Glucose-6-phosphate Dehydrogenase

PURIFICATION AND PARTIAL CHARACTERIZATION

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Glucose-6-phosphate dehydrogenase has been purified 1000-fold from pig liver. This enzyme exists as an active dimer of molecular weight 133,000 and an inactive monomer of molecular weight 67,500. The pH of maximum activity is 8.5 and the ionic strength maximum is 0.1 to 0.5 M. Glucose-6-phosphate dehydrogenase is highly specific for NADP⁺ and glucose 6-phosphate. Apparent $K_m$ values of 5.6 $\mu$M and 5.4 $\mu$M were obtained for glucose 6-phosphate and NADP⁺. This enzyme is located almost entirely within the soluble portion of the cellular cytoplasm.

The pentose phosphate shunt occurs widely in living cells where one of its main functions is to provide the NADPH necessary for the synthesis of fatty acids and other specific reductions. The biosynthesis of fatty acids is related to the oxidative part of the shunt where the enzymes glucose-6-phosphate dehydrogenase and 6-phosphogluconate dehydrogenase produce the necessary NADPH. The above facts along with the strategic position of glucose-6-phosphate dehydrogenase (glucose-6-phosphate:NADP oxidoreductase EC 1.1.1.49) at a metabolic branch point, suggest that the glucose-6-phosphate dehydrogenase reaction is an important site of metabolic control. This view is supported by several investigators who have shown variations in enzyme activity as a function of hormone and nutritional levels (1, 2), enzyme quaternary structure, and various metabolites including ATP, ADP(3), spermidine, and palmitoyl-CoA(4).

It is our purpose to study glucose 6-phosphate dehydrogenase from pig liver and to determine the effect that various metabolites have on its kinetic properties. Glucose-6-phosphate dehydrogenase has been previously isolated from microorganisms, erythrocytes, and various mammalian tissues (5–17). In this work, we report the isolation, purification, and partial characterization of this enzyme from pig liver. The purification scheme includes homogenization, acid denaturation, Triton X-100 treatment, Sephadex gel filtration, and ion exchange chromatography with DEAE-cellulose. Characterization studies include molecular weight determination, pH, and ionic strength effects, a subcellular fractionation, and preliminary kinetics.

MATERIALS AND METHODS

Chemicals—Glucose 6-phosphate, glucose oxidase, NADPH, NADP⁺, bovine serum albumin, catalase, and lactate dehydrogenase were purchased from Sigma Chemical Co. Blue dextran, yellow dextran, and Sephadex were purchased from Pharmacia Fine Chemicals. DEAE-cellulose was obtained from Bio-Rad Laboratories. Other reagent grade chemicals were purchased either from the California Biochemical Co. or Sigma Chemical Co. DEAE-cellulose was obtained from Bio-Rad Laboratories. Other reagent grade chemicals were purchased either from the California Biochemical Co. or Sigma Chemical Co.

Experimental Procedures—Glucose-6-phosphate dehydrogenase was routinely assayed spectrophotometrically. The usual assay mixture contained 2.6 ml of 0.05 M NaOH/glycine buffer, pH 9.5. 0.1 ml of 30 mM MgCl₂, 0.1 ml of 1.5 mM NADP⁺, 0.1 ml of 30 mM glucose 6-phosphate, and 0.1 ml of enzyme. The reaction was followed at 340 nm using a Gilford DU spectrophotometer equipped with a Texas Instruments recorder and connected to a constant temperature bath set at 30 + 0.1°C. The formation of NADPH produced a linear increase in absorbance readings for periods of 3 min or longer after the addition of glucose 6-phosphate to a 1-cm cuvette. All activities were recorded as change in absorbance per min and later converted to concentrations of NADPH/min at 30°C. Protein concentration was determined either by the method of Warburg and Christian (18) or by the microburet method of Goo (19).

Localization of Enzymes—For the determination of the subcellular localization of the enzyme, freshly slaughtered pig liver was homogenized and fractionated according to a modified method of Schneider and Hoegboen(20). The liver was first cut into small pieces and 2 g were suspended in 14 ml of 0.25 M sucrose containing 0.02 M sodium phosphate buffer, pH 7.4. The cells were homogenized in a Potter-Elvehjem type glass homogenizer. The operation was repeated four times such that 8 g of liver were homogenized in a total volume of approximately 60 ml. The homogenate was centrifuged at 1,000 × g for 20 min and the precipitate containing nuclei, blood, and cellular debris was discarded. The supernatant fraction was then centrifuged for 10 min at 9,000 × g. The resulting pellet was washed twice in the same medium and centrifuged twice at the same speed. The washed pellet was designated as the mitochondrial fraction. The 9,000 × g supernatant fraction was further centrifuged at 20,000 × g for 20 min to remove any unwanted mitochondria still remaining. The supernatant portion of this treatment was centrifuged at 100,000 × g for 40 min. The pellet collected at this stage was washed once in the same medium and was presumed to contain the microsomal fraction. The liquid remaining after 100,000 × g centrifugation was designated as the soluble supernatant fraction. The soluble supernatant fraction was treated with ammonium sulfate at 55% saturation and the precipitate was dissol

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fraction was finally centrifuged at 40,000 \( \times g \) for 20 min and the precipitate discarded. The microsomal fraction was centrifuged at 100,000 \( \times g \) for 20 min, and the supernatant portion retained. Both glucose-6-phosphate dehydrogenase and glucose dehydrogenase were assayed in the clear supernatant portions of the various fractions. Glucose dehydrogenase was assayed with glucose (55.3 mM) and NAD (50 \( \mu \)M) as substrates in 0.05 M glycine buffer (1 mM EDTA) at pH 10, 30°.

RESULTS AND DISCUSSION

**Purification of Enzyme**—Hog liver fresh from the slaughter-house was cut into 2- cm chunks, and 75- g amounts were homogenized in a Waring Blender for 90 s with 0.2 M pH 7 phosphate buffer. The pH of the resulting solution was lowered to 5.5 with 20% acetic acid, and then stored at 4° for at least 2 hours. At this point, the solution was centrifuged at 6,000 \( \times g \) for 30 min at 4° and the precipitate discarded. The remaining liquid usually had a specific activity of 0.004 unit/mg of protein. (NH₄)₂SO₄ (21 g/100 ml) was slowly added to the solution with gentle stirring and then allowed to stand for at least 4 hours at 4°. The final suspension was centrifuged at 10,000 \( \times g \) for 30 min at 4°, and the precipitate retained. The precipitate was treated with Triton X-100 (4 drops of Triton X-100/3 ml of precipitate) in a tissue homogenizer and ground by hand for approximately 9 min. The resulting suspension was increased in volume by 50% using 0.2 M phosphate buffer, pH 7.0 and stored overnight at 4°. The solution was then centrifuged at 10,000 \( \times g \) for 30 min at 4° and the precipitate and any suspended material were discarded. The specific activity of the liquid was approximately 0.01 unit/mg of protein.

The solution was then added in 5-ml batches to a column (2.5 \( \times \) 45 cm) of Sephadex G-200 previously equilibrated overnight with 0.005 M phosphate buffer, pH 7 containing 10\(^{-3}\) M EDTA, 10\(^{-4}\) M NADP\(^+\), and 10\(^{-3}\) M \( \beta \)-mercaptoethanol. Fifteen-minute fractions of approximately 3 ml were collected by means of a Gilson fraction collector.

Fig. 1 is the plot of relative protein and relative activity versus fraction number for glucose-6-phosphate dehydrogenase. The specific activity of the most active fractions is approximately 0.1 unit/mg of protein.

The most active fractions from the Sephadex G-200 column were chromatographed in 7- to 9-ml batches on a DEAE-cellulose column (5 \( \times 1 \) cm) previously equilibrated with 0.005 M phosphate buffer, pH 8 containing 10\(^{-3}\) M EDTA, 10\(^{-3}\) M \( \beta \)-mercaptoethanol, and 10\(^{-4}\) M NADP\(^+\). The enzyme was then eluted in a stepwise fashion with 0.005, 0.01, 0.05, 0.1, and 0.2 M phosphate buffers, pH 8. Three-minute fractions of approximately 3 ml were collected.

The enzyme was then eluted in a stepwise fashion with 0.005, 0.01, 0.05, 0.1, and 0.2 M phosphate buffers, pH 8. Three-minute fractions of approximately 3 ml were collected. Figs. 1 and 2 are presented in miniprint format immediately following this paper. For the convenience of those who prefer to obtain them in the form of full size photocopies, these figures are available as JBC Document No. 75M-1240. Orders should specify the title, authors, and reference to this paper and the JBC Document Number, and the number of copies desired. Orders should be addressed to The Journal of Biological Chemistry, 9560 Rockville Pike, Bethesda, Md. 20014, and must be accompanied by a remittance to the order of the journal in the amount of $1.00.

<table>
<thead>
<tr>
<th>Step</th>
<th>Co-enzyme form</th>
<th>Protein Specific activity</th>
<th>Volume</th>
<th>Purification (fold)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogenate</td>
<td>NADP(^+)</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>Acid denaturation</td>
<td>NADP(^+)</td>
<td>143 0.0011</td>
<td>750</td>
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<tr>
<td>Triton X-100 treatment</td>
<td>NADP(^+)</td>
<td>99 0.0039</td>
<td>300</td>
<td>3.55</td>
<td>240</td>
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<tr>
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<td>63 0.0044</td>
<td>750</td>
<td>4.4</td>
<td>193</td>
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<tr>
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<td>10.9</td>
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<tr>
<td>Sephadex G-200</td>
<td>NADPH</td>
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<tr>
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<td>100</td>
<td>90</td>
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<tr>
<td>DEAE-cellulose ion exchange</td>
<td>NADPH</td>
<td>1.66 0.065</td>
<td>600</td>
<td>65</td>
<td>67</td>
</tr>
</tbody>
</table>
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1.2

I.8

Fig. 3. Molecular weight of the dimer and monomer forms of the enzyme using a Sephadex G-200 column. LDH, lactate dehydrogenase; BSA, bovine serum albumin; G6PDH, glucose-6-phosphate dehydrogenase.

Table II

Localization of glucose-6-phosphate dehydrogenase and glucose dehydrogenase from pig liver

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Glucose-6-phosphate dehydrogenase</th>
<th>Glucose dehydrogenase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specific activity</td>
<td>Activity</td>
</tr>
<tr>
<td></td>
<td>units/mg x 10^6</td>
<td>%</td>
</tr>
<tr>
<td>Mitochondrial</td>
<td>0.33</td>
<td>0.116</td>
</tr>
<tr>
<td>Microsomal</td>
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<td>0</td>
</tr>
<tr>
<td>Soluble</td>
<td>0.73</td>
<td>2.94</td>
</tr>
<tr>
<td>precipitate</td>
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<td>96.2</td>
</tr>
</tbody>
</table>

67,500) as shown in Fig. 3. The dimer was the major peak and the only one that catalyzed the reaction with NADP⁺ and glucose 6-phosphate.

Finally, electrophoresis according to the method of Weber and Osborn (28) gave a single subunit band whose mobility was identical with bovine serum albumin (67,000).

**Optimum pH**—It has been reported that the activity of this enzyme from human erythrocytes is a function of ionic strength and pH (27). We have studied the effect of pH on activity in 50 mM glycine/NaOH and 50 mM Tris/maleate/NaOH buffers. A slow rise in activity is observed with increasing pH to a maximum at pH 8.5, followed by a gradual decrease in activity.

**Ionic Strength**—In this study, the ionic strength was varied at a constant pH of 8.5 in glycine/NaOH buffer. Sodium chloride was first added to increase the ionic strength. We observed a marked increase in activity from an ionic strength of 0.01 to 0.5 M, at which point the activity gradually decreased. When only the glycine/NaOH concentration was increased, the activity was seen to gradually increase until 0.5 M.

**Subcellular Fractionation**—The results of this experiment are given in Table II. Unlike glucose dehydrogenase, which is found in all fractions, glucose-6-phosphate dehydrogenase is localized almost exclusively in the soluble portion of the cell.

**REFERENCES**

Glucose-6-phosphate dehydrogenase. Purification and partial characterization.
M I Kanji, M L Toews and W R Carper