Cerebral Blood Flow Regulation: Vascular Resistance Adjustments in the Circle of Willis

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SUMMARY Continuous measurements of systemic blood pressure (BP), cerebral perfusion pressure and CBF were accomplished in the cat during transient hypertension, hypercapnia and bilateral carotid artery occlusion. From these measurements resistance values in the circle of Willis and in the cerebral arteries distal to the circle were calculated. The results indicate that the arteries of the circle of Willis and the arteries distal to the circle of Willis dilate and contract independently.

THE CIRCLE OF WILLIS and its source arteries provide capacity to shift blood flow from one cerebral hemisphere to the other, to reverse the direction of flow between carotid and basilar arterial systems, and to divert circulation across extracranial-intracranial boundaries. Measurements of flow and pressure in various segments of mechanical models of the circle of Willis and electrical analogues of the system demonstrate that distribution is determined by pressure gradients at various junctions and by resistances in the components of the network of arteries forming the anastomoses. Although spasm of arterial segments has been observed in various pathological conditions, other vasomotor functions of this area are difficult to examine, in an intact state, because of anatomical seclusion. These continuous measurements of cerebral blood flow (CBF), systemic blood pressure (BP) and cerebral supply pressure (CPP) provide a basis for calculations of resistance in the cerebral supply arteries and their anastomoses (Rec), and also in the arteries distal to the circle of Willis (Ric). This was done to demonstrate vasomotor activity in these areas in response to inhaled CO₂, intravenous epinephrine, norepinephrine and angiotensin, and bilateral common carotid artery occlusion.

Methods

All experiments utilized adult mongrel cats conforming to guidelines contained in the Animal Welfare Regulations. CBF was monitored using a thermal diffusion method as described previously. The method provides a continuous relative value for CBF in a 3-mm radius sphere. This flow measurement is used as an index of total hemispheric blood flow supply. CPP is measured as lingual artery or carotid wedge pressure. Ric represents total resistance between the circle of Willis and the venous return, although it is in fact derived from caudate regional flow and the pressure drop between the circle of Willis and the venous return. It parallels the total cerebral vascular resistance only as well as the flow in the caudate parallels total hemispheric flow. Since the resistance values are based on calculations derived from pressure and relative flow measurements, they have no precise numerical value, but reflect proportional changes in brain vascular resistance (Ric) and collateral vascular resistance (Rec).

K = max df at zero flow

When a zero flow level is established, increases in flow can be calculated as a function of increases above average flow.

Procedure

Under light nembutal anesthesia (30 mg per kilogram), a cannula was threaded into the inferior vena cava for instillation of cold saline. The cannula and the definitive arterial catheters were placed under light local anesthesia. Once the arterial catheters were placed and in position, the cat was placed in a plastic hood to maintain stable temperature relationships. This can be verified by applying the experimental condition with probes in place, unheated. If during induced blood flow change the thermocouple indicates no gradient between junctions, the experiment is continued. Subsequently, absolute brain temperature is constantly monitored at the reference thermal junction as an index of ambient brain temperature. When this precaution is maintained, the heating current parallels blood flow. Results under these conditions show complete reproducibility from one test animal to another.
FIGURE 1 The source of potential error when the environment of the reference junction varied from the environment of the heated junction was plotted as a function of the change in power required to maintain gradient at 1.5°C (— — — —) and at 2.5°C (— — — —).

FIGURE 2 CO₂ indicates beginning of CO₂ inhalation. As CBF rose, brain resistance decreased and the collateral resistance remained unchanged.

FIGURE 3 The effect of angiotensin began after one minute of control period. Brain resistance increased and paralleled systemic BP elevation.

The increase in CBF during CO₂ inhalation occurs as a result of dilation of cerebral arteries, i.e., there is a marked reduction of Ric while Rec remains stable (fig. 2).

RESPONSES TO DRUG-INDUCED HYPERTENSION

Each of three agents (epinephrine, norepinephrine and angiotensin) were given intravenously in a single bolus to produce transient 50% increase in systemic BP. The patterns of pressor response to each were not alike. Maximum response to angiotensin occurred more gradually than the response to either epinephrine or norepinephrine, and was persistent for four to five minutes. BP elevation after a single injection of norepinephrine dissipated in one to two minutes and gradually reached control level. BP elevation after a
single injection of epinephrine was apt to last less than one
minute and then fall below control levels.

A marked increase in Ric occurred almost simultaneously
with the elevation of systemic BP and CPP following angiotensin infusion. This limited the increase in CBF. Rec remained unchanged (fig. 3). BP and CPP were maintained at maximum for approximately 45 seconds, then there was a gradual return to baseline during the next three minutes. The small increase in CBF caudate began to decline as peak BP rise receded. During the three-minute interval when systemic and perfusion pressures were greater than control levels, CBF caudate fell below control value as a result of residual
increase in Ric.

There was minimal change in CBF after a single injection
of epinephrine (fig. 4). The rise in systemic BP caused an im-
mediate and a marked increase in Ric; it peaked in eight to
ten seconds. There was also a slight rise in Rec with a max-
imum increase at 15 seconds. This peak of Rec increment
occurred after Ric had begun to fall and had dropped below
control levels. Both Ric and Rec then remained below con-
control levels for two minutes. During this interval when BP and
CPP remained below control levels, CBF was stable, since
the reduced level of resistance offset the effect of relative
hypotension.

Pressure increase after single injection of norepinephrine
resulted in prompt increase in Ric. CBF rose slightly during
the hypertensive period. Increased Ric began to dissipate in
less than 30 seconds and resistance reached control levels in
one minute but did not fall below control levels as it did after
epinephrine. Rec was not affected by norepinephrine (fig. 5).

The initial regulatory responses to induced transient
hypertension were simultaneous with a pressure increase in-
duced by all three agents. Vasoconstriction of brain arteries
persisted following peak BP rise, with angiotensin for three
minutes, with norepinephrine for 50 to 60 seconds, and with
epinephrine for only 15 seconds. The changes in brain
resistance (Ric) paralleled each of the systemic BP responses.
The increase in Ric was a nonspecific response to hyper-
tension. This had been demonstrated in the cat and monkey
and in human studies. The additional vasodilator effect of
epinephrine which occurs in the brain may be explained by
either its metabolic action or directly as a result of β-
receptor response.

Pharmacological effects on resistance measurements are
summarized in table 1.

The vasodilating effect of CO₂ inhalation was reversed
during epinephrine-induced or norepinephrine-induced
hypertension. When epinephrine or norepinephrine was
given during a period of hypercapnic vasodilation, the Ric
and Rec responses remained as in a normocapnic state (figs.
6 and 7).

**RESPONSE TO BILATERAL CAROTID OCCLUSION**

Bilateral common carotid artery occlusion initiated a
series of changes in CBF, systemic BP, brain perfusion
pressure and vascular resistance.

The immediate effects were an abrupt and marked in-
crease in vascular resistance in the perfusing arteries (Rec),
a noticeable diminution in CBF caudate, usually in excess of
30%, and a decrease concurrently with flow reduction in
brain vascular resistance (Ric). At the same time systemic
BP rose. As these changes occurred, there was vasodilation
of the circle of Willis and the CBF caudate began to be
restored within ten seconds, systemic BP remained stable,
and resistance in perfusing vessels (Rec) continued to
decline. The increase in CBF caudate was accomplished by
this lowered resistance in Rec. After 30 to 40 seconds a

**Table 1 Pharmacologic Effects on Resistance Measurements**

<table>
<thead>
<tr>
<th>Agent</th>
<th>Immediate response (&lt;20 seconds)</th>
<th>Late response (&gt;20 seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angiotensin</td>
<td>Ric +</td>
<td>Ric +</td>
</tr>
<tr>
<td></td>
<td>Rec 0</td>
<td>Rec 0</td>
</tr>
<tr>
<td>Epinephrine</td>
<td>Ric +</td>
<td>Ric -</td>
</tr>
<tr>
<td></td>
<td>Rec +</td>
<td>Rec 0</td>
</tr>
<tr>
<td>Norepinephrine</td>
<td>Ric +</td>
<td>Ric +</td>
</tr>
<tr>
<td></td>
<td>Rec 0</td>
<td>Rec 0</td>
</tr>
</tbody>
</table>

+ = increase, − = decrease, and 0 = no change.
steady state was maintained; CBF caudate sometimes remained slightly below the control level, systemic BP remained elevated, Ric increased slightly or remained stable, and Rec decreased slowly. Upon release of occlusion, systemic BP promptly fell back to the control level, and collateral (CPP) artery pressure was restored. Vascular resistance in perfusing arteries (Rec) reached the pre-occlusion level in ten seconds. However, brain vascular resistance (Ric) rose slowly and, until it reached control level, CBF caudate sometimes exceeded pre-occlusion levels. A gradual return to baseline values occurred within one to two minutes of release of occlusion (fig. 8).

The immediate response to bilateral carotid occlusion was the opening of collateral channels including the circle of Willis. This partially restored CBF. Additional increases in CBF occurred as Rec was further reduced in spite of a slight increase in Ric.

**Conclusion**

The arteries in the brain contract and dilate independently of the arteries of the circle of Willis and its supply channels.

**References**

Cerebral blood flow regulation: vascular resistance adjustments in the circle of Willis.
L L Levy, J D Wallace, J A Stolwijk and E R Poindexter

Stroke. 1976;7:147-150
doi: 10.1161/01.STR.7.2.147

Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0039-2499. Online ISSN: 1524-4628

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World Wide Web at:
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