Effect of Ca²⁺ and K⁺ on the intracellular pH of an Escherichia coli L-form

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The L-form NC7, derived from Escherichia coli K12, grew in a complex medium containing 0.2 M-CaCl₂ as osmotic stabilizer, but not at pH values above 7.8. The cessation of growth at alkaline pH was not due to cell death. In complex media containing K⁺ or Na⁺, the L-form grew over a wide pH range. Growth at alkaline pH was inhibited by 1 mM-amiloride, indicating that Na⁺/H⁺ antiport activity was required for growth at alkaline pH. The internal pH (pHᵢ) of the L-form in media containing K⁺, Na⁺ or Ca²⁺ was constant at about 7.8 to 8.0 at external pH (pHₑ) values of 7.2 and 8.2. The rates of O₂ consumption by intact cells, lactate oxidation by membrane vesicles from cells grown in Ca²⁺-containing medium, and cell division were all strongly repressed under alkaline conditions.

Introduction

In general, bacterial cells maintain an internal osmolarity higher than that of the external medium, resulting in turgor pressure which is necessary for cell growth (Epstein & Laimins, 1980). Bacterial L-forms are osmotically fragile, requiring salts such as KCl and NaCl, or carbohydrates such as sucrose, as osmotic stabilizers to survive (King, 1986). In hypotonic environments, ionic pumps are generally thought to extrude salts and water to regulate cell volume and maintain an almost constant intracellular pH (pHᵢ) (Padan et al., 1981). Escherichia coli has three distinct antiport systems that function to extrude cations from the cytosol, namely a Ca²⁺/H⁺ system (Brey et al., 1978; Brey & Rosen, 1979; Rosen, 1987), a Na⁺/H⁺ system (Schulzinger & Fishkes, 1978; Beck & Rosen, 1979; Zilberstein et al., 1982) and a K⁺/H⁺ system (Brey et al., 1980). Although a Na⁺/H⁺ antiporter is thought to be involved in the regulation of pHᵢ when the external pH (pHₑ) is alkaline, it remains unclear whether other antiport systems are involved in the regulation of pHᵢ, and how pHᵢ is regulated in E. coli. The L-form NC7, derived from E. coli K12, also has three distinct antiport systems (Na⁺/H⁺, K⁺/H⁺ and Ca²⁺/H⁺ antiporters) (Onoda et al., 1989). Recently, we found that the L-form NC7 can grow in the presence of high Ca²⁺ concentrations at neutral pHₑ, but not at alkaline pHₑ. This paper examines pHₑ homeostasis and cation antiport activity in the L-form NC7 at neutral and alkaline pH.

Methods

Organisms and growth conditions. The parent, Escherichia coli K12 strain 3301, and the L-form NC7 (Onoda, 1986) derived from it were used. Both strains were grown at 32°C without shaking in a complex medium (PY) which contained (g L⁻¹): 10 g peptone, 5 g yeast extract and 2 g glucose. In addition, KPY, CaPY and NaPY media contained 0.34 M-KCl, 0.2 M-CaCl₂ and 0.34 M-NaCl, respectively. The pHₑ in NaPY and KPY media was adjusted to 7.2 with NaOH or KOH. In some experiments, Tris/HCl was used to adjust pHₑ. The pHᵢ in CaPY medium was adjusted to 7.2 or 8.2 with Tris/HCl. Cells were harvested in the exponential phase of growth by centrifugation (2000 g, 15 min), washed once with growth medium supplemented with appropriate osmotic stabilizer, and inoculated into 100 ml of fresh medium in 300 ml flasks. Growth was monitored by measuring the optical density at 600 nm (1 cm path length). The initial OD₆₀₀ was about 0.02. The concentrations of contaminating Na⁺, K⁺ and Ca²⁺ in PY medium were determined using an Hitachi model 170-40 flame photometer and

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Abbreviations: Δψ, membrane potential; ΔpH, transmembrane pH difference; ΔpH⁺, electrochemical proton gradient; pHᵢ, internal pH; pHₑ, external pH; DMO, 5,5'-dimethyl-2,4-oxazolidinedione; MA, methylamine; TPP, tetraphenylphosphonium; CCCP, carbonyl cyanide m-chlorophenylhydrazone.
were found to be approximately 9.2 mM-Na⁺, 6.5 mM-K⁺ and 0.15 mM Ca²⁺.

Preparation of everted membrane vesicles. The L-forms were grown to stationary phase in KPY, NaPY or CaPY medium, harvested, washed twice and suspended in a buffer containing 10 mM-Tris/HCl, pH 7.2, 140 mM-choline chloride, 5 mM-dithiothreitol and 10% (v/v) glycerol. In other experiments, 0.5 mM-choline chloride was used instead of 10% (v/v) glycerol. Everted membrane vesicles were prepared by passing the cells in a French press. The suspension was centrifuged for 5 min at 12000 g to remove unbroken cells and the supernatant solution was centrifuged at 541 000 g for 30 min. The pelleted membrane vesicles were suspended in the same buffer.

Fluorescence assay. Changes in ΔpH, the transmembrane pH difference, were estimated from the energy-linked quenching of quinacrine fluorescence. Assays were done in 10 mM-Tris/HCl, pH 7.2 or 8.0, containing 1 μM-quinacrine, 140 mM-choline chloride, 5 mM-MgCl₂, 0.5 mM-dithiothreitol and 100 to 400 μg ml⁻¹ of membrane protein in a final volume of 2 ml. The samples used were 140 mM-KCl and 140 mM- or 500 mM-choline chloride. On addition of 0.25 mM-CCCP or 0.25 μM-ngericin, the fluorescence intensity rapidly recovered due to the dissipation of ΔpH. In all experiments, fluorescence was measured using an Hitachi model 850 fluorescence spectrophotometer. For quinacrine excitation was at 420 nm and emission was measured at 454 nm, respectively. The cuvette was filled with 2 ml of test solution together with 10 μM-9-aminoacridine. Cells were pre-incubated in CaP or NaPY media for 120 min at 32°C, centrifuged, resuspended in test medium and transferred into a cuvette.

Measurement of Δψ and pHi, pH, and the membrane potential, Δψ, were estimated from the distribution across the cell membrane of [14C]DMO, [14C]MA or [3H]TPP. Cells were grown overnight in CaPY medium, and suspended in CaPY media adjusted to pH 7.2 or 8.2 with Tris/HCl. One ml of a cell suspension (0.1 to 0.2 mg of cell protein) was transferred into tubes containing 2 ml of CaPY medium at the same pH value and 17 μM-[14C]MA (35 Ci mol⁻¹) or 17 μM-[14C]DMO (35 Ci mol⁻¹) for pH measurements, or 5 μM-[3H]TPP (157 Ci mol⁻¹) for Δψ measurements (1 Ci = 37 GBq). Cells grown in KPY or NaPY medium were also used in experiments for Δψ and pH measurements. The assays were the same as those for measurements of Δψ and pHi, in Ca-grown cells, except that the pH values of the KPY and NaPY media were adjusted with KOH and NaOH, respectively. The reaction mixture was incubated for 1 min and filtered through a polycarbonate membrane filter (Jayakumar & Barnes, 1983). The filters were transferred into toluene/Triton scintillation liquid and radioactivity was measured with an Aloka scintillation counter. To calculate the concentration of isotopes within the cells, the intracellular space (10 μl (mg protein)⁻¹) was estimated by determining the distribution volume of [14C]ulin (87±6 μl, 11±4 μCi μmol⁻¹) and 3H₂O (12 μCi, 5 mCi ml⁻¹) (Rottenberg, 1979).

Protein determination. Protein was determined by using the Bradford protein assay (Bio-Rad). Bovine albumin was used as a standard.

Chemicals. Nericin and CCCP were supplied by Sigma. EGTA, quinacrine and 9-aminacridine were from Nacalai tesqu. [14C]MA, [14C]DMO and [14C]ulin carboxyl were products of American Radio Labeled Chemicals. [3H]TPP and 3H₂O were supplied by Amersham. All other chemicals were reagent grade and obtained from commercial sources.

Results

Effects of calcium on growth

Previous work demonstrated that growth of the L-form NC7 in NaPY or KPY medium was calcium-dependent (Onoda & Oshima, 1988), with optimal growth at 0.2 mM-Ca²⁺ in KPY and 1.0 mM-Ca²⁺ in NaPY medium, respectively. In this study, the L-form was able to grow at high CaCl₂ concentrations. The optimum concentration of calcium for growth in PY medium was between 0.1 and 0.2 mM and growth was markedly reduced at concentrations above 0.3 mM (Fig. 1). In PY medium containing relatively low concentrations of CaCl₂ (0.15 to 0.2 mM), growth occurred only in the presence of 0.2 mM-sucrose, implying that the osmolarity of the medium was insufficient to osmotically protect the L-form. The relationship between OD₅₀₀ and the amount of cell protein is shown in Fig. 1. No significant growth was observed over a wide range of Ca²⁺ concentrations in the presence or absence of 0.2 mM sucrose (Fig. 1). The effects of a combination of Mg²⁺ and Ca²⁺ on growth of the L-form were also examined. In this case, because the MgPY medium used in this experiment contained about 0.2 mM contaminating Ca²⁺, external calcium was removed by chelating with 0.2 mM-EGTA. Addition of 0.2 mM-Ca²⁺ to MgPY medium resulted in stimulation of growth, but in the absence of Ca²⁺ no growth was observed. These results imply that Ca²⁺ plays an important physiological role other than as an osmotic stabilizer.

Effects of pH on growth

In KPY medium, the L-form grew over the pH range 6.0 to 9.0 (Fig. 2a), and acidified the medium during growth (Fig. 2b). Similar results were also obtained in NaPY medium containing 1.0 mM-Ca²⁺ (data not shown). In CaPY medium the L-form grew well at a pH of 7.8 or less and caused acidification of the medium. However, it did not grow above pH 7.8 and acidification of the medium was not observed.

Effect of amiloride on cell growth in KPY and NaPY media

Amiloride is a potent inhibitor of the Na⁺/H⁺ antiporter (Mochizuki-Oda & Oosawa, 1985). When the L-form was incubated in KPY or NaPY medium over the pH range 6.5 to 8.6, growth was inhibited by amiloride at alkaline pH (Fig. 3). This result indicated that Na⁺/H⁺ antiport activity plays an important role in growth of the L-form at alkaline pH in KPY and NaPY media. In E. coli, the Na⁺/H⁺ antiporter and external Na⁺ are
Effect of Ca\(^{2+}\) and K\(^{+}\) on pH\(_i\) in E. coli

Fig. 1. Effect of salt concentrations on growth. Cells were grown at 32 °C in NaPY medium containing Ca\(^{2+}\) or Mg\(^{2+}\) at various concentrations. Sucrose was added to the cultures at a final concentration of 0.2 M. All PY media were treated with 0.2 mM-EGTA to remove contaminating Ca\(^{2+}\) and salts of K\(^{+}\), Na\(^{+}\), Ca\(^{2+}\) and Mg\(^{2+}\) were added as osmotic stabilizers. The OD\(_{600}\) was measured after 48 h incubation. Cells were grown in PY medium containing CaCl\(_2\) at various concentrations (O), CaCl\(_2\) at various concentrations plus 0.2 M-sucrose (O), MgCl\(_2\) at various concentrations (■) and MgCl\(_2\) at various concentrations plus 0.2 M-sucrose (□). A, Protein content ml\(^{-1}\) in PY medium containing CaCl\(_2\) at various concentrations.

Fig. 2. Effect of pH on cell growth. Cells were cultured in media with the indicated initial pH values at 32 °C, and the OD\(_{600}\) was measured after 48 h incubation in NaPY (b) and KPY (d) media with (■) and without (○) 1 mM-amiloride. Amiloride was added to NaPY and KPY media at zero time and 24 h after incubation, respectively. The pH of the media was measured at the end of the growth experiments in NaPY (a) and KPY (c) media with (■) and without (△) amiloride. CaCl\(_2\) (1 mM) was added to all NaPY media.

required for growth at alkaline pH (McMorrow et al., 1989), so NaCl was added to CaPY medium at pH 8.0 at a final concentration of 50 or 100 mM. At a pH\(_i\) of 8.0 in CaPY medium, no growth was observed in the presence of 50 or 100 mM-NaCl. Similar results were obtained when KCl was added at the same concentrations as NaCl.

**Oxygen consumption at pH\(_i\) 7.2 and 8.2**

Growth of the L-form, was inhibited completely by the presence of a protonophore (10 μM-CCCP) in KPY and NaPY media (Onoda et al., 1988) and in CaPY medium, (data not shown). This indicated that in the presence of hypertonic calcium, the L-form required a protonmotive force for growth, which was dissipated by the protonophore. Extrusion of protons by the respiratory chain and/or the H\(^{+}\)-ATPase should result in the generation of a ΔpH. Therefore, oxygen consumption by intact cells in media at pH 7.2 and 8.2 was examined (Table 1). Oxygen consumption by intact cells in KPY and NaPY media was almost the same at both pH 7.2 and 8.2. In CaPY medium, however, O\(_2\) uptake by intact cells was less at
Fig. 4. Formation of a ΔpH and antiporter activities in right-side-out membrane vesicles. ΔpH formation and activities of cation/proton antiporters were measured by fluorescence quenching. The assay medium contained: 10 mM-Tris/HCl (pH 7.2 or 8.2), 140 mM-choline chloride, 5 mM-MgCl2, 0.5 mM-dithiothreitol, 1 µM quinacrine, and about 100 µg of membrane vesicle protein ml⁻¹. Quenching was initiated by addition of Tris/1 mM-ATP (a) or Tris/10 mM-DL-lactate (b), respectively. At the times indicated by arrows, either CaCl2, KCl or NaCl were added to give a final concentration of 1 mM for Ca²⁺ and 10 mM for K⁺ and Na⁺.

Table 1. Effect of Ca²⁺ and K⁺ on the rate of oxidation of glucose at pH 7.2 and 8.2 by the E. coli L-form NC7

<table>
<thead>
<tr>
<th>Medium</th>
<th>pH 7.2</th>
<th>pH 8.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaPY</td>
<td>465</td>
<td>510</td>
</tr>
<tr>
<td>KPY</td>
<td>503</td>
<td>584</td>
</tr>
<tr>
<td>CaPY</td>
<td>379</td>
<td>133</td>
</tr>
</tbody>
</table>

pH 8.2 compared to pH 7.2. This indicated that in CaPY medium the respiration-driven H⁺ extrusion was strongly suppressed under alkaline conditions.

Cation transport systems

The pH of everted K⁻ or Ca-vesicles (membrane vesicles from KPY- or CaPY-grown cells) was monitored by changes in fluorescence of quinacrine. When the membrane vesicles were energized with Mg-ATP at pH 7.2 or 8.2, the fluorescence was rapidly quenched, reflecting the formation of a ΔpH across the membrane of the everted vesicles (Fig. 4a). When K-vesicles were energized a ΔpH was formed (acid interior), which was slightly lower at pH 8.2 than at 7.2. Three distinct cation/proton antiporter activities were also detected at both pH values. Similar results were obtained with Na-vesicles. In the energized Ca-vesicles, fluorescence quenching was lower at pH 8.2 than at pH 7.2. A rapid exchange of Ca²⁺ for H⁺ was observed at both pH values, while the Na⁺/H⁺ and K⁺/H⁺ antiporter activities appeared to be lower at pH 8.2 than at pH 7.2. Addition of Dl-lactate to the vesicles decreased the fluorescence quenching (Fig. 4b). When Ca-vesicles were energized with Dl-lactate, only slight quenching of fluorescence was observed at pH 8.2 compared to pH 7.2. However, the formation of a ΔpH in K-vesicles following addition of Dl-lactate was similar at both pH values.

Changes in pHᵦ and Δψ in L-form cells after pHᵦ transitions

DMO and MA distribution in the L-form were examined at pHᵦ values of 7.2 and 8.2, respectively, after
Effect of Ca\(^2+\) and K\(^+\) on pH\(_i\) in E. coli

![Graph](image)

**Table 2. Effect of NaCl, KCl and CaCl\(_2\) on \(\Delta\muH^+\) and its components in the E. coli L-form NC7**

<table>
<thead>
<tr>
<th>Cation</th>
<th>pH(_o)</th>
<th>pH(_i)</th>
<th>(\Delta\psi) (mV)</th>
<th>(\Delta\muH^+) (mV)</th>
<th>(\Delta\muH^+) (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na(^+)</td>
<td>7.2</td>
<td>7.79</td>
<td>-94</td>
<td>35</td>
<td>-129</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>7.89</td>
<td>-89</td>
<td>19</td>
<td>-77</td>
</tr>
<tr>
<td>K(^+)</td>
<td>7.2</td>
<td>7.92</td>
<td>-142</td>
<td>42</td>
<td>-184</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>7.98</td>
<td>-148</td>
<td>13</td>
<td>-135</td>
</tr>
<tr>
<td>Ca(^+)</td>
<td>7.2</td>
<td>7.73</td>
<td>-87</td>
<td>31</td>
<td>-118</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>7.81</td>
<td>-95</td>
<td>23</td>
<td>-72</td>
</tr>
</tbody>
</table>

We also determined the pH\(_i\) of the L-form NC7 equilibrated with either NaPY or CaPY medium at pH 7.2 and 8.2 using 9-aminoacridine. When the pH\(_i\) of a bacterium is lower than the pH\(_o\), the fluorescence of 9-aminoacridine decreases on mixing with intact cells (Deamer et al., 1972). Cells were incubated in medium at pH 7.2 or 8.2 for 120 min and resuspended in 2 ml of the test media at different pH values. When the pH\(_i\) of the cells was lower than pH\(_o\), a quenching of the fluorescence was expected. No fluorescence change was expected when the pH\(_i\) was the same or higher than pH\(_o\). By determining this 'null-point' value, we could estimate pH\(_i\). When cells were incubated in CaPY medium at pH 7.2 or 8.2, quenching of the fluorescence was observed when pH\(_i\) was lower than pH\(_o\) (Fig. 5), indicating that the estimated value of pH\(_i\) was 7.6 to 7.8. The pH\(_i\) of cells incubated in NaPY medium at a pH\(_o\) of either 7.2 or 8.2 was 7.6 to 7.8.

**Morphology of cells cultured in alkaline CaPY medium**

The non-growing L-form in alkaline CaPY medium showed many large cells, which seemed to be the result of disturbed cell division. When the L-form was incubated for 12 h in CaPY medium at pH\(_i\), 8.2 and shifted to 7.2, growth resumed, implying that the cells remained viable for at least 12 h under the non-permissive conditions. Thereafter, the cells continued to grow at the rate characteristic of pH 7.2.

**Discussion**

Many neutrophiles maintain a constant pH\(_i\) at around 7.5 over a wide range of pH\(_o\) values (Booth, 1985). The Na\(^+\)/H\(^+\) antiporter has been shown to be part of the pH homeostasis mechanism in *E. coli* and alkalophilic *Bacillus* species (Padan et al., 1981; Booth, 1985; McMorrow et al., 1989). An *E. coli* mutant with a
defective Na+/H+ antiporter did not grow at alkaline pH, but it had K+/H+ antiporter and Ca2+/H+ antiporter activities that were normal (Ishikawa et al., 1987). Everted membrane vesicles derived from the L-form have three distinct cation antiport systems: a K+/H+ antiport for K+, Rb+ and Na+; a Na+/H+ antiport for Na+ and Li+; and a Ca2+/H+ antiport for Ca2+ and Mn2+ (Onoda et al., 1989). When the L-form was grown in alkaline NaPY and KPY media, growth was inhibited by amiloride, which blocks activity of the Na+/H+ antiporter, indicating that in NaPY and KPY media at alkaline pH, the activity of the Na+/H+ antiporter plays an important role in growth of the L-form, probably in pH regulation. We found, however, that in CaPY medium the L-form grew well at pH values below 7-8, but was unable to grow above pH 7-8, although the cells grew at pH values from 6-0 to 9-0 in NaPY and KPY media. Growth on CaPY medium was completely inhibited by addition of 10 µM-CCCP, indicating that the L-form requires a Δ\( \mu \)H+ for growth. Primary proton pumps such as the respiratory chain or H+-ATPase would be needed for the generation of ΔpH. In CaPY medium, oxygen uptake by intact cells and quenching of lactate-energized fluorescence of Ca-vesicles were repressed at alkaline pH. Roth et al. (1985) reported that osmotic stress, such as a hypertonic salt solution, inhibited the active transport of sugar by E. coli. They suggested that deformation of the membrane by osmotic stress resulted in the conversion of a membrane component of the transport system to a less functional conformation. With the L-form grown in CaPY medium, it was expected that deformation of membrane components by hypertonic Ca2+ may have inhibited electrogenic Na+/H+ antiporter activity. The generation of a ΔpH by primary proton pumps may have lead to cessation of cell division. Brey et al. (1980) reported that a more likely function of the K+/H+ antiporter would be as a regulator of pH. However, it is still uncertain whether this is so. The Ca2+/H+ antiporter is the other antiporter system found in many bacteria. However, the molecular mechanism of active transport of Ca2+ in bacterial membrane vesicles is unclear. Recently, we reported that the L-form requires an external Ca2+ concentration of 0-1 mM for optimal growth in KPY medium and 1-0 mM in NaPY medium (Onoda et al., 1987; Onoda & Oshima, 1988). We have shown here that the L-form can grow at high calcium concentrations and requires an external Ca2+ concentration of about 0-2 M for optimal growth, but the physiological relationship of Ca2+ to carrier proteins remains unclear. Activities of cation antiporters and respiratory enzymes present on the cell membrane in hypertonic calcium solution may be regulated by pHo.

References


