Intracarotid Saline Infusion Improves Outcome From Incomplete Ischemia in Rats

William E. Hoffman, PhD; Lawrence Ferguson, MD; Chinamma Thomas, MD; and Ronald F. Albrecht, MD

Previous studies suggest that rheological changes associated with ischemia may produce postischemic hypoperfusion. We tested whether intracarotid or intravenous infusions of saline improve neurological outcome from incomplete cerebral ischemia in rats. Rats were anesthetized with 1.4% isoflurane in air, and ischemia was produced by unilateral carotid artery ligation combined with hemorrhagic hypotension to 30 mm Hg for 30 minutes. Intracarotid (n=10) or intravenous (n=10) saline infusion (0.3 ml/min) decreased hematocrit 20% compared with control rats (n=10). Neurological outcome was significantly improved in rats infused with intracarotid (p<0.05) but not intravenous saline during ischemia without a change in brain temperature. Cerebral blood flow, measured in a separate study using laser Doppler flowmetry (n=5), decreased 70% (p<0.01) during carotid ligation and hypotension but was not changed by intracarotid saline infusion (p>0.30). These results show that perfusion of ischemic brain with saline improves outcome by factors not related to changes in hematocrit, brain temperature, or intraischemic tissue blood flow.

It has been suggested that rheological factors contribute to ischemic injury. Increased blood viscosity, platelet aggregation, and the accumulation of polymorphonuclear leukocytes may worsen ischemic perfusion and produce delayed postischemic hypoperfusion.1-3 Hypervolemic hemodilution has been reported to improve neurological outcome from stroke by improving blood flow and brain tissue oxygenation.4 However, these results are controversial.5-6 Another possibility is that direct perfusion of the ischemic vasculature with nonblood solutions may improve outcome by removing metabolic byproducts and/or pathophysiological blood components. We evaluated whether the intravenous or intracarotid infusion of saline during incomplete ischemia improves neurological outcome in rats and whether this effect is mediated by alterations in brain temperature or brain blood flow.

Materials and Methods

These experiments were performed following approval from the Institutional Animal Care Committee. Thirty-five nonfasted male Sprague-Dawley rats weighing 350–450 g were anesthetized in a bell jar with isoflurane, their tracheae were intubated, and their lungs were mechanically ventilated with 2% isoflurane in room air. Catheters were inserted into one femoral artery and both femoral veins for continuous blood pressure monitoring, blood sampling, and drug and fluid administration. A catheter was inserted into the right jugular vein for blood withdrawal during ischemia. The right common carotid artery was isolated. Vecuronium was given as a continuous infusion (0.1 mg x kg⁻¹ x min⁻¹) to maintain paralysis. The rats were equilibrated with 1.4% inspired isoflurane in room air for 30 minutes.

In group 1 (n=10) the right carotid artery was ligated. These rats served as controls for the saline groups. In Group 2 (n=10) the right carotid artery was isolated and ligated, and these rats were infused with 0.3 ml/min i.v. normal saline during the 30-minute ischemic period. In group 3 (n=10) the right carotid artery was isolated and catheterized with a saline-filled PE50 tubing catheter. The catheter extended 5 mm into the artery, and the lumen was placed at the level of the carotid bifurcation. The catheter was tunneled subcutaneously 12 cm and exited from a small incision in the back to equilibrate the saline to body temperature. This catheter was infused with 0.3 ml/min normal saline during the 30-minute ischemic period. In groups 2 and 3, the saline syringes were warmed to body temperature using an overhead heating lamp before infusion. The temperature of the saline infusate was 37°C. In all groups the carotid ligation was not removed.

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A score of 0 represents no detectable neurological deficit, and a score of 18 represents stroke-related death. Stroke-related death was determined a minimum of 3 hours following extubation only if the rat showed progressive signs of stroke impairment. The evaluators were blinded to the rat's group.

Those rats surviving the 3-day evaluation period were anesthetized with isoflurane and killed by transcardiac perfusion of 20 ml isotonic saline followed by 20 ml 10% buffered formalin. Following removal, the brain was stored in formalin over 8 days for subsequent histological examination. The forebrain was dissected into coronal blocks and imbedded in paraffin, and 7-μm sections were cut and mounted on slides. The slides were stained using hematoxylin and eosin and examined in a blinded manner by a neuropathologist using light microscopy. Neuronal histopathology was evaluated at the levels of the caudate nucleus and hippocampus. The caudate section was graded on a six-point scale according to the following markers: 0, no observable neuronal death; 1, scattered neuronal death; 2, small focal infarcts in the caudate and cortical areas; 3, large infarcts involving 50% of the ischemic caudate; 4, infarcts involving at least 50% of the total ischemic hemisphere; and 5, total hemispheric infarction. Brain tissue damage of the hippocampal section was graded using a five-point scale according to the following markers: 0, no damage; 1, 0–50% of ischemic hemisphere's hippocampus pyramidal cells injured; 2, 50–100% of ischemic hemisphere's hippocampus pyramidal cells injured; 3, 50% of ischemic hemisphere infarcted; and 4, 100% of ischemic hemisphere infarcted. The histopathology score is the total of the score for the caudate section and the score for the hippocampal section.

To evaluate whether intracarotid saline infusion altered ischemic blood flow or brain temperature, additional studies were performed in five rats. Brain and skull temperatures were measured separately using needle thermistor probes (Yellow Springs Instrument Co., Yellow Springs, Ohio). Brain perfusion was evaluated using a Perimed laser Doppler device (Stockholm, Sweden). The rats were surgically prepared for intracarotid saline infusion and unilateral ischemia as described above. The head of each rat was placed in a Kopf rat head holder. The skull was exposed, and two 1-mm holes were drilled in the skull over the forebrain ipsilateral to the carotid ligation. A thermistor probe and laser Doppler needle probe were inserted 3 mm into the tissue through separate holes. After the rat had stabilized for 30 minutes, hemorrhagic hypotension to 30 mm Hg was induced for 10 minutes. At the end of 10 minutes the intracarotid saline infusion was started at a rate of 0.3 ml/min and continued for 10 minutes with continued hypotension. At the end of this time, the intracarotid saline infusion was stopped and hypotension was continued for an additional 10 minutes. At the end of this period the withdrawn blood was reinfused, and final brain temperature and perfusion measurements were made 20 minutes later. The rat was then killed.
TABLE 2. Arterial Blood Pressure, Blood Gas Tensions, pH, Plasma Glucose Concentration, and Hematocrit During Ischemia in Rats

<table>
<thead>
<tr>
<th>Group</th>
<th>Blood pressure (mm Hg)</th>
<th>PaCO₂ (mm Hg)</th>
<th>PaO₂ (mm Hg)</th>
<th>pH</th>
<th>Plasma glucose (mg/100 ml)</th>
<th>Hematocrit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>68±4</td>
<td>37.6±0.8</td>
<td>84±4</td>
<td>7.40±0.01</td>
<td>190±4</td>
<td>42±1</td>
</tr>
<tr>
<td>Ischemia</td>
<td>30±1*</td>
<td>38.8±0.8</td>
<td>81±6</td>
<td>7.38±0.01</td>
<td>325±20*</td>
<td>30±1*</td>
</tr>
<tr>
<td>Recovery</td>
<td>77±4</td>
<td>39.3±0.8</td>
<td>68±3</td>
<td>7.39±0.01</td>
<td>222±17</td>
<td>39±1</td>
</tr>
<tr>
<td>Intravenous saline (n = 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>65±2</td>
<td>39.3±0.8</td>
<td>84±3</td>
<td>7.40±0.01</td>
<td>181±5</td>
<td>42±1</td>
</tr>
<tr>
<td>Ischemia</td>
<td>30±1*</td>
<td>38.1±0.9</td>
<td>8.9±3</td>
<td>7.37±0.01</td>
<td>266±15*</td>
<td>24±1*†</td>
</tr>
<tr>
<td>Recovery</td>
<td>85±4*</td>
<td>38.0±0.9</td>
<td>69±3</td>
<td>7.41±0.01</td>
<td>169±13</td>
<td>38±1</td>
</tr>
<tr>
<td>Intracarotid saline (n = 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>68±3</td>
<td>36.9±0.9</td>
<td>85±3</td>
<td>7.41±0.01</td>
<td>180±7</td>
<td>41±1</td>
</tr>
<tr>
<td>Ischemia</td>
<td>30±1*</td>
<td>26.1±0.9</td>
<td>93±3</td>
<td>7.37±0.01</td>
<td>304±18*</td>
<td>23±1*†</td>
</tr>
<tr>
<td>Recovery</td>
<td>93±3*</td>
<td>37.2±0.8</td>
<td>67±3</td>
<td>7.38±0.01</td>
<td>213±15</td>
<td>37±1</td>
</tr>
</tbody>
</table>

Data are mean±SEM. *p<0.05 different from baseline condition by two-way analysis of variance. †p<0.05 different from control group by two-way analysis of variance.

Results

Skull temperature remained between 36.5°C and 37°C throughout the study, with no differences between groups. There were also no differences between groups in physiological variables at baseline (Table 2). During ischemia, plasma glucose concentration increased and hematocrit decreased in each group (p<0.05). The decrease in hematocrit was greater in groups 2 and 3 than in group 1 (p<0.05). Spontaneous respiration and extubation occurred 10–15 minutes after turning off the isoflurane, with no differences between groups.

Neurological outcome scores are shown in Figure 1. Five rats in groups 1 and 2 and two rats in group 3 had stroke-related death. The score in group 3 was significantly better on day 3 than the score in group 1 (p<0.05). The histopathology scores of the five rats that survived in group 1 were 1, 1, 4, 5, and 8; scores in the five rats that survived in group 2 were 0, 1, 2, 5, and 8. Scores for the eight surviving rats in group 3 were 0, 0, 0, 1, 1, 2, 5, and 9. Although the histopathology scores suggested less neuronal damage with intracarotid saline perfusion, this difference with an overdose of the anesthetic. Arterial blood gases and pH during ischemia were controlled as described above. Skull and brain temperatures and Doppler perfusion units were measured continuously and recorded at the end of each condition.

Data are reported as mean±SEM. Nonparametric data including neurological outcome score and histopathology score were compared between the control and experimental groups using a Kruskal-Wallis analysis. Physiological data were analyzed using a two-way analysis of variance. A repeated-measures analysis of variance was used to evaluate condition effects for the laser Doppler study. Tukey's tests were used for post-hoc comparisons between groups and conditions. Significance was assumed at p<0.05.

![Figure 1. Bar graphs of neurological outcome score in control (top), intravenous saline-perfused (middle), and intracarotid saline-perfused (bottom) rats. Individual scores for each rat are shown for 3 days. There was significant difference between control group and group receiving intracarotid saline over scoring period (p<0.05).](http://stroke.ahajournals.org/content/images/2017/09/24/fig1.png)
was not significant ($p>0.05$). There was no neuronal injury in the nonischemic hemisphere in rats from any group. There was a significant correlation between neurological outcome score and histopathology score in the ischemic hemisphere ($r=0.46$, $p<0.05$).

In the study of brain temperature and blood flow during ischemia and intracarotid saline infusion, blood gas tensions and pH were maintained at baseline levels. The results shown in Table 3 indicate that ischemia reduced brain perfusion by 70%, which was not significantly altered by intracarotid saline infusion. Brain and skull temperatures did not change significantly during any condition.

**Discussion**

The results of this study show that an intravenous saline infusion during incomplete cerebral ischemia in rats decreases hematocrit but does not improve neurological outcome compared with control rats. This is consistent with clinical reports that normovolemic or hypervolemic hemodilution does not improve outcome from stroke.$^{5,6}$ The intracarotid infusion of saline during ischemia significantly improved neurological outcome compared with the control group, without changes in brain temperature or tissue perfusion. Since hematocrit was decreased to the same levels in groups 2 and 3, we conclude that the improvement in outcome in group 3 was due to the infusion of saline into the ischemic zone rather than to hemodilution. Intracarotid saline infusion may improve outcome by increasing local perfusion pressure in the ischemic zone. Although this treatment does not increase cerebral blood flow, it may improve blood flow distribution by mechanically opening ischemic blood vessels. This may also wash out ischemic metabolic by-products and ameliorate postischemic hypoperfusion by inhibiting platelet aggregation and the accumulation of polymorphonuclear leukocytes.$^{7,8}$ These actions may be important in limiting postischemic neuronal injury.

In this model of incomplete cerebral ischemia in rats, neurologic outcome worsens until the second day after ischemia and neuronal death progresses for several days after ischemia.$^{7}$ This is consistent with other models of ischemia in which neuronal injury increases for several days after the insult.$^{8}$ Neuronal injury may continue after ischemia because of an accumulation of polymorphonuclear leukocytes in the ischemic zone that inhibits postischemic reperfusion. Polymorphonuclear leukocytes are viscoelastic cells that normally adhere to the endothelium. The deformation and passage of these cells through the capillaries require 1,000 times longer than for red blood cells.$^9$ During low-flow states such as ischemia, polymorphonuclear leukocytes may accumulate, acting as plugs in the ischemic microcirculation.$^{10,11}$ The cells may also degranulate within the capillary, releasing tissue-damaging substances. This is consistent with the results of Grogaard et al.$^3$ who showed that depletion of circulating polymorphonuclear leukocytes before the induction of ischemia improved postischemic reperfusion compared with a control treatment. Mechanical or biochemical obstruction of capillaries during ischemia may be an important mechanism of progressive postischemic neuronal injury.

Besides washout of polymorphonuclear leukocytes, there are other possible mechanisms for the improvement of ischemic outcome with intracarotid saline infusion. Although there was no difference in hematocrit between groups 2 and 3, it is likely that the local hematocrit in ischemic tissue was decreased with intracarotid saline infusion. This may improve metabolite and ion or fluid exchange between the vascular and tissue spaces and decrease edema formation. Intracarotid saline infusion may also improve tissue perfusion by increasing the local perfusion pressure. We did not see a significant change in ischemic tissue perfusion with intracarotid saline infusion using laser Doppler flowmetry. The perfusion units so measured are a function of the number of red blood cells and their velocity within the illuminated area (1–2 mm$^2$). This technique does not measure absolute blood flow but produces a close correlation of changes in regional blood flow with other techniques such as $[14C]$iodoantipyrine autoradiography.$^{12}$ Our results indicate that intracarotid saline infusion does not change blood flow within the ischemic zone.

Another possibility is that intracarotid saline infusion may improve the oxygenation of ischemic tissue. Blood flow to the ischemic forebrain (1 g tissue) is approximately twice the saline infusion rate.$^{13,14}$ However, not all of the saline infused would reach the ischemic brain since we are infusing into the common carotid artery. Oxygen dissolved in the saline would provide $<1\%$ of the oxygen carried by the blood flow to the ischemic hemisphere. This indicates that the oxygen carried by the saline is probably not an important factor for decreasing ischemic injury. However, an increase in the intravascular filling pressure may enhance oxygenation by opening more capillaries for perfusion without changing red blood cell velocity.

It is unclear whether hemodilution improves outcome following acute stroke. Koller et al$^4$ reported that hypervolemic hemodilution in patients with
acute ischemic stroke improved outcome up to 90 days after ischemia. Harrison et al. also saw a positive correlation between hematocrit and cerebral infarct size following ischemia. In contrast, other studies have shown no improvement in the stroke outcome of patients treated with normovolemic or hypervolemic hemodilution. Lowering the hematocrit may improve cerebral blood flow and enhance oxygen delivery. Experimental data suggest that a hematocrit of 30–35% provides optimal rheological and oxygen-carrying properties of the blood. However, this may not relate to ischemic stroke. We saw a decrease in hematocrit to 23–24% during ischemia in the saline-perfused rats compared with 30% in the control rats. However, no difference in outcome was seen between the intravenous saline–treated and control rats. We conclude that decreases in hematocrit occur in this model of hypotensive ischemia but that decreases below 30% do not improve outcome.

In conclusion, a significant improvement in neurological outcome from ischemia was observed with intracarotid infusion of saline during ischemia compared with the control treatment. Another group of rats treated with an intravenous saline infusion showed no change in outcome compared with the control rats. The improvement in outcome with intracarotid saline infusion cannot be explained by a difference in measured physiological variables or hematocrit between groups. Intracarotid saline infusion may facilitate the washout of ischemic metabolic by-products or decrease platelet aggregation or the accumulation of polymorphonuclear leukocytes in ischemic tissue. Ischemic perfusion may also be improved by a mechanical effect of increased local perfusion pressure, which may keep blood vessels open and improve blood flow distribution and oxygenation.

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References

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