Purification and Properties of S-Formylglutathione Hydrolase from Human Liver*

LASSE UOTILA† AND MARTTI KOIVUSALO

From the Department of Medical Chemistry, University of Helsinki, Siltavuorenponent 10 A, SF-00170 Helsinki 17, Finland

SUMMARY

S-Formylglutathione hydrolase, a new glutathione thiol esterase from human liver, has been purified into homogeneity according to disc electrophoretic and ultracentrifugal criteria. The final preparation catalyzes the hydrolysis of 4100 pmol of S-formylglutathione per min per mg of protein at 25°C and represents 2,350-fold purification over 23,000 x g supernatant of liver homogenate. In addition to S-formylglutathione, the enzyme can catalyze the hydrolysis of S-acetylglutathione at a 100-fold slower velocity but has no activity with S-lactylglutathione.

The elution volume of the enzyme in a gel filtration column gives an apparent molecular weight of 52,500 and a diffusion coefficient of 6.57 x 10^-7 cm^2 s^-1. The enzyme has a sedimentation coefficient of 4.24 S as judged from sedimentation velocity in analytical ultracentrifuge. From a sedimentation equilibrium experiment, the molecular weight of the enzyme is 55,500. Dodecyl sulfate gel electrophoresis indicates a subunit molecular weight of 30,000. Thus, the enzyme probably consists of 2 subunits. The isoelectric point of the enzyme obtained from electrofocusing experiments is 5.41.

The enzyme apparently contains a reactive —SH group and purification is possible only in the presence of thiols. Activity is rapidly lost when the thiols are removed, but diethiothreitol can regenerate part of the activity. Several types of —SH reagents are inhibitory. Dithiothreitol can reverse completely the effect of mercaptide-forming and oxidizing agents.

Amino group reagents also rapidly inactivate the enzyme. In addition, ascorbate and folate are inhibitory. Chelating agents and organophosphates do not inhibit the enzyme.

We have reported previously the presence of three separate glutathione thiol esterases in human liver (1), but thus far only one of them, glyoxalase II, has been thoroughly purified and characterized (2). In the previous report of this series, we showed that formaldehyde dehydrogenase purified from human liver catalyzes the formation of S-formylglutathione from formaldehyde and GSH (3). It was also shown that S-formylglutathione is hydrolyzed very actively by crude human liver preparations. In this work, we describe the purification and properties of S-formylglutathione hydrolase, a specific enzyme which is responsible for most of the hydrolysis of S-formylglutathione in human liver.

EXPERIMENTAL PROCEDURE

Materials

The sources of many materials used have been described in the previous report (3). N-Acetylimidazole, folinic acid, and tetrahydrofolate were purchased from Sigma. Pyruvic acid was from Aldrich, coenzyme A (free from GSH) from P-L Biochemicals, N,N-dicyclohexylcarbodiimide and ascorbic acid from Fluka, and thioiglycic acid from Merck. Formylthioesters of mercaptoethanol and diithiothreitol were prepared by a method analogous to the synthesis of formylthioglycollate (1). S-Formylglutathione and S-formyl-N-acetylcysteine were obtained by transferring the formyl group from formylthioglycollate to GSH and N-acetylcysteine, respectively, at pH 5. Details of these and other thioester syntheses, except those described below, have been presented earlier (1). Formyl and pyruvyl thioesters were stored at -70°C and were in this way usable for at least 2 months.

S-Pyruvylglutathione

Pyruvic acid (4 mmol) and thioglylic acid (4 mmol) were coupled by adding 2 g of N,N-dicyclohexylcarbodiimide dropwise to 20 ml of N,N-dimethylformamide over a period of 90 min. The vessel was equipped with a drying tube, its contents were constantly mixed at 0°C, and the mixing was continued 2½ hours after the addition of the reagents. Water (10 ml) was then added and the mixture was filtered. The filter was washed with water. The filtrate was concentrated in vacuo and adjusted to pH 3.0 after the addition of water. It was then extracted seven to eight times with 1 volume of ether. According to hydroxamate analysis (4), the pyruvyl ether was then in the ether phase. After evaporation of the ether, 6 volumes of water were added and the cloudy mixture was cleared by filtration. The filtrate was concentrated in vacuo. The yield of S-pyruvylglutathione thus obtained was 2 mmol (60%).

The pyruvyl group was transferred to GSH by shaking a 5-fold excess of pyruvylglutathione with GSH at pH 7.5 and at room temperature for 8 min. The cooled solution was then adjusted to pH 3.0 and freed from pyruvylthioglycollate by at least six ether extractions. The yield of S-pyruvylglutathione was 30% based on GSH. The product was purified further by Sephadex G-10 gel filtration where it had smaller elution volume than impurities, which absorb strongly below 235 nm. The thiol ester was concentrated by lyophilization.

* This work was supported by grants from the Emil Aaltonen Foundation, the Sigrid Juvelius Foundation, and the National Research Council for Medical Sciences, Finland.

† To whom correspondence concerning the manuscript should be addressed.
Formyl Coenzyme A

The preparative procedures closely followed those presented for S-pyruvylglutathione. The yield of formylthioglycolate (80%) was better than Trams and Brady (6) and Sly and Stadtman (6) obtained in their analogous methods with thiophenyl esters as intermediates. Formyl-CoA after gel filtration was 74% pure, and the rest was as CoA. This result was achieved by comparing the ultraviolet spectra of the preparation before and after treatment with hydroxylamine (6 of CoA at 260 nm = 16,060 cm⁻¹ (7) and the \( \Delta A_M \) of the thiol ester bond = 3,300 cm⁻¹ at 240 nm (1)).

Protein Measurement

In crude solutions, the butanol method (8) was used. If necessary, deoxycholate (0.2% in final volume) was added to make the solutions clear. At the later stages of purification, the method of Lowry et al. (9) or Waddell (10) was used. These two methods gave accordant results for the purified enzyme preparations.

Determination of Enzyme Activity

The hydrolysis of S-formylglutathione and other thiol esters was measured at 240 nm with a Zeiss PMQ II spectrophotometer thermostated at 25°. The assay mixture contained 90 mM potassium phosphate buffer (pH 7.1), 0.5 mM thiol ester, and an enzyme in a total volume of 1.0 ml. Activities were calculated as international units (micromoles per min) in these conditions by using \( \Delta A_M = 3300 \) for S-formylglutathione (1). A blank without an enzyme was always included. It contained all of the low molecular weight components like mercaptans introduced in the enzyme sample, and the nonenzymic rate was subtracted from the enzymic. The hydrolysis of carboxyl esters was measured by the method of Hestrin (11), hydrolysis of p-nitrophenyldiazotetrazolyl according to Kezdy and Bender at 400 nm (12), and hydrolysis of N-acetylmercaptoimidazol, at 250 nm (13).

Molecular Weight Determinations by Gel Filtration

These were performed in a calibrated Sephadex G-100 column according to Andrews (14).

Subunit Molecular Weight

Dodecyl sulfate gel electrophoresis according to Weber and Osborn (15) was used. Standards, bovine serum albumin (67,000), ovalbumin (45,000), glyceraldehyde 3-phosphate dehydrogenase (36,000), chymotrypsinogen (25,000), and cytochrome c (12,400), gave a linear plot of log molecular weight versus mobility from which the molecular weight of the unknown was calculated.

Analytical Ultracentrifugation

These experiments were conducted in the Department of Medical Biochemistry, University of Oulu, Finland. A MSE Centriscan 75 ultracentrifuge equipped with a photoelectric scanner was used. The sedimentation velocity run was performed at 60,000 rpm (282,000 x g). The equilibrium ultracentrifugation was first run for 2 hours at 22,000 rpm and then for 2 days at 12,000 rpm. The position of the enzyme was constant 12 hours before the data used in the calculations were taken. In both experiments, the protein (1 mg per ml) was in 0.05 M phosphate buffer, pH 6.5, containing 1 mM DTT. Schlieren optics were used and the temperature was 20°. The sedimentation coefficient was calculated from a plot of log \( S \) versus time (16). The equilibrium data were treated by the procedure described by Blair et al. (17, 18).

Disc Electrophoresis

The methods followed those described by Davis (19) except that no sample gel was used. Polyacrylamide gels (7.5%) at pH 8.9 and 7.5 were prepared according to Mauer (20). In order to locate the enzyme activity, part of the gels were cut into about 40 pieces with a gel slicer (Yeda, Rehovot, Israel). The pieces were incubated for 20 min in 0.5 ml of potassium phosphate buffer (0.1 M, pH 7.1) containing 1 mM DTT with several shakings. Enzyme activity was then determined by adding an aliquot of the supernatant to the standard assay system (see above). After removing the supernatant, the pieces were stained separately with 1% Amido black and destained with 7% acetic acid. Part of the gels were similarly stained and destained without slicing.

Determination of Formate

The formyltetrahydrofolate synthetase method of Rabinowitz (21) was used with the following modifications: tetrahydrofolate was dissolved in 50 mM GSH, pH 7, instead of 1 M mercaptoethanol; the tubes containing the sample, assay mixture, and enzyme were incubated for 60 min at 0° instead of 37° and triethanolamine buffer was used at pH 7.2. These modifications were done in order to prevent the nonenzymic decomposition of S-formylglutathione, which is accelerated by mercaptoethanol during incubation. A calibration curve prepared by formate in the modified conditions was not significantly different from a curve obtained by using the original method (21).

Preparation of Intracellular Fractions

The methods followed those described by Schneider and Hoggomun (22).

Purification of Enzyme

S-Formylglutathione hydrolyase was, in most cases, co-purified at the first stages with formaldehyde dehydrogenase, and Steps 1 to 3 have been described in the preceding paper (5).

Step 4. Hydroxylapatite Chromatography—The pooled preparation of S-formylglutathione hydrolyase activity from the preceding DEAE-cellulose column (Fig. 1 in Ref. 3) was concentrated 5-fold (Amicon, 400-ml ultrafiltration cell, PM-10 membrane) and then dialyzed against 10 mM potassium phosphate (pH 6.8) containing 6 mM mercaptoethanol. One-half of the total solution was then applied to a hydroxylapatite column (Hyapatite C, 1.5 X 31 cm, flow rate, 40 to 60 ml per hour). After the enzyme had been applied, the column was eluted with the equilibration buffer. The enzyme was purified effectively in this step because it was adsorbed only loosely (Fig. 1). Most impurities were bound in the column more strongly than the enzyme.

Step 5. Preparative Isoelectric Focusing—The enzyme pooled...

1 We are indebted to Associate Professor Ilmo Hassinen, Department of Medical Biochemistry, University of Oulu, Finland, for his valuable guidance in the analytical ultracentrifugation experiments.

2 The abbreviations used are: DTT, dithiothreitol; PMB, p-hydroxymercuribenzoate; Nbs, 5,5'-dithiobis(2-nitrobenzoate); MalNes, N-ethylmaleimide; Dansyl, 5-dimethylaminonaphthalene-1-sulfonyl.
from two hydroxylapatite columns was concentrated 20 to 30 fold with an Amicon ultrafiltration cell as above, and then applied to a 110-ml isoelectric focusing column (LKB, Stockholm, model 8101). The enzyme was put in the light solution where it replaced a comparable amount of water. The gradient solutions contained 1 mM DTT. The ampholytes (pH gradient 4 to 6) were used in 1% (w/v) final concentration. The focusing time was 48 hours.

**RESULTS**

**Purification**

The summary of purification of S-formylglutathione hydrolase, presented in Table I, shows that about 2300-fold purification was obtained. The enzyme had already in crude solution an unusually high specific activity, and the final preparation had a specific activity of 4100 i.u. per mg of protein. The same final value was obtained from two different human livers, and the methods of Lowry et al. (9) and Waddell (10) for protein content agreed within a few per cent for the final preparations.

**Disc Electrophoresis**

Electrophoreses were performed for the purified preparations at two pH values, 7.5 and 8.9. In both conditions only a single protein band was constantly obtained (Fig. 4, a and b). Activity determinations and protein staining from gel slices showed that all of the activity was associated with the only protein band seen.

**Molecular Weight**

The elution volume of S-formylglutathione hydrolase in a Sephadex G-100 column calibrated with standard proteins gave an apparent molecular weight of 52,500 ± 1400 (n = 5). No change occurred during purification. When the elution volumes of the standards were plotted against 10^-6/D (14), a diffusion coefficient of 6.57 x 10^-6 cm^2 s^-1 could be calculated for S-formylglutathione hydrolase (Fig. 5).

The purified enzyme sedimented in analytical ultracentrifuge as a single symmetrical peak. A plot of log r versus time (16) was linear (Fig. 6). From its slope, the enzyme has a sedimentation coefficient of 4.24 S (s_{20,w}, protein concentration of 1 mg per ml). The molecular weight of the enzyme calculated from sedimentation and diffusion coefficients is 58,200, if the partial specific volume of the enzyme is assumed to be 0.73 ml per g.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Volume (ml)</th>
<th>Total activity (units)</th>
<th>Total protein (mg)</th>
<th>Specific activity (units/mg)</th>
<th>Purification factor</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Supernatant of liver homogenate</td>
<td>1570</td>
<td>128,000</td>
<td>74,100</td>
<td>1.73</td>
<td>1.0</td>
<td>100</td>
</tr>
<tr>
<td>2. Ammonium sulfate (45 to 67%)</td>
<td>232</td>
<td>93,200</td>
<td>26,200</td>
<td>3.56</td>
<td>2.0</td>
<td>72.7</td>
</tr>
<tr>
<td>3. DEAE</td>
<td>430</td>
<td>56,000</td>
<td>973</td>
<td>50.7</td>
<td>34.5</td>
<td>45.3</td>
</tr>
<tr>
<td>4. Hydroxylapatite</td>
<td>805</td>
<td>36,400</td>
<td>23.1</td>
<td>1570</td>
<td>910</td>
<td>28.4</td>
</tr>
<tr>
<td>5. Isoelectric focusing</td>
<td>12.7</td>
<td>17,500</td>
<td>n.d.</td>
<td>3.34 (W)</td>
<td>3.34 (W)</td>
<td>2350</td>
</tr>
<tr>
<td>6. Sephadex G-100</td>
<td>30.0</td>
<td>13,700</td>
<td>3.38 (L)</td>
<td>4060 (L)</td>
<td>10.7</td>
<td></td>
</tr>
</tbody>
</table>

*a n.d. = not determined.

b L = protein determined according to Lowry et al. (9), W = according to Waddell (10).
FIG. 4. Disc electrophoresis of S-formylglutathione hydrolase at pH 7.5 (a, 10 µg of protein per gel) and at pH 8.9 (b, 17 µg of protein per gel). Gels were stained with Amido black. c, dodecyl sulfate polyacrylamide gel electrophoresis (15) of S-formylglutathione hydrolase. Fifteen micrograms of protein were used per gel. Gel was stained with Coomassie brilliant blue. Cathode is at top, anode at bottom, run from cathode to anode.

FIG. 5. Determination of the molecular weight and diffusion coefficient of S-formylglutathione hydrolase (○) by gel filtration on Sephadex G-100. The standard proteins (□) were: 1, catalase; 2, aldolase; 3, bovine serum albumin; 4, chymotrypsinogen; and 5, cytochrome c. The experimentally determined elution volumes of the standards are plotted against log molecular weight and $10^{4}\gamma/D$, where $D$ is the diffusion coefficient.

The data of the equilibrium ultracentrifugation gave a linear plot of area versus $1/r y$ (17) (Fig. 6). Thus, the preparation used was homogeneous with respect to molecular weight. The molecular weight from this experiment is 55,500.

Subunits

Purified S-formylglutathione hydrolase had, in sodium dodecyl sulfate gel electrophoresis (Fig. 4c), a mobility which corresponds to a subunit molecular weight of 30,000 ± 1,300 (n = 4), calculated from a linear plot formed by the five standard proteins (15). We conclude that S-formylglutathione hydrolase is formed of 2 subunits of similar molecular weight.

Isoelectric Point

Preparative and analytical isoelectric focusing experiments were performed for enzyme preparations from Steps 3 and 4. As a mean of four experiments, the enzyme has an isoelectric point of 5.41 ± 0.10 at 4°C.

Substrate Specificity

Of the 10 thiol esters of glutathione which were tested, S-formylglutathione was by far the most active substrate. Slight activity was noted for S-acetylglutathione and negligible activities for S-propionylglutathione, S-pyruvylglutathione, and S-glycolylglutathione, whereas S-laetylglutathione which is the most active substrate of human liver glyoxalase II (2), and four other tested thiol esters did not react at all (Table II).

The enzyme showed slight activity towards formylthiokesters of other mercaptans, but all were at least 200-fold less reactive than S-formylglutathione, and formyl-CoA was almost inactive as a substrate (Table II).

The two carboxyl esters studied, ethyl formate and ethyl acetate, were inactive as substrates, as was N-acetylimidazole. p-Nitrophenyl acetate was hydrolyzed by the pure enzyme, but at a very low velocity.

The Michaelis constant for S-formylglutathione was 0.29 mM, whereas for S-acetylglutathione a lower value, 0.12 mM, was obtained. Both substrates gave a linear Lineweaver-Burk plot.
The activities were determined with the purified enzyme by the methods described under "Experimental Procedure." The initial concentrations of thiol esters were 0.5 mM except for formyl-CoA, which was used at 0.3 mM. p-Nitrophenyl acetate was 1 mM, N-acetylimidazole, 0.5 mM, and carboxyl esters, 5 mM.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Formylglutathione</td>
<td>100</td>
</tr>
<tr>
<td>S-Acetylglutathione</td>
<td>0.59</td>
</tr>
<tr>
<td>S-Propionylglutathione</td>
<td>0.19</td>
</tr>
<tr>
<td>S-Pyrurylglutathione</td>
<td>0.10</td>
</tr>
<tr>
<td>S-Lactylglutathione</td>
<td>0.07</td>
</tr>
<tr>
<td>S-Pyruvylglutathione</td>
<td>0</td>
</tr>
<tr>
<td>S-Glycolylglutathione</td>
<td>0</td>
</tr>
<tr>
<td>S-Acetylglutathione</td>
<td>0</td>
</tr>
<tr>
<td>S-Succinylglutathione</td>
<td>0</td>
</tr>
<tr>
<td>Formyl-CoA</td>
<td>0.08</td>
</tr>
<tr>
<td>Formylthioglycolate</td>
<td>0.05</td>
</tr>
<tr>
<td>Formylmercaptoethanol</td>
<td>0.59</td>
</tr>
<tr>
<td>Formylthiothreitol</td>
<td>0.02</td>
</tr>
<tr>
<td>S-Formyl-N-acetylcysteine</td>
<td>0.60</td>
</tr>
<tr>
<td>N-Acetylimidazole</td>
<td>0</td>
</tr>
<tr>
<td>Ethyl formate</td>
<td>0</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>0</td>
</tr>
<tr>
<td>p-Nitrophenyl acetate</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The purified enzyme had a typical protein spectrum with no absorbance in the visible area and an absorption maximum at 278 nm. In a concentration of 10 mg per ml, the enzyme has an absorbance of 18.0 cm⁻¹ at 278 nm.

pH Optimum
The enzyme has optimal activity at pH 6.9 to 7.1. The activity was highest in phosphate, pyrophosphate, and acetate buffers, with no difference between sodium and potassium salts. In Tris and imidazole buffers, the activity was about 80% of the activity in phosphate, and in N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid and triethanolamine, 65%. All of the buffers were used at a concentration of 90 mM.

pH Stability
Partially purified enzyme (Step 3) was stable between pH 6.9 and 7.1. The activity was high in phosphate, pyrophosphate, and acetate buffers, with no difference between sodium and potassium salts. In Tris and imidazole buffers, the activity was about 80% of the activity in phosphate, and in N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid and triethanolamine, 65%. All of the buffers were used at a concentration of 90 mM.

### Absorption Spectrum
The purified enzyme had a typical protein spectrum with no absorbance in the visible area and an absorption maximum at 278 nm. In a concentration of 10 mg per ml, the enzyme has an absorbance of 18.0 cm⁻¹ at 278 nm.

### pH Optimum
The enzyme has optimal activity at pH 6.9 to 7.1. The activity was highest in phosphate, pyrophosphate, and acetate buffers, with no difference between sodium and potassium salts. In Tris and imidazole buffers, the activity was about 80% of the activity in phosphate, and in N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid and triethanolamine, 65%. All of the buffers were used at a concentration of 90 mM.

### pH Stability
Partially purified enzyme (Step 3) was stable between pH 6.9 and 7.1. The activity was high in phosphate, pyrophosphate, and acetate buffers, with no difference between sodium and potassium salts. In Tris and imidazole buffers, the activity was about 80% of the activity in phosphate, and in N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid and triethanolamine, 65%. All of the buffers were used at a concentration of 90 mM.

### Absorption Spectrum
The purified enzyme had a typical protein spectrum with no absorbance in the visible area and an absorption maximum at 278 nm. In a concentration of 10 mg per ml, the enzyme has an absorbance of 18.0 cm⁻¹ at 278 nm.

### pH Optimum
The enzyme has optimal activity at pH 6.9 to 7.1. The activity was highest in phosphate, pyrophosphate, and acetate buffers, with no difference between sodium and potassium salts. In Tris and imidazole buffers, the activity was about 80% of the activity in phosphate, and in N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid and triethanolamine, 65%. All of the buffers were used at a concentration of 90 mM.
enzyme, but in aged fractions some reactivation by DTT was seen. The preparations from Step 3 and thereafter were sensitive to slow freezing at -20° but lost no activity when rapidly frozen at -70°.

DTT was an excellent stabilizer of the purified hydrolase both at 0° and at -70°. Mercaptoethanol was also a good stabilizer for a few days at 0°, but not for a long period. At -70°, freezing appeared to cause rapid inactivation of the enzyme over control when the solution contained 5 mM mercaptoethanol. Mercaptoethanol at 2 mM or below did not sensitize the enzyme at 70°. Glycerol and serum albumin were ineffective at 0°, but had a protective effect at -70°.

**Intracellular Distribution of Enzyme**

Cell fractionation performed for one human liver obtained 4 hours after death gave the following distribution of S-formylglutathione hydrolase activity: 91% in 105,000 × g supernatant, 2.3% in mitochondria, 2.7% in microsomes, and 2.1% in the nuclear fraction. Mitochondria and microsomes were treated with 0.2% deoxycholate to liberate the activity. Activities of cell fractions were also determined by S-laeythylglutathione as the substrate. The distribution of this activity was similar to the distribution of activity with S-formylglutathione. In order to obtain the true S-formylglutathione hydrolase activity a small correction was made on the supposition that glyoxalase II caused all of the activity with S-laeythylglutathione and that the activity of glyoxalase II with S-formylglutathione was always 40% of the activity with S-laeythylglutathione (3). We conclude that S-formylglutathione hydrolase of human liver is for the most part a cytosolic enzyme.

### Inhibitors

**Sulfhydryl Reagents**—In order to obtain data on the effect of —SH reagents on the enzyme, a preparation from hydroxylapatite stage (Step 4) was concentrated by ultrafiltration to contain at least 500 i.u. per ml. It was then dialyzed at 4° for 6 hours against 10 mM Tris-HCl, pH 7.6, with one change of the buffer to remove most of the low molecular weight thiols. Only 10 to 15% of the original activity was recovered, and if dialysis was continued more activity was lost rapidly. Addition of 2 mM mercaptoethanol or 1 mM DTT to the dialysis buffer fully stabilized the enzyme. Complete removal of thiols by Sephadex G-25 gel filtration resulted in loss of all of the activity. A dialyzed preparation had still enough activity to permit activity measurements both with S-acetylglutathione and S-formylglutathione. The preparation, after dialysis, was activated over 300% by DTT. Several minutes were needed for the complete effect at 25°. Other mercaptans were much less effective (Fig. 7).

**Table IV**

<table>
<thead>
<tr>
<th>Inhibitor</th>
<th>Concentration (mM)</th>
<th>Substrate S-formylglutathione (0.5 mM)</th>
<th>Substrate S-acetylglutathione (0.5 mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HgCl₂</td>
<td>0.0005</td>
<td>0</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>0</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>93</td>
<td>100</td>
</tr>
<tr>
<td>PMB</td>
<td>0.001</td>
<td>0</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>0.004</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Nbs₂</td>
<td>0.0005</td>
<td>0</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>0.005</td>
<td>78</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>0.067</td>
<td>88</td>
<td>100</td>
</tr>
<tr>
<td>MalNEt</td>
<td>0.025</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>81</td>
<td>77</td>
</tr>
<tr>
<td>Iodoacetate</td>
<td>1.0</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td>30</td>
<td>27</td>
</tr>
<tr>
<td>Arsenite</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The enzyme preparation (Step 4, concentrated) was freshly dialyzed before use to remove mercaptans as described in text. Enzyme and inhibitor were allowed to react for 5 min at 20° in potassium phosphate buffer (pH 7.1). The reaction was then started with the substrate.
FIG. 8. Inhibition of S-formylglutathione hydrolase (Step 4, obtained as in the experiment of Fig. 7 and similarly freed from most thiols) by -SH reagents and the reversibility of the inhibition by DTT. a, enzyme treated by 0.002 mM HgCl₂ (○) and a control without an inhibitor (□); the hydrolysis of the substrate (0.5 mM S-acetylglutathione) was followed at 240 nm. At the time marked by the arrow, DTT (3 mM) was added to both solutions. b, the activities of the enzyme treated by 0.002 mM Nbs₂ (△) and a control (○) similarly followed at 240 nm, and DTT, then added at the time of the arrow. c, the activities of the enzyme treated by 0.5 mM MalNEt (×) and a control (○) followed at 240 nm as in a and b and at 3 mM DTT again added at the time marked by the arrow. The enzyme preparation used in Fig. 8c was different from the preparation used in a and b and appeared to require a longer time for full reactivation by DTT. The rate of the MalNEt-treated sample was followed over 60 min, but the rate did not increase over that seen between 25 and 30 min.

FIG. 9. Inactivation of S-formylglutathione hydrolase (Step 4) by 1 mM 2,4,6-trinitrobenzene sulfonate. The enzyme was incubated together with a control without the inhibitor at 25° in the following conditions: , pH 5.7 (acetate buffer); ⊗, pH 6.6 (phosphate buffer); Δ, pH 7.4 (phosphate buffer); ▲, pH 8.5 (pyrophosphate buffer); ○, pH 8.9 (pyrophosphate buffer); and ×, pH 9.7 (carbonate buffer). All buffers were 0.1 M. Activities were measured according to the standard assay system (see "Experimental Procedure"). Activities are expressed as per cent of the activity of a control without the inhibitor.

Amino Group Reagents—The effect of 2,4,6-trinitrobenzene sulfonate was followed with respect to time at different pH values. The rate of inactivation was strongly pH-dependent and decreased continuously to pH 9.7, which is the highest pH it is possible to study due to the increasing instability of the control enzyme without the inhibitor in alkaline pH values. The way of inactivation of the enzyme by 2,4,6-trinitrobenzene sulfonate (Fig. 9) is in accordance with a reacting free amino group. Dansyl chloride (0.1 mM) inactivated the enzyme rapidly with a half-life of about 3 min throughout the studied pH range (5.7 to 9.0). Therefore, besides amino group(s), —SH group(s), and possible other groups of the enzyme may be reacting.

Hydroxylamine, a carboxylic group reagent (25), was not inhibitory. The enzyme was treated with increasing concentrations of neutral hydroxylamine up to 1 M, after which free hydroxylamine was dialyzed off. N-Acetylimidazole, a tyrosine reagent (26), was also ineffective (phosphate buffer, pH 7.5) at least up to 1 mM.

Chelating Agents—The following reagents were studied: EDTA (5 mM), ethylene glycol bis(β-aminoethyl ether)-N,N'-tetraacetic acid (3 mM), o-phenanthroline (2 mM), α,α'-dipyridyl (2 mM), and 8-hydroxyquinoline (2 mM). Not one of them was inhibitory (30 min incubation at pH 7.1 with the enzyme at 20°).

Ion Effects—NaCl, KCl, and NH₄Cl, all 0.1 M, had no effect on the enzyme. CaCl₂ in the same concentration inhibited 60%. MgSO₄ and MnSO₄ (10 mM) had no effect, but 0.2 mM zinc-acetate inhibited 45% and 1 mM, 95%. Co(NO₃)₂ and copper-acetate were similarly inhibitory. These heavy metals were studied in 0.05 M N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid buffer pH 7. Fluoride inhibited 30% at 8 mM and 60% at 20 mM.

Other Agents—GSH inhibited 18% at 5 mM and 37% at 10 mM. GSSG inhibited 26% at 2.5 mM and 78% at 5 mM. S-Methylglutathione (3 mM) and S-hexylglutathione (1 mM) had no effect. Formaldehyde (10 mM) and methylglyoxal (10 mM) were without effect alone or in the presence of GSH. Thus the hemimercaptals, which these aldehydes form with GSH, are not inhibitory either.

Ascorbate lowered S-formylglutathione hydrolase activity, 0.4 mM inhibiting 35% and 1 mM, all activity. Other reducing agents like thiols or borohydride were not inhibitory. L-Gulonolactone had no effect. Folic acid and tetrahydrofolic acid were inhibitory, 0.2 mM inhibiting 40% and 0.5 mM, 100%.
**Organophosphates**—Both diisopropylphosphorofluoridate (1 mM) and diethyl-p-nitrophenylphosphate (0.5 mM) were ineffective towards S-formylglutathione hydrolase.

**Reversibility of Reaction**

Formate, up to 0.1 M, had no effect on the rate of the reaction. It was not possible to show formation of a thiol ester from formate and GSH by the enzyme at pH 7.1. Addition of ATP had no effect.

**Transfer Reactions**

The formyl group cannot be transferred enzymically from GSH to other mercaptans (mercaptoethanol, DTT) because their presence did not slow the absorption decrease at 240 nm, as is expected if a new thiol ester is obtained instead of the hydrolysis. In the presence of imidazole, S-acetyl- or S-formylglutathione and enzyme, absorption decrease only was seen at 250 to 260 nm. Thus, a formation of the respective N-acyl imidazole does not occur. From the experiments made on the stoichiometry of the reaction catalyzed by S-formylglutathione hydrolase, it is also evident that S-formylglutathione hydrolase does not catalyze the formation of N³-formyltetrahydrofolic acid from S-formylglutathione and tetrahydrofolic acid.

**DISCUSSION**

The results of the present investigation show that human liver contains a specific enzyme which very actively catalyzes the hydrolysis of S-formylglutathione. We have also demonstrated (3) that human liver formaldehyde dehydrogenase catalyzes the formation of S-formylglutathione, and it seems probable that these enzymes, which are both cytoplasmic, function together in vivo. The physiological significance of this potentially very active reaction sequence is not, however, clear at present. Formaldehyde can also be oxidized actively to formic acid by the unspecific NAD-linked aldehyde dehydrogenase and by a tetrahydrofolic acid-dependent reaction sequence (27). A transferase function for S-formylglutathione hydrolase would seem plausible to conserve the thiol ester bond energy, but there is no experimental evidence for it at present.

Other sources than human liver have not been studied yet for the presence of S-formylglutathione hydrolase. Because formaldehyde dehydrogenase appears to be distributed generally (3), the same probably applies also to S-formylglutathione hydrolase. At least in human liver glyoxalase II also can catalyze the hydrolysis of S-formylglutathione, and its activity is more than enough to hydrolyze all S-formylglutathione formed by formaldehyde dehydrogenase (2, 3). Glyoxalases I and II are distributed ubiquitously in the living cells (28). Rose and Racker (29) have reported that S-formylglutathione is hydrolyzed actively in yeast by a source different from glyoxalase II. Kelley and Bradley (30) have partially purified a thiol esterase from mouse liver which hydrolyzed S-acetylglutathione but not S-actetylglutathione, and it is possible that this activity was at least in part due to S-formylglutathione hydrolase.

S-Formylglutathione hydrolase has a molecular weight of about 55,000, which is higher than that of glyoxalase II, 22,900 (2). Sodium dodecyl sulfate gel electrophoresis gives a single subunit with a molecular weight of 30,000, and the enzyme is thus apparently composed of 2 identical subunits. In isoelectric focusing S-formylglutathione hydrolase has an acidic isoelectric point, pI of 5.41 in contrast to glyoxalase II, which is a basic protein with a pI of 8.35 (2).

S-Formylglutathione hydrolase like glyoxalase II and the other glutathione thiol esterases studied (1, 2) is not inhibited by organophosphates. It is sensitive to several types of —SH reagents and is easily oxidized in vitro by the oxygen in air. The reactivity of the —SH group(s), the easy reversal of this inhibition by DTT, and perhaps also the greater sensitivity of the enzyme for —SH reagents with S-acetylglutathione as substrate, when compared to the more reactive S-formylglutathione suggest the presence of an —SH group at or near the active center of the enzyme. Also, an amino group seems to be important to the function of this enzyme according to the inhibition results obtained with 2, 4, 6-trinitrobenzene sulfonate. No metal is needed by S-formylglutathione hydrolase.

In the previous paper from this laboratory (2), the presence of a fourth hydrolase for glutathione thiol esters was anticipated in human liver in addition to glyoxalase I, S-formylglutathione hydrolase, and S-succinylglutathione hydrolase. Because the last named enzyme seems to be specific for S-succinylglutathione (1*) and the specificities of glyoxalase II and S-formylglutathione hydrolase are known, approximate calculations can be made to find further evidence for possible additional hydrolases. It seems that no more than 60 to 70% of the hydrolytic activities of unpurified human liver preparations for S-acetylglutathione and S-propionylglutathione can originate from S-formylglutathione hydrolase and glyoxalase II.

**Acknowledgement**—The most skilful technical assistance of Mrs. Eija Haasanen is gratefully acknowledged.

**REFERENCES**

1. Uotila, L. (1973) Biochemistry 12, 3938-3943
2. Uotila, L. (1973) Biochemistry 12, 3944-3951

* L. Uotila, unpublished results.
Purification and Properties of S-Formylglutathione Hydrolase from Human Liver
Lasse Uotila and Martti Koivusalo


Access the most updated version of this article at http://www.jbc.org/content/249/23/7664

Alerts:
• When this article is cited
• When a correction for this article is posted

Click here to choose from all of JBC's e-mail alerts

This article cites 0 references, 0 of which can be accessed free at
http://www.jbc.org/content/249/23/7664.full.html#ref-list-1