Dose-related Changes in the Rate of Cerebrospinal Fluid Formation and Resistance to Reabsorption of Cerebrospinal Fluid Following Administration of Thiopental, Midazolam, and Etomidate in Dogs

Alan A. Artru, M.D.*

The rate of cerebrospinal fluid (CSF) formation (Vf) and resistance to reabsorption of CSF (Rf) were determined in dogs at four doses of thiopental (6, 12, 18, and 24 mg·kg⁻¹·h⁻¹), midazolam (0.5, 1.0, 1.5, and 2.0 mg·kg⁻¹·h⁻¹), and etomidate (0.86, 1.72, 2.58, and 3.44 mg·kg⁻¹·h⁻¹). Results were compared within and between groups and to previously reported normal values for Vf (0.030–0.054 ml/min) and Rf (220–240 cmH2O·ml⁻¹·min) in dogs. At the two lower doses of thiopental, midazolam, or etomidate Vf was not significantly different than previously reported normal values. At the two higher doses of each drug Vf was 0.019–0.024 ml/min, significantly reduced compared to Vf at the two lower doses of each drug. The pattern of Rf data was more varied. With thiopental Rf was elevated at the lowest dose, (554 ± 17 cmH2O·ml⁻¹·min, mean ± SD) reduced at the highest dose (156 ± 19 cmH2O·ml⁻¹·min), and not significantly different than previously reported normal values at the two intermediate doses. With midazolam Rf was elevated at the lowest dose (332 ± 25 and 378 ± 18 cmH2O·ml⁻¹·min) and normal at the two intermediate doses. With etomidate Rf was normal at the lowest dose and reduced at the highest dose (187 ± 13 cmH2O·ml⁻¹·min). It is concluded that CSF volume may be increased and the CSF pressure at which CSF volume contracts may be increased by doses of thiopental or midazolam that increase Rf, but not increased by etomidate. (Key words: Anesthetics, intravenous; etomidate; midazolam; thiopental. Brain: Intracranial pressure. Cerebrospinal fluid: formation; pressure; reabsorption. Hypnotics: etomidate; midazolam; thiopental.)

THE HYPNOTICS thiopental, midazolam, and etomidate are recommended as part of a balanced anesthetic technique for patients with increased intracranial pressure (ICP) or decreased intracranial compliance.1-3 One factor in determining the suitability of these hypnotics for patients with increased ICP or decreased intracranial compliance is the effect of the drug on cerebrospinal fluid (CSF) dynamics, i.e., the rate of CSF formation (Vf) and resistance to reabsorption of CSF (Rf). Previously, there have been no reports on the effects of thiopental, midazolam, or etomidate on these variables.

Vf and Rf are important in patients with increased ICP or decreased intracranial compliance because they determine CSF volume, which, in turn, is one of the principal determinants of ICP. Increase of Vf and/or Rf elevates ICP and opposes contraction of CSF volume in response to expansion of cerebral blood volume (CBV) or brain tissue volume. Conversely, decrease of Vf and/or Rf lowers ICP and favors contraction of CSF volume in response to expansion of CBV or brain tissue volume. Preservation of normal Vf and Rf does not change ICP and permits contraction of CSF volume in response to expansion of CBV or brain tissue volume.

The present studies were designed to determine the effects of thiopental, midazolam, or etomidate on Vf and Rf in dogs. Four doses of each drug were examined to determine whether the effects varied with the amount of drug administered.

Methods

ANIMAL PREPARATION

This study was approved by the Animal Care Committee of the University of Washington. Eighteen unmedicated mongrel dogs (15–22 kg) were studied. Anesthesia was induced with halothane (> 1.2%, end-expired value determined intermittently by gas chromatography) and nitrous oxide (N2O, 66%, inspired) in oxygen. The trachea was intubated, expired CO2 was continuously monitored (Beckman Medical Gas Analyzer, Model LB2, Beckman Instruments, Inc., Fullerton, California), and ventilation was regulated by a servo controller to maintain expired CO2 at normocapnia. The right femoral artery was cannulated to permit arterial blood sampling for blood gas analysis and to permit continuous monitoring of systemic arterial pressure and heart rate. Mean arterial pressure (MAP) was determined by electronic integration. A urinary catheter was inserted, the right femoral vein was cannulated for saline and drug administration, and temperature was monitored by a nasopharyngeal thermistor probe. Intravenous infusion of vecuronium 2–4 mg/h maintained muscle relaxation.

The electroencephalogram (EEG) was recorded using bilateral frontoparietal electrodes and a Beckman Acutrace® polygraph (Beckman Instruments, Inc.) with a bandpass of 0.3–75 Hz. The EEG was recorded to eval-
Table 1. Dose Regimens of Thiopental, Midazolam, and Etomidate

<table>
<thead>
<tr>
<th>Drug</th>
<th>Initial Infusion (mg/kg)</th>
<th>Subsequent Infusion (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thiopental</td>
<td>0.0</td>
<td>6.0</td>
</tr>
<tr>
<td>(n = 6)</td>
<td>0.0</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Midazolam</td>
<td>1.6</td>
<td>0.5</td>
</tr>
<tr>
<td>(n = 6)</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Etomidate</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>(n = 6)</td>
<td>0.86</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>0.86</td>
<td>2.58</td>
</tr>
<tr>
<td></td>
<td>0.86</td>
<td>3.44</td>
</tr>
</tbody>
</table>

Table 1: Dose Regimens of Thiopental, Midazolam, and Etomidate

To evaluate the effects of thiopental, midazolam, and etomidate on cortical activity and to determine whether those effects remained constant throughout each infusion period. Electrodes were adjusted to maintain impedances between electrode pairs at <3 KΩ. Computer (Digital Equipment Corp. MINC-29, Digital Equipment Corp., Marlboro, Massachusetts) analysis of the EEG was performed using a Compressed Spectral Array (CSA) program, which averaged the EEG power spectra of four epochs (1 epoch = 4 s) every 30 s. Data from the CSA program were evaluated as the amount of EEG activity in the standard frequency bins: delta (1-4 Hz), theta (4-8 Hz), alpha (8-14 Hz), beta-1 (14-20 Hz), and beta-2 (20-32 Hz).

A burr hole was placed over the left hemisphere and a catheter was directed into the underlying lateral ventricle. The posterior neck muscles were surgically separated to expose the atlanto-occipital membrane, and a catheter was directed into the cisterna magna. A 0.3-ml sample of CSF was obtained from the cisternal cannula for measurement of osmolality using a Wescor Model 5100 B Vapor Pressor Osmometer (Wescor, Inc., Logan, UT). Mock CSF of matching osmolality was prepared by mixing standard solutions (osmolality 290, 300, or 310 mosm kg) labeled with blue dextran (1 mg/ml) (Sigma Chemical Co., St. Louis, Missouri). Wound edges were infiltrated with bupivacaine (0.5%) and the concentration of halothane was decreased (N₂O unchanged) to 0.2% (end-expired value determined intermittently by gas chromatography). Details of this animal preparation have been previously reported.

Mock CSF was infused into the ventricle, and the mixture of mock and native CSF was permitted to flow passively out of the cisterna magna through a short length of tubing attached to the cisternal cannula. The infusion rate (\( \dot{V}_I \)) was controlled with a roller pump and gradually increased to 0.6 ml/min while ventricular CSF pressure was continuously monitored. The open end of the cisternal outflow tubing was placed at the same height as the CSF level present in the cisternal and ventricular cannula before perfusion was begun. This arrangement did not alter CSF pressure from the value normally occurring in the intact animal because the height of the open end of the outflow tubing determines CSF pressure during open ventriculocisternal perfusion. Successful ventriculocisternal perfusion was indicated by outflow of labeled CSF from the cisternal cannula with no increase in ventricular CSF pressure above preperfusion values. This initial period of open ventriculocisternal perfusion allowed for equilibration of labeled mock CSF with native CSF in the intracranial and cisternal CSF spaces of the dog. Details of this modified open ventriculocisternal perfusion technique have been previously reported.

After 1 h of ventriculocisternal perfusion, \( \dot{V}_I \) was gradually reduced to 0.3 ml/min. Concentrations of blue dextran in cisternal outflow samples were determined intermittently using light absorbance at 620 nm on a Beckman DU-2 Spectrophotometer (Beckman Instruments, Inc.) (fitted with a Gilford absorbance indicator, Gilford Instrument Laboratories, Inc., Oberlin, Ohio). Equilibration of the tracer was considered complete when measured blue dextran concentrations in three consecutive samples of cisternal outflow (collection time = 4–6 min/sample) agreed within 2%.

**Experimental Period**

The experimental period began once tracer equilibration was complete. \( \dot{V}_I \) and \( \dot{R}_c \) were determined during thiopental, midazolam, or etomidate in six dogs each. For all three drugs each dog received four dose regimens iv of the drug (table 1). Within each drug group doses were given in sequence, progressing from smallest to largest dose. The duration at each infusion level was about 90 min and there were no intervals between infusions. Drug doses and infusion rates were based on previously reported data with the aim of achieving comparable and steady levels of depression of cerebral cortical activity during each infusion period. At each dose of all three drugs dogs were studied at two CSF pressures (normal and elevated) so that \( \dot{R}_c \) could be determined.

Normal CSF pressure was defined as that when the open end of the cisternal outflow tubing was placed at the same height as the CSF level present in the cisternal and ventricular cannula before perfusion was begun. Elevated CSF pressure was defined as CSF pressure when the open end of the cisternal outflow tubing was placed 10 cm above the level used for normal CSF pressure. The sequence of normal and elevated CSF pressures were altered within each group of six dogs so that six different combinations were employed over the four drug doses. \( \dot{V}_f \) and the rate of reabsorption of CSF (\( \dot{V}_a \)) were de-
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termined at each of the eight conditions. At least 27 min
(the first 17 min with \( V_t = 0.6 \) ml/min followed by
at least 10 min with \( V_t = 0.3 \) ml/min) was allowed between
conditions to permit reequilibration of the tracer. At each
condition three consecutive samples of cisternal outflow
were collected (collection time = 4–6 min/sample) for
determinations of \( V_t \) and \( V_n - V_t \) and \( V_t \) were calculated as
previously described according to the formulas of
Heisey et al. For these calculations concentrations of
blue dextran in samples of the labeled mock CSF being
perfused into the ventricle also were determined using
light absorbance at 620 nm. Values for \( V_n \) at normal and
elevated CSF pressures were used to calculate \( R_n \). By
definition \( R_n \) is a reciprocal measure of the slope relating
\( V_n \) (expressed as ml/min) to CSF pressure (expressed as
cm H₂O). The EEG and systemic variables also were
recorded at each experimental condition.

STATISTICAL ANALYSIS

Statistical comparisons within groups were made using
repeated-measures analysis of variance (ANOVA), and
comparisons between groups were made using one-way
ANOVA. Comparisons between the present groups and
previously reported normal values for \( V_t \) and \( R_n \) for
dogs were made using one-way ANOVA. Where the
calculated F value exceeded the critical value for the
0.05 probability level, the Student-Newman-Keuls test
was used to determine which differences were significant
at \( P < 0.05 \). Values are tabulated as mean ± SD.

Results

At the two lower doses of thiopental, midazolam, or
etomidate \( V_t \) was not significantly different than previ-
ously reported normal values (table 2; fig. 1). At the two
higher doses of each drug \( V_t \) decreased by 33%, 46%,
and 39%, respectively, compared to the two lower doses
of each drug.

\( R_n \) during thiopental increased by 53% at the lowest
dose, decreased by 33% at the highest dose, and was not
different than previously reported normal values at the
two intermediate doses (fig. 2). \( R_n \) during midazolam in-
creased by 61% and 41% at the lowest and highest doses,
respectively, and was normal at the two intermediate
doses. \( R_n \) during etomidate was normal at the three lower
doses and decreased by 21% at the highest dose.

In all groups \( V_t \) was not different at elevated CSF pres-
Sure than at normal CSF pressure. \( V_t \) at low drug doses
was not different between groups and \( V_t \) at high drug
doses was not different between groups. \( R_n \) at intermediate
drug doses also was not different between groups. In all
groups CSF pressure increased by 10 cm H₂O when the
open end of the cisternal outflow tubing was placed
10 cm above the level used for normal CSF pressure.
Drug Dose

FIG. 1. Rates of CSF formation are shown for all four doses of thiopental (solid circles), midazolam (open circles), and etomidate (open triangles). For each drug, rates of CSF formation at the two higher doses were less than rates of CSF formation at the two lower doses; *P < 0.05. Previously reported normal values for \( V_f \) range from 0.30 ± 0.11 to 0.54 ± 0.10 ml·min⁻¹ (mean ± SD) for dogs.⁷⁻⁹,¹⁶⁻²² With thiopental the EEG showed loss of high frequency activity and a decrease of theta, alpha, and beta-I activity that decreased as the dose of thiopental was increased. With midazolam the EEG showed loss of high frequency activity and either continued moderate theta and alpha activity or variable, alternating periods of minimal and moderate theta and alpha activity. With etomidate the EEG showed prominent theta, alpha, and beta-I activity that increased as the dose of etomidate was increased. At all four rates of infusion of the three drugs the pattern of EEG activity characteristic of each dose remained constant throughout each infusion period.

Within each treatment group systemic variables were not significantly different between conditions. Systemic variables were therefore combined within groups (table 3). Combined systemic variables did not differ between treatment groups, although a trend toward lower heart rate values was observed with etomidate.

Discussion

In previous studies of CSF dynamics control or normal values for \( V_f \) and \( R_a \) were determined during inhalation of \( N_2O \) and low concentrations of volatile anesthetic or administration of pentobarbital.⁷⁻⁹,¹⁶⁻²¹,²⁴⁻³² The reported range of control or normal values for \( V_f \) was 0.030 ± 0.011 to 0.054 ± 0.010 ml/min (mean ± SD) for dogs.⁷⁻¹⁶⁻²² Assuming that 0.030–0.054 ml/min represents normal canine \( V_f \), the results of the present study indicate that \( V_f \) is unchanged at the two lower doses of thiopental, midazolam, or etomidate and is reduced at the two higher doses of each drug.

The reported range of control or normal values for \( R_a \) for dogs is ~220–240 ± 5 cmH₂O·ml⁻¹·min⁻¹.²¹,²²,²⁴,²⁵ Assuming that 220–240 cmH₂O·ml⁻¹·min represents normal canine \( R_a \), the results of the present study indicate that \( R_a \) is elevated at the lowest dose of thiopental, unchanged at the intermediate doses, and reduced at the highest dose. With midazolam \( R_a \) is elevated at the lowest, and highest doses and unchanged at the intermediate doses. With etomidate \( R_a \) is reduced at the highest dose and unchanged at the other three doses.

It should be noted that in the present studies the sequence of administration of thiopental, midazolam, and etomidate always proceeded from lowest dose to highest dose. Consequently, it is possible that the reduction of \( V_f \) observed with the two higher doses of each drug occurred because of time-related changes rather than drug effect. However, previous studies with this model reported no time-related change in \( V_f \) during inhalation of \( N_2O \) and low concentrations of halothane⁷⁻¹⁷,¹⁸,²¹ (the "background" anesthetic used here), inhalation of 1 MAC halothane,¹⁷,¹⁸ or inhalation of \( N_2O \) and low concentrations of halothane combined with iv infusion of fentanyl.¹⁷,¹⁸ Thus, it seems likely that the reduction of \( V_f \)

TABLE 3. Combined Systemic Variables from Eight Experimental Conditions and CSF Osmolality for the Three Treatment Groups

<table>
<thead>
<tr>
<th>Systemic Variables</th>
<th>Thiopental Group (n = 6)</th>
<th>Midazolam Group (n = 6)</th>
<th>Etomidate Group (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{aO_2}$ (mmHg)</td>
<td>153 ± 11</td>
<td>141 ± 10</td>
<td>145 ± 13</td>
</tr>
<tr>
<td>$P_{aCO_2}$ (mmHg)</td>
<td>35 ± 3</td>
<td>36 ± 3</td>
<td>34 ± 2</td>
</tr>
<tr>
<td>$pH$</td>
<td>7.39 ± 0.03</td>
<td>7.40 ± 0.02</td>
<td>7.37 ± 0.03</td>
</tr>
<tr>
<td>Bicarbonate (mEq L$^{-1}$)</td>
<td>21.1 ± 1.4</td>
<td>21.8 ± 1.2</td>
<td>19.4 ± 1.8</td>
</tr>
<tr>
<td>Hemoglobin (g L$^{-1}$)</td>
<td>14.8 ± 2.4</td>
<td>12.1 ± 2.0</td>
<td>14.0 ± 1.3</td>
</tr>
<tr>
<td>Mean arterial blood pressure (mmHg)</td>
<td>114 ± 6</td>
<td>100 ± 9</td>
<td>110 ± 8</td>
</tr>
<tr>
<td>Heart rate (beats min$^{-1}$)</td>
<td>112 ± 7</td>
<td>98 ± 14</td>
<td>80 ± 18</td>
</tr>
<tr>
<td>Temperature, nasopharyngeal ($^\circ$C)</td>
<td>37.4 ± 0.6</td>
<td>37.2 ± 0.4</td>
<td>37.2 ± 0.4</td>
</tr>
<tr>
<td>CSF osmolality (mossm kg$^{-1}$)</td>
<td>293 ± 17</td>
<td>296 ± 14</td>
<td>298 ± 17</td>
</tr>
</tbody>
</table>

Values are given as mean ± SD. Values are the combined results of determinations made at four drug doses, each at normal and elevated (+10 cmH$_2$O) CSF pressure.

observed in the present study with the two higher doses of thiopental, midazolam, and etomidate was not due solely to the effect of time of this model. Regarding $R_a$, no consistent pattern was observed at the highest dose of each drug in this study (elevation of $R_a$ with midazolam, reduction of $R_a$ with thiopental and etomidate). Thus, no time-related effect on $R_a$ is suggested. Because each drug was given in sequence, progressing from smallest to largest dose, the results at all but the lowest infusion rate include the influence of preceeding drug doses.

About two-thirds of CSF formation occurs via energy-dependent, active transport processes and about one-third of CSF formation occurs via passive filtration.\textsuperscript{35,34} The reduction of $V_f$ that occurred at the two higher doses of thiopental, midazolam, and etomidate in this study may be related to decrease of choroid plexus blood flow and/or metabolism. Some authors have reported that thiopental, midazolam, and etomidate decrease cerebral blood flow (CBF) and the cerebral metabolic rate for oxygen (CMRO$_2$) in dogs.\textsuperscript{10,11,35} Decrease of CBF reduces $V_f$, presumably due to impaired delivery of water, ions, and the substrate needed for energy production for active transport processes at the choroid plexus.\textsuperscript{33,34} Decrease of CBF also may reduce $V_f$ due to impaired delivery of water and ions to sites of passive filtration of CSF, i.e., the choroid plexus and ependyma.\textsuperscript{34} Decrease of CMRO$_2$ reduces $V_f$, presumably due to a slowing in the rate of the energy-requiring processes necessary for active CSF formation.\textsuperscript{28,34,35} It is also possible that these hypotonicity reduce $V_f$ by direct action (not related to slowing of metabolism) to impair the activity of the catalytic enzymes or membrane pumps of the choroid plexus, or to decrease the permeability of membranes to water or ions at the choroid plexus or ependyma.\textsuperscript{34}

The increase or reduction of $R_a$ that occurred in this study may result from changes in conductance at the arachnoid granulations or changes in the pressure gradient across the arachnoid granulations. Conductance at the arachnoid granulations is altered by changes in the architecture of the one-way valves or changes in transport across the basement membrane.\textsuperscript{34} The pressure gradient across the arachnoid granulations is altered by changes in cerebral venous pressure (sagittal sinus and lateral lacunae) and CSF pressure.\textsuperscript{37} It is unlikely that changes in CSF pressure altered the pressure gradient across the arachnoid granulations in this study because CSF pressure was fixed at the value determined by the height of the distal end of the cisternal outflow tubing.

In summary, the principal findings of this study were that thiopental, midazolam, and etomidate caused no change in $V_f$ at the two lower doses and decreased $V_f$ at the two higher doses. $R_a$ was elevated at the lowest and highest dose of midazolam and at the highest dose of thiopental, and unchanged or decreased with etomidate. Drug-induced changes in $V_f$ and/or $R_a$ are of interest because the balance between $V_f$ and $R_a$ is a major determinant of CSF volume. The present results indicate that, under the conditions of this study, CSF volume should be increased at the lowest doses of midazolam and thiopental and may be increased at the highest dose of midazolam. CSF volume should be normal or decreased at the other doses of midazolam and thiopental and with all four doses of etomidate. Also, drug-induced changes in $R_a$ are of interest because $R_a$ is a major determinant of the response of CSF volume to changes in CBV and brain tissue volume. Increased $R_a$ should be disadvantageous when intracranial compliance is reduced because CSF volume can contract in response to increase of CBV or brain tissue volume only if CSF pressure rises. In contrast, unchanged or lowered $R_a$ should be advantageous because a rise in CSF pressure is not needed to permit CSF volume to contract.

References

2. Camplin TV, Turner JM: Intracranial, effects of anaesthetic...
11. Michenfelder JD: The interdependency of cerebral functional and metabolic effects following massive doses of thiopental in the dog. ANESTHESIOLOGY 41:231–236, 1974
19. Arru AA: Isoflurane does not increase the rate of CSF production in the dog. ANESTHESIOLOGY 60:193–197, 1984
22. Arru AA: Muscle relaxation with succinylcholine or vecuronium does not alter the rate of CSF production or resistance to reabsorption of CSF in dogs. ANESTHESIOLOGY 68:392–396, 1988