessary to maintain low cytoplasmic Ca\(^{2+}\) concentrations in the range 0.05–1 \(\mu\)M, against extracellular concentrations of 1 mM. In plant cells, this is achieved by intracellular Ca\(^{2+}\) pumps located in different organelles. For example, there are P-type Ca\(^{2+}\)-ATPases in the plasma membrane (Carnelli *et al.*, 1992) and in the endoplasmic reticulum (Wimmers *et al.*, 1992). Although this method of regulating intracellular Ca\(^{2+}\) seems to be reasonably well established for animals and plants, evidence for such a system in fungal cells has not yet been found. To date, there has only been a partial characterization of the respective proteins involved in the fungal plasma membrane and no clear evidence has emerged as to their nature (Stroobant & Scarborough, 1979; Giannini *et al.*, 1988). In yeast, recent studies with membrane vesicles have demonstrated the presence of Ca\(^{2+}\) pumps in different intracellular membranes (Okorokov *et al.*, 1993; Halachmi *et al.*, 1992). Physiological studies have postulated the necessity for a Ca\(^{2+}\)-ATPase in fungal plasma membranes (Miller *et al.*, 1990), although, so far, no such pump has been characterized in isolated fungal plasma membrane vesicles.

In this work, we present evidence for a primary Ca\(^{2+}\)-ATPase in *Ustilago maydis* plasma membrane vesicles, which is MgATP- or MgGTP-dependent. We have also examined the effects of Ca\(^{2+}\)-channel blockers and erythrosin B on Ca\(^{2+}\) transport.

**METHODS**

**Strain and culture.** *Ustilago maydis* (IMI 103761) was maintained in frozen aliquots with 9% (v/v) DMSO at -70 °C. Liquid cultures were inoculated with 80 mg (fresh weight) of cells and cultured for 48 h in minimal medium on a rotary shaker at 25 °C (Hargreaves & Turner, 1992).

**Plasma membrane purification.** Sporidia were harvested at the exponential growth phase by centrifuging at 6000 \(g\) for 10 min (typical harvest 35 g), mixed with 50 ml homogenization buffer [50 mM HEPES to pH 7.5 with KOH, 330 mM sucrose, 5 mM EDTA, 5 mM EGTA, 0.2% BSA, 0.2% casein hydrolysate, 1 mM PMSF, 2% (w/v) choline and 5 mM DTT] and 75 g glass beads (0.125 mm diam.). Cells were homogenized in a 'Bead-Beater' (Biospect Products), the homogenate filtered through nylon cloth (240 \(\mu\)m) and centrifuged at 10000 \(g\) for 15 min. The pellet (unbroken cells, cell debris and intact mitochondria) was discarded and the supernatant centrifuged at 100000 \(g\) for 30 min to produce a microsomal pellet, which was resuspended in 5 mM potassium phosphate buffer, pH 7.8, and 330 mM sucrose. Plasma membranes were isolated and purified using the two-phase aqueous polymer technique, as described by Larsson *et al.* (1987) with the following modifications. The microsomal
Table 1. Specific activities of markers for the microsomal and plasma membrane fractions from *U. maydis* obtained by two-phase partitioning

<table>
<thead>
<tr>
<th>Marker Enzyme Activity</th>
<th>[μmol min⁻¹ (mg protein)⁻¹]</th>
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<tbody>
<tr>
<td></td>
<td>Microsomes</td>
</tr>
<tr>
<td>ATPase (pH 6-7) Control</td>
<td>0.166 ± 0.009</td>
</tr>
<tr>
<td>+ Vanadate</td>
<td>0.080 ± 0.007</td>
</tr>
<tr>
<td>Latency*</td>
<td>(3.6)*</td>
</tr>
<tr>
<td>Glucan synthetase</td>
<td>1.72 × 10⁻³ ± 0.020 × 10⁻³</td>
</tr>
<tr>
<td>Cytochrome c oxidase</td>
<td>0.52 ± 0.002</td>
</tr>
<tr>
<td>NADH-cytochrome c</td>
<td>0.107 ± 0.001</td>
</tr>
<tr>
<td>oxidoeductase</td>
<td></td>
</tr>
<tr>
<td>ATPase (pH 7.5) Control</td>
<td>0.051 ± 0.006</td>
</tr>
<tr>
<td>+ Nitrate</td>
<td>0.084 ± 0.000</td>
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* Values given as a percentage of right-side-out vesicles.

Microsomes contained 0.67 mg protein, the plasma membrane fraction 390.4 mg. Data are from a representative experiment ± sd.

The concentration of free Ca²⁺ in solution was evaluated by using a computer program (socol) developed by Dr D. S. White (University of York, York, UK) and Dr Y. E. Goldman (University of Pennsylvania, Philadelphia, PA, USA). This program uses published association constants for all components of the reaction media, adjusted to the ionic strength and temperature of the assay (Martell & Smith, 1982; Dawson et al., 1986).

RESULTS

Aqueous two-phase partitioning in *U. maydis* produced preparations of highly enriched plasma membrane vesicles (at least fivefold, over microsomes), as determined from enzyme marker assays, and which were mainly (about 90%) inside-out (Table 1). Transport experiments, over a 20 min time-course, showed apparent Ca²⁺ accumulation in both plasma membrane vesicles and in microsomes (Fig. 1), although it was more than fivefold greater in the fraction (200–250 mg protein) was loaded on to six 20 g aqueous two-phase systems (typical load 30 mg per system) with the following final composition: 70% (w/v) dextran T500, 70% (w/v) PEG, 5 mM potassium phosphate buffer, pH 7.8, 330 mM sucrose and 3 mM KCl. After centrifuging at 3000 g for 3 min, the top phase was removed, diluted three times with dilution medium (DM; 10 mM MOPS/BTP, pH 7.5, 330 mM sucrose) and centrifuged at 100000 g for 30 min. The resulting pellet, which represented the plasma membrane fraction, was re-suspended in DM and stored at −20 °C with no longer than 24 h before use.

Measurement of proton-pumping in PM vesicles. The generation of a MgATP-dependent ΔpH was assayed by monitoring the change in fluorescence emission of the fluorescent probe 9-amino-6-chloro-2-methoxyacridine (ACMA) (Molecular Probes), as described in Coupland et al. (1991). Vesicle suspension (about 250 μl, enough to contain at least 100 μg of protein), was added to a cuvette containing 20 mM BTP/MES (pH 6.5), 5 mM ATP, 25 mM KNO₃, 2 μM ACMA and water to 1980 ml. The cuvette was placed in a luminescence spectrophotometer and maintained at 30 °C with constant stirring. The reaction was started by the addition of 20 μl 0.5 M MgCl₂ and the change in fluorescence emission was measured at 485 nm, with excitation at 415 nm.

Measurement of Ca²⁺ uptake. Ca²⁺ transport was measured by a membrane filtration technique (Ramón et al., 1993). Plasma membrane vesicles were incubated as described above in the proton-pumping assay at pH 7.5, which is within the optimal range for the Ca²⁺ pump and for Ca²⁺ transport determinations (Evans et al., 1991). When the proton gradient reached a steady-state, Ca²⁺ transport measurements were initiated by the addition of 45Ca²⁺ (500 kBq ⁴⁵CaCl₂) in 0–10 mM CaCl₂ to achieve 1–100 μM total Ca²⁺ in a volume of 2 ml. Normally, 1 mM CaCl₂ (20 μl) was added to give 10 μM total Ca²⁺, calculated to be equal to a free Ca²⁺ concentration of 2.5 μM, in the presence of MgATP (5 mM). Samples of 50 μl were taken at intervals of 5 min, filtered through pre-washed cellulose nitrate filters (Whatman, 0.45 nm pore size) and washed three times with 1 ml buffer [20 mM BTP/MES, pH 7.1, 1 mM 1,2-bis(2-amino-phenoxo)ethane-N,N',N",N"-tetraacetic acid (BAPTA)]. Ca²⁺ transport was confirmed by its release from the vesicles with Triton X-100 (0.008% final concentration) after 20 min. Ca²⁺ release was also examined with greater concentrations of Triton X-100 (0.016 and 0.032%) and with the calcium ionophore A23187 in increasing concentrations (2.5–20 μM). The filters were dried, suspended in 3 ml scintillant and the radioactivity determined. Blanks were run in the absence of ATP. Ca²⁺ transport was also measured with GTP in place of ATP, the Ca²⁺-ATPase inhibitor erythrosin-B (10–100 μM), the P-type ATPase inhibitor sodium orthovanadate (10–400 μM), the protonophores CCCP (2.5 μM) and gramicidin (3 μM), and the Ca²⁺-channel blockers verapamil (100 μM), diltiazem (100 μM) and nifedipine (100 μM).

Determination of protein. Protein concentration was determined by the method of Bradford (1976) using Bio-Rad reagent and thyroglobulin as the standard.

Determination of free Ca²⁺ content. The concentration of free Ca²⁺ in solution was evaluated by using a computer program (socol) developed by Dr D. S. White (University of York, York, UK) and Dr Y. E. Goldman (University of Pennsylvania, Philadelphia, PA, USA). This program uses published association constants for all components of the reaction media, adjusted to the ionic strength and temperature of the assay (Martell & Smith, 1982; Dawson et al., 1986).
Calcium accumulation in *Ustilago maydis*

**Fig. 1.** Net Ca\(^{2+}\) transport across *U. maydis* plasma membrane and microsomal membrane vesicles, measured in the presence of ATP. Blank values, obtained in the absence of ATP, have been subtracted. Triton X-100 (0.008 %) was added to both experiments at 20 min. △ Microsomal membranes; ○, plasma membranes: 10 μM Ca\(^{2+}\) added to give 2.5 μM free Ca\(^{2+}\). Results are the means of three independent experiments; least significant difference between mean values = 1.06 at 95% level of confidence.

**Fig. 2.** Net Ca\(^{2+}\) transport across *U. maydis* plasma membrane vesicles, measured in the presence of ATP, GTP or ATP+erythrosin-B (15 μM). Blank values, obtained in the absence of ATP, have been subtracted. Triton X-100 (0.008 %) was added to all experiments at 20 min. □ ATP; △, GTP; ○, erythrosin-B (15 μM): 10 μM Ca\(^{2+}\) added to give 2.5 μM free Ca\(^{2+}\). Results are the means of three independent experiments; least significant difference between mean values = 0.80 at 95% level of confidence.

former fraction. The 45Ca\(^{2+}\) accumulated over a 20 min period could be released from plasma membrane vesicles by treating them with Triton X-100 (0.008 %). In contrast, with microsomes, there was no release of Ca\(^{2+}\) by Triton X-100, which may be indicative of non-specific binding rather than true transport (Fig. 1). Increasing concentrations of Triton X-100 (0.008, 0.016 and 0.032 %) showed there was a concentration-dependent release of Ca\(^{2+}\) from the plasma membrane vesicles (51, 57 and 73 % of total uptake, respectively). With the addition of A23187, no consistent release was observed; at 2.5 μM, no Ca\(^{2+}\) was released from the vesicles. However, with 5, 10 and 20 μM, there was an 81, 91 and 83 % release of total uptake, respectively. Therefore, because it gave a more consistent release of Ca\(^{2+}\), it was decided to use Triton X-100 at the lowest concentration, to avoid the possibility of destroying the membrane vesicles.

In plasma membrane vesicles, when GTP was used instead of ATP, Ca\(^{2+}\) transport activity was about 25 % of the ATP-driven accumulation (Fig. 1). Addition of erythrosin-B (15 μM) to the assay mixture, in the presence of ATP, resulted in about 50 % inhibition of transport (Fig. 2). Additions of increasing amounts of erythrosin-B to the assays showed that inhibition was concentration-dependent with an *I*\(_{50}\) of 16.1 μM (Fig. 3).

To determine whether Ca\(^{2+}\) transport depended on the
A. Fig. 5. ATP+nifedapine (100 pM): 10 M Ca2+ added to give Triton X-100 (0.008%) was added to both experiments at vesicles, measured in the presence of ATP+diltiazem (100 pM), free Ca2+. Results are the means of three independent experiments; least significant difference between mean values 0.05 at 95% level of confidence.

B. Fig. 6. Dissipation by verapamil (0.1 mM) of the proton gradient, measured as fluorescence quenching of ACMA. The reaction (at pH 6.5 with 50 µg protein ml⁻¹) was done in the presence of ATP and started by adding 20 µl MgCl₂ (0.5 M). The reaction was finally stopped with 5 µl gramicidin (2 mg ml⁻¹).

The increased level of Ca²⁺ transport in plasma-membrane-enriched vesicles of U. maydis with respect to the microsomes indicated that this activity was plasma-membrane-bound (Fig. 1). Accumulated Ca²⁺ was released by small concentrations of Triton X-100, which was an indication of true transport against a concentration gradient (Tada et al., 1988). With A23187 (2.5 µM), no release of Ca²⁺ occurred (data not shown). This is consistent with results from experiments with Penicillium notatum, in which Ca²⁺ was not released by A23187 from any sub-cellular fraction, including plasma membrane vesicles, although with the exception of mitochondria where a rapid release was observed (Pitt & Barnes, 1993). However, at higher concentrations of A23187 (5–20 µM), Ca²⁺ was released, but unlike with Triton X-100, this was not concentration-dependent.

Although physiological studies have pointed to the necessity for a Ca²⁺-ATPase in the fungal plasma membrane (Millet et al., 1990), previous studies using vesicles have suggested that Ca²⁺ extrusion at the plasma membrane is achieved by a H⁺/Ca²⁺ antiport (Scarborough, 1989; Giannini et al., 1988). However, our results indicated the presence of a P-type Ca²⁺-ATPase which is erythrosin-B-sensitive (I₅₀ 16.1 µM), vanadate-sensitive (I₅₀ 19.4 µM) and MgATP/GTP-dependent (Figs 2, 3 and 4), criteria described as essential characteristics of plant plasma membrane Ca²⁺-ATPases (Williams et al., 1990; Ramón et al., 1993). Furthermore, the addition of the protonophores CCCP or gramicidin to the assay medium, reduced Ca²⁺ transport only to a slight extent and verapamil had no effect at all (Figs 4 and 5). This suggests that Ca²⁺ transport was not strictly dependent on the proton gradient generated by the H⁺-ATPase.

Verapamil is widely used as a Ca²⁺-channel blocker. However, experiments with fungi, in which verapamil was used, have often given contradictory results (Frazer & Moore, 1993; Jackson & Heath, 1993). Our results indicated that verapamil dissipated the proton gradient generated by the primary proton pump (Fig. 6) which may explain some of these anomalies. This result is in agreement with the observation made by Clarkson et al. (1988) that verapamil transiently depolarized the membrane potential of root hair cells.

Thus, we can conclude that in U. maydis plasma membranes, as in plants and animals, there is a primary Ca²⁺-transporting ATPase, and that Ca²⁺ transport is not strongly dependent on the existence of a proton gradient across the plasma membrane. The operation of this Ca²⁺ pump depends on MgATP although it can use MgGTP with lesser efficiency. It is sensitive to erythrosin-B and vanadate and, thus, resembles, in most important respects, the P-type Ca²⁺-ATPases of plant plasma membranes (Evans et al., 1991; Ramón et al., 1993).
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REFERENCES


