The Effects of Increased Intracranial Pressure on Flow Through Major Cerebral Arteries In Vitro

BY J. K. FARRAR, JR., AND MARGOT R. ROACH, M.D., PH.D.

Abstract: The effect of transmural pressure (TMP) (intraluminal minus extraluminal pressure) on flow was measured for 26 isolated major cerebral arteries from human autopsies. The maximum flow rate through an artery was determined by the perfusion pressure (PP), the maximum vessel caliber, and the presence and magnitude of external resistances. Assuming a diastolic PP of 85 mm Hg, intracranial pressure increases above 33 ± 2 SEM mm Hg (45 ± 3 cm H2O) resulted in a reduction of flow through these arteries. For atherosclerotic arteries, flow was reduced by 50% at a TMP of 12 ± 1 mm Hg; for nonatherosclerotic arteries, the critical TMP for 50% flow reduction was 20 ± 1 mm Hg. Flow ceased at a TMP of +3 mm Hg for small (cerebellar) arteries to −7 mm Hg for large (posterior cerebral) arteries. For grossly atherosclerotic arteries, this closing pressure was as low as −15 mm Hg. When two arteries were cannulated and perfused in parallel, preferential flow reductions of up to 50% were noted in one of the arteries with no flow change in the other at the same TMP. This preferential narrowing depended on the relative sizes and degree of atherosclerosis of the two arteries.

Wall thickness to lumen diameter ratios were obtained for all arteries and their relevance to the possibility of active closure was discussed.

Additional Key Words
- atherosclerosis
- subarachnoid hemorrhage
- cerebral blood flow
- cerebrovascular hemodynamics
- perfusion pressure
- wall/lumen ratio

Introduction

The narrowing of a cerebral vessel can occur in two ways which we will call active and passive. The term "active narrowing" (often called spasm) refers to narrowing caused by the contraction of smooth muscle cells in the arterial wall, whereas the term "passive narrowing" will be used to describe the decrease in vessel diameter caused by a reduction of the forces acting to distend the walls. This paper will describe the passive narrowing of human cerebral vessels obtained from autopsies.

Since brain arteries behave like distensible tubes, their internal diameter is determined by the difference between intraluminal and extraluminal pressures (i.e., the force distending the walls), as well as by the smooth muscles in the arterial wall. In this case, the intraluminal and extraluminal pressures are the arterial blood pressure and the cerebrospinal fluid (CSF) pressure, respectively, and the difference between the two will be termed the transmural pressure (TMP).

According to Poiseuille's law, $F = \Delta P / R$, where $F$ is the flow, $\Delta P$ is the internal pressure gradient, and $R$ is the resistance of the vessel. The resistance ($R$) is inversely proportioned to the fourth power of the radius ($r$) of the vessel so that we may rewrite Poiseuille's law in the form: $F < \Delta P r^4$. Flow through an artery therefore can be reduced by decreasing the internal pressure gradient or by decreasing the radius ($r$), (i.e., by reducing the TMP and/or contraction of the arterial smooth muscle). Passive reductions in flow occur when the CSF pressure is elevated, thereby lowering the TMP.

Increased intracranial pressure (ICP) is a common occurrence following subarachnoid hemorrhage, subdural hemorrhage, and in the presence of intracranial tumors. It is well known that increased ICP decreases total cerebral blood flow (CBF), which can cause severe anoxia if not corrected.

Kety et al. have shown, on patients with cerebral tumors, that increases in ICP above 450 mm H2O (approximately 35 mm Hg) result in an overall CBF decrease. Langfitt et al. obtained similar results on anesthetized Rhesus monkeys and also found that CBF ceases when ICP equals arterial pressure (i.e., when TMP is zero).
These, and other similar observations, are limited to measurements of total CBF and it is not known whether these flow reductions are the result of capillary, arteriolar, or arterial narrowing. The aim of these in vitro experiments was to study the flow through the major arteries of human circles of Willis under reduced TMP without smooth muscle intervention.

One of us (MRR) has shown theoretically that closure of an artery due to smooth muscle contraction requires a minimum wall thickness to lumen diameter ratio of 0.43 (assuming that these vessels cannot shorten by more than 10%, because of tethering, and that the maximum circumferential smooth muscle contraction is 50%). We have obtained wall to lumen ratios for 26 human cerebral arteries and our results suggest that obstruction of the arterial lumen is not possible by smooth muscle contraction alone unless there is some intraluminal projection, such as an intimal cushion or atherosclerotic plaque, to aid in this closure. We suggest that muscle contraction coupled with reduced TMP (increased ICP) could produce closure of a major cerebral artery as seen clinically in angiograms.

**Methods**

All arteries used in this experiment were human cerebral arteries from the circle of Willis and its branches, obtained at autopsy, and immediately stored in 0.9% (isotonic) saline at ~3°C for at least 24 hours. This procedure eliminated active smooth muscle contraction during the experiment. This fact was verified when repeated attempts to stimulate the arteries with 10^{-4} M 5-hydroxytryptamine and 10^{-4} noradrenaline failed to elicit any response. The arteries were then studied in two groups: one group (10 arteries) in which single arteries were perfused, and the other group (16 arteries) in which two arteries, cannulated in parallel, were perfused simultaneously.

**Perfusion of Single Arteries**

The apparatus (fig.1) consisted primarily of a plexiglass box or housing, to simulate the skull, and inflow and outflow cannulas to mount the artery. The housing was filled with isotonic saline and coupled to a brass cylinder with a micrometer-driven piston. Injections of saline then could be made and the resultant increases in housing pressure (ICP) were monitored by a mercury manometer and recorded by a Statham pressure transducer (Model P23Db). The artery was mounted in the housing and perfused from a constant pressure reservoir (10 liter capacity) of isotonic saline. Flow through the artery was measured with an electromagnetic flowmeter (Carolina Medical) and pressure on both sides of the artery monitored with pressure transducers. All pressure and flow measurements were recorded on a Beckman dynograph (type R). Screw clamps allowed the resistance at either end of the artery (outside the housing) to be varied and the perfusion pressure (intraluminal pressure gradient) could be increased and decreased by raising or lowering the reservoir. In all experiments the housing pressure (ICP) was varied from 0 to 100 mm Hg and each run was repeated two or three times.

**Perfusion of Two Arteries in Parallel**

The apparatus employed was essentially the same as that described above, except that the housing was increased in size to accommodate two arteries cannulated in parallel. Proximal to the arteries in the housing, a glass Y-tube was introduced providing a symmetrical bifurcation (outside the box). Flow and pressure for each artery were measured and recorded as previously described.

**Wall to Lumen Ratios**

At the conclusion of each experiment, all arteries used were fixed in 10% formalin at 100 mm Hg (provided by constant pressure reservoir). The arteries were then sectioned and stained with Gomori-Trichrome. At least four measurements of wall thickness and lumen diameter were made on each section using a traveling microscope, and the results obtained for three such sections were combined to arrive at the average luminal diameter and wall thickness of the artery. Fixation artifacts (shrinkage) probably make our absolute values about 10% too small but, assuming this affects both the wall thickness and lumen diameter, we feel that the ratios obtained are realistic.

**Results**

**The Perfusion of Single Arteries**

**Outflow Pressure**

Initially, it was assumed that the outflow pressure was constant (at 0 mm Hg), but measurements showed that it varied between 0 and 3 mm Hg over the range of flow rates and inflow pressures (0 to 100 mm Hg) used. The difference between the inflow and outflow pressures is the internal pressure gradient or perfusion pressure (PP), that is, \( PP = \Delta P \). Since practically all of the pressure drop occurred across the artery, we can be sure that the

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**FIGURE 1**

Schematic diagram of the apparatus used showing the cannulated artery (A), plexiglass housing (H), reservoir, adjustable clamps (C), mercury manometer (MM), micrometer syringe (MS), flow transducer (FT), pressure transducers (PT), inflow (IF) and outflow (OF).
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Figure 2
This illustrates that the force acting to distend the walls of the artery is the transmural pressure (TMP) (intraluminal \( P_l \) — extraluminal \( P_e \) pressure). This force (TMP) can be reduced by decreasing \( P_l \) or increasing \( P_e \).

artery was providing the major resistance to flow and that changes in flow were due primarily to resistance changes of the artery.

Transmural Pressure (TMP)
The TMP, as previously defined, is the intraluminal minus the extraluminal pressures (fig. 2). The intraluminal pressure is the blood pressure inside the artery and the extraluminal pressure is the pressure of the surrounding fluid. In the cerebral circulation, the extraluminal pressure is the intracranial pressure (ICP) supplied by the CSF (in our experiment, ICP = housing pressure). The intraluminal pressure is not as easily defined. The total pressure drop of the cerebral circulation is the arterial minus the venous blood pressures. The incremental pressure drops along individual arteries, however, are not easily measured and consequently not known. The inflow pressure (aortic arch pressure is approximately equal to carotid pressure) is easily obtainable and is a measure of the force available to keep the vessels open. Since the TMP at the different levels of the circulation cannot be accurately defined, we will use the inflow pressure minus the ICP as a measure of the TMP tending to distend the arteries.

Effect of Perfusion Pressure on Flow (When ICP = 0)
For a rigid tube (constant radius), the flow is directly proportional to the PP which gives rise to a

![Diagram showing the variation of flow with perfusion pressure (PP). At PP greater than 23 mm Hg the artery is maximally distended and flow increases linearly with PP. Below 23 mm Hg, the artery is collapsing and the curve becomes nonlinear.](http://stroke.ahajournals.org/)

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straight line graph with a zero intercept and a slope determined by the resistance of the tube. However, in a distensible and collapsible tube such as an artery, the resistance will vary because the radius changes with TMP. Figure 3 shows that the flow-pressure curve is linear at pressures greater than 25 mm Hg, indicating that the artery is maximally distended and is behaving like a rigid tube. Below 25 mm Hg, the flow-pressure curve becomes nonlinear as the vessel collapses and there are large changes in flow for small PP changes. The question remains as to whether the TMP or the PP is the variable that determines flow.

**Effect of TMP on Flow**

Figure 4 shows the graph of flow versus TMP (solid line) and the flow versus PP curve of figure 3 (dotted line). The area between the curves can be divided into two regions. The area above 23 mm Hg will be called the linear region and that below, the collapsing region.

Consider first the **linear region**. The PP in this region is more than sufficient to maintain the vessel diameter at its maximum value when the ICP in the housing is zero. Since the artery is already maximally distended, any increase in TMP above the PP value (e.g., by making the ICP negative) will not increase the flow. Therefore, as long as the PP is greater than 23 mm Hg, the maximum flow through the artery will be determined by the magnitude of the PP (the maximum flow increases as the PP increases). At any given PP in this region, the TMP may be lowered below the PP value, by increasing the ICP in the housing, and no change in flow occurs until a critical value is reached (e.g., in going from point A to point B on the graph, the TMP is lowered but no change in flow occurs). The distance from A to B represents the internal pressure present in excess of that required to maintain the artery at its maximum diameter and flow rate. It follows, therefore, that this distance is the minimum increase in ICP that will cause a flow reduction when the PP assumes the value at point A. The TMP at point B is then the critical TMP. If the TMP is decreased beyond this critical value, the radius, and consequently the flow, will decrease along the flow versus TMP curve until flow ceases (in this case, at a TMP of -0.5 mm Hg).

In the **collapsible region**, the PP alone is no longer sufficient to maintain maximum vessel
diameter (when the ICP is zero) and decreases in PP result in decreases in radius. In this region, if the TMP is increased above the PP (by creating a negative ICP), the vessel diameter can be increased to its maximum diameter, thus increasing the flow through the artery. Therefore, at any given PP, the TMP determines the vessel caliber and hence the maximum flow rate. The critical TMP is greater than the PP, indicating that to obtain a maximum flow rate at any given PP, a negative ICP is necessary. Increases in ICP above this value will decrease the radius and flow along the flow-TMP curve.

Figure 5 is a plot of the PP versus the minimum value of ICP that will cause a reduction in flow through the artery (i.e., PP-critical TP). If the PP is known (e.g., carotid diastolic blood pressure), the increase in ICP which will cause a flow reduction through the artery being considered (superior anterior cerebellar in this case) can be found. Assuming a value of 85 mm Hg for the diastolic blood pressure, this average value of increased ICP for all 26 arteries tested was 33 ± 2 (SEM) mm Hg (45 ± 3 cm H₂O).

**Effect of External Resistance**

Figure 6 shows the effects of proximal and distal resistance (provided by the screw clamps) on the flow versus TMP curve. Curve A shows the variation of flow with TMP at a PP of 90 mm Hg. The flow has a maximum value which is determined by the PP (as previously discussed) and the maximum diameter of the artery. Curve B represents the plot obtained when a resistance was introduced proximal to the cannulated artery. This curve mimics curve A exactly except for its lower maximum value of flow. There is a pressure drop across the external resistance such that the inflow pressure at the artery has been reduced. This lowers the PP at the artery and therefore reduces the maximum flow rate. A resistance distal to the artery yields a similar result (curve C). This distal resistance causes an increase in the outflow pressure, thereby reducing the PP at the artery and decreasing the maximum flow rate. In all cases, however, once the TMP has been reduced to a critical value, the same curve results and flow decreases to zero. These observations were identical in all experiments.

![Diagram of the minimum increase in intracranial pressure which will cause a reduction in flow plotted against the PP. When the PP is 85 mm Hg, intracranial pressures greater than 35 mm Hg (48 cm H₂O) will cause a decrease in flow through the artery.](image)
FIGURE 6

Shows the effects of distal and proximal resistance on the linear region of the flow versus TMP curve. Curve A is the flow-TMP curve for an artery with an internal diameter of 0.121 cm (at 100 mm Hg) when no external resistance is present. Curves B and C show the flow-limiting effect of a proximal and distal resistance (respectively). The maximum flow rate depends on the magnitude of the resistance only.

Effect of Vessel Diameter

Figure 7 shows the variance of flow with TMP, at a PP of 90 mm Hg, for six arteries with maximum internal diameters ranging from 0.084 to 0.202 cm. (Diameters were calculated from histological sections fixed at 100 mm Hg.) The curves are all similar in shape and the major differences are the maximum flow rates and the TMP at which the flow ceases (these curves are representative of all nonatherosclerotic arteries). Since a PP of 90 mm Hg was used in all cases, the maximum flow rate is determined only by the internal diameter (radius) of the perfused artery (recall that $F = \Delta P r^4$). The TMP at which flow ceased varied from +2 mm Hg for the smallest artery to −3 mm Hg for the largest. Since the larger arteries have thicker (stiffer) walls and a larger lumen to close off, this result is not unexpected. For grossly atherosclerotic arteries (i.e., very stiff walls) this closing pressure was as low as −15 mm Hg.

THE PERFUSION OF TWO ARTERIES IN PARALLEL

Since the arteries of the circle of Willis are joined to one another through various bifurcations and communicating arteries, it is important to investigate the effects of TMP on the flow through arteries joined by a bifurcation. This allows us to examine the possibility of preferential closure of one artery over another. The PP used for all arteries was 90 mm Hg.

Nonatherosclerotic Arteries

When the arteries in parallel were of equal diameter (or nearly equal), the flow in both arteries decreased simultaneously and approximately equally as the TMP was decreased (fig. 8). The closing pressures were approximately equal and the curves closely resembled those obtained by single artery perfusion. This effect was observed in three different experiments in which the arterial diameters were approximately equal.

When the perfused arteries were of different diameters (e.g., anterior cerebral [0.216 cm] and its first generation branch [0.112 cm]), the variation of flow with TMP was quite different (fig. 9). The flow through the smaller artery began to decrease at a TMP of 70 mm Hg, whereas the flow in the larger artery remained constant until the TMP fell below 42 mm Hg. There was a 20% decrease in the flow through the smaller artery before there was any noticeable decrease in that of the larger artery. This
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**FIGURE 7**

Effects of lumen diameter (measured at 100 mm Hg) on the flow-TMP relationship. The maximum flow rate is determined by the vessel diameter and larger arteries close at a lower TMP. All curves were obtained at a perfusion pressure of 90 mm Hg.

**FIGURE 8**

Diagram showing the variation of flow with TMP for two arteries of approximately equal diameter cannulated and perfused in parallel. There is no significant difference in their behavior.

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effect was observed in four pairs of arteries in which the diameters differed by more than 0.05 cm and the average decrease in flow through the smaller artery was 16% (± 1.5 SEM).

**Effect of Atherosclerosis**

In two sets of paired arteries, one of the two cannulated arteries was visibly atherosclerotic (AS). The walls of the AS arteries were much more rigid (due to the sclerosis) and consequently the ICP at which the flow begins to decrease is much higher than for the nonatherosclerotic (N) case (i.e., the TMP must be greatly decreased to cause a reduction in flow).

Figure 10 shows the results obtained for two middle cerebral arteries of approximately equal diameter (both taken from the same circle of Willis). As can be seen from the graph, the flow through the AS artery is unaffected until the TMP falls below 33 mm Hg, whereas the flow in the normal artery has been reduced by 47% at this TMP. The closing pressures also differ significantly (+1 mm Hg for the normal artery and −7 mm Hg for the AS artery).

Similar results were obtained for arteries with unequal diameters (fig. 11) in which the larger artery was visibly AS. A posterior cerebral artery (AS) was perfused in parallel with a superior anterior cerebellar artery (N). At a TMP of 23 mm Hg, the flow through the AS artery remained unchanged, whereas that through the N artery was decreased by 50%. Again, the closing pressures were quite different (−15 mm Hg for the AS artery and −0.5 mm Hg for the N artery).

**Sclerotic Versus Nonsclerotic Narrowing**

The results presented above make it desirable to compare all arteries tested with one another on the basis of lumen diameter and the presence of atherosclerosis. The presence of atherosclerosis was determined visually or histologically and the arteries were grouped according to lumen diameter using 0.130 cm as the dividing point. Assuming that a 50% decrease is a dangerous reduction in CBF, we determined the TMP at which the flow through the artery was decreased from its maximum value by 50% (the half-flow TMP). The results are given in table 1.
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Two middle cerebral arteries of approximately equal diameter (cannulated in parallel), one of which was visibly sclerosed. Flow through the normal artery was decreased by 47%, at a TMP of 33 mm Hg, while that through the atherosclerotic artery was unchanged at the same TMP.

The half-flow TMP of large and small atherosclerotic (AS) arteries showed no significant difference (P < 0.30), whereas that for the large nonatherosclerotic (N) arteries was significantly lower (16 mm Hg) than for small N arteries (21 mm Hg) (P < 0.01). Comparing the half-flow TMP of all large arteries (14 mm Hg) to that of all small arteries (20 mm Hg), the larger arteries have a half-flow TMP which is significantly lower than that of the small arteries (P < 0.001). The half-flow TMP of AS arteries was found to be consistently lower than that of the N arteries (an average of 12 mm Hg for AS compared to an average of 20 mm Hg for N arteries [P < 0.001]).

These comparisons confirm our observations from the parallel studies showing that small arteries

TABLE 1
Half-Flow TMP of 26 Human Cerebral Arteries

<table>
<thead>
<tr>
<th>Lumen diameter at 100 mm Hg (cm)</th>
<th>Number of arteries</th>
<th>Condition AS or N*</th>
<th>Half-flow TMP ±SEM (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater than 0.130</td>
<td>7</td>
<td>AS</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Less than 0.130</td>
<td>3</td>
<td>AS</td>
<td>14 ± 1</td>
</tr>
<tr>
<td></td>
<td>P &lt; 0.30</td>
<td>No significant difference</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td>Greater than 0.130</td>
<td>5</td>
<td>N</td>
<td>16 ± 2</td>
</tr>
<tr>
<td>Less than 0.130</td>
<td>11</td>
<td>N</td>
<td>21 ± 1</td>
</tr>
<tr>
<td></td>
<td>P &lt; 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greater than 0.130</td>
<td>12</td>
<td>ALL</td>
<td>14 ± 1</td>
</tr>
<tr>
<td>Less than 0.130</td>
<td>14</td>
<td>ALL</td>
<td>20 ± 1</td>
</tr>
<tr>
<td></td>
<td>P &lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All arteries</td>
<td>10</td>
<td>AS</td>
<td>12 ± 1</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>N</td>
<td>20 ± 1</td>
</tr>
<tr>
<td></td>
<td>P &lt; 0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*AS — Atherosclerotic.
N — Nonatherosclerotic.
(<0.130 cm in diameter) will narrow more easily than large arteries under reduced TMP and that N arteries narrow more easily than AS arteries. There are, therefore, two factors influencing preferential flow reduction—the diameter of the lumen and the presence of atherosclerosis (stiffness of the wall).

**WALL TO LUMEN RATIOS (ACTIVE CLOSURE)**

We have obtained the wall thickness and lumen diameters (at 100 mm Hg) for all arteries tested, and have calculated the wall/lumen ratios. The results are shown in table 2. Since cerebral arteries are tethered (held in place) by connective tissue and by their side branches entering the brain, we estimate that they cannot shorten in length by more than 10%. If we assume that the circumferential muscle fibers cannot shorten in length by more than 50% (probably a high estimate), the wall thickness to lumen diameter ratio required to completely obstruct the lumen of the artery by muscle contraction can be calculated. By performing this calculation we find that a wall to lumen ratio of 0.43 is necessary if active muscle contraction is to completely obstruct the vessel lumen. Our measured wall to lumen ratios for cerebral arteries are four to eight times smaller than this value. We conclude from this that the

**TABLE 2**

<table>
<thead>
<tr>
<th>Artery (number)</th>
<th>Lumen diameter (cm)</th>
<th>Wall thickness (cm)</th>
<th>Wall/lumen ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebellar³</td>
<td>0.098 ± 0.001*</td>
<td>0.0059 ± 0.0003</td>
<td>0.061 ± 0.005</td>
</tr>
<tr>
<td>Posterior communicating²</td>
<td>0.123 ± 0.002</td>
<td>0.0112 ± 0.0015</td>
<td>0.091 ± 0.011</td>
</tr>
<tr>
<td>Middle cerebral⁴</td>
<td>0.133 ± 0.009</td>
<td>0.0116 ± 0.0007</td>
<td>0.088 ± 0.002</td>
</tr>
<tr>
<td>Anterior communicating¹</td>
<td>0.137</td>
<td>0.0157</td>
<td>0.115</td>
</tr>
<tr>
<td>Vertebral²</td>
<td>0.170 ± 0.007</td>
<td>0.0098 ± 0.0015</td>
<td>0.058 ± 0.009</td>
</tr>
<tr>
<td>Anterior cerebral⁴</td>
<td>0.177 ± 0.018</td>
<td>0.0103 ± 0.0012</td>
<td>0.059 ± 0.009</td>
</tr>
<tr>
<td>Posterior cerebral³</td>
<td>0.185 ± 0.009</td>
<td>0.0098 ± 0.0009</td>
<td>0.054 ± 0.007</td>
</tr>
</tbody>
</table>

*± SEM.
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closure of a human cerebral artery is not possible by arterial smooth muscle alone.

Discussion and Conclusions

Many investigators have reported that CBF decreases when ICP is increased.\textsuperscript{7-12} Their observations regarding the ICP at which this phenomenon begins are varied (Kety et al: 45 cm H\textsubscript{2}O, Langfitt et al: 35 to 50 mm Hg, Heilbrun et al: 40 to 50 mm Hg). Our data, presented here, are in good agreement with these observations predicting the onset of CBF reduction at an ICP of 30 to 45 mm Hg (40 to 60 cm H\textsubscript{2}O), depending on the diastolic PP (80 to 100 mm Hg). Langfitt et al.,\textsuperscript{9} using Rhesus monkeys, found that CBF ceased when the ICP approximated the arterial blood pressure (i.e., when TMP is approximately zero). This is also in good agreement with our present data. The variation of flow with TMP between these two end-points is shown by Heilbrun et al.\textsuperscript{7} in their graph of CBF versus TMP. [Note that the quantity they term perfusion pressure is the difference between mean ICP and mean arterial blood pressure, this is the same quantity we call TMP.] A similar variance of CBF with TMP may be obtained from the data on graph 4 of Lowell and Bloor's work\textsuperscript{10} with Rhesus monkeys (fig. 12). [Again, note that their term "perfusion pressure" is identical to our term TMP (i.e., mean arterial blood pressure minus ICP).] In all aspects these results are similar to those we have obtained for the major arteries of the circle of Willis. Since we have shown that this occurs in the major vessels which distribute the total cerebral blood flow, this type of flow reduction will be diffuse and, if sufficiently severe, widespread areas of anoxia will occur.

Increased ICP following subarachnoid hemorrhage has been shown to last for days\textsuperscript{2} at pressures above 40 cm H\textsubscript{2}O (i.e., pressures capable of decreasing CBF). In patients with severe neurological disorders (e.g., tumors), extremely high ICPs have been recorded\textsuperscript{7,8} resulting in proportional CBF losses. CBF was increased and improved recovery was noted when this increased ICP was reduced by the removal of CSF. In cases of subarachnoid hemorrhage, however, several parameters must be considered. When an aneurysm of cerebral artery ruptures, it creates a direct channel from the arterial

\[\text{Modified from Lowell & Bloor, 1971 (Fig. 4)}\]

\[\text{Diagram showing the variance of total cerebral blood flow with TMP for a Rhesus monkey. These data were calculated from Lowell and Bloor,\textsuperscript{10} figure 4. (} \text{*The TMP was measured as the mean arterial blood pressure [\text{MABP}] minus the sagittal sinus wedge pressure [\text{SSWP}].)}\]
system to the subarachnoid space which results in a large pressure gradient creating a flow of blood from the artery into the CSF. This injection of fluid into the subarachnoid space results in an increase in CSF pressure which can approach arterial blood pressures levels. This reduces the pressure gradient through the rupture and bleeding will stop. At this point, however, the increase in ICP will have caused severe blood flow reductions to all parts of the brain (this may be the “diffuse spasm” seen angiographically). If the ICP is then reduced by the removal of fluid, the pressure gradient through the rupture will reappear and more bleeding will take place, thereby restoring the increased ICP and its concurrent loss of blood flow. It is imperative, therefore, that the rupture be repaired before the ICP is artificially reduced. Following intracranial hemorrhage, surgery is usually postponed until the patient stabilizes and major arterial “spasm” subsides (usually 3 to 7 days). The rationale behind this procedure is the thought that the presence of blood in the subarachnoid space causes active spasm of individual arteries (and therefore focal losses in blood flow) and that surgery will increase the amount of blood present and enhance this active spasm. We suggest that long-term, diffuse reductions in blood flow caused by increased ICP are potentially dangerous and should be considered along with the possibility of local spasm when postponing surgery.

We have shown that there can be preferential narrowing of one artery compared to another at the same reduced TMP. If these two arteries were viewed angiographically, the closing artery would appear narrower and flow through it would be reduced. These are the criteria used in the diagnosis of arterial “spasm” and distinction between this passive narrowing and active spasm would not be possible. We are currently investigating the possibility that preferential passive narrowing due to increased ICP accounts for some of the “spasm” diagnosed angiographically. Our wall to lumen ratios indicate that the complete obstruction of the arterial lumen by active muscle contraction is not possible (unless there is a plaque, intimal cushion, or thrombus present to partially obstruct the lumen). When angiography reveals a closed artery, with no prior indication of plaquing or obstruction, the closure must be due, in part, to reduced TMP.

Summary
Reduction of cerebral blood flow and the resulting anoxia of brain tissue is a major cause of morbidity and mortality in patients suffering from a cerebral hemorrhage or tumor. We have shown that increased intracranial pressure causes severe flow decreases in the major cerebral arteries and feel that its reduction should consequently be an important consideration when dealing with these disorders.

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References
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