Integrity of Blood-Brain Barrier During Ethanol Intoxication and Withdrawal in the Rat: Normal Glucose Transfer and Permeability to Na\(^+\) and Cl\(^-\)

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SUMMARY The unidirectional brain uptake of \(^{14}\)C-D-glucose, \(^{14}\)Na\(^+\) and \(^{14}\)Cl\(^-\) was measured by the Oldendorf tissue uptake method in order to test whether severe ethanol intoxication or withdrawal affected the glucose transfer across the blood-brain barrier (BBB) or the integrity of the BBB to small ions. The Oldendorf technique rests upon the assumption that water is freely diffusible across the BBB, but in the present study a correction was applied, which takes into account the fact that the water extraction actually depends upon the different cerebral blood flow (CBF) in the groups.

The \(^{14}\)Na\(^+\) and \(^{14}\)Cl\(^-\) extraction values were about 1% as reported in other studies and this suggests that there was no major effect on the BBB reaction to small ions during severe ethanol intoxication or during withdrawal. The permeability surface area product did not deviate significantly from control values in any group and thus there was no indication that glucose transfer across the BBB differed during ethanol intoxication or withdrawal.

IT IS EVIDENT from the literature that chronic ethanol intoxication and ethanol withdrawal is accompanied by a major reduction in the rate of cerebral protein synthesis, possibly due to abnormal ribosome function.\(^1\)\(^2\) Furthermore, it is known that acute ethanol intoxication significantly reduces cerebral consumption of glucose and oxygen\(^6\)\(^7\) and inhibits energy consuming transport systems in the brain probably through allosteric changes of enzyme molecules,\(^8\) whereas ethanol withdrawal is followed by increased neuronal activity in the brain as reflected through increased oxygen consumption\(^7\) and through changed EEG pattern.\(^6\) The exact mechanism by which ethanol causes central nervous system (CNS) suppression is unknown, but nonspecific membrane expanding effects may be of importance.\(^6\)\(^8\)

The purpose of the present study was to investigate 1) whether severe ethanol intoxication or withdrawal caused detectable perturbation of the facilitated (protein carrier mediated) diffusion of glucose across the blood-brain barrier* (BBB) in rats and 2) whether under the same conditions the functional integrity of the BBB to small ions (Na\(^+\), Cl\(^-\)) was disturbed.

For this study of blood to brain transfer of glucose and small ions we have used the methodology described by Oldendorf.\(^10\) Intracarotid injection of tritiated water as reference substance (ref.), together with the test substance, enables determination of brain content of test relative to reference substance and this leads to the so-called brain uptake index

\[
\text{index (BUI)} = \frac{c_{\text{test (brain)}}/c_{\text{ref (brain)}}}{c_{\text{test (injectate)}}/c_{\text{ref (injectate)}}} = \frac{E_{\text{test}}}{E_{\text{ref}}}
\]

where \(c\) is concentration and \(E\) is the unidirectional uptake, the extraction. The fact is stressed that \(E_{\text{test}}\) is the relevant parameter in permeability studies whereas BUI in itself is without meaning.

Materials and Methods

Ethanol Intoxication and Withdrawal

Four groups of 250-300 g male Wistar rats were studied under conditions of 1) acute severe ethanol intoxication; 2) chronic severe ethanol intoxication, the intoxication period lasting 80 hours; 3) animals expressing a severe ethanol withdrawal reaction; and 4) normal controls.

Ethanol intoxication and the physical dependence on ethanol was established by intragastric intubation technique.\(^9\)\(^10\) Briefly, the intoxicated state was rated as follows: neutrality, sedation, ataxia, loss of righting reflex and coma. The withdrawal reaction was rated using the following signs: tremor, rigid posture, stereotyped movements, general seizure, enhanced startle reflex, tonic neck reflex, squealing. During intoxication the animals had severe ataxia or loss of righting reflex and during withdrawal all animals studied showed tremor, rigid posture, stereotyped movements, enhanced startle reflex and tonic neck reflex. The acutely intoxicated animals received a single intragastric ethanol dose of 8-10 g ethanol/kg, whereas the chronically intoxicated animals received 9-12 g ethanol/kg body weight/day.

General Procedure

The animals were anesthetized with 0.8% halothane in 70% \(\text{N}_2\text{O}:30\% \text{O}_2\) and ventilated with an animal respirator. After surgical exposure of the common carotid artery and catherization of a femoral artery and vein for blood sampling and infusions, the animals...
were immobilized with succinyl choline 20 mg/kg i.v. Halothane was then switched off and the animals left undisturbed for 20 min. In all animals the following physiological variables were monitored and adjusted: arterial PCO2 was kept between 32–42 mm Hg, arterial PO2 above 90 mm Hg, pH between 7.31–7.50, mean arterial blood pressure between 130–160 mm Hg and rectal temperature at 37.0 ± 0.5°C. These variables did not differ significantly between the groups. Plasma glucose concentrations and blood ethanol concentrations were determined using enzymatic methods. A hypodermic needle (external diameter 0.4 mm) was placed in the common carotid artery and 50 μl of an isotope mixture (1 μCi 14C-D-glucose (10 mmol/1), 3 μCi 3H-HO2, 1 μCi 42Na+, 0.5 μCi 35Cl, 5 μCi 112mIn-DTPA in isotonic saline) was injected as a bolus; decapitation and using a reference substance with an extraction factor based on EHOH = 0.75 obtained from reactions in animals with a blood ethanol concentration compatible with life there was no major effect upon cerebral blood flow (CBF) varying between 0.35 and 0.74 at a CBF of 465 ml/100 g/min and 0.74 at a CBF of 64 ml/100 g/min.

Comments on Methodology

Oldendorf's method originally rested on the assumption that the reference substance, water, is freely diffusible across the blood-brain barrier, i.e. that the extraction of water (EHOH) is 1.0. This assumption has been reported not to be valid13–18 and thus a correction has to be applied. EHOH is dependent upon cerebral blood flow (CBF) varying between 0.35 and 0.74 at a CBF of 465 ml/100 g/min and 0.74 at a CBF of 64 ml/100 g/min.14 BUI is in reality ETEST/EHOH and thus a correction has to be applied for the amount of substance present within the intravascular correction, so

\[ E_{\text{test}} = \frac{c_{\text{test(brain)}}}{c_{\text{test(bolus)}}} \times E_{\text{HOH}} \]

where CBF was lower. Within each group the extraction values for the 2 ions did not deviate. The PS-product in the experimental groups did not deviate significantly from control values. The blood ethanol concentration in the intoxicated groups was almost identical, i.e. about 4.7–4.8 g/l.

Table 2 gives the plasma glucose concentrations, the 14C-D-glucose extraction values and the PS-products for glucose. The plasma glucose concentration in the control group, the acutely intoxicated group and the withdrawal group did not differ whereas the plasma glucose concentration was significantly elevated in the chronically intoxicated group. Also the glucose extraction value was higher in the chronically intoxicated group. The PS-product in the experimental groups did not deviate significantly from the control value.

Discussion

The extraction values for 42Na+ of about 1% were in accordance with values reported earlier by the same and other methods in the rat,13,18 and the 35Cl extraction values did not differ from those found in man.19

The tendency toward an increase in the extraction values for the 2 ions in the intoxicated groups was probably due to the lower CBF which has previously been shown to prevail during ethanol intoxication (see also figure). Topical application of an ethanol solution of a very high osmolality (corresponding to approximately 50% W/V ethanol solution) on the arachnoid surface may cause irreversible opening of the BBB to Evans blue albumin,20 but in the present experiments in animals with a blood ethanol concentration compatible with life there was no major effect on the BBB reaction to the small ions we investigated. This is in accordance with our preliminary finding (Barry and Hemmingsen, unpublished data) that no
BLOOD-BRAIN BARRIER IN ETHANOL INTOXICATION/Hemmingsen et al.

TABLE 1  Blood Ethanol Concentration, $^{14}Na^+$ Extraction ($E_{Na^+}$) and $^{14}Cl^-$ Extraction ($E_{Cl^-}$) and Permeability Surface Area Products (PS-products) for $Na^+$ and $Cl^-$ in the groups. Means ± SEM are given.

<table>
<thead>
<tr>
<th>Group</th>
<th>Blood ethanol concentration (g/l)</th>
<th>$E_{Na^+}$ (%)</th>
<th>$E_{Cl^-}$ (%)</th>
<th>PS-product ($Na^+$) (ml/100 g/min)</th>
<th>PS-product ($Cl^-$) (ml/100 g/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls (n = 11)</td>
<td>—</td>
<td>0.5 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.49 ± 0.10</td>
<td>0.39 ± 0.10</td>
</tr>
<tr>
<td>Acute intoxication (n = 7)</td>
<td>4.8 ± 0.5</td>
<td>1.1 ± 0.3*</td>
<td>1.0 ± 0.3</td>
<td>0.66 ± 0.18</td>
<td>0.60 ± 0.18</td>
</tr>
<tr>
<td>Chronic intoxication (n = 5)</td>
<td>4.7 ± 0.5</td>
<td>0.8 ± 0.1*</td>
<td>0.6 ± 0.1</td>
<td>0.63 ± 0.08</td>
<td>0.47 ± 0.08</td>
</tr>
<tr>
<td>Withdrawal (n = 6)</td>
<td>—</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.35 ± 0.12</td>
<td>—</td>
</tr>
</tbody>
</table>

*p < 0.05; Student's t-test for comparison with control values; n = number of animals.

TABLE 2  Plasma Glucose Concentration, $^{14}C$-D-glucose Extractions ($E_{glucose}$) and Permeability Surface for Glucose (PS-product) in Control Animals, Acutely and Chronically Intoxicated Animals and in Withdrawing Animals. Means ± SEM are given.

<table>
<thead>
<tr>
<th>Group</th>
<th>Plasma glucose concentration (mmol/l)</th>
<th>$E_{glucose}$ %</th>
<th>PS-product (glucose) (ml/100 g/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls (n = 11)</td>
<td>10.6 ± 1.0</td>
<td>15.9 ± 1.7</td>
<td>17.0 ± 2.0</td>
</tr>
<tr>
<td>Acute intoxication (n = 10)</td>
<td>12.1 ± 1.2</td>
<td>18.2 ± 4.0</td>
<td>12.7 ± 3.1</td>
</tr>
<tr>
<td>Chronic intoxication (n = 5)</td>
<td>14.9 ± 0.8*</td>
<td>23.9 ± 1.9*</td>
<td>21.4 ± 2.2</td>
</tr>
<tr>
<td>Withdrawal (n = 6)</td>
<td>10.7 ± 0.9</td>
<td>17.5 ± 2.2</td>
<td>22.6 ± 3.2</td>
</tr>
</tbody>
</table>

*p < 0.05; Student's t-test for comparison with control values; n = number of animals.

FIGURE  CBF values from experimental groups studied by Hemmingsen and Barry* and Hemmingsen et al.* These groups were exactly comparable to the present experimental series (see text); AI = acute intoxication; CI = chronic intoxication; C = controls; W = withdrawal. These CBF values were used to obtain the corresponding water extraction values ($E_{HOH}$) from the data of Bolwig and Lassen. The resulting $E_{HOH}$ values used to correct for varying uptake of reference substance are also indicated in the figure.

extravasation of Evans blue albumin occurred in the rat brain during ethanol intoxication and withdrawal.

The mean glucose extraction value in the control group was in good accordance with the value ($E_g = 12.5$) reported by others using the indicator dilution technique of Crone where all methodological precautions were taken to obtain quantitatively correct values. During acute intoxication and withdrawal the glucose extraction did not deviate significantly from the control value.

The statistically insignificant tendency to a higher (15%) glucose extraction during acute intoxication was not unexpected because this group had a lower CBF than controls and hence the resulting PS-products were quite similar. During chronic ethanol intoxication the glucose extraction was significantly increased, and although the PS-product was not statistically different from control values it tended to be somewhat higher. This finding might be related to the high plasma glucose concentration in the group. Recently Lund-Andersen pointed at the possible role of accelerative exchange diffusion causing an increased unidirectional tracer flux when the glucose concentration is increased on the side of the membrane (the BBB) toward which the flux is directed. If we assume that the absolute CBF in one hemisphere in a rat brain is about 600 $\mu l/min = 10 \mu l/sec$ then an intracarotid injection of a 50 $\mu l$ bolus over less than 1 sec will definitely clear the cerebral vessels of that hemisphere for blood in a considerable part of the period from bolus injection to decapitation. If the bolus concentration of radioactively labelled glucose is lower than the plasma injection concentration of the animal then the essentially unchanged brain glucose...
concentration during bolus transmission is higher than the intravascular concentration. Consequently an increased extraction of radioactively labelled glucose may be measured due to the accelerative exchange diffusion phenomenon. It may be concluded that during acute and chronic ethanol intoxication and during ethanol withdrawal there was no major functional perturbation of the specific D-glucose carrier system of the BBB in the rat.

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