SEPARATION OF MITOCHONDRIAL MEMBRANES OF *NEUROSPORA CRASSA*

II. Submitochondrial Localization of the Isoleucine-Valine Biosynthetic Pathway

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**ABSTRACT**

Separation of *Neurospora* mitochondrial outer membranes from the inner membrane/matrix fraction was effected by digitonin treatment and discontinuous density gradient centrifugation. The solubilization of four isoleucine-valine biosynthetic enzymes was studied as a function of digitonin concentration and time of incubation in the detergent. The kinetics of the appearance of valine biosynthetic function in fractions outside of the inner membrane/matrix fraction, coupled with enzyme solubilization patterns similar to that for the matrix marker, mitochondrial malate dehydrogenase, indicate that the four isoleucine-valine pathway enzymes are localized in the mitochondrial matrix.

**INTRODUCTION**

The submitochondrial localization of enzymes involved in oxidative phosphorylation (1), carbohydrate metabolism (2), protein metabolism (3), lipid metabolism (4), heme synthesis (5), and nucleic acid metabolism (1) has been studied over the past few years by a number of workers. The major portion of this work has been done with mammalian mitochondria, employing different methods of mitochondrial disruption, e.g. osmotic-sonic shock, digitonin, diethylstilbestrol, and phospholipase. Submitochondrial localization of these enzymes has been dependent upon the development of enzymatic markers for outer membrane (1, 6), matrix (3), and inner membrane (7). Lately, in this laboratory, Cassady and Wagner (8) used an osmotic-sonic method to subfractionate the mitochondria of *Neurospora crassa* and characterized the enzyme L-kynurenine-3-hydroxylase (KH) as an outer membrane marker, and succinate-cytochrome c reductase (SCCR) as an inner membrane marker. In this study, digitonin subfractionation has been used to uncover evidence that a group of four enzymes catalyzing the over-all biosynthesis of two branched chain amino acids, isoleucine and valine, from pyruvate-14C in isolated *Neurospora* mitochondria (9), behave as soluble enzymes loosely associated in the mitochondrial matrix. These enzymes are an acetohydroxy acid synthetase (AAS), an acetohydroxy acid reductoisomerase (RI), a dihydroxy acid dehydratase (DH), and a branched amino acid amino transferase (AT).
Submitochondrial fractionation of digitonin-treated mitochondria on discontinuous sucrose density gradient. Each gradient contained 40 mg of digitonin-treated mitochondrial protein in 0.1 M sucrose. Centrifugation at 39,000 g for 1 hr produced a transparent, pale orange layer, designated B1, and a heavy brownish-orange membranous band, designated B2.

**MATERIALS AND METHODS**

**Purification of Mitochondria**

Mitochondria from wild type *Neurospora crassa* strain LSDT(1969A) were prepared by the sandground method previously described (8). The crude mitochondrial fraction was washed once with 0.25 M sucrose, 0.15% bovine serum albumin (BSA), then centrifuged at 37,000 g in a Sorvall SS-34 rotor. Washed mitochondria were resuspended in 0.25 M sucrose, and 5 ml samples were placed on top of a discontinuous sucrose gradient composed of 4 ml of a 1.9 M sucrose cushion, followed by 2 ml of 1.0 M sucrose. A final 1.0 ml layer of 0.25 M sucrose was placed on top of the sample. The gradients were then centrifuged in a Spinco SW-41 rotor at 201,000 g for 60 min, and the mitochondrial band at the 1.0-1.9 M interface was collected. The mitochondria were diluted with 30 ml of 0.2 M sucrose solution and centrifuged for 12 min in a Spinco 50 rotor at 190,000 g. The final mitochondrial pellet was resuspended in 0.25 M sucrose, 0.15% BSA to give an adjusted protein of 40 mg/ml.

**Digitonin Treatment and Submitochondrial Fractionation**

Digitonin (Calbiochem, Los Angeles, Calif., 2 X recrystallized) at the desired concentration was dissolved by heating in an amount of 0.1 M sucrose which, when mixed 1:1 with the resuspended mitochondria, gave a protein concentration of approximately 20 mg/ml. The suspension was carefully mixed by five strokes of a Teflon pestle, transferred to a beaker, and magnetically stirred at 4°C for the times indicated. At the end of the treatment, the mixture was centrifuged at 37,000 g for 60 min, and the supernatants were carefully removed and assayed for soluble enzymes. Controls (minus digitonin) were processed as above, and were assayed to give control levels of enzyme activity in the intact mitochondrial pellet.

Separation of the submitochondrial fractions after digitonin treatment was accomplished with a discontinuous sucrose gradient as previously described (8), with the modification that 1.0 ml of 1.9 M sucrose was used as a cushion; 1.5 ml of 1.0 M sucrose was layered above this, and a 2.0 ml sample of digitonin-treated mitochondria was layered on top. The gradient fractions observed, after centrifugation, are shown diagrammatically in Fig. 1.

**Electron Microscopy**

The B1 and B2 fractions were fixed in 2% buffered glutaraldehyde, pH 7.2, postfixed in 1% osmium tetroxide for 1 hr, stained in 0.5% uranyl acetate, and prepared for electron microscopy with a Siemens Elmiskop 1 as previously described (8).

**Enzyme Assays**

AAS was assayed by the method of Kuwana et al. (10). RI was assayed spectrophotometrically in a Cary model 14, using a 1 cm light path cuvette, by the method of Armstrong and Wagner (11). DH was assayed by the method of Altmliller and Wagner (12). Malate dehydrogenase (MDH) was assayed by the method of Ochoa (13). SCCR was assayed by the method of Tisdale (14), using a modification by Cassady and Wagner (8). KH was assayed by the method of Ghosh and Forrest (15). AT was assayed by the method of Coleman and Armstrong (16). Two systems were used in combination for over-all synthesis of valine from pyruvate: (a) the nonrespiring assay of Kiritani et al. (17), and (b) the respiring assay of Bergquist et al. (18). When used in combination, these systems are referred to as the "combined assay." Protein was estimated by the method of Lowry et al. (19). Total enzyme activities are expressed as percentage of total untreated control mitochondrial pellet levels except in the reductoisomerase assays, where a digitonin concentration of 0.025 mg per mg of mitochondrial protein was included in the assay of "control" pellets to remove a latency of the enzyme for its substrate without producing any solubilization of the activity.

**RESULTS**

Preliminary studies employing digitonin concentrations in the range used by Schnaitman and Greenawalt (1) to subfractionate rat liver mitochondria into inner and outer membrane components (0.5-2.0 mg/10 mg mitochondrial...
protein) showed these levels ineffective for sub-
fractionation of *Neurospora* mitochondrial mem-
branes. The optimum concentration of digitonin
for solubilization of *Neurospora* mitochondria was
determined over a range of 2-6 mg/10 mg mito-
chondrial protein by sedimenting purified
mitochondria, previously incubated in digitonin
for 20 min, at 37,000 g for 60 min, and assaying
the supernatant for solubilized enzyme activities.
Units of enzyme activity are as follows: Fig. 2 a, succinate cytochrome c reductase (SCCR), µmoles
cytochrome c reduced per minute; kynurenine hydroxylase (KH), µmoles 3-OH kynurenine produced
per hour. Fig. 2 b, acetoxydrol acid synthetase (AAS), µmoles α-acetolactate produced per hour;
reductoisomerase (RI) µmoles NADPH oxidized per hour; dihydroxy acid dehydratase (DH), µmoles
ketovalerate produced per hour; branch chain amino acid aminotransferase (AT), µmoles ketoisole-
lucine produced per 10 min; malic dehydrogenase (MDH), µmoles NADH oxidized per min.

![Figure 2](https://example.com/figure2.png)

**Figure 2** Mitochondrial enzymes present in 37,000 g supernatant as a function of digitonin concentra-
tion. A mitochondrial suspension at 40 mg per ml was treated with the indicated levels of digitonin for
20 min, and the suspension was centrifuged at 37,000 g for 60 min. Total enzyme activities were deter-
mined in the pellet only on the "0" digitonin control, unless otherwise stated in the text. The levels of
activity present in the 37,000 g supernatant are expressed as percentages of the control pellet activity.

The decrease in KH activity observed at high digitonin concentrations (Fig. 2 a) may be due to disruptive interaction of digitonin with components of the outer mitochondrial mem-

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brane, perhaps lipid essential for enzyme activity. Cassady and Wagner (8) have observed that Neurospora KH is rather tightly bound to the outer mitochondrial membrane after disruption with sonication. Mayer and Staudinger (23) have shown that KH of rat liver mitochondria has a lipid dependency for activity.

The release of the four mitochondrial enzymes necessary for isoleucine-valine biosynthesis was also studied as a function of digitonin concentration, and as shown in Fig. 2 b, the pattern of release of these enzymes (AAS, RI, DH, and AT) closely resembles that of soluble matrix enzyme MDH, and not that produced by either of the membrane-bound marker enzymes KH or SCCR. The soluble nature of one of the isoleucine-valine (iv) pathway enzymes, the DH, is further illustrated in Fig. 3. Mitochondria were incubated for 20 min in 4 mg digitonin/10 mg protein; the inner membrane marker SCCR had an activity peak sharply concentrated in the heavy membranous B2 fraction, while the peak activity of the outer membrane marker KH was sharply concentrated in the light membranous B1 fraction. DH, while distributed throughout the gradient, was predominantly found in the light sucrose S1 fraction. Using osmotic-sonic disruption, Cassady and Wagner (8) found a similar gradient distribution for RI. Cassady (20) has also observed a similar gradient distribution for DH and AAS after disruption of mitochondria with deoxycholate. The presence of isoleucine-valine enzymes in the S1 fraction suggests their release by digitonin from a matrix pool of soluble enzymes, both before and during discontinuous gradient centrifugation. Not only was this release of soluble iv enzymes a function of digitonin concentration, but also, as shown in Table I, of incubation time in the detergent.

Electron microscope examination of the B1 and B2 fractions revealed that the pale, transparent orange B1 layer was comprised predominantly of empty vesicles bounded by single membranes (Fig. 4 a). Similar vesicles were seen in digitonin-treated rat liver mitochondrial preparations by Schnaitman and Greenawalt (1) and interpreted to be outer mitochondrial membrane. The dark brown-orange pigmented B2 fraction was composed of larger vesicles bounded by a single smooth membrane and frequently containing an electron-opaque matrix (Fig. 4 b). The B1 and B2 fractions obtained by digitonin fractionation are ultrastructurally similar to the same fractions obtained by

### Table I

<table>
<thead>
<tr>
<th>Incubation time in digitonin (min)</th>
<th>S1</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>533</td>
<td>199</td>
<td>1548</td>
</tr>
<tr>
<td>10</td>
<td>1073</td>
<td>239</td>
<td>1377</td>
</tr>
<tr>
<td>15</td>
<td>2383</td>
<td>333</td>
<td>1809</td>
</tr>
</tbody>
</table>

*“Combined assay” for valine was prepared in a standard assay mixture containing 0.25 M sucrose, 0.15% bovine serum albumin, 20 mM L-phenylalanine, and 3 mM MgCl2 in 0.1 M Tris at pH 7.8. Pyruvate concentration was 5 µmoles/ml assay medium. “Cofactor assay” components added were 0.25 mM nicotinamide adenine dinucleotide phosphate (NADP), 0.3 mM TPP, 0.4 mM pyridoxal-5-phosphate, and 25 mM glucose-6-phosphate. “Respiring assay” components added were 1 mM ADP, 2 mM inorganic phosphate, and 5 mM succinate. Assays were run 2 hr at 37°C. Digitonin treatment was performed as described in Materials and Methods, using 4.8 mg digitonin/10 mg mitochondrial protein.
FIGURE 4 Appearance of B1 fraction (Fig. 4 a) and B2 fraction (Fig. 4 b) after 5 min digitonin treatment (4.8 mg digitonin/10 mg mitochondrial protein). The B2 fraction contains large, single membrane-bounded vesicles, but no intact mitochondria. Electron-opaque material is seen inside the membranes. The B1 vesicles are at least three to four times smaller than the B2 vesicles and exhibit no interior ultrastructure. The length of the bar represents 1 μm X 33,000.

the osmotic-sonic treatment reported previously (8).

The difficulty in assigning a specific submitochondrial localization for the iv enzymes was that these enzymes, as well as valine biosynthetic activity, were never found discretely localized in any one fraction, but were spread through the discontinuous gradients between the S1 and B2 regions, making it difficult to eliminate the possibility of a ubiquitous distribution. However, it was possible to rule out this consideration since it could be demonstrated not only that the digitonin-mediated solubilization of iv enzymes was a function of detergent concentration, but also that the appearance of valine biosynthetic activity into fractions above the B2 (including the four enzymes whose activities are required for valine synthesis) was a function of the time of incubation in digitonin before centrifugation. As shown in Table I, incubation in digitonin for 5, 10, and 15 min before centrifugation produced a marked increase over time of valine synthetic activity in the B1 fraction, and more particularly the S1 fraction, where a greater than 300% increase over the 5-min valine level was observed at 15 min. The levels of valine synthesis in the B2 fraction, on the contrary, either remained relatively stable, as seen in Table I, or, in some experiments, dropped as much as 43% in 15 min. In this experiment (Table I), it is observed that the total specific activity of valine synthesis increases with increasing incubation time in digitonin. This is probably due to the increasing degradation of inner membrane/matrix compartmentation by digitonin, resulting both in the release of latent activity which is not assayable when compartmentation is intact, and in the elimination of permeability or other factors which might normally limit the amount of pyruvate or thiamine pyrophosphate (TPP) cofactor accessible to the AAS.

It is not surprising that the levels of valine synthesis in the B2 fraction relative to the other fractions remained high over time, even as considerable units of the enzymes were leached out of the matrix and into the upper fractions of the gradients, since one of the two components of the "combined assay" for valine synthesis, the "respiring assay," contains adenosine diphosphate (ADP), inorganic phosphorus, and succinate. These respiratory cofactors have been observed to stimulate valine synthesis from pyruvate at high specific activity only in intact Neurospora mitochondria capable of respiration coupled with oxidative phosphorylation (9) and the inner membrane/matrix mitochondrial subfraction containing the Krebs cycle and electron-transport
chain enzymes (unpublished observation). Presumably, actively respiring, coupled mitochondria are capable of generating endogenous pools of reduced cofactors, such as NADPH, which are supplied exogenously in the "cofactor assay." With increased incubation time in digitonin, more inner membrane/matrix surface would become exposed, thus permitting greater availability of the respiratory substrates and, consequently, greater efficiency of valine synthesis, despite the loss of enzyme units into the gradients. Accordingly, under these experimental conditions, the B2 fraction, consisting of inner membrane/matrix, exhibited continuously high levels of valine production since only this fraction is capable of utilizing both component assay systems of the "combined assay" (20).

**DISCUSSION**

It has been previously speculated (21) that the four enzymes in the biosynthetic pathway from pyruvate may reside inside the mitochondrion as an organized multi-enzyme complex. While our data neither completely confirm nor negate this speculation, the demonstration in vitro that any enzyme is matrix-localized, but on the basis of the kinetics of appearance of pathway enzymes outside the inner membrane/matrix fraction, coupled with enzyme solubility properties similar to mitochondrial malate dehydrogenase, we can state with some confidence that all four enzymes are localized in the matrix. We wish to thank Mrs. Esther Eakin for her excellent technical assistance, and Mr. Robert Riess for taking the electron micrographs. Dr. Marvin Collins kindly performed the transaminase assays.

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