ALLANTOINASE FROM PSEUDOMONAS AERUGINOSA

PURIFICATION, PROPERTIES AND IMMUNOCHEMICAL CHARACTERIZATION OF ITS IN VIVO INACTIVATION

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The catabolic enzyme allantoinase is rapidly inactivated in cells of Pseudomonas aeruginosa when the stationary phase of growth is reached. This process is irreversible since the protein synthesis inhibitor chloramphenicol completely blocked the reappearance of allantoinase activity that is observed when allantoin is added to stationary cells. Purified allantoinase appeared to be a protein composed of four identical subunits with a molecular weight of 38000. With antibodies raised against purified allantoinase it was found that allantoinase inactivation is accompanied by a parallel decrease in immunologically reactive material. This suggests that allantoinase inactivation is caused or followed by rapid proteolysis.

Introduction

Allantoinase (allantoin amidohydrolase, EC 3.5.2.5) catalyzes the hydrolysis of the purine catabolism intermediate allantoin to allantoic acid. In Pseudomonas aeruginosa, an organism able to use allantoin as energy, carbon and nitrogen source, the formation of allantoinase is induced in the presence of allantoin, allantoate, or some of their structural analogues in the growth medium [1]. The cellular level of allantoinase is further regulated by catabolite repression and nitrogen control (Janssen et al., unpublished data) and by rapid inactivation, which occurs in induced cells upon carbon starvation [2].

Earlier results suggested the presence of a low molecular weight inhibitor as the cause of allantoinase inactivation [3]. However, the yields with which this presumptive inhibitor could be isolated were irreproducible and always far too low to account quantitatively for the inactivation observed (Janssen, unpublished data). This raised doubt about the physiological significance of the proposed inhibitor and therefore we decided to follow an immunological approach to this problem. Our results demonstrate that the loss of enzyme activity during the in vivo inactivation is accompanied by a decrease in cross-reactive material. This suggests that allantoinase is subject to proteolytic degradation during carbon starvation [4–6].

Materials and Methods

Organism and growth conditions. Ps. aeruginosa strain V3003 was used in all experiments. Allantoin medium contained per l: 10 g allantoin, 4.3 g Na2HPO4·2 H2O, 2.2 g KH2PO4, 100 mg MgSO4·7H2O and 1 ml of the chloride and sulfate solutions described previously [2]. Cells were grown in 500 ml or 81 batch cultures at 37°C with vigorous aeration. The stationary phase of growth was reached at A600 nm of 0.8, when the organism was grown on allantoin medium. Citrate/am-
monia medium contained per 1 10g trisodium-citrate·2H₂O and 2 g (NH₄)₂SO₄, instead of al-
lantoin.

Preparation of cell-free extracts. All steps were
performed at 0–4°C. Cells were harvested by
centrifugation, washed once with buffer 1 (40 mM
phosphate, pH 7.0, containing 0.01% sodium azide
and 1 mM β-mercaptoethanol) and resuspended in
buffer 1. After ultrasonic treatment and centrifu-
gation (100000 × g for 30 min) a crude extract was
obtained.

Purification of allantoinase. Allantoinase was
isolated from crude extract of cells grown on al-
lantoin medium and harvested in the exponential
phase. To the crude extract 0.1 volume of a neu-
tralized streptomycin sulfate solution (10% w/v)
was added. After stirring for 30 min, the precipi-
tate was removed by centrifugation and the super-
natant was fractionated further with a saturated
(NH₄)₂SO₄ solution. The precipitate obtained be-
tween 35 and 50% saturation (22°C) was collected
by centrifugation, dissolved in buffer 1 and di-
alyzed 3 times against 20 volumes of this buffer.
The dialyzed material was loaded on a Sephadex
G-200 column (100 × 5 cm) previously equi-
librated with buffer 1 and di-
alyzed with buffer 1 and the fractions with the highest activity
were pooled. This pool was loaded on a DEAE-
cellulose column (Whatman DE-52, 20 × 1.8 cm)
equilibrated with buffer 1. Protein was eluted with
buffer 1 and the fractions with the highest activity
were pooled. The molecular weight of purified allantoinase was determined by
gel filtration on a Sephadex G-200 column (100 × 2.4 cm) according to Andrews [7], using buffer 1
for equilibration and elution. Markers used were
bovine serum albumin (Mr, 68000), alcohol dehy-
drogenase (Mr, 150000), catalase (Mr, 240000) and
ferritin (Mr, 450000). As an alternative, elec-
rophoresis on 7.5 and 10% polyacrylamide gels was
used [8] with the markers bovine serum albumin,
uricase (Mr, 100000), alcohol dehydrogenase and
phosphorylase A (Mr, 370000). The molecular
weight of allantoinase subunits was estimated by
polyacrylamide gelelectrophoresis (13% gels) in the
presence of SDS as described by Weber and
Osborn [9]. The markers were lysozyme (Mr,
14300), trypsin inhibitor (Mr, 21500), aldolase (Mr,
40000), glutamate dehydrogenase (Mr, 56000) and
bovine serum albumin (Mr, 68000).

Isoelectric point determination. An LKB model
8100 isoelectric focusing apparatus was used for
the determination of the isoelectric point of al-
lantoinase. The 110 ml column was loaded with 2
mg purified allantoinase and 1% carrier ampho-
lines (pH 3.5–10). After focusing, 2 ml fractions
were collected and the allantoinase activity was
measured.

Immunological techniques. Antibodies against al-
lantoinase were raised in two 2.5 kg New Zealand
rabbits. The first injection contained 300 µg puri-
fied allantoinase in Freund complete adjuvant and
four subsequent injections contained each 150 µg
allantoinase in Freund incomplete adjuvant. The
injections were given subcutaneously at 1 week
intervals. 1 week after the last injection the animals
were bled and serum was prepared.

The specificity of the serum could be increased
by treatment with extract from non-induced cells.
The crude serum was mixed with an equal volume of
extract (10 mg/ml protein) from cells grown on
citrate/ammonia medium, and after 15 min at
20°C the precipitate was removed by centrifuga-
tion. The resulting purified serum was specific for
allantoinase and used in all subsequent experi-
ments.

Immunodiffusion was carried out according to
Ouchterlony [10]. Immunelectrophoresis [11] was
performed on agarose gels using a veronal buffer
system (pH 8.6). After electrophoresis (1 h at 3
mA) and development with serum, the plates were washed and stained with Amido black. Rocket immunoelectrophoresis was carried out on agarose gels according to Laurell [12]. Antigen levels were calculated from the rocket heights obtained. There was a linear relationship between rocket height and the amount of purified allantoinase applied up to 0.1 μg of protein.

Immunotitration of allantoinase activity in crude extract was performed as described by Maurizi et al. [4]. Removal of the antibody-allantoinase complex by centrifugation prior to activity determinations was necessary because the complex retained enzymatic activity.

**Allantoinase determination.** Allantoinase activities were determined by following the production of allantoate from allantoin in an incubation mixture consisting of 1 ml 50 mM allantoin in 150 mM triethanolamine·HCl buffer, pH 8.4, and 0.2 ml enzyme. The allantoate formation was measured with the differential glyoxylate method [13]. 1 unit of activity is defined as the amount of enzyme that produces 1 μmol of product per min under the incubation conditions used.

Protein was determined according to Lowry et al. [14], using bovine serum albumin as the standard.

**Materials.** The molecular weight standards were obtained from Boehringer, F.R.G. Chloramphenicol was obtained from Gist-Brocades, Holland. CCCP (carbonylcyanide- m-chlorophenylhydrazone) was from Sigma, MO, U.S.A., and p-chloromercuribenzoate from Fluka, Switzerland. N-Ethylmaleimide was supplied by Koch-Light, DTNB (2,2'-dinitro-5,5'-dithiodibenzoic acid) and all other chemicals were from Merck, F.R.G.

**Results**

**Allantoinase inactivation in vivo.** When *Ps. aeruginosa* was cultured in a medium containing 1% allantoin as sole carbon and nitrogen source, growth continued until a final absorbancy of 0.8 at 600 nm was reached. During the subsequent stationary phase, allantoinase was subject to rapid inactivation and the enzyme activity dropped to about 10% of the original value within 6 h (Fig. 1) [2].

The addition of allantoin to cells containing inactivated allantoinase caused a rapid increase in cellular levels of allantoinase (Fig. 1). This reappearance was completely blocked by the simultaneous addition of the protein synthesis inhibitor chloramphenicol. Apparently, the increase of allantoinase activity was dependent on de novo protein synthesis and reactivation of inactivated enzyme did not occur.

In order to test the energy requirement of allantoinase inactivation, the effect of uncouplers of oxidative phosphorylation was measured. Both 2,4-dinitrophenol and carbonyl cyanide- m-chlorophenylhydrazone (CCCP) blocked allantoinase inactivation (Fig. 2).

**Purification of allantoinase.** For the purification of the enzyme, cells were grown on allantoin medium and harvested in the exponential growth phase. Crude extract was prepared and allantoinase was purified as described under Materials and Methods. The purification scheme is summarized in Table I. Upon polyacrylamide gel electrophoresis, 100 μg of the resulting preparation showed one major and two very faint additional protein bands. The major band was identified as allantoinase by slicing an unstained gel, followed...
Altantoinase activity (U/mg protein)

Starvation time (h)

Fig. 2. Allantoinase inactivation during starvation of cells, and the effect of uncouplers. An exponential culture in allantoin medium was centrifuged, and after washing the cells were suspended in minimal medium, divided in three parts, and incubated under aeration at 37°C. ⋄, Control, no addition; ○, 0.01 mM CCCP added; △, 0.1 mM DNP added.

by measurement of allantoinase activity and comparison of mobilities.

The presence of 1 mM β-mercaptoethanol or 1 mM EDTA was essential during the purification and subsequent storage of the enzyme in order to prevent inactivation. The purified allantoinase did not show any loss of activity for up to 4 months when stored in buffer 1 at 4°C.

Physicochemical characterization. The molecular weight of the purified allantoinase was estimated by means of gel filtration. By interpolation of the elution volumes obtained with known markers, a molecular weight of 140000–150000 was calculated for the native enzyme. The same value was found when polyacrylamide gelelectrophoresis on gels with different concentrations of acrylamide was used.

For the determination of the subunit molecular weight of allantoinase, electrophoresis on SDS-polyacrylamide gels was used. Only one band was observed and a value of 38000 was calculated.

The isoelectric point of allantoinase appeared to be 4.2.

Catalytic parameters. Optimal activity of the purified allantoinase was found at pH 8.4 in both triethanolamine·HCl buffer and Tris·HCl buffer.

The activity-temperature curve showed a steady increase from 20 to 45°C. At higher temperatures the activity dropped sharply and allantoinase was rapidly inactivated at temperatures above 50°C.

Under the standard assay conditions (see Materials and Methods) the enzyme followed typical Michaelis-Menten-type kinetics with respect to allantoin concentration. A $K_m$ value of 5 mM $S(+)$-allantoin and a $V_{max}$ of 1000 μmol/mg protein per min were found.

Inhibitors. The effect of a number of potential inhibitors upon allantoinase activity was tested (Table II). It appeared that compounds, that react with sulfhydryl groups, such as p-chloromercuribenzoate, N-ethylmaleimide, DTNB and heavy metal ions caused strong inhibition. Chelators did not influence the activity. Probably, allantoinase

<table>
<thead>
<tr>
<th>Table I</th>
<th>PURIFICATION OF ALLANTOINASE FROM P. AERUGINOSA</th>
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</thead>
<tbody>
<tr>
<td>Purification step</td>
<td>Volume (ml)</td>
</tr>
<tr>
<td>Crude extract</td>
<td>276</td>
</tr>
<tr>
<td>Streptomycin precipitation</td>
<td>300</td>
</tr>
<tr>
<td>Ammonium sulfate precipitation</td>
<td>78</td>
</tr>
<tr>
<td>Gel filtration</td>
<td>310</td>
</tr>
<tr>
<td>DEAE-cellulose chromatography</td>
<td>90</td>
</tr>
<tr>
<td>Hydroxyapatite chromatography</td>
<td>25</td>
</tr>
<tr>
<td>Ammonium sulfate precipitation</td>
<td>4</td>
</tr>
</tbody>
</table>
TABLE II
EFFECT OF POTENTIAL INHIBITORS ON AL-LANTOINASE ACTIVITY

A volume of 0.9 ml allantoinase (0.105 unit) was preincubated for 1 h at 30°C with 0.1 ml of the inhibitor to be tested. The remaining allantoinase activity was then determined.

<table>
<thead>
<tr>
<th>Potential inhibitor</th>
<th>Final concentration (mM)</th>
<th>Inhibition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>p-Chloromercuribenzoate</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>N-Ethylmaleimide</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>DTNB</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Hydroxylamine</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>Phenylmethanesulfonylfluoride</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>HgCl₂</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>CuSO₄</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>EDTA</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1,10-Phenanthroline</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

contains sulfhydryl groups that are essential for its enzymatic activity.

Preparation and purification of antiserum. Purified allantoinase was used for immunization of rabbits and antiserum was obtained. The serum was tested for specificity by Ouchterlony immunodiffusion. On precipitin band was formed with purified allantoinase, but two additional faint bands were produced with crude extract from allantoin-grown cells. Preimmune serum failed to produce a reaction both with purified allantoinase and with crude extract. Antiserum produced two bands with extract from non-induced cells, which were grown in medium containing citrate plus ammonia. Apparently, the serum was contaminated by antibodies that were not directed against allantoinase. Therefore, we have treated the serum with crude extract containing only a very low allantoinase activity, as described under Materials and Methods. Upon immunodiffusion, the resulting purified serum did not react with extract from non-induced cells and formed only one precipitin band with purified allantoinase or crude extract from allantoin-grown cells. This antiserum was used in all subsequent experiments.

Immunodiffusion and immunoelectrophoresis. The fate of the allantoinase protein during the course of the inactivation process was studied with Ouchterlony immunodiffusion (Fig. 3). The antiserum was found to give the strongest reaction with crude extract from exponentially growing cells. During the stationary phase, in which allantoinase becomes inactivated, the amount of immunoprecipitable protein appeared to diminish because fainter bands were formed. Allantoinase was hardly detectable by immunodiffusion in extracts from cells that were left in the stationary phase for 10 h. Apparently, allantoinase becomes immunologically undetectable during the course of inactivation. The immunodiffusion experiments further suggested that the allantoinase protein from stationary cells is immunologically identical to allantoinase from exponential cells.

The relationship between allantoinases from different growth phases was further studied with immunoelectrophoresis. This technique should allow the detection of important structural changes in the allantoinase molecule that are not accompanied with a loss of immunologically reactivity.

No immunologically detectable proteins with an electrophoretic mobility different from al-

Fig. 3. Ouchterlony immunodiffusion of purified allantoinase and crude extracts from allantoin-grown cells. The wells contained: A, antiserum; 1, purified allantoinase; 2, extract from exponential cells; 3, extract from cells at the beginning of the stationary phase; 4, extract from cells left in the stationary phase for 2 h; 5, extract from cells left in the stationary phase for 10 h; 6, control extract prepared from cells grown in citrate/ammonia medium. All extracts contained 12 mg/ml protein and 25 μl was applied per well.
lantoinase were found during the course of the inactivation (Fig. 4).

Quantitation of immunoreactive material. The amount of allantoinase protein present during inactivation was related to the amount of active allantoinase by determination of the amount of antibody required for the inhibition of allantoinase activity in different extracts. It appeared that

<table>
<thead>
<tr>
<th>Growth phase</th>
<th>Specific allantoinase activity (U/mg protein)</th>
<th>Allantoinase applied (μg)</th>
<th>Rocket height (mm)</th>
<th>Allantoinase detected (μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential</td>
<td>4.2</td>
<td>0.10</td>
<td>40</td>
<td>0.10</td>
</tr>
<tr>
<td>Stationary for 0.5 h</td>
<td>3.7</td>
<td>0.09</td>
<td>35</td>
<td>0.09</td>
</tr>
<tr>
<td>Stationary for 2 h</td>
<td>2.4</td>
<td>0.06</td>
<td>22</td>
<td>0.055</td>
</tr>
<tr>
<td>Stationary for 5 h</td>
<td>1.3</td>
<td>0.03</td>
<td>12</td>
<td>0.030</td>
</tr>
<tr>
<td>Stationary for 10 h</td>
<td>0.6</td>
<td>0.015</td>
<td>5</td>
<td>0.013</td>
</tr>
<tr>
<td>Stationary for 15 h</td>
<td>0.4</td>
<td>0.01</td>
<td>3</td>
<td>0.008</td>
</tr>
</tbody>
</table>
no enzymatically inactive material cross-reacting with the antiserum was present in extracts from stationary cells. The amount of activity inhibited per µl of antibody was the same for extracts prepared from exponentially growing cells and for extracts that were left in the stationary phase for different periods of time (Fig. 5).

The amount of immunoreactive protein present during allantoinase inactivation was also quantitated by rocket immunoelectrophoresis. Essentially the same result was obtained. The amount of immunoprecipitated protein, as calculated from rocket heights, showed a decrease during the stationary phase that was parallel with the decrease of allantoinase activity (Table III).

Discussion

Allantoinase from Ps. aeruginosa is subject to rapid inactivation when cellular growth is stopped as a result of exhaustion of the carbon source in the medium [2]. This process seems to be irreversible since the increase of allantoinase activity observed on addition of allantoin to stationary cells, is dependent on de novo protein synthesis. The protein synthesis inhibitor chloramphenicol blocked the reappearance of allantoinase activity.

Although allantoinase inactivation occurs when the cells are depleted from a carbon source [2], it was found to be an energy-dependent process. The inactivation was stopped when inhibitors of oxidative phosphorylation, such as 2,4-dinitrophenol or CCCP, were added. This is probably related to the requirement for protein synthesis shown by the inactivation [2].

Allantoinase was purified from exponential cells, growing on allantoin medium. The results of molecular weight determinations suggested that the enzyme is composed of four identical subunits of molecular weight 38000. The inactivation of the purified allantoinase by compounds reacting with sulfhydryl groups shows that these groups play a role in the catalytic activity of the enzyme.

The inactivation of allantoinase in stationary cells was accompanied by a parallel decrease in the amount of material cross-reacting with antibodies against allantoinase. This could be shown with quantitative Laurell rocket immunoelectrophoresis. Also from immunotitration experiments it appeared that during the course of inactivation there is no accumulation of inactive enzyme that reacted with the serum. Finally, with immunoelectrophoresis we could not detect a change in the electrophoretic mobility of immunologically detectable allantoinase during inactivation.

A parallel decrease in cross-reacting material during the inactivation of microbial enzymes is generally believed to point to a proteolytic mechanism. The catabolite inactivation of gluconeogenic enzymes of Saccharomyces cerevisiae was shown to be accompanied by a loss of material immunochemically related to the enzymes [6,15,16], and the same was found for the inactivation of the NAD- and NADP-dependent glutamate dehydrogenases [5,17]. Definite proof for proteolysis would be obtained by the elucidation of the mechanism and by the isolation of protease mutants with altered inactivation. However, this has not yet been achieved and some mutants of S. cerevisiae with a defect in protease production appear to show normal inactivation of the NADP-dependent glutamate dehydrogenase [18] and gluconeogenic enzymes [15,19]. Also the inactivation of aspartate transcarbamylase in stationary Bacillus subtilis cells is accompanied by a disappearance of cross-reacting material, but is not caused by a known protease [4].

Our results suggest that allantoinase inactivation is caused or followed by rapid proteolysis of the enzyme, although it cannot be excluded that chemical modification alters the immunological properties. A proteolytic cleavage of the enzyme is consistent with the observed irreversibility. Allantoinase activity could not be detected in the growth medium of stationary cultures (data not shown), which argues against excretion of the enzyme from the cells.

Allantoinase inactivation occurs in stationary cells under carbon-starvation conditions [2], and also during nitrogen-starvation (Janssen et al., unpublished data). The inactivation was found to be dependent on energy and protein synthesis, since the addition of uncouplers or chloramphenicol caused rapid cessation of the decrease in allantoinase activity [2]. If the observed loss of cross-reacting material is caused by protease production, this points to a proteolytic enzyme with a high turnover rate. On the other hand, if protein
modification is the cause of inactivation, our data are consistent with a labile protein being involved in this modification.

Reconstruction of the inactivation in vitro and the isolation and analysis of mutants altered in allantoinase inactivation will be necessary for a better understanding of this process.

References