Response of the Cerebral Circulation in Baboons to Changing Perfusion Pressure after Indomethacin

John D. Pickard, Lindsay A. MacDonell, Eric T. MacKenzie, and A. Murray Harper

SUMMARY An earlier study has demonstrated that indomethacin, a prostaglandin synthesis inhibitor, blocks the cerebrovascular response to hypercapnia. This response is believed to be mediated by a lowering of pH in the cerebral interstitial fluid. Should autoregulation of cerebral blood flow (CBF) to changing perfusion pressure also be mediated by a changing interstitial pH (the "metabolic" theory), then indomethacin should impair autoregulation. This hypothesis was tested in anesthetized baboons. CBF was measured by the intracarotid 133 Xe clearance technique; the preparation and the indomethacin protocol were identical to those of our previous investigation. Arterial pressure was increased by the intravenous infusion of angiotensin and decreased by controlled hemorrhage. Indomethacin was given by continuous infusion into the internal carotid artery. Although it reduced resting CBF, the cerebrovascular response to changing perfusion pressure was unchanged. Because indomethacin affects the metabolic response to changing CO2 but not that to changing perfusion pressure, the mechanisms for these two reactions presumably are different and it is improbable that changing interstitial pH is responsible for autoregulation in the cerebral circulation.

CEREBRAL BLOOD FLOW is maintained relatively constant despite moderate changes in perfusion pressure, a phenomenon that commonly is termed autoregulation. Apart from possible neurogenic influences, there are two main hypotheses to account for autoregulation within the cerebral circulation: the myogenic and the metabolic. The myogenic theory asserts that cerebral smooth muscle will constrict in response to an increase in transmural pressure, and relax following a reduction in pressure. This (the Bayliss effect) adjusts cerebrovascular resistance to changing perfusion pressure and tends to maintain constant blood flow within the brain. The metabolic theory asserts that autoregulation is a function of changes in metabolite concentration around the cerebral resistance vessels. The metabolite most commonly implicated is the cerebral interstitial fluid hydrogen ion.

It is widely believed that the increase in cerebral blood flow (CBF) induced by hypercapnia is due to a concomitant increase in the hydrogen ion concentration of the cerebral interstitial fluid. Indeed, it has been demonstrated that pial arteries will respond to local variations in hydrogen ion concentrations; acidity dilates and alkalinity constricts.

Dissociated vasoparalysis is a well described clinical condition in which the cerebrovascular response to hypercapnia is impaired and that to changing perfusion pressure is intact (or vice versa). This phenomenon has been noted in a variety of different pathological conditions, suggesting that these two responses are not mediated by a common mechanism. An agent that selectively abolishes either the hypercapnic response or autoregulation might lead to some further understanding of the fundamental physiological responses of the cerebral circulation, as well as to further understanding of the mechanisms involved in dissociated vasoparalysis. Indomethacin, a potent inhibitor of prostaglandin synthesis, has been shown greatly to impair the increase in CBF associated with hypercapnia.

From the Medical Research Council Cerebral Circulation Group, University of Glasgow, Department of Neurosurgery, Southern General Hospital, Glasgow, and the Wellcome Surgical Research Institute, Glasgow, Scotland.

Dr. MacDonell's present address is: Department of Pharmacology, Dalhousie University, Halifax, Nova Scotia, Canada.

Supported by a grant from the Medical Research Council. Dr. MacKenzie was supported by a grant from Tenovus (Scotland).

Received March 9, 1976; accepted for publication September 10, 1976.
the effects of the intracarotid infusion of indomethacin on autoregulation within the cerebral circulation were studied in anesthetized baboons. It was hoped that this might help to distinguish between the fundamental mechanisms involved in autoregulation and those involved in the CO₂ responsiveness of the cerebral vasculature. The debate over whether or not indomethacin affects autoregulation of renal blood flow was a further stimulus to this work.15, 12

Methods

Eight baboons (Papio anubis and Papio cynocephalus), weighing approximately 10 kg, were sedated with phencyclidine (12 mg, im) and anesthesia was induced with thiopental sodium (7.5 mg/kg, iv). After endotracheal intubation, anesthesia was maintained with 75% N₂O and 25% O₂ through an intermittent positive-pressure ventilator in open circuit. This was supplemented by half-hourly injections of phencyclidine (2–4 mg, im), and muscular relaxation was ensured by administration of suxamethonium chloride (50–100 mg, im). End-tidal carbon dioxide tension was monitored continuously by an infrared analyzer.

Normocapnia (arterial Pco₂ = 40 mm Hg) was maintained around 37°C by heating lamps. Body temperature was measured the infusion was interrupted for 20 seconds to inject the 133 Xe. Then the infusion was restarted after the withdrawal of a small volume of blood so that no secondary washout of 133 Xe occurred.

ExPERIMENTAL DESIGN

The lower range of autoregulation was examined by subjecting the baboons to stepwise bleeding. Great care was taken to ensure that the MAP was not reduced by more than 40% from the baseline MAP because retransfusion, after greater falls in MAP, may be accompanied by a reactive hyperemia and abolition of autoregulation within the cerebral circulation.4, 16

The upper range of autoregulation was tested by increasing MAP by using an intravenous infusion of angiotensin. Angiotensin, as opposed to norepinephrine, was used because the former has been shown to be without effect on either CBF or cerebral oxygen consumption.17 The initial concentration of angiotensin employed was 5 × 10⁻⁸ g/ml but, as tachyphylaxis commonly developed, somewhat higher doses were necessary to achieve a stable level of hypertension. Excessive infusions of fluid were avoided by increasing the concentration of angiotensin.

Again, care was taken to ensure that the MAP did not exceed 40% above the baseline value during the angiotensin infusion, because this figure is close to the “breakthrough” of autoregulation in anesthetized baboons.18

Autoregulation to induced hypertension was examined in six baboons and autoregulation to induced hypertension in four, both before and during the infusion of indomethacin. In two baboons both the upper and lower ranges of autoregulation were examined. In all baboons, whether or not indomethacin affects autoregulation within the cerebral circulation was studied in anesthetized baboons. It was hoped that this might help to distinguish between the fundamental mechanisms involved in autoregulation and those involved in the CO₂ responsiveness of the cerebral vasculature. The debate over whether or not indomethacin affects autoregulation of renal blood flow was a further stimulus to this work.15, 12

Statistical analysis was performed in two ways. First, the figures for CBF, cerebral oxygen consumption, and other measured variables were divided into equal MAP bins.
(61–70 mm Hg, 71–80 mm Hg, etc.) and Student's *t*-test analysis was performed between bins for all parameters. Second, linear regression analysis of cerebrovascular resistance (CVR) against MAP was performed by the least squares method, thus allowing further comparison between the control and indomethacin values. An analysis of covariance was used to test for similarity of the two regression slopes. CVR was defined as: \( \text{CVR} = \frac{(\text{MAP} - \text{SSP})}{\text{CBF}} \).

**Results**

CBF was always measured at least 20 minutes after the indomethacin infusion was begun. Indomethacin, by itself, had no effect on arterial Pco2 or end-tidal CO2 tension. Approximately 1 minute after the intracarotid indomethacin infusion was started the sagittal sinus pressure (SSP) began to decrease, the maximum decrease being seen about 10–15 minutes later.

The autoregulatory response of the cerebral circulation obtained prior to indomethacin infusion can be seen in the upper section of Figure 1. Intracarotid indomethacin infusion significantly reduced the absolute value of CBF at all levels of MAP by an average of 32%. The mean and standard errors for all the observations of CBF and calculated CVR in each bin are listed in Table 1, which also includes the results of the Student's analyses. The bin with 61–70 mm Hg was used for comparison with all the other groups to provide the most stringent condition for this test. Within the range 61–120 mm Hg there was no statistical evidence for a relative change in CBF with changing perfusion pressure, either before or after indomethacin, although the CBF in the bin with 121–130 mm Hg was significantly higher than that of the bin with 61–70 mm Hg in the indomethacin-treated baboons. However, linear regression analysis indicated that the overall slope of this CVR/MAP relationship was not significantly altered by indomethacin; only the intercept was changed.

The regression equations found for CVR against MAP were:

- **Control:** CVR = 0.42 + 0.010 MAP (r = 0.52; *P* < 0.001).
- **Indomethacin:** CVR = 0.73 + 0.013 MAP (r = 0.62; *P* < 0.001).

The gradients of these regression equations are not significantly different on a test of covariance (F = 0.75; *P*, not significant) (Fig. 2).

No significant changes in cerebral oxygen consumption

<table>
<thead>
<tr>
<th>MAP bins (mm Hg)</th>
<th>Cerebral blood flow (ml/100 g per min)</th>
<th>Cerebrovascular resistance (mm Hg/ml per 100 g per min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>59.7</td>
<td>67.3</td>
</tr>
<tr>
<td>± SEM</td>
<td>5.8</td>
<td>3.2</td>
</tr>
<tr>
<td><em>P</em></td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Indomethacin†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>41.2</td>
<td>43.4</td>
</tr>
<tr>
<td>± SEM</td>
<td>3.8</td>
<td>3.6</td>
</tr>
<tr>
<td><em>P</em></td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* *P* value, when compared to the bin with 61–70 mm Hg. NS = not significant.
† Indomethacin infusion = 0.2 mg/kg per min; total dose of 10–36 mg/kg.
occurred, either at differing levels of MAP or between control and indomethacin values at any given MAP (Table 2). It was noticeable, however, that during indomethacin infusion the cerebral oxygen consumption, at the lower levels of MAP, was reduced from baseline values. This might be ascribed to methodological errors in the estimation of low oxygen saturation (in this instance, venous saturation) with the instrument used (Kipp and Zonen). However, reduction in cerebral oxygen consumption, with decreasing perfusion pressure, has been noted in other animal models and may not be an artifact. This point requires further elucidation.

Carotid angiography in three baboons demonstrated that indomethacin had no major occlusive effect on the larger visible intracranial vessels, even during hypercapnia when its effect on CBF was greatest.

Discussion

The results of this study demonstrate that indomethacin, a potent inhibitor of prostaglandin synthesis, does not affect the cerebral circulatory response to changing perfusion pressure, although the absolute values of CBF are lowered. The upper limit of autoregulation possibly was lowered during the infusion of indomethacin, but this effect might be seen with all vasoconstrictor agents, since the capacity for further vasoconstriction could be limited. It is not clear what criteria can be used to identify a minor impairment of autoregulation in a vasoconstricted vascular bed. Perhaps comparison with the cerebral circulation constricted by hypocapnia would be a suitable test: however, the upper limit for autoregulation during hypocapnia is not accurately known. The methods used in the present study cannot be used to demonstrate whether transient cerebrovascular responses to changes in perfusion pressure were affected by indomethacin.

Other conditions, such as carotid ligation and serotonin-induced internal carotid artery spasm, which impair the cerebral circulatory CO2 response, tend to abolish or radically alter the vascular responses to changes in perfusion pressure within the brain. Even so, there was no angiographic evidence to suggest that any occlusion of either the internal carotid artery or the major intracranial vessels resulted from the intracarotid administration indomethacin.

Fujishima and his colleagues have shown that a reduction in brain metabolism is associated with not only a reduced CBF but also a markedly reduced response to CO2, a finding that recently has been confirmed. However, indomethacin would appear to have no effect on the overall metabolic activity of the brain and thus reduced cerebral metabolism cannot account for the dissociation between the effect of indomethacin on the CO2 response and on autoregulation.

Despite the poor penetration of indomethacin into the brain (blood-brain partition coefficient of 0.02) and its high binding to plasma proteins (90%), the dose of indomethacin used in these experiments should be sufficient to block prostaglandin synthesis within the brain (concentration required to inhibit 50% of the prostaglandin synthase activity in rabbit brain homogenates is 3.6 μM). This has been demonstrated in the spinal cord and cerebrospinal fluid of the cat and cerebral cortex of the rat. It remains to be demonstrated that this is true in the baboon.

TABLE 2 Values of Cerebral Oxygen Consumption at Different Levels of Mean Arterial Blood Pressure (MAP) before and during Intracarotid Infusions of Indomethacin

<table>
<thead>
<tr>
<th>MAP bins (mm Hg)</th>
<th>61-70</th>
<th>71-80</th>
<th>81-90</th>
<th>91-100</th>
<th>101-110</th>
<th>111-120</th>
<th>121-130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral oxygen consumption (ml O2/100 g per min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>3.45</td>
<td>3.04</td>
<td>2.97</td>
<td>2.98</td>
<td>3.25</td>
<td>2.79</td>
<td>2.95</td>
</tr>
<tr>
<td>± SEM</td>
<td>0.34</td>
<td>0.64</td>
<td>0.37</td>
<td>0.23</td>
<td>0.20</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td>n</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>13</td>
<td>11</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Indomethacin*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>2.59</td>
<td>3.30</td>
<td>2.77</td>
<td>3.02</td>
<td>2.87</td>
<td>2.84</td>
<td>2.90</td>
</tr>
<tr>
<td>± SEM</td>
<td>0.25</td>
<td>0.18</td>
<td>0.14</td>
<td>0.47</td>
<td>0.47</td>
<td>1.04</td>
<td>0.40</td>
</tr>
<tr>
<td>n</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>P*</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* Indomethacin infusion = 0.2 mg/kg per min; total dose of 10-36 mg/kg.
† P values for control vs. indomethacin. NS = not significant.
The time course of on and off effects on blood flow was similar in brain to that described for the kidney, where it is possible to demonstrate that the time course of the reduction in prostaglandin output mirrors that of reduction in blood flow. A preliminary report by Vlahov suggests that prostaglandin \( F_2 \alpha \) will reverse the effect of indomethacin on CBF in the cat. Our own unpublished data indicate that niflumic acid (Squibb), an inhibitor of prostaglandin synthesis that is chemically unrelated to indomethacin, mimics the action of the latter agent on the cerebral circulation.

Of the other, reported actions of indomethacin, none appears to explain the effect of indomethacin on the cerebral circulation. Both Flower and Pace-Acsiak and Cole draw attention to the fact that indomethacin can influence a variety of prostaglandin-metabolizing enzymes. The large reduction in levels of prostaglandins produced by indomethacin in the central nervous system of cat and rat suggest that this is not, overall, the significant mechanism. Furthermore, the prostaglandin dehydrogenases, whose inhibition would directly affect levels of active prostaglandins, are not affected except at much higher doses of indomethacin than enzymes that act later in the degradative pathway. As recently discussed by Flower and by Ryan and Zimmerman, all other effects of indomethacin occur at much higher doses. Of those actions not mentioned by these authors, the effects on calcium and other ionic fluxes in various human and guinea pig tissues required indomethacin concentrations of the order of 0.5 \( \mu \)M. Non-narcotic analgesics, including indomethacin, increase the potassium permeability and decrease the chloride permeability in molluscan neurons, but again concentrations around 1 \( \mu \)M were required. Such membrane phenomena — when applied to the in vivo situation — would predict that indomethacin would result in vasodilation, not vasoconstriction as observed in the present study.

Both Tuvemo and Wide and Terragno and co-workers have demonstrated vascular wall synthesis of prostaglandins; when this synthesis is blocked by indomethacin the tone of the vessel is reduced. Very similar findings have been noted in the bovine middle cerebral artery. In keeping with the results from experiments in vitro, Vlahov and Betz found that indomethacin caused dilation of the pial arteries in cats when infused into the perivascular space surrounding these vessels. It is difficult to reconcile the unanimity of evidence from the basic studies described above with the finding of indomethacin-induced vasoconstriction in the whole organ situation. Apart from species differences, one possibility might be that the large arteries that supply the brain may not react in the same way as the parenchymal arteriolar vessels to vasoactive agents. This would appear to be the case for compounds such as norepinephrine and 5-hydroxytryptamine. From such studies has arisen the hypothesis that the intraparenchymal arteriolar vessels are governed primarily by local metabolic factors, whereas the extra parenchymal arteriolar (the inflow tract to the brain) are affected by humoral and neurogenic factors. Although the evidence is not strong, it is possible that the pial vessels fall into the latter category. This possibility is worthy of further attention, because one of the attractions of the pial vessel micropuncture technique is that the underlying cerebral metabolism is thought to be minimally disturbed, as pointed out by Wahl et al. Therefore, it is possible that the site of action of the indomethacin-induced vasoconstriction is at the level of the cerebral arterioles within the parenchyma.

It has been shown previously that indomethacin can effectively block the cerebrovascular responses to hypercapnia. Accordingly, we think it is unlikely that carbon dioxide (or the interstitial fluid hydrogen ion concentration) can be involved in the cerebrovascular response to changing perfusion pressure. However, this finding does not preclude other metabolic mediators such as potassium, adenosine, or other nucleotides from being involved in autoregulation.

Acknowledgments

We are grateful to Merck Sharp and Dohme for the generous donation of indomethacin, to the staff of the Wellcome Surgical Research Institute, University of Glasgow, for nursing and technical assistance. We also thank J. Rubython and W. McDermd for typing the manuscript.

References

blood flow autoregulation at high arterial pressures and different levels of carbon dioxide tension in dogs. Eur Neurol 6: 6-10, 1972
Response of the cerebral circulation in baboons to changing perfusion pressure after indomethacin.

J D Pickard, L A MacDonell, E T MacKenzie and A M Harper

Circ Res. 1977;40:198-203
doi: 10.1161/01.RES.40.2.198

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1977 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/40/2/198

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org/subscriptions/