Effect of the α₂-Agonist Dexmedetomidine on Cerebral Neurotransmitter Concentrations during Cerebral Ischemia in Rats

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Background: This study investigates whether neuroprotection seen with dexmedetomidine is associated with suppression of peripheral or central sympathetic tone.

Methods: Thirty fasted male Sprague-Dawley rats were intubated and ventilated with isoflurane and N₂O/O₂ (fraction of inspired oxygen = 0.33). Catheters were inserted into the right femoral artery and vein and into the right jugular vein. Cerebral blood flow was measured using laser Doppler flowmetry. Bilateral microdialysis probes were placed into the cortex and the dorsal hippocampus. At the end of preparation, the administration of isoflurane was replaced by fentanyl (bolus: 10 μg/kg; infusion: 25 μg · kg⁻¹ · h⁻¹). Animals were randomly assigned to one of the following groups: group 1 (n = 10): control animals; group 2 (n = 10): 100 μg/kg dexmedetomidine administered intraperitoneally 30 min before ischemia; group 3 (n = 10): sham-operated rats. Ischemia (30 min) was produced by unilateral carotid artery occlusion plus hemorrhagic hypotension to a mean arterial blood pressure of 30–35 mmHg to reduce ipsilateral cerebral blood flow by 70%. Pericranial temperature, arterial blood gases, and pH were maintained constant. Cerebral catecholamine and glutamate concentrations and plasma catecholamine concentrations were analyzed using high-performance liquid chromatography.

Results: During ischemia, dexmedetomidine suppressed circulating norepinephrine concentrations by 95% compared with control animals. In contrast, brain norepinephrine and glutamate concentrations were increased irrespective of dexmedetomidine infusion before ischemia.

Conclusions: The current data show that the increase of circulating catecholamine concentrations during cerebral ischemia was suppressed with dexmedetomidine. In contrast, dexmedetomidine does not suppress elevation in brain norepinephrine and glutamate concentration associated with cerebral ischemia. This suggests that the neuroprotective effects of dexmedetomidine are not related to inhibition of presynaptic norepinephrine or glutamate release in the brain.

STUDIES in rats subjected to incomplete cerebral ischemia have shown that the preischemic administration of blocking agents, α₂-agonists, and anesthetics improves neurologic outcome and reduce histopathologic damage.¹–³ Although these data generally suggest that neuroprotection is related to a reduced sympathetic tone, it is unclear whether this is a function of suppressed plasma catecholamine or brain catecholamine concentrations. Therefore, this study investigates the effect of the α₂-agonist dexmedetomidine on circulating and cerebral catecholamine concentrations during incomplete cerebral ischemia in rats.

Materials and Methods

Preparation

After obtaining approval from the institutional animal care committee (Government of Bavaria), 30 male Sprague-Dawley rats (weighing 300–420 g) were anesthetized in a bell jar saturated with isoflurane. Rats were tracheally intubated and mechanically ventilated with 1.5 vol% isoflurane in nitrous oxide and oxygen (fraction of inspired oxygen = 0.33). Catheters were inserted into the right femoral artery and vein and into the right jugular vein for blood withdrawal, administration of drugs, and blood sampling. A loose ligature was placed around the right common carotid artery for later clamping. The rats were then placed in a stereotactic “U”-frame with nonpenetrating ear bars (Model 962; David Kopf Instruments, Tujunga, CA). After incision of the skull, penetrating burr holes (1 mm in diameter) were drilled into the cranium 4.2 mm posterior and 2.5 mm lateral of the bregma over both hemispheres according to the stereotaxis coordinates of the rat brain.⁴ The tip of the drill was continuously flushed with saline to avoid thermal injury. After incision of the dura, the microdialysis probes (CMA12, 4.0 mm length, 0.5 mm diameter; CMA/Microdialysis AB, Solna, Sweden) were carefully inserted into the cortex and the dorsal hippocampus. The probes were then fixed using a zinc polycarboxylate cement (Poly-F Plus; Dentsply, York, PA) and perfused with Ringer’s solution (Boehringer Ingelheim Delta Pharm GmbH, Pfullingen, Germany; 147 mM Na⁺, 2.25 mM Ca²⁺, 4 mM K⁺, 155.5 mM Cl⁻) at a rate of 1.0 μl/min. Small collector vials were filled with 10 μl of 0.5 M perchloric acid to stabilize catecholamines and placed in a refrigerated fraction collector (CMA 170; CMA/Microdialysis AB). Ninety minutes after implantation of the microdialysis probes, sample fractions of 30 min were

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collected and subsequently stored at −70°C. Non-
penetrating burr holes were drilled 0.5 mm anterior and
1 mm lateral of the bregma into the cranium over both
hemispheres for continuous measurement of erythro-
cyte flow velocity using a laser Doppler flowmeter (Peri-
Flux System 4001; Perimed, Järfalla, Sweden). Local ce-
rebral blood flow (CBF) was continuously measured and
expressed in arbitrary perfusion units, which were sam-
pelled over 0.3 s. The laser Doppler flow probes (Probe
403; Perimed) were placed over both hemispheres and
fixed using the stereotactic frame. Care was taken to
place the probes over a tissue area devoid of large blood
vessel visible through the thinned bone, and correct
placement of laser Doppler probes was confirmed by
transient hypoventilation. Pericranial temperature
was measured with a 22-gauge stainless steel needle ther-
mistor (model 73A, Yellow Springs Instrument Co., YSI
Temperature Controller; Yellow Springs, OH) placed
beneath the right temporal muscle and was maintained
constant at 37.5°C throughout the experiment by a ser-
vomechanism using an overhead heating lamp and a
heating mat.

Cerebral Ischemia
At the end of the preparation, all surgical incisions
were infiltrated with 0.5% bupivacaine, and the admin-
istration of isoflurane was replaced by fentanyl (bolus:
10 μg/kg; infusion: 25 μg · kg⁻¹ · h⁻¹) while ventilation
was continued with nitrous oxide and oxygen (fraction of inspired oxygen = 0.33). Mechanical ventilation was
adjusted to maintain arterial carbon dioxide tension at
38–42 mmHg. The nonpenetrating ear bars of the ste-
reotactic frame were released. During cerebral ischemia,
arterial pH was maintained at physiologic levels by intra-
venous infusion of bicarbonate. Vecuronium was given
as a continuous infusion (0.1 mg · kg⁻¹ · min⁻¹) to
maintain neuromuscular blockade. Animals were ran-
domly assigned to one of the following treatment
groups. Group 1 (n = 10) represents the control group,
with no additional treatment. Animals in group 2
(n = 10) received 100 μg/kg dexmedetomidine admin-
istered intraperitoneally 30 min before the onset of isch-
emia. Animals in group 3 (n = 10) were sham-operated
(i.e., complete instrumentation, no ischemia) with no
additional treatment. After an equilibration period of 2 h,
cerebral ischemia was induced by hemorrhagic hypoten-
sion and clip occlusion of the right common carotid
artery. Mean arterial blood pressure was maintained
within the range of 30–35 mmHg to reduce CBF in the
ischemic hemisphere by 70%. After 30 min of cerebral
ischemia, the clip was released and the shed blood was
reinfused over 15 min. Arterial blood gases and plasma
glucose concentrations were analyzed at baseline, 30 min
during ischemia, 15 min after ischemia (reperfusion),
and 90 min after ischemia (recovery). Blood samples for
measurement of plasma catecholamine concentrations
were collected at baseline, at the end of ischemia, and
90 min after cerebral ischemia. The blood samples were
centrifuged at 4°C for 10 min, and the plasma was stored
at −70°C. Brains were removed 4 h after ischemia and
placed in tissue-freezing medium (Jung Tissue Freezing
Medium; Leica Instruments GmbH, Nussloch, Germany),
frozen in methylbutan on dry ice, and stored at −70°C.
The correct position of the microdialysis probes was
verified, and histologic damage caused by the microdi-
alysis probes was evaluated in 7-μm brain slices, stained
with hematoxylin and eosin, and animals were excluded
from the study in case of major bleeding.

High-performance Liquid Chromatography
Samples for plasma norepinephrine, epinephrine, and
dopamine analyses were processed using the ClinRep
test kit for high-performance liquid chromatography
analysis of catecholamines (Recipe Chemicals and In-
struments GmbH, Munich, Germany). Plasma samples
(0.25 ml) were mixed with 50 μl dehydroxybenzylamine
(internal standard). The mixture was passed through the
sample preparation column filled with aluminum oxide.
The remaining particles of plasma proteins were washed
out. Norepinephrine, epinephrine, and dopamine were
eluted by adding 120 μl elution buffer. No pretreatment
was necessary to analyze cerebral dialysate for extracel-
ular norepinephrine and dopamine concentration. Sam-
ples were placed into a cooled autosampler (AS2000A;
Merck Hitachi, Darmstadt, Germany). Sixty microliters of
the plasma elute or 10 μl of the cerebral dialysate was
injected into the high-performance liquid chromatogra-
phy circulation system (mobile phase ClinRep; Recipe
Chemicals and Instruments GmbH) for electrochemical
detection (0.5 V potential). The elute and the cerebral
dialysate was passed over the analytical column (Clin-
Rep; Recipe Chemicals and Instruments GmbH) with a
flow of 1.0 ml/min to the electrochemical detector (Wa-
ters 460; Waters, Milford, MA). The whole system was
controlled and data were stored by the high-perfor-
mance liquid chromatography systems manager soft-
ware (Merck Hitachi, Darmstadt, Germany). The system
was calibrated with a catecholamine standard (ClinRep;
Recipe Chemicals and Instruments GmbH).
For analysis of the cerebral glutamate and aspartate
concentration, the microdialysis samples were placed
into an autoinjector (Gina 50 Probengeber; Dionex,
Germering, Germany). Ortho-phthaldialdehyde (20 μl),
diluted with boracic buffer (1:10), was mixed with 10 μl
cerebral dialysate for derivatization. This mixture was
injected into the high-performance liquid chromatogra-
phy circulation system (Pumpsystem M480; Dionex)
for fluorometric detection and was passed over the an-
alytical column (Grom-Sil OAA-2, 250 × 4 mm; Grom,
Herrenberg, Germany) with a flow of 0.8 ml/min to the
fluorescence detector (Fluoreszenzdetektor RF-2000;
Dionex; wavelength: extinction 280 nm–emission 475 nm).

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The mobile phase A consisted of 23 mM sodium acetate adjusted with HCl to a pH of 6.0. The mobile phase B consisted of 600 ml methanol and 50 ml acetonitril. The gradient was changed as follows: after beginning, 100% phase A–0% phase B; after 29.8 min, 79% phase A–21% phase B; after 32.5 min, 47% phase A–53% phase B; after 34 min, 0% phase A–100% phase B. The analysis refers to a four-point standard curve of a custom-made standard.

Statistical Analysis

Data (mean ± SD) of four consecutive time points were evaluated: before hemorrhagic hypotension (baseline), at 30 min of cerebral ischemia (ischemia), 15 min after cerebral ischemia upon reinfusion of the withdrawn blood (reperfusion), and 90 min after cerebral ischemia (recovery).

Data of variables that are available from two hemispheres and at each time point (CBF and cerebral neurotransmitter concentrations) were subjected to a two-way repeated-measurements analysis of variance with the within-groups factor (time2 and hemisphere), the between-groups factor (group), and all possible interaction terms (time2 × hemisphere; time2 × group; hemisphere × group). To evaluate the following three hypotheses, respective post hoc analyses were performed in a stepwise manner if “time2 × group” was significant (P < 0.05).

Differences between groups during ischemia: Once “time2 × group” or “time2 × hemisphere × group” proved to be significant in the global test (P < 0.05), another two-way repeated-measurements analysis of variance was performed with the within-groups factor (hemisphere), the between-groups factor (group), and their interaction term. Once “hemisphere × group” proved to be significant (P < 0.05), values during ischemia of the ipsilateral and the contralateral side were compared using paired t tests separately in each group (P < 0.05/3 = 0.016 for multiple comparison correction).

Data of variables that are available at each time point (physiologic variables and plasma catecholamine concentrations) were subjected to a two-way repeated-measurements analysis of variance with the within-groups factors (time2), the between-groups factor (group), and their interaction term (time2 × group). To evaluate the following two hypotheses, respective post hoc analyses were performed in a stepwise manner if “time2 × group” was significant (P < 0.05).

Differences between groups during ischemia: Values during ischemia were analyzed with a factorial analysis of variance, with “group” as independent factor and, if significant (P < 0.05), followed by three unpaired t tests (P < 0.05/3 = 0.016 for multiple comparison correction).

Differences between baseline and ischemia within each group: Values at baseline and during ischemia were compared using paired t tests in each group (P < 0.05/3 = 0.016 for multiple comparison correction).

All variables are presented as mean ± SD. Statistical analyses were performed using SPSS 10.0 for Windows (SPSS Inc., Chicago, IL).

Results

Table 1 shows the physiologic variables. According to the study protocol, mean arterial blood pressure was decreased in control animals (group 1) and in dexmedetomidine-treated animals (group 2) during cerebral ischemia compared with sham-operated animals (group 3). There were no differences for arterial oxygen and carbon dioxide tensions within (baseline vs. ischemia) and between groups. In control animals and animals treated with dexmedetomidine, plasma glucose concentration decreased during ischemia compared with baseline. During ischemia, plasma glucose concentration was higher with sham-operated animals compared with control animals and dexmedetomidine-treated animals.

Table 2 shows the results of the statistical analysis testing the differences between both hemispheres. As expected, the decrease of cortical CBF (laser Doppler flowmetry) was more severe in the ischemic hemisphere compared with the nonischemic hemisphere in control animals (group 1) and animals treated with dexmedetomidine (group 2). Cerebral norepinephrine and glutamate concentration was significantly higher in the ischemic hemisphere compared with the nonisch-
Cerebral Ischemia and Catecholamines

Table 1. Mean Arterial Blood Pressure (MAP), Arterial Blood Gas Tensions, and Plasma Glucose Concentration during Baseline, Ischemia, Reperfusion, and Recovery (90 min after Cerebral Ischemia)

<table>
<thead>
<tr>
<th>Group</th>
<th>Baseline</th>
<th>Ischemia</th>
<th>Reperfusion</th>
<th>Recovery</th>
<th>Time × Group</th>
<th>Baseline vs. Ischemia</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAP (mmHg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Control</td>
<td>118 ± 8</td>
<td>33 ± 2†</td>
<td>127 ± 20</td>
<td>98 ± 16</td>
<td></td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Dexametomidine</td>
<td>133 ± 8</td>
<td>31 ± 1†</td>
<td>128 ± 21</td>
<td>70 ± 6</td>
<td></td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Sham operated</td>
<td>120 ± 9</td>
<td>122 ± 11</td>
<td>123 ± 10</td>
<td>125 ± 10</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>PaO₂ (mmHg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Control</td>
<td>135 ± 25</td>
<td>140 ± 16</td>
<td>145 ± 35</td>
<td>137 ± 32</td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Dexametomidine</td>
<td>116 ± 15</td>
<td>122 ± 6</td>
<td>110 ± 21</td>
<td>100 ± 4</td>
<td>ns</td>
<td>na</td>
</tr>
<tr>
<td>Sham operated</td>
<td>108 ± 16</td>
<td>95 ± 22</td>
<td>103 ± 10</td>
<td>109 ± 9</td>
<td></td>
<td>na</td>
</tr>
<tr>
<td>PacO₂ (mmHg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Control</td>
<td>40 ± 2</td>
<td>37 ± 4</td>
<td>40 ± 4</td>
<td>39 ± 4</td>
<td>ns</td>
<td>na</td>
</tr>
<tr>
<td>Dexametomidine</td>
<td>42 ± 1</td>
<td>41 ± 5</td>
<td>43 ± 3</td>
<td>41 ± 4</td>
<td>ns</td>
<td>na</td>
</tr>
<tr>
<td>Sham operated</td>
<td>40 ± 4</td>
<td>41 ± 3</td>
<td>40 ± 4</td>
<td>42 ± 3</td>
<td></td>
<td>na</td>
</tr>
<tr>
<td>Glucose (mg/dl)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Control</td>
<td>55 ± 9</td>
<td>44 ± 5†</td>
<td>50 ± 7</td>
<td>71 ± 9</td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Dexametomidine</td>
<td>77 ± 6</td>
<td>50 ± 6†</td>
<td>56 ± 7</td>
<td>69 ± 10</td>
<td></td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Sham operated</td>
<td>57 ± 6</td>
<td>60 ± 5*</td>
<td>60 ± 11</td>
<td>61 ± 11</td>
<td></td>
<td>P &lt; 0.001</td>
</tr>
</tbody>
</table>

Mean ± SD; * P < 0.05 compared with control group during ischemia; † P < 0.05 compared with sham operated animals during ischemia.
ns = not significant; na = not applicable.

Discussion

Consistent with previous investigations using this animal model, the current results show that cerebral ischemia (induced by hemorrhagic hypotension and clipping of the right common carotid artery) causes an increase in plasma norepinephrine and epinephrine but not in dopamine concentrations. This elevation in peripheral sympathetic tone did not occur in the presence of the α₂-agonist dexametomidine. Likewise, cerebral norepinephrine, glutamate, and aspartate, but not dopamine concentrations were increased during ischemia. How-
ever, the ischemia-induced increase of cerebral norepinephrine and glutamate could not be suppressed by administration of dexmedetomidine. This suggests that neuroprotection observed with dexmedetomidine is not related to presynaptic inhibition of catecholamine and glutamate release in the brain.

Cerebral ischemia is associated with an increase in circulating and extracellular brain catecholamine concentrations. Interventions to reduce sympathetic tone (e.g., administration of ganglionic blocking agents, anesthetics, or $\alpha_2$ agonists) improved neurologic outcome. Neuroprotection observed with reduced sympathetic activity may be related to several mechanisms. (1) Catecholamines stimulate cerebral metabolic rate for oxygen, an effect that further imbalances the ratio between cerebral oxygen demand and oxygen supply. (2) High catecholamine concentrations also increase the sensitivity of pyramidal neurons to excitatory neurotransmitters such as glutamate, which results in elevated intracellular Ca$^{2+}$ concentrations with consecutive activation of intracellular catabolic enzymes (excitotoxicity). (3) Catecholamines may exert a direct neurotoxic effect when exposed to neuronal tissue in excessive concentrations. (4) It is also possible that increased sympathetic activity decreases perfusion in the ischemic penumbra because ischemic hypotension would produce greater decrease in CBF in sympathetically intact rats (i.e., sympathetic vasoconstriction) as compared...
with animals subjected to ganglionic blockade. Therefore, suppression of catecholamine concentrations may be neuroprotective by economizing the ratio between cerebral oxygen demand and oxygen supply, reducing excitotoxicity, reducing toxic effects, or improving perfusion in the ischemic penumbra.

We expected a suppression of the ischemia-induced increase in cerebral catecholamine concentration in the presence of dexmedetomidine. This assumption was based on the current understanding of the pharmacologic mechanisms of $\alpha_2$-adrenergic agonists and a study in rabbits subjected to global ischemia in which norepinephrine concentration in the striatum was less with dexmedetomidine compared with control animals. However, dexmedetomidine did not attenuate the stress response to incomplete hemispheric ischemia (group 2) in the current study. It is possible that the different results between the two studies are related to differences in regions of interest (i.e., the striatum represents dopaminergic territory) or the use of different ischemia models. The data also suggest that presynaptic stimulation of $\alpha_2$-adrenergic receptors with consecutive decrease in extracellular catecholamine concentrations occurs to a lesser extent than previously believed.

The excitatory amino acid neurotransmitter glutamate triggers neuronal death when released in excessive concentrations during cerebral ischemia. In hippocampal rat brain slices, dexmedetomidine suppressed the excessive glutamate release during potassium chloride-evoked depolarization or hypoxic stress. It was therefore expected that dexmedetomidine would decrease the ischemia-induced glutamate release in the current

**Fig. 3.** Cerebral norepinephrine concentration (A) and glutamate concentration (B) in the ischemic and nonischemic hemisphere before, during, and after cerebral ischemia. Both cerebral norepinephrine and glutamate concentrations increased in the ischemic hemisphere during ischemia irrespective of treatment. *$P < 0.05$ compared with control group during ischemia; $\#P < 0.05$ compared with sham-operated animals during ischemia; $\#P < 0.05$, baseline versus ischemia within control group; $\$P < 0.05$, baseline versus ischemia within dexmedetomidine-anesthetized animals.
study. However, during cerebral ischemia, the elevation of extracellular brain glutamate concentrations was similar between rats treated with dexmedetomidine compared with control animals. Consistently, dexmedetomidine did not decrease the hippocampal glutamate concentration in a model of global cerebral ischemia in rabbits. These data suggest that the neuroprotective potential of dexmedetomidine is not related to changes in extracellular glutamate concentrations. An in vitro study in cultured astrocytes has shown that dexmedetomidine activates the oxidative metabolism of glutamine, a precursor of the neurotoxic glutamate, and thereby reduces the glutamate availability. However, our results did not demonstrate a reduction in cerebral glutamate concentration, an effect that would have been expected from the mechanism of glutamine disposal suggested by Huang et al. and, therefore, this mechanism is not supposed to be a major factor of brain protection with dexmedetomidine.

Experiments using isolated canine stellate ganglia have shown that dexmedetomidine inhibited the synaptic conduction by decreasing the postsynaptic response to a late, slow excitatory presynaptic stimulation through an $\alpha_2$-receptor–mediated process. In addition, studies in isolated primary cortical neurons (i.e., tissue deprived from glial supporting layers and presynaptic receptors) demonstrate neuroprotection with dexmedetomidine, an effect that was reversible by the $\alpha_2$-receptor antagonist yohimbine. It is therefore possible that dexmedetomidine is neuroprotective by postsynaptic action with consecutive reduction in $\text{Ca}^{2+}$ currents.

In the current model of incomplete cerebral ischemia in which decreased sympathetic tone was always associated with improved outcome, plasma but not extracellular brain catecholamine concentrations were suppressed. Similarly, intraischemic plasma catecholamine concentrations were lower with the neuroprotective anesthetics isoflurane or ketamine compared with control rats anesthetized with fentanyl–nitrous oxide that provides adequate anesthesia in nonstressed animals, as rats given fentanyl–nitrous oxide demonstrate an identical electrophysiologic pattern (electroencephalogram decreased to $\delta$ frequency) compared with animals receiving 1.0 minimum alveolar concentration isoflurane or desflurane. At the end of preparation before termination of isoflurane, all surgical incisions were infiltrated with 0.5% bupivacaine. Thereafter, rats were not exposed to any painful stimuli. Therefore, fentanyl–nitrous oxide seems to provide sufficient analgesia and sedation in rats not exposed to surgical stress. The dose of dexmedetomidine used during the current study results from previous experiments using this ischemia model, where 10 $\mu$g/kg dexmedetomidine produced moderate and 100 $\mu$g/kg dexmedetomidine produced profound improvement of neurologic outcome. Likewise, studies in rats have shown that a hypnotic anesthetic effect, as characterized by loss of righting reflex, occurs at doses greater than 100 $\mu$g/kg dexmedetomidine intraperitoneal. We therefore decided to assess cerebral and peripheral neurotransmitter concentrations using a dose of 100 $\mu$g/kg dexmedetomidine based on our previous experiences and the dose-dependent hypnotic anesthetic action of dexmedetomidine via activation of central $\alpha_2$-adrenoceptors.

In conclusion, dexmedetomidine did not inhibit the intraischemic increase of cerebral extracellular catecholamine or glutamate concentrations, whereas peripheral catecholamine concentrations were suppressed. These data indicate that modulation of cerebral catecholamine and glutamate release is not related to the neuroprotective effect of dexmedetomidine previously demonstrated in this model.

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