Brain Aldehyde Dehydrogenase

LOCALIZATION, PURIFICATION, AND PROPERTIES*

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V. Gene Erwin‡ and Richard A. Deitrich§

From the Department of Pharmacology, University of Colorado School of Medicine, Denver, Colorado 80220

SUMMARY

Aldehyde-oxidizing capacity has been measured in rat, monkey, and bovine brain with the use of indole-3-acetaldehyde and nicotinamide adenine dinucleotide as substrates. The enzyme activity was found to be uniformly distributed in various areas of bovine brain.

Mitochondria, prepared by differential and density gradient centrifugation of rat brain homogenates, contained a major portion of the total aldehyde-oxidizing activity while smaller amounts were present in the supernatant fraction. The enzyme was purified from fresh bovine brain and also from frozen and thawed bovine and monkey brains. It has been separated from succinic semialdehyde dehydrogenase. The apparent pH optimum is 10, above which irreversible deactivation occurs.

A number of aliphatic aldehydes ranging from formaldehyde to palmitic aldehyde and aldehydes derived from serotonin, epinephrine, and dopamine (3,4-dihydroxyphenyl-ethyamine) were substrates for the enzyme. The rates of oxidation could be correlated with the electropositive nature of the carbonyl carbon atom. The $K_m$ values were exceptionally low and ranged from 2 x 10^{-7} M to 7 x 10^{-5} M. The enzyme was specific for NAD and NADP analogues. No activity was observed with NADP.

The effect of several sulphhydryl-characterizing reagents on the monkey brain enzyme was determined. Tetraethylthiuram disulfide and p-chloromercuribenzoate produced 50% inhibition at approximately 5 x 10^{-5} M while the enzyme was much less sensitive to $\gamma$-(p-arsenophenyl)-n-butyrate.

This study provides direct evidence for the oxidation of aldehydes arising from biologically active amines in the brain. Brain aldehyde dehydrogenase may also be important in oxidizing toxic aldehydes derived from exogenous sources, e.g. acetaldehyde from ethanol.

It is known that a number of aldehydes occur in brain tissue. Blaschko, Richter, and Schlossmann (1) and Pugh and Quastel (2) first presented evidence that aldehydes arise in brain tissue by the oxidative deamination of monoamines. Since these early investigations, the presence of monamine oxidase in brain has been well established (3). The enzyme from isolated brain tissue (9, 10), shows by inference that the brain normally contains small amounts of various aldehydes and the enzymes necessary to oxidize these aldehydes to the corresponding acids. Brady and Koval (11) and Hoshishima, Vignais, and Zabin (12) have reported that palmitic aldehyde is oxidized by brain tissue following ethanol administration (13).

It has been shown that succinic semialdehyde is a product of $\gamma$-aminobutyric acid metabolism in the brain (14). Albers and Salvador (15), Albers and Koval (16), and Pitts and Robins (17) have shown that this aldehyde is oxidized in the brain by a specific NAD-dependent succinic semialdehyde dehydrogenase. Further, acetaldehyde has been found in brain tissue following ethanol administration (13).

The pathways involved in the oxidation of aldehydes have been studied in some tissues (18-21). Ridge (22) has presented indirect evidence that acetaldehyde is oxidized by brain tissue. Also, Brady, Formica, and Koval (23) have noted that palmitic aldehyde is oxidized by NAD and NADP in rat brain preparations. Lovenberg, Levine, and Sjoerdsma (24) presented indirect evidence for the existence of aldehyde dehydrogenase in a number of tissues. Deitrich (25) presented indirect evidence for the existence of aldehyde dehydrogenase in a number of tissues including rat brain. However, the enzyme systems in brain that catalyze aldehyde oxidation have not been well characterized as to the distribution in various areas, subcellular localization, substrate and cofactor specificities, or the nature of inhibitors. Therefore, this study was directed toward elucidation of some of these aspects.

Methods

Water used was deionized and double distilled in quartz. All reagents were of high quality. Aldehydes were distilled under nitrogen at atmospheric pressure whenever possible. The preparation and extraction of 3,4-dihydroxyphenylacetaldheyde-
hyde, 3,4-dihydroxyphenylglycolaldehyde, and 5-hydroxyindole-3-acetaldehyde were performed by the method of Renson, Weissbach, and Udenfriend (25). The concentration of freshly prepared aldehyde solutions was determined immediately before use by addition of a limiting amount of aldehyde to quartz cuvettes containing an excess of NAD, 10 mM pyrophosphate buffer, pH 9.6, and bovine liver aldehyde dehydrogenase prepared by the method of Deitrich, Hollerman, and Wein (26). After completion of the reaction, the change in absorbance at 340 mμ was determined.

Sucinic semialdehyde was prepared from diethylformylsuccinate (kindly supplied by Dr. Albers9), by a modification of the method of Bessman, Rossen, and Layne (14) by refluxing 1 volume of diethylformylsuccinate in 40 volumes of 0.2 M HCl for 4 hours. The refluxed material was evaporated to near dryness under nitrogen and the remaining material was dissolved in a small quantity of water. Sucinic semialdehyde and its 2,4-dinitrophenylhydrazone prepared by this procedure cochromatographed with similar material prepared from glutamic acid by a number of methods (27-29).

Monkey brain succinic semialdehyde dehydrogenase, prepared by the method of Albers and Koval (16) was used to assay the succinic semialdehyde.

Bovine brains were obtained from a local slaughter house approximately 30 min after decapitation and iced at once in polyethylene bags. The leptomeninges were removed and the brains were dissected in a cold room at 2℃. The tissues were washed in ice-cold 0.25 M sucrose, blotted on filter paper, weighed, and homogenized in sufficient 0.25 M sucrose to give a 30% homogenate. Homogenization was performed in a glass homogenizer with a tightly fitting Teflon pestle. Rat brains were removed immediately after decapitation of the animals and homogenized as described above. Fractionation of homogenates into various subcellular components was performed by the methods of De Robertis et al. (30) and Whittaker et al. (31) with a Servall RC-2 or Spinco model L centrifuge as described with the tables and figures. Monkey brains were obtained frozen from Asiatic Imports, Inc., San Francisco, California.

The aldehyde-oxidizing activity of the various preparations was determined in duplicate by measuring the amount of indole-3-acetic acid formed in 10 min at 30℃ with indole-3-acetaldehyde or its sodium bisulfite compound as the substrate in the presence of NAD and tissue. The indole-3-acetic acid formed was determined by modification of the fluorometric method of Weissbach et al. (32) and is described in greater detail elsewhere.1 Assay conditions are described in the respective tables and figures. Recovery of added indole-3-acetic acid from reaction mixtures was approximately 90%. Unless otherwise indicated, protein was determined by the biuret method with bovine serum albumin as the standard.

Sucinate dehydrogenase activity was determined by the method of Slater and Bonner (33) and iminoamine oxidase activity was assayed by the method of Weissbach et al. (34).

In the purification of aldehyde dehydrogenase from bovine brain, the mitochondria were isolated as described previously3 except that 0.25 M sucrose was the homogenizing fluid (35). All purification procedures were carried out at 0-4℃. The mitochondria were suspended in water and centrifuged at 12,000 X g for 30 min. The pellet was suspended in one-half the original homogenizing volume of a mixture of 0.25 M sucrose and 0.01 M 2-mercaptoethanol. The preparation was sonically treated at 3.5 to 4 amperes for four 1-min periods with a Branson Sonifier model S75 at a setting of 4 and then centrifuged at 100,000 X g for 3 hours. The clear supernatant fluid was fractionated with solid ammonium sulfate. The precipitated material obtained at 0.5 to 0.8 saturation was dissolved in a mixture of 0.05 M phosphate buffer, pH 7.4, and 0.01 M 2-mercaptoethanol. Protein was determined by the method of Murphy and Kies (36).

Aldehyde dehydrogenase was also partially purified from frozen and thawed bovine brain. The whole frozen and thawed brain was homogenized in 4 volumes of 0.32 M sucrose in a Servall Omnimixer at 16,000 rpm for three 20-sec periods and centrifuged at 30,000 X g for 1 hour. The supernatant fluid was treated with ammonium sulfate. The material that precipitated between 0.4 to 0.6 saturation was dissolved in a mixture of 0.5 M phosphate buffer, pH 7.4, and 0.5 M 2-mercaptoethanol. The material was dialyzed against a 100-fold excess of a mixture of 0.5 M phosphate buffer and 0.5 M 2-mercaptoethanol for two 3-hour periods and one 12-hour period. Of the material, 400 mg was placed on a diethylaminoethyl cellulose column, 15 X 2.5 cm, previously equilibrated with 5 M phosphate buffer, pH 7.4. The column was washed with 30 ml of 5 M phosphate buffer, pH 7.4. The enzyme was then eluted with a concentration gradient of phosphate buffer formed by 50 ml of 5 M phosphate buffer, pH 7.4, in the mixing flask and 50 ml phosphate buffer, pH 7.4, in the reservoir. Some fractions of enzyme purified in this manner contained endogenous activity with added NAD. In this case the endogenous reaction was allowed to go to completion before aldehyde substrate was added (about 5 min).

Aldehyde dehydrogenase activity was measured spectrophotometrically or fluorometrically. Spectrophotometric measurements were made with a Gilford model 2000 attachment for the Beckman DU monochromator. Fluorometric determinations of the rate of NADH formation were performed with a Turner model 110 fluorometer with primary and secondary filters No. 7-60 and No. 8, respectively. The increase in fluorescence was determined at 1-min intervals for 5 min. The increase in the 1st min was used as the initial rate. The fluorescence of NADH was linear with concentration and the minimum quantity that could be determined was 0.2 μmole. The authenticity of NADH was checked by a complete disappearance of fluorescence (measured as above) and absorbance at 340 mμ upon adjusting the pH of the system to 1.0 or by addition of crystalline horse liver alcohol dehydrogenase (Sigma) to the reaction mixture.

RESULTS

Localization—Aldehyde-oxidizing activity was present in all areas of bovine brain studied. The specific activity with indole-3-acetaldehyde bisulfite and NAD ranged from a low of 1.8 in the cerebellum to a high of 4.9 in the caudate nucleus (Table I).

Table II shows the aldehyde-oxidizing activity in various subcellular fractions of rat brain. The mitochondrial fraction contained 60% of the total activity, while 20% was found in the 20,000 X g supernatant fluid. These values fluctuate somewhat depending on individual techniques used in isolation of the mitochondria. The percentage recovery of aldehyde-oxidizing activity in the mitochondrial fraction, the hypomotically shocked mitochondrial fraction, and the density gradient pellet

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9 Laboratory of Neuroanatomical Sciences, National Institutes of Health, Bethesda, Maryland.
was similar to the percentage recovery of succinate dehydrogenase and monamine oxidase. Aldehyde-oxidizing activity was released from the mitochondrial fraction by freezing and thawing or by sonically treating this fraction. From these data it was concluded that a major portion of rat brain aldehyde-oxidizing activity is associated with the mitochondria. However, the possibility of a second enzyme localized in the 20,000 × g supernatant fluid cannot be ruled out.

The NAD requirement for aldehyde oxidation by aged or dialyzed rat brain homogenates was investigated. The dialyzed homogenate, which possessed little activity in the absence of NAD, was stimulated 11-fold by addition of this coenzyme. These results suggest that the major aldehyde-oxidizing system of brain homogenates is an NAD-linked dehydrogenase. Addition of NADP instead of NAD to whole undialyzed homogenates resulted in some stimulation of indole-3-acetic acid production but this was not additive with the stimulation of activity afforded by NAD.

Purification from Mitochondria—Aldehyde-oxidizing activity was purified approximately 9-fold from the supernatant fraction of sonically treated bovine brain mitochondria by treatment with solid (NH₄)₂SO₄. The material precipitated by 0.5 to 0.8 saturation of (NH₄)₂SO₄ contained most of the enzymatic activity. A second experiment gave similar results but somewhat less purification. The best preparation obtained had an activity of 230 mmoles of indole-3-acetic acid formed per mg of protein in 10 min. (This represented a 191-fold increase over the whole bovine brain.) The preparations were free of NADH oxidase and alcohol dehydrogenase, and were NAD-dependent. NADP was ineffective as a cofactor for this system.

The activity of the enzyme was essentially linear with protein concentration. In addition, the reaction was stoichiometric.

### Table I

<table>
<thead>
<tr>
<th>Area</th>
<th>Mean (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebellum</td>
<td>1.8 (1.4-2.1)</td>
</tr>
<tr>
<td>Cerebral cortex</td>
<td>3.5 (2.3-3.8)</td>
</tr>
<tr>
<td>Pons-medulla</td>
<td>3.8 (2.3-4.4)</td>
</tr>
<tr>
<td>Caudate nucleus</td>
<td>4.9 (4.0-5.8)</td>
</tr>
<tr>
<td>Thalamus</td>
<td>3.4 (2.9-3.8)</td>
</tr>
<tr>
<td>Lentiform nuclei</td>
<td>2.9 (2.4-3.4)</td>
</tr>
<tr>
<td>Midbrain-hypothalamus</td>
<td>3.2 (3.1-3.4)</td>
</tr>
<tr>
<td>Pineal gland</td>
<td>2.0</td>
</tr>
</tbody>
</table>

* Values represent millimicromoles of indole-3-acetic acid formed per 10 min per mg of protein.

* Head of the caudate nucleus.

* Medial nuclei of the thalamus.

* Includes internal capsule and lateral thalamic nuclei along with globus pallidus and putamen.

### Table II

**Subcellular localization of aldehyde-oxidizing activity of rat brain**

The mitochondrial fraction was hypsosmotically shocked with distilled water to rupture the nerve ending particles as described by De Robertis et al. (30), or was centrifuged through a discontinuous sucrose gradient as described by Whittaker et al. (31) consisting of 1-ml layers of 1.4 M, 1.2 M, 1.0 M, and 0.8 M sucrose in tubes for the SW-39 rotor of a Spinco model L centrifuge. The tubes were centrifuged at 100,000 × g for 65 min. After centrifugation each fraction was removed by suction and resuspended in water to the original volume of mitochondrial suspension. This table is a composite of nine separate experiments.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aldehyde-oxidizing activity</td>
</tr>
<tr>
<td>Homogenate</td>
<td>1.45</td>
</tr>
<tr>
<td>Supernatant, 20,000 × g</td>
<td>0.80</td>
</tr>
<tr>
<td>Mitochondria</td>
<td>3.04</td>
</tr>
<tr>
<td>Mitochondria (hyposmotic)</td>
<td>4.00</td>
</tr>
<tr>
<td>Density gradient pellet</td>
<td>1.4 M sucrose</td>
</tr>
</tbody>
</table>

* Aldehyde-oxidizing activity was determined as described in Table I and is given as millimicromoles of indole-3-acetic acid formed per 10 min per mg of protein or per g of brain, wet weight.

* Succinate dehydrogenase activity was measured spectrophotometrically with KFe(CN)₆ according to the method of Slater and Bonner (33).

* Monoamine oxidase activity was measured spectrophotometrically with kynuramine according to the method of Weissbach et al. (34).

as indicated by the formation of indole-3-acetic acid and NADH in an amount equivalent to the indole-3-acetaldehyde added. The reaction was not reversed by NADH and acetate, or NADH and acetyl coenzyme A.

The apparent optimal pH for the reaction was 10; however, the decrease in enzyme activity above pH 10 was not reversed by adjusting the pH to 9.0. At pH 9.0 irreversible denaturation occurs, necessitating a rapid determination of initial rates. At pH 9.6 the reaction rate was linear for several minutes. As a result, subsequent experiments with the partially purified enzyme system were performed at pH 9.6.

Results presented in Table III show that aldehyde dehydrogenase from bovine brain mitochondria is nonspecific and oxidizes a number of aliphatic aldehydes ranging from formaldehyde to p-amintic aldehyde. Also, glyceraldehyde and betaine aldehyde as well as aldehydes derived from the biologically active amines, namely 5-hydroxyindole-3-acetaldehyde, 3,4-dihydroxyphenylglycolaldehyde, and 3,4-dihydroxyphenylacetaldehyde were oxidized by this enzyme system. The Michaelis constants for the various aldehydes are exceptionally low. If, indeed, the enzyme behaves in vivo as it does in vitro, these results could explain the inability to detect these aldehydes in normal brain tissue. This preparation also catalyzes the oxidation of succinic semialdehyde. However, the rates of oxidation...
The rate of the reaction was determined by dehydrogenase purified from bovine brain mitochondria, as described in the text. Aldehyde dehydrogenase, purified 9-fold from beef brain mitochondria, was added to fluorometer tubes containing a final concentration of 10 mM sodium pyrophosphate buffer, pH 9.6; 1 mM NAD; various concentrations of aldehydes; and sufficient water to give 3 ml.

### Table III

<table>
<thead>
<tr>
<th>Substrate</th>
<th>$K_m$ (m)</th>
<th>$V_{max}$ (μmol NADH formed/min/mg protein)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formaldehyde</td>
<td>$7.0 \times 10^{-3}$</td>
<td>218</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>$3 \times 10^{-7}$</td>
<td>192 and 132</td>
</tr>
<tr>
<td>Propionaldehyde</td>
<td>$2.0 \times 10^{-7}$</td>
<td>182</td>
</tr>
<tr>
<td>Butyraldehyde</td>
<td>$2.3 \times 10^{-7}$</td>
<td>166</td>
</tr>
<tr>
<td>Isobutyraldehyde-NaHSO₃</td>
<td>$1.6 \times 10^{-7}$</td>
<td>130</td>
</tr>
<tr>
<td>Heptylaldehyde</td>
<td>$3.5 \times 10^{-7}$</td>
<td>200</td>
</tr>
<tr>
<td>Decylaldehyde</td>
<td>$1.3 \times 10^{-7}$</td>
<td>357</td>
</tr>
<tr>
<td>Palmitic aldehyde-NaHSO₃</td>
<td>$1.3 \times 10^{-8}$</td>
<td>122</td>
</tr>
<tr>
<td>Glycolaldehyde</td>
<td>$1.1 \times 10^{-8}$</td>
<td>296</td>
</tr>
<tr>
<td>Trimethylacetaldehyde</td>
<td>$2.0 \times 10^{-9}$</td>
<td>123</td>
</tr>
<tr>
<td>Monoethylacetaldehyde</td>
<td>$6.0 \times 10^{-9}$</td>
<td>385</td>
</tr>
<tr>
<td>Phenylacetaldehyde</td>
<td>$4.0 \times 10^{-9}$</td>
<td>264</td>
</tr>
<tr>
<td>5-Hydroxyindoleacetaldehyde</td>
<td>$2.5 \times 10^{-9}$</td>
<td>84</td>
</tr>
<tr>
<td>3,4-Dihydroxyphenylacetaldehyde</td>
<td>$1.0 \times 10^{-9}$</td>
<td>156</td>
</tr>
<tr>
<td>3,4-Dihydroxyphenylglycoaldehyde</td>
<td>$3.0 \times 10^{-10}$</td>
<td>101</td>
</tr>
<tr>
<td>Betaine aldehyde</td>
<td>$2.0 \times 10^{-10}$</td>
<td>77</td>
</tr>
<tr>
<td>Succinic semialdehyde</td>
<td>$2.0 \times 10^{-10}$</td>
<td>161</td>
</tr>
</tbody>
</table>

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*Although this preparation does catalyze the oxidation of succinic semialdehyde, see Table IV and the text.*

### Fig. 1

Double reciprocal plot with acetaldehyde. Aldehyde dehydrogenase purified from bovine brain mitochondria was used. The rate of the reaction was determined by measuring NADH formation fluorometrically as described in Table III and in the text.

### Table IV

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Specific activity</th>
<th>Yield</th>
<th>Amount of NADH formed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogenate</td>
<td>0.61</td>
<td>100%</td>
<td>89.5</td>
</tr>
<tr>
<td>Supernatant, 30,000 × g for 1 hour</td>
<td>2.97</td>
<td>79%</td>
<td>2.7</td>
</tr>
<tr>
<td>(NH₄)₂SO₄ (0.4-0.6 saturation)</td>
<td>6.75</td>
<td>53%</td>
<td>4.9</td>
</tr>
<tr>
<td>DEAE-cellulose</td>
<td>68.86</td>
<td>59%</td>
<td>31%</td>
</tr>
</tbody>
</table>

*Specific activity is given as millimicromoles of indole-3-acetic acid formed per 10 min per mg of protein.*

Assay for indole-3-acetic acid formation was performed as described in the text and Table I. NADH formation was measured spectrophotometrically at 25°C at 340 nm with either 0.5 mM acetaldehyde or 0.5 mM succinic semialdehyde as substrate. The aldehydes were added to quartz cuvettes containing a final concentration of 10 mM sodium pyrophosphate buffer, pH 9.6; 1 mM NAD; enzyme and water to give 1 ml. Protein concentration of the DEAE-cellulose fraction was determined by the method of Murphy and Kies (36).

The higher the $K_m$ and the lower the $V_{max}$, the greater the enzyme affinity for the corresponding substituent groups. Similar results have been obtained by other investigators (37-39). Other substrates used did not give this type of plot.

### Purification of NAD-dependent aldehyde dehydrogenase from frozen bovine brain

Comparison of Enzyme Preparations—Several experiments were undertaken in order to determine whether or not the enzyme purified from brain mitochondria was the same as that purified from frozen and thawed brain. These experiments also serve to define further the enzymatic properties of the preparations. Fig. 2 is a plot of the log of the ratio of the maximal velocity with various substrates compared to the maximal velocity with propionaldehyde (taken as 100) as a function of the Taft $\sigma$ values (40) for the corresponding substituent groups. The higher the $\sigma$ values, the greater the electron withdrawal from the carbonyl carbon atom. It can be seen that the relative velocities obtained with the mitochondrial enzyme are virtually identical with those obtained with the use of the enzyme from brain mitochondria.
FIG. 2. Illustration of the maximal rate of oxidation of various aliphatic aldehydes as correlated with the Taft sigma values (\( \sigma^* \)). Rates are calculated as a percentage of the maximal rate obtained with propionaldehyde and plotted as a log versus Taft's \( \sigma^* \) values (40). (\( \Delta \)), aldehyde dehydrogenase purified from bovine brain mitochondria; the rate of NADH formation was measured fluorometrically. (\( \bigcirc \)), aldehyde dehydrogenase purified from frozen-thawed bovine brain supernatant fluid; the rate of formation of NADH was measured spectrophotometrically.

**TABLE V**

Cofactor specificity of bovine brain aldehyde dehydrogenase

Rates were measured spectrophotometrically as described in the text. Acetaldehyde, final concentration of 1 mM, was added to quartz cuvettes containing a final concentration of 10 mM sodium pyrophosphate buffer, pH 9.6; various concentrations of NAD or NAD analogues; enzyme and water to give 1 ml. Molar extinction coefficients and \( \lambda \) used for NAD, deamino-NAD, and 3-acetylpyridine-NAD were 6220 (340 m), 6220 (340 m), and 9100 (363 m), respectively.

<table>
<thead>
<tr>
<th>NAD analogue</th>
<th>From frozen brain*</th>
<th>From mitochondria*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( K_m )</td>
<td>( V_{max} )</td>
</tr>
<tr>
<td>NADP</td>
<td>( 1 \times 10^{-3} )</td>
<td>32</td>
</tr>
<tr>
<td>NAD</td>
<td>( 3 \times 10^{-4} )</td>
<td>25</td>
</tr>
<tr>
<td>Deamino-NAD</td>
<td>( 1 \times 10^{-3} )</td>
<td>32</td>
</tr>
<tr>
<td>3-Acetylpyridine-NAD</td>
<td>( 1 \times 10^{-3} )</td>
<td>32</td>
</tr>
</tbody>
</table>

* Aldehyde dehydrogenase was purified by the methods described in the text and Table IV.

† Expressed as millimicromoles of NADH or NADH analogue formed per min per mg of protein.

Frozen and thawed brains. This relationship is relevant to the enzymatic mechanism, as will be discussed below.

Both enzymes were active with several NAD analogues (Table V). The \( K_m \) and \( V_{max} \) values, while not identical, do not differ to any significant degree for the two enzyme preparations. Since the two enzyme preparations are purified by different procedures, it is likely that different contaminating proteins are present. This might serve to explain the differences noted between the two preparations as shown in Table V.

**TABLE VI**

Effect of inhibitors on partially purified monkey brain aldehyde dehydrogenase in vitro

The rate of NADH formation was measured spectrophotometrically at 340 m as described in the text. Partially purified enzyme was added to cuvettes containing a final concentration of 10 mM sodium pyrophosphate buffer, pH 9.6; 0.5 mM NAD; 0.5 mM acetaldehyde; and inhibitor or water to give 1 ml, at 25°. The initial rate in the absence of the inhibitor was 12 mmoles of NADH formed per min per mg of protein.

<table>
<thead>
<tr>
<th>Inhibitor</th>
<th>Concentration producing 50% inhibition</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-Chloromercuribenzo-ate</td>
<td>( 6 \times 10^{-3} )</td>
<td>H_2O</td>
</tr>
<tr>
<td>( \gamma )-(p-Arsenosophenyl)-n-butyrurate</td>
<td>( 1 \times 10^{-4} )</td>
<td>H_2O</td>
</tr>
<tr>
<td>Chloral hydrate</td>
<td>( 5 \times 10^{-5} )</td>
<td>H_2O, 1% propylene glycol</td>
</tr>
<tr>
<td>Tetraethylthiuram disulfide</td>
<td>( 5 \times 10^{-4} )</td>
<td></td>
</tr>
</tbody>
</table>
listed from frozen and thawed monkey brain. The sulfhydryl-
characterizing reagents, p-chloromercuribenzoate and γ-(p-
arsenosophenyl)-n-butyrate, produced 50% inhibition at 6 \times 10^{-4} \text{ M} and 1 \times 10^{-4} \text{ M}, respectively. These results suggest that sulfhydryl groups are important for the activity of the enzyme. Tetrathylthiram disulfide and chloral hydrate produced a 50% inhibition at 5 \times 10^{-4} \text{ M}.

**Discussion**

The aldehyde-oxidizing activity of brain tissue observed, at
least 1 \mu mole per hour per g of tissue, wet weight, is in great
excess of the amount required to oxidize the aldehydes derived
from the biologically active amines in normal brain tissue. Spec-
tor, Melmon, and Sjoerdsma (41) and Udenfriend and Weissbach
(42) have estimated that the half-life of norepinephrine in the
rat is approximately 1 to 2 hours while the half-life of 5-hydroxy-
tryptamine is less than 1 hour. The normal levels of these
amines are 3 to 4 \mu moles per g of brain, wet weight (43).
Thus, a maximum of 1 to 2 \mu moles of the aldehydes from these
amines normally would be formed per hour per g of brain. The
above data indicate that under optimal conditions, brain tissue
has the capacity to metabolize aldehydes derived from exogenous
sources as well as those arising endogenously. Other factors
such as compartmentalization of the aldehydes may be impor-
tant, but no information is currently available.

A number of compounds, thought to inhibit aldehyde dehy-
rogenase in vivo (see references in Reference 38), cause a marked
increase in blood acetaldehyde concentration after ethanol
administration. Under these conditions, brain aldehyde de-
hydrogenase may be inhibited by such compounds and could
thus be saturated with acetaldehyde; hence, the rate of oxidation
of aldehydes derived from the biologically active amines would
be much lower. It is possible that aldehydes derived from these
amines are involved in the physiological response to aldehyde
dehydrogenase inhibitors.

The ability of the various regions of the brain to oxidize alde-
hydes is in keeping with the observations of Weiner (44) and
Bogdanski, Weissbach, and Udenfriend (45) that monoamine
oxidase is present in all areas of the brain. One would expect
aldehyde-oxidizing activity to have a distribution similar to
monoamine oxidase; otherwise, oxidative deamination of amines
would result in the accumulation of aldehydes which are known
to inhibit various metabolic processes (46, 47).

A major portion of the aldehyde-oxidizing activity was asso-
ciated with the mitochondrial fraction, while the 20,000 \times g
supernatant fluid contained a substantial amount of the total
activity. The possibility that more than one enzyme is present
has been considered. After homogenization of frozen and
thawed bovine brain, all of the activity was found in the
30,000 \times g supernatant fluid indicating that the mitochondrial
enzymes was released by this procedure. If more than one en-
yzme is present in the 30,000 \times g supernatant fluid and these
enzymes are purified together, one might expect this prepara-
tion to have different kinetic properties from the bovine brain
mitochondrial enzyme preparation. However, these values for
the enzyme systems were similar, suggesting that the same en-
zyme system was purified from both sources. The question of
the presence of a separate enzyme in the soluble portion of brain
homogenates is unanswered by these experiments.

The data obtained with various aldehydes indicate that the
maximal velocity of the enzyme reaction is related to the elec-
tropositive nature of the carbonyl carbon atom. Greater rates
are obtained as this carbon atom becomes more positive. This
concept is in agreement with the results of Deitrich, Hellerman,
and Wein (26) with respect to the correlation of the rates of
oxidation of substituted benzaldehydes with Hammett's \sigma
values. Several other investigators have made use of Hammett's
equation as applied to enzymatic reactions (48, 49). The investi-
gation of \alpha-amino acid oxidase by Neims, De Luca, and Helle-
man (49) is of particular interest because of the very large effect
noted as the electronic nature of the carbon atom was altered.
The present study shows that the Taft equation may be useful
for this type of correlation.

The fact that succinic semialdehyde was not oxidized by the
enzyme preparations purified by DEAE-cellulose column chro-
matography indicates that aldehyde dehydrogenase is distinct
from succinic semialdehyde dehydrogenase. The presence of
succinic semialdehyde dehydrogenase activity in the 9-fold
purified preparation from bovine brain mitochondria is in keep-
ing with the results obtained by Salganicoff and De Robertis
(50). These investigators found that succinic semialdehyde
dehydrogenase is a mitochondrial enzyme which is easily solu-
bilized by various mechanical procedures. Other workers have
found succinic semialdehyde dehydrogenase to be virtualy spe-
cific for succinic semialdehyde (16, 17).

The relationship between enzyme activity and pH is similar
to that found for aldehyde dehydrogenase from bovine liver (18,
26). In addition, the broad substrate specificity is comparable
to the bovine liver enzyme.

Recently, in a study of succinic semialdehyde dehydrogenase,
Pitts and Quick (51) have found that small amounts (0.1 \mu g, dry
weight) of brain do not catalyze the oxidation of several alde-
hydes by NAD. Calculation from our data show that such small
amounts of tissue do not contain sufficient nonspecific aldehyde-
oxidizing capacity to be measurable, even with the sensitive
techniques used by these workers.

Previous reports of isolation of an aldehyde dehydrogenase
from brain are those of Brady and Koval (11) and Brady et al.
(23). These investigators observed the presence of a reversible
NADP-linked palmitic aldehyde dehydrogenase in particles
(presumably microsomes) from brain. Particles, sedimented
between 20,000 and 100,000 \times g, also contained an NAD-linked
palmitic aldehyde dehydrogenase. The enzyme described in
this report is certainly distinct from the NAD-linked enzyme
described by Brady et al. but the relationship to the NAD-linked
enzyme is not clear.

Although the enzyme from monkey brain is inhibited by a
number of sulfhydryl-characterizing reagents, the preparation
is relatively crude and as such may not reveal the full sensitivity
of the preparation to these compounds.

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**References**

J.*, 31, 2187 (1937).
(1937).
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V. G. Erwin and R. A. Deitrich

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