Effects of Inhibitors on Mitochondrial Adenosine Triphosphatase of
Tetrahymena pyriformis ST

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Mitochondrial adenosine triphosphatase (ATPase) of the ciliate protozoon Tetrahymena pyriformis ST is completely inhibited by antiserum prepared against F$_1$-ATPase purified from Schizosaccharomyces pombe, and by naturally occurring inhibitor proteins from this yeast and from bovine heart mitochondria. An ATPase inhibitor protein is also present in extracts of T. pyriformis. Mitochondrial ATPase of T. pyriformis is only partially inhibited by the F$_0$-ATPase inhibitors N,N'-dicyclohexylcarbodiimide, oligomycin, leucinostatin, triethyltin sulphate and venturicidin, and (at high titres) by the F$_1$-ATPase inhibitors Dio-9, efrapeptin, 4-chloro-7-nitrobenzofurazan and spargarzinine. Aurovertin, citreoviridin and quercetin were not inhibitory. Resistance to inhibitors distinguishes this mitochondrial ATPase from all those previously examined.

INTRODUCTION

The adenosine triphosphatases (ATPases) of protozoa have been less well studied than those in yeast and mammalian systems. Tetrahymena pyriformis possesses (a) a mitochondrial Mg$^{2+}$-dependent ATPase (Turner & Lloyd, 1971); (b) a cytosolic Ca$^{2+}$-dependent ATPase isolated from a post-ribosomal supernatant fraction (Chua et al., 1976); (c) a dynein ATPase (Gibbons, 1966) which has a pH optimum of 8.5–9.0 and is dependent on the presence of Mg$^{2+}$, Ca$^{2+}$, Fe$^{2+}$, Co$^{2+}$ or Ni$^{2+}$ for activity; and (d) a Mg$^{2+}$-dependent ATPase found in cell homogenates (Conner et al., 1963), the activity of which was only slightly enhanced by Na$^+$ and K$^+$ and was not inhibited by the cardiac glycoside, ouabain [Frasch et al. (1978) were also unable to find a Mg$^{2+}$-dependent Na$^+$/K$^+$ ATPase in Trypanosoma cruzi]. The components of mitochondrial energy conservation show remarkable similarities in most eukaryotic cell types (Lloyd, 1974) but exceptions have been noted for the protozoa. The cytochromes c of T. pyriformis (Lloyd & Chance, 1972), Crithidia fasciculata (Hill et al., 1971) and Acanthamoeba castellanii (Edwards et al., 1977) all have unusual difference spectra; in addition, the amino acid sequence of cytochrome c of T. pyriformis differs considerably from that of all other known eukaryotic cytochromes c (Tarr & Fitch, 1976). The mitochondrial ATPase of Crithidia lucilieae is also exceptional in that it is only partially inhibited by oligomycin and N,N'-dicyclohexylcarbodiimide. Activity is not inhibited by either aurovertin or by the naturally occurring ATPase inhibitor (F$_1$-inhibitor protein) from beef heart mitochondria (Opperdoes et al., 1976). The mitochondrial ATPase of C. fasciculata is inhibited by oligomycin, venturicidin, triethyltin sulphate, N,N'-dicyclohexylcarbodiimide, leucinostatin, Dio-9 and quercetin, but not by sparginazine or by compounds which interact with the $\beta$-subunit of F$_1$-ATPase (Yarlett & Lloyd, 1981).

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In this paper we show that the mitochondrial ATPase of *T. pyriformis* is unusual in being highly resistant to inhibition by compounds which are potent inhibitors of the mammalian and yeast enzyme complexes.

**METHODS**

*Maintenance, growth and harvesting of organisms.* *Tetrahymena pyriformis* strain ST (obtained from Dr Y. Suyama, Department of Biology, University of Pennsylvania, Philadelphia, U.S.A.) was maintained and grown as previously described (Lloyd *et al.*, 1971) in a medium containing 2% (w/v) proteose peptone (Difco), 0·1% yeast extract (Difco), 0·5% glucose, 5 μg FeC13.6H2O ml−1 and 0·1% antifoam RD emulsion (Hopkin & Williams, Chadwell Heath, Essex, U.K.), adjusted to pH 7·2 with 5 M-KOH (Dickinson *et al.*, 1976). In this medium cell populations grew with a mean cell generation time of 182 min (range 18 min in 15 experiments) to a cell density of 2·2 × 10⁵ (range 1·4 × 10⁵) organisms ml⁻¹. Organisms were harvested from cultures (4 l) at a density of 2·2 × 10⁵ (range 1·4 × 10⁵) organisms ml⁻¹ as previously described (Lloyd *et al.*, 1971).

*Disruption of organisms and preparation of mitochondria.* Harvested cells were washed once in a buffer consisting of 3·2 M-sucrose, 10 mM-EGTA, 24 mM-Tris/HCl pH 7·2, and resuspended in this buffer at 4 °C at 20–30 mg protein ml⁻¹. The cells were disrupted by homogenization at 4 °C in a chilled 50 ml glass homogenizer fitted with a PTFE plunger (Jencons Scientific, Hemel Hempstead, Herts. U.K.) Cell breakage was followed microscopically until about 70% breakage was achieved. Mitochondria were prepared by differential centrifugation as previously described (Turner *et al.*, 1971).

*Preparation and gel filtration of submitochondrial particles.* Mitochondrial fractions (3–5 ml samples containing 10–15 mg protein ml⁻¹) were treated with ultrasound for 30 s (20 kHz, 500 W; MSE sonicator, power setting 5) to produce a suspension of submitochondrial particles. Gel filtration of submitochondrial particles was done by passage through a Sephadex G-50 column (10 cm × 1 cm) eluted with preparation buffer. The particles were eluted in the void volume (4·6 ml).

*Preparation of ATPase inhibitor proteins.* Suspensions of *T. pyriformis* submitochondrial particles were heated (90 °C for 5 min) and then cooled on ice and centrifuged (38000 g for 20 min). The supernatant containing the inhibitor protein was purified by filtration through an XM-100 membrane filter (Amicon, Lexington, Mass., U.S.A.) under N₂ (1·37 × 10⁶ Pa) at 4 °C (removing about 70% of proteins of mol. wt > 20000) and concentrated by removing about 50% of the liquid by filtration through a PM-10 membrane filter (Amicon) under N₂ (3·44 × 10⁶ Pa) at 4 °C. ATPase inhibitor proteins from beef heart mitochondria and *Schizosaccharomyces pombe* mitochondria were prepared by the same technique but purification by membrane filtration was omitted. Inhibitor peptides from all three sources were shown to be single peptides of mol. wt < 15000 by sodium dodecyl sulphate gel electrophoresis.

*Immunological assay of ATPase.* Antiserum raised by injecting a rabbit with 25 mg F₁, ATPase prepared from submitochondrial particles from *S. pombe* (Beechey *et al.*, 1975) was kindly prepared by Dr J. Edwards (Sully Hospital, South Glamorgan, Wales).

*Enzyme assays.* ATPase (EC 3.6.1.3) was routinely assayed by two methods. (a) Proton release was measured using a Pye model 79 pH meter fitted with an EIL combination micro-pH-electrode (Chance & Nishimura, 1967). The output of the pH meter was connected via an amplifier to a 50 mV potentiometric recorder. Calibration was done by adding known volumes of 100 mM-HCl. Extract was added to a stirred medium (2 ml) at 29 °C containing 4 mM-ATP, 4·5 mM-MgSO₄ and 10 mM-Tris/HCl pH 7·15 with a trace of carbonic anhydrase to prevent pH drift caused by absorption of atmospheric CO₂. (b) ATPase was incubated at 29 °C in a medium (1 ml) containing 4 mM-ATP, 4·5 mM-MgSO₄ and 50 mM-Tris/HCl pH 7·15. After the reaction was stopped by addition of 0·1 ml 50% (w/v) trichloroacetic acid, the protein was removed by centrifugation at 12000 g min and the supernatant was assayed colorimetrically for P₁ by the method of Fiske and Subba-Rao (1925). Corrections for enzyme and substrate blanks were done as routine. All enzyme assays were performed within 7 h of preparation of extracts.

Protein was measured by the Lowry method with bovine serum albumin as standard.

*Chemicals.* ATP, carbonic anhydrase, quercetin (3,3',4',5,7-pentahydroxyflavone) ouabain (octahydrate), EGTA, and oligomycin (approx. composition 65% oligomycin A, 20% oligomycin B, 15% oligomycin C) were from Sigma. Bovine serum albumin powder was from Armour Pharmaceutical Co., Eastbourne, Sussex, U.K. Sephadex G-50 was from Pharmacia. *N,N'-Dicyclohexylcarbodiimide* and venturicidin (approx. 4:1 mixture of venturicidin A and B) were from BDH. Citroviridin (C7026) was from Cambrian Chemicals, Beddington Farm Road, Croydon, London. Dio-9 was from Koninklijke Nederlandsche Lord and Spiritus fabric, Delft, The Netherlands: a solution of Dio-9 containing 1 mg ml⁻¹ gives a value of A₃₀₀ − A₄₀₀ = 0·1 (Guillory, 1964); on this basis the commercial product was found to be only 40% pure. 4-Chloro-7-nitrobenzofurazan was from Aldrich Chemical Co., Gillingham, Dorset, U.K. Aurovertin, triethyltin sulphate and dibutylchloromethyltin chloride were gifts from Dr D. E. Griffiths and Dr T. G. Cartledge, Department of Molecular Sciences, University of Warwick,
RESULTS AND DISCUSSION

ATPase assays with submitochondrial particles at various pH values (Fig. 1a) indicated the presence of three pH optima, at pH 6.3, 7.15 and 7.35. The optima at pH 6.3 and pH 7.15 correspond with those determined for the F$_1$-ATPase activity of mitochondria purified on density gradients (Turner & Lloyd, 1971) and are different from the pH optima for dynein ATPase (Gibbons, 1966) and soluble ATPase (Chua et al., 1976). The inclusion of vanadate (as an impurity in ATP from Sigma) in reaction mixtures inhibits any contribution to ATPase activity from sarcoplasmic reticulum Ca$^{2+}$-ATPase, plasma membrane Ca$^{2+}$/Mg$^{2+}$-ATPase, plasma membrane Mg$^{2+}$-ATPase and Na$^+$/K$^+$-ATPase but not from mitochondrial ATPase or plasma membrane Ca$^{2+}$-ATPase (Ó'Neal et al., 1979). Insensitivity to 10 mM-ouabain also suggested that the ATPase activity was not due to a Na$^+$/K$^+$-ATPase. Inhibition of ATPase activity by F$_i$ inhibitor proteins from different cell types and by antiserum prepared against F$_1$-ATPase further confirmed that the ATPase is mitochondrial (Table 1).

The optimum Mg$^{2+}$:ATP ratio, at 4 mM-ATP (Fig. 1b) at both the pH 6.3 and the pH 7.15 optima, was 1:1.25 for preparations of both mitochondria and submitochondrial particles. The optimum at pH 7.15 was used in all further work.

The specific activities of ATPase in preparations of mitochondria, submitochondrial particles and submitochondrial particles after gel filtration were in the ratio 1:1.7 (S.D. 0.45):2.25 (S.D. 0.5) (11 experiments) when assayed by proton release.

None of the agents known to inhibit the enzyme complex at F$_i$ in yeast and mammalian mitochondria (Lloyd, 1974) gave complete inhibition, even at high titres (Table 1). N,N'-Dicyclohexylcarbodiimide was the most inhibitory. All preparations were 10- to 100-fold less sensitive to inhibitors than those from the yeast Schizosaccharomyces pombe (Lloyd & Edwards, 1976). Similarly, the F$_1$-ATPase inhibitors Dio-9, efrapeptin, 4-chloro-7-nitrobenzofurazan and spegazzinine gave only partial inhibition, and aurovertin, citreoviridin and quercetin were without effect. That similar results were obtained in all cases with mitochondria and submitochondrial particles indicates that it is unlikely that limited accessibility to inhibitor-binding sites leads to the small extent of inhibition observed. Gel filtration to remove any endogenous natural inhibitor did not markedly increase the maximum extent of inhibition attainable (except for that by oligomycin and N,N'-dicyclohexyl-carbodiimide). Thus it seems unlikely that prior occupancy by the natural inhibitor of binding sites specific for added inhibitors can explain resistance to inhibition.

The mitochondrial ATPase of T. pyriformis is thus similar in some respects to that of Crithidia fasciculata (Yarlett & Lloyd, 1981), which lacks some inhibitor-binding sites associated with the β-subunit of F$_1$-ATPase. It is however, strikingly different from the enzyme complex of Acanthamoeba castellanii, which possesses a full complement of inhibitor-binding sites, and is similar in many respects to the ATPases of yeast and mammals (S. W. Edwards & D. Lloyd, unpublished results).

Comparison of the inhibitor-binding properties of ATPase of mitochondria-enriched fractions of T. pyriformis with other proton-translocating ATPases is facilitated by reference to data collected by Linnett & Beechey (1979). Resistance to aurovertin distinguishes the mitochondrial ATPase of T. pyriformis from that of beef heart and rat liver mitochondrial ATPases and from the ATPase activity of Rhodospirillum rubrum chromatophores, but not from chloroplast ATPase, which is also resistant to aurovertin; citreoviridin inhibits beef heart mitochondrial ATPase and ATPase activity of R. rubrum chromatophores in a similar...
Table 1. Effect of inhibitors on the ATPase activity of mitochondria and submitochondrial particles of *T. pyriformis*

Uninhibited activities were within the range 20–90 nmol ATP hydrolysed min⁻¹ (mg protein)⁻¹. Titration curves for each inhibitor were obtained by adding small known volumes of inhibitor solutions (in ethanol, except for efrapeptin, leucinostatin and the naturally occurring inhibitors) to the ATPase reaction mixture (proton release method (a), or Pi release method (b)), at pH 7.15. Ethanol (1%, v/v) gave 20% inhibition of ATPase; solvent concentrations never exceeded this value and corrections were employed for its contribution to total inhibition at each addition. I₀ and I₁₀₀ values are expressed as µg inhibitor (or inhibitor protein) per mg protein necessary to give 50% or 100% inhibition, respectively, of total inhibitor-sensitive ATPase. I₅₀ values were determined by addition of excess inhibitor and are expressed as a percentage of total ATPase activity. Treatment of submitochondrial particles by gel filtration is described in Methods.

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<td>I₁₀₀</td>
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<td>F₄ inhibitor (from bovine heart mitochondria)</td>
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ND, Not determined.
Mitochondrial ATPase in Tetrahymena

Fig. 1. Effects of pH and Mg$^{2+}$ concentration on ATPase activity of Tetrahymena pyriformis. (a) Submitochondrial particles (2.0 mg protein ml$^{-1}$) were incubated at 29 °C in buffer containing 4 mM-ATP, 4.5 mM-MgSO$_4$ and 50 mM-Tris. Tris/acetate buffer was used for the pH range 6.0–6.6, and Tris/HCl for the range 6.6–8.0. ATPase activity was measured by P$_i$ release; 100% activity represents 67 nmol P$_i$ released min$^{-1}$ (mg protein)$^{-1}$. (b) Submitochondrial particles (1.0 mg protein ml$^{-1}$) (O, ●) and mitochondria (2.0 mg protein ml$^{-1}$) (Δ, △) were incubated at 29 °C in buffer containing 4 mM-ATP and 50 mM-Tris, with a range of Mg$^{2+}$ concentrations. The pH was maintained at 7.15 (open symbols) or 6.3 (filled symbols). ATPase activity was measured by P$_i$ release. Activity is expressed as a percentage of the maximum at 4.5 mM-Mg$^{2+}$ for submitochondrial particles incubated at pH 7.15, i.e. 72 nmol P$_i$ released min$^{-1}$ (mg protein)$^{-1}$.

manner to aurovertin; quercetin inhibits purified soluble ATPase and membrane-bound ATPase from beef heart mitochondria, spinach chloroplasts and Escherichia coli whilst T. pyriformis mitochondrial ATPase is totally resistant to these inhibitors. Complete inhibition of beef heart mitochondrial ATPase, spinach chloroplast ATPase, and E. coli ATPase by 4-chloro-7-nitrobenzofurazan contrasts with the incomplete inhibition observed in the present study. Efraepetin, an antibiotic thought to react at, or close to, the active site of F$_{1}$-ATPase (Lardy et al., 1975), completely inhibits beef heart [I$_{50}$ = 1.2 μg (mg protein)$^{-1}$] and yeast mitochondrial F$_{1}$-ATPases and E. coli ATPase (at high titres), whereas chloroplast ATPase is only partially inhibited (I$_{max}$ = 60–70%). Leucinostatin, organotin derivatives and venturicidin do not inhibit soluble F$_{1}$-ATPase, but they are more potent inhibitors of rat liver and beef heart membrane-bound mitochondrial ATPases than they are of T. pyriformis mitochondrial ATPase.

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REFERENCES


