A Primate Model of Subarachnoid Hemorrhage: Change in Regional Cerebral Blood Flow, Autoregulation Carbon Dioxide Reactivity, and Central Conduction Time

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SUMMARY An experimental model of subarachnoid haemorrhage has been developed in the baboon to allow accurate measurements of the changes of ICP and cortical blood flow, auto-regulation, reactivity changes and central conduction time extending over a period up to three months. Twelve hydrogen electrodes were implanted in pairs allowing CBF measurements in standard areas A, B, C of each hemisphere. Bleeding was produced by the transection of the posterior communicating artery with a specially constructed snare. The snare was implanted by the transorbital route, and measurements were made in six animals and subarachnoid haemorrhage produced in five. All animals survived and were graded clinically after 48 hours as Grade I — one animal; Grade II — two animals; Grade III — one animal; and Grade IV — one animal. Transection of the artery produced a dramatic rise in ICP in all five animals, reaching a mean value of 90 mm Hg. The cerebral perfusion pressure was preserved in all five animals but reduced to an average of 37% normal. The CBF fell dramatically within 10 minutes following bleed in all animals. Thereafter two patterns of change were established. In Grade I and II animals there was an immediate rapid recovery in CBF significantly exceeding pre-bleed values. A second hyperaemic peak was observed two days after the bleed. In Grade III and IV animals the initial post-bleed recovery was limited and a second hyperaemic peak did not occur. The most significant reduction in CBF was recorded in both Grade III/IV animals in regions A (operculum), corresponding to their hemiparesis. There was also a depression in CBF in other areas in the Grade IV animal. CCT was significantly prolonged in both Grade III and IV animals. The prolongation was most prominent two days after the bleed. Autoregulation was globally depressed in all five animals without regional differences. However, at 48 hours, animals in Grade I and II showed better recovery than those in Grade III and IV. Reactivity to pCO₂ was regionally depressed in areas corresponding to neurological deficit only in both Grade III and IV animals. We believe that our observations relate to clinical practice in the management of patients after subarachnoid haemorrhage and that 1. post-haemorrhagic hyperaemia is a favourable prognostic sign, 2. prolongation of CCT may indicate an ischaemic incident in a clinically affected animal, and 3. disturbance of autoregulation and reactivity justify the use of arterial hypertension and controlled ventilation in some cases following aneurysmal surgery.

ANEURYSM SURGERY forms a large and technically demanding part of neurosurgical practice, and despite the technical advances, the fate of the patient is still dependent on the stability and reserves of the cerebral circulation before and after surgery. The uncertainty of treatment of circulatory disturbance following subarachnoid haemorrhage (SAH) is manifest by the plethora of therapeutic advice in the literature. The management of arterial narrowing, ischaemia and oedema depend on a knowledge of the disordered physiology of the cerebral circulation produced by aneurysm rupture. The major therapeutic possibilities to minimise ischaemia that may follow subarachnoid haemorrhage (SAH), are limited to manipulation of systemic blood pressure, alteration of blood volume and viscosity, and control of arterial carbon dioxide tension. If ischaemic oedema supervenes, control of intracranial pressure (ICP) and blood pressure (BP) becomes relevant to the maintenance of cerebral perfusion pressure (CPP).

The best combination of therapy in an individual patient is often elusive, because the reactivity and autoregulatory capacity of the damaged cerebral circulation is unknown. The present experiments were designed to produce a primate model of SAH that reproduces the changes following human aneurysmal SAH as closely as is possible in a laboratory model. The parameters to be measured following the haemorrhage are those difficult to measure accurately in humans. Central conduction time, changes in ICP during initial bleed, regional blood flows in cortical tissue and the assessment of reactivity and autoregulation in damaged areas are of particular interest. Measurements need to be continued for days and weeks after the SAH to allow conclusion to be relevant to patients commonly presenting many hours after the ictus, and operated upon some day later.

Method

Ten baboons with a weight range of 7 to 17 kg were used, and the anaesthetic and surgical protocols were evolved and perfected in four animals. The 6 remaining baboons were used for the experiments, and five
were subjected to SAH. The sixth animal underwent all the surgery and measurements, but SAH was not produced, forming a sham operated control.

The experiments were planned over a 3 month period, and an individual experiment was terminated earlier on humanitarian grounds if the animal showed signs of distress.

**Anaesthesia**

All 6 animals were anaesthetised by a neuroanaesthetist (DMF) for surgery and for measurements. Premedication carried out was with phencyclidine (1 mg/kg) and atropine (0.03 mg/kg) given intramuscularly, and anaesthesia was induced with intravenous sodium thiopentone (5 mg/kg). Following endotracheal intubation the animal was mechanically ventilated and anaesthesia was maintained with 0.5% Halothane in 50% N₂O and O₂ and intermittent doses of pancuronium bromide (0.05 mg/kg). End-tidal CO₂ and B.P. cisterna Magna ICP and ECG was continuously monitored.

Rectal temperature was maintained at a constant 37 degrees C and fluid requirements were met. Post-anaesthetic recovery was given in the laboratory.

**Surgical Techniques**

The terminal carotid artery was approached trans-orbitally and the right posterior communicating artery was identified at its origin with a Zeiss operating microscope. A loop of 5'0' nylon was passed around the origin of the posterior communicating artery using a specially constructed guide. The tails of nylon were then threaded up the bore of a 23 gauge hypodermic needle with a bevelled end, which was positioned adjacent to, but not touching, the vessel wall. The needle was anchored to the wall of the orbit with acrylic, and after closing the small dural defect with cottonoid, the orbit was sealed with acrylic, leaving the hub of the needle accessible. The nylon tails were secured in the needle hub with bone wax, and the eyelids closed over the orbital contents (fig. 1a, b).

Next a coronal scalp incision was made and the scalp was reflected posteriorly. The temporalis muscles were then reflected laterally. Then burrholes were made for insertion of CBF and EP electrodes. The areas selected for CBF measurements symmetrically comprised of: (1) 'A' the Sylvian operculum, predominantly supplied by middle cerebral artery, (2) Area 'B' the cortical sensory area supplied from the watershed of anterior and middle cerebral arteries and identified by localising the somatosensory evoked potential from stimulation of the contralateral median nerve, and (3) Area 'C', the frontal para-saggital region, supplied predominantly by the anterior cerebral artery.

An additional burrhole was made in the midline in the anterior frontal region for EP reference electrode, and a screw EP electrode was placed in the spinal process of C2 vertebra. The burrholes were closed with acrylic.

Connections from the electrodes were taken to a multiway connector sealed with epoxy resin, and fixed to the occiput. The wound was closed in anatomical layers and the multiway connector left protruding through a button hole incision in the scalp.

**Central Conduction Time (CCT) Measurements**

In all animals pairs of silver cup stimulating electrodes were placed on the shaved wrist, over the median nerve. The Somato-Sensory Evoked Potential (SSEP) was recorded from upper cervical spine and from both hemispheres (via implanted electrodes). By
delivering the stimulus through an isolator as a 200 us wide voltage pulse (10-60 v) with pulse repetition frequency of 1 Hz, the amplitude being adjusted so that a thumb twitch occurred, (supra maximal stimulus was thereby obtained as confirmed by Hume and Cant.4) The EP was amplified and averaged by a Biomac 1000 computer. The peaks analysed were: N.10 representing the first major negative peak in the cortex (corresponding to N.20 in humans). N.7 representing the first major negative peak in the cervical spine — Dorsal Cervical Nucleus (corresponding to N.14 in humans).

The central conduction time (CCT) was then calculated by subtracting the latencies of those two peaks. 

\[ \text{CCT} = \text{N.10 (cortical)} - \text{N.7 (cervical)} \]

CBF Measurements

Cortical blood flows were measured using the hydrogen clearance technique5.6 the implantable 12 electrode system was designed to withstand long term exposure to tissue fluids. Paired cortical platinum/iridium electrodes were introduced into areas A, B, C of each hemisphere. A silver chloride reference electrode was implanted in the thoracic wall before each set of measurements, and removed prior to reversal of anaesthesia.

Calculation of blood flow was made using the “initial slope” technique.7

Autoregulation and Reactivity to pCO₂

Changes in rCBF before and after SAH were measured in response to elevation of systemic blood pressure (BP) in response to continuous IV infusion of metaraminol (2–20 mg/hr).

The slope of the regression line of flow against BP was calculated. Changes in auto-regulation were expressed numerically by the slope, a value close to zero representing normal autoregulation, and values higher than control measurements representing a progressive impairment of autoregulation, as a passive relationship between flow and BP supervened.

To evaluate carbon dioxide reactivity normotensive blood flow measurements were made at varying PaCO₂ values (between 40–30 mg/Hg) before and after SAH and the percentage change in CBF per torr change in PaCO₂ was calculated for each area of brain. On the first day of the experiment the electrode system and the posterior communicating artery snare were implanted.

On the third day, the fully recovered neurologically normal animal was re-anæsthetised. Control measurements of all parameters were made, and SAH was then produced by transecting the posterior communicating artery with the nylon snare (fig. 2a, b, c). Measurements were repeated over the ensuing 3 hours and the animals were then allowed to recover.

On the fifth day the animals were graded by neurological examination on a modified Botterell scale for primates8 (table 1). All measurements were repeated under anaesthesia two days after the haemorrhage. Further measurements were made at 7 days, 5 weeks and at 3 months from the date of the haemorrhage for animals that were allowed to survive.

![Figure 2. a) Control angiogram before SAH. b) Angiogram during SAH, arrows show extravasated blood. c) Distribution of blood around the brain base six hours after SAH.](http://stroke.ahajournals.org/Downloaded from)
TABLE 1  Neurological Grading of Baboons

<table>
<thead>
<tr>
<th>Grade</th>
<th>Neurological Grading</th>
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</table>
| 1     | No neurological deficit  
Active and vocal ("croaking")  
Accepting food and water |
| 2     | Mildly obtunded  
Not as active or vocal  
No neurological deficit |
| 3     | Moderately obtunded by responding to sound  
Recumbent spontaneously, but will sit up  
Neurological deficit: hemiparesis, cranial nerve palsy |
| 4     | Severely obtunded  
Responding to painful stimuli  
Neurological deficit: hemiplegia |
| 5     | Moribund  
Unresponsive  
Unstable vital signs |

Results

All 5 animals survived the haemorrhage. Five hours after recovering from anaesthesia one animal had no neurological deficit (SAH 7). One animal was slightly obtunded but had no limb deficit (SAH 9). Three animals (SAH 6, 8, 10), had obvious hemiparesis; addi-
tionally SAH 6 and 10 were drowsy and obtunded.

Two days after the bleed SAH 7 remained neurologically intact and was classified as Grade I. SAH 8 recovered from a left-sided hemiparesis and together with SAH 9 was classified as Grade II. SAH 6 was moderately obtunded with a right-sided hemiparesis and was classified as Grade III, and finally SAH 10 was grossly obtunded with a marked right-sided weakness and was classified as Grade IV.

Changes in ICP and Systemic BP

Transection of the posterior communicating artery produced a dramatic rise in intracranial pressure in all 5 animals within twenty seconds of the bleed (fig. 3a, b), similar to that recorded during human aneurysmal re-bleeding. The pressure reached a mean value of 90 mm Hg for the 5 animals and fell slowly after an interval of between one and twelve minutes. After a period of 15 to 30 minutes, ICP had stabilized at approximately 50% above the pre-bleed value.

A mean rise of 6 times in the intracranial pulse pressure was also observed, together with an increase in the respiratory excursion in ICP as the haemorrhage...
progressed (fig. 3b). In 4 animals the rise in ICP was followed by an increase in systemic blood pressure (BP), the most dramatic rise being observed when ICP reached 85% of the mean systemic arterial pressure. The peak of systemic hypertension persisted for somewhat longer than the peak elevation of ICP and subsequently followed its course. In one animal, sinoatrial block developed and persisted during the period of ICP elevation. This animal did not show an increase in BP, but the pulse pressure increased during the ICP peak (fig. 3a).

Cerebral perfusion pressure (CPP) was preserved in all animals, but reduced to an average of 37% of normal within the first minutes after the bleed (fig. 4). In 2 animals CPP returned close to normal within 10 minutes, but in 3 others it remained grossly reduced for a much longer period of time. The patterns of alteration in ICP, BP and CPP did not correlate directly with the clinical grade of the animal after SAH, or its subsequent progress.

**ECG Changes**

The absolute value of systolic ICP attained did, however, correlate with irregularities in the ECG. The higher the ICP rose, the more serious the ECG irregularities became, and this concurs with findings in the dog. In the Grade IV (SAH 10) animal with a peak systolic ICP of 105 mm Hg, ST segment elevation was observed. In the Grade I (SAH 7) animal at a peak ICP of 110 mm Hg, sino-atrial block developed and Q waves were seen in association with inversion of the T waves.

In a Grade II (SAH 9) animal the ICP reached 120 mm Hg and a marked sinus tachycardia with multifocal ventricular ectopics developed. All these changes occurred within minutes of the bleed, and the ECGs reverted towards normal as the ICP began to fall.

**CBF Changes**

The mean control value for CBF averaged over all measurement sites in the six animals was 69.9 ml/100g cortex per minute (± 27.4 s.d.) at an arterial pCO₂ of 40 mm Hg. The changes in total CBF throughout the experiment are displayed in table 2a,b. Following the bleed there was an immediate reduction in CBF to an average of 61% (± 24 s.d.) of the normal value observed and this figure is in agreement with earlier work.11 Thereafter two patterns of CBF were observed, in SAH 7, 8 and 9 (Grades I and II) following an initial reduction there was an immediate recovery of CBF exceeding pre-SAH values by approximately 20%. It was followed by a second increase in CBF two days later to over 30% above control (pre-haemorrhage) values. In animals with more severe neurological deficits SAH 6 and SAH 10 (Grades III and IV) recovery of CBF initially was minimal and only moderate within the first seven days. The difference between these two groups was significant in the first 30 minutes (p < 0.01) and at 2 days (p < 0.05) (Student’s two tailed ‘T’ test) following the bleed (fig. 5).

In the 3 animals that had no hemispheral deficit following SAH (Grade I and II) there were no major regional differences in CBF behaviour. In the 2 animals with deficits (Grade III and IV) the rCBF changed in relation to the type and extent of the deficit.

In the Grade III animal that remained alert but had a marked right hemiparesis, rCBF in the right operculum (A) showed a period of increase in flow above normal immediately following the initial post-bleed reduction. However, there was no second increase in rCBF 2 days after the bleed.

The left operculum showed an immediate drop in rCBF to around 30% of normal figure. There was some recovery noticed within one hour (70%), however at 2 days post-bleed, left opercular flow was still below 50% of the pre-bleed value (fig. 6a, table 3a).

In the Grade IV animal that became markedly obtunded and exhibited a mild left hemiparesis, a post-haemorrhagic restoration of rCBF was not seen in any region. The initial reduction in CBF was considerable and only moderate improvement occurred two hours following the bleed. Throughout the whole experiment the depression of flow was most marked in the right opercular region, although flow in the rest of the brain was also depressed (fig. 6b, table 3b).

**Changes in Autoregulation**

Autoregulatory capacity was globally affected by the SAH, with no discernable regional differences. The slope of the regression line of CBF against aBP increased from a pre-bleed value of 0.015 (± 0.030 s.d.) to 0.52 (± 0.31 s.d.) at 2 hours after SAH.

Thereafter autoregulation appeared more impaired
### Table 2a,b Changes in Total and Hemispherical CBF Following Experimental SAH

<table>
<thead>
<tr>
<th></th>
<th>CBF prior to SAH</th>
<th>% of Normal following SAH</th>
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<tbody>
<tr>
<td></td>
<td>ml/100g/min</td>
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<tr>
<td></td>
<td>9 mins.</td>
<td>15 mins.</td>
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<tr>
<td></td>
<td>20 mins.</td>
<td>36 mins.</td>
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<tr>
<td></td>
<td>72 mins.</td>
<td>2 days</td>
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<td></td>
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<tr>
<td>SAH 6, Grade 3</td>
<td>114 ± 29.6</td>
<td>66.6 ± 2.1</td>
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<tr>
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<td>(2)</td>
<td>(2)</td>
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<tr>
<td>SAH 7, Grade 1</td>
<td>42.5 ± 4</td>
<td>50 ± 18.4</td>
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<td>(5)</td>
<td>(5)</td>
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<tr>
<td>SAH 8, Grade 2</td>
<td>67.6 ± 7.2</td>
<td>67 ± 16.5</td>
</tr>
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<td></td>
<td>(6)</td>
<td>(6)</td>
</tr>
<tr>
<td>SAH 9, Grade 3</td>
<td>79 ± 4.1</td>
<td>88.5 ± 12.5</td>
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<td>(6)</td>
<td>(6)</td>
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<tr>
<td>SAH 10, Grade 4</td>
<td>88.5 ± 7.9</td>
<td>23 ± 3.3</td>
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<table>
<thead>
<tr>
<th></th>
<th>Control CBF</th>
<th>% of Control CBF following SAH</th>
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<tbody>
<tr>
<td></td>
<td>ml/100g/min</td>
<td>0-15 mins. 16-45 mins. 46-105 mins. 106-180 mins. 2 days 7 days 5 weeks 3 months</td>
</tr>
<tr>
<td>SAH 7, Grade 1</td>
<td>43 ± 4.0</td>
<td>37 ± 5.9 (2) 143 ± 30 (2) 110 ± 16 (2) 98 ± 9 (2) 112.6 ± 20.3 (2) 94 (1)</td>
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<td>(3)</td>
<td>(3)</td>
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<tr>
<td>SAH 7, Grade 2</td>
<td>42 ± 4.0</td>
<td>59 ± 10.4 (5) 133 ± 24.0 (5) 116 ± 11.6 (5) 99 ± 6.1 (5) 113.7 ± 16.4 (5) 96 ± 2.8 (2)</td>
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<td>(5)</td>
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<tr>
<td>SAH 8, Grade 1</td>
<td>60 ± 7.2</td>
<td>50 ± 8.0 (2) 100 ± 6.6 (2) 106 ± 9.0 (2) 145 ± 26.5 (2) 92 ± 14.2 (2) 100 ± 17.2 (2)</td>
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<td></td>
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<tr>
<td>SAH 8, Grade 2</td>
<td>70 ± 9.0</td>
<td>76 ± 26.5 (3) 116 ± 15.0 (3) 106 ± 11.0 (3) 141 ± 11.1 (3) 95.4 ± 6.1 (3) 100 ± 6.3 (3)</td>
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<td>(5)</td>
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<tr>
<td>SAH 9, Grade 1</td>
<td>83 ± 2.3</td>
<td>72 ± 30.0 (3) 98 ± 20.0 (3) 96 ± 2.0 (3) 93 ± 17.0 (3) 128 ± 20.0 (3) 113 ± 22.2 (2)</td>
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<td>(3)</td>
<td>(3)</td>
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<tr>
<td>SAH 9, Grade 2</td>
<td>78 ± 4.2</td>
<td>78 ± 25.0 (5) 111 ± 15.0 (5) 96 ± 4.2 (5) 104 ± 4.7 (5) 163 ± 12.4 (5) 106 ± 10.5 (4)</td>
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#### Changes in CO2 Reactivity

In the control periods, normotensive reactivity to changes in arterial pCO2 from 40 to 30 mm Hg, averaged 2.43% per torr (± 0.55 s.d.), and reactivity did not change significantly in any region over the 48 hours after SAH, in animals of Grade I & II. In the Grade III animal with the right hemiparesis, reactivity in the left opercular area (A) fell to 0.55% per torr at 48 hours, whilst the right operculum (A) showed a normal value of 2.53% per torr.

In the Grade IV obtunded animal with a left hemiparesis reactivity in the right operculum (A) became negative, with a value of −4.20% per torr at two hours post-bleed and −0.05% per torr at 48 hours. In the rest of the brain, reactivity was almost abolished two hours post-bleed, with a value of 0.20% per torr; but had recovered to a normal value of 3.35% per torr at 48 hours (fig. 7, table 4).

#### CCT Changes

The mean control values of CCT recorded in six animals prior to subarachnoid haemorrhage were 3.3 mSec ± 0.4, and mean values for each hemisphere were: right hemisphere 3.3 ± 0.3, left hemisphere 3.2 ± 0.5.

Following SAH reliable recordings were obtained in four animals. Detailed results are presented in table 6. In 2 animals Grade I and Grade II CCT was not significantly affected throughout the experiment. In animals of Grade III and Grade IV there was a considerable prolongation of CCT which was particularly signifi-
affected hemisphere was more prolonged during the day of the bleed; however, 2 days later both hemispheres were equally affected.

**Discussion**

Many models of SAH have been devised since 1927 when Bagley injected autologous venous blood into the subarachnoid space of dog. Refinements of the animal method and site of injection of the blood have continued in the evolution of this model, which, however, suffers shortcomings implicit in the source of blood from an extracranial vessel, whose immediate effects are controlled mechanically rather than by arterial pressure.

An alternative way of producing the haemorrhage is to connect a peripheral artery to the subarachnoid space of an animal via a shunt. The imposition of an electronic drop recorder in the shunt circuit allows precise measurements of the volume and rate of bleeding during SAH. The haemorrhage is limited by the intracranial counter pressure and subarachnoid clot

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**Figure 5. Changes in total CBF following SAH in the two clinical groups of animals.**

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**Table 3a Changes in Opercular CBF in Grade III Animal**

<table>
<thead>
<tr>
<th>SAH 6 GRADE 3</th>
<th>Control CBF</th>
<th>% of Control CBF following SAH</th>
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<tbody>
<tr>
<td></td>
<td>ml/100 mg/min</td>
<td>0 min.</td>
</tr>
<tr>
<td>R Operculum</td>
<td>93</td>
<td>65</td>
</tr>
<tr>
<td>L Operculum</td>
<td>135</td>
<td>68</td>
</tr>
</tbody>
</table>

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**Table 3b Changes in Right Opercular CBF in Relation to the Flow in the Rest of the Brain in Grade IV Animal**

<table>
<thead>
<tr>
<th>SAH 10 GRADE 4</th>
<th>Control CBF</th>
<th>% of Control CBF following SAH</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>ml/100 mg/min</td>
<td>0 min.</td>
</tr>
<tr>
<td>R Operculum</td>
<td>72.5</td>
<td>19</td>
</tr>
<tr>
<td>Rest of Brain</td>
<td>54.8 ± 10</td>
<td>24 ± 7</td>
</tr>
</tbody>
</table>

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PaCO₂ 39-41 mmHg.
cranial vessel, and this criterion is met by anterior cerebral artery transection and puncture of the terminal carotid artery with a needle. The middle cerebral artery has also been punctured with needles and with needles, and this has been severed with siliconised silk.

The withdrawal of a needle previously inserted into the posterior communicating artery of the dog comes close to the ideal, but the vessel becomes traumatized before base line measurements are established. Both this model and our own are open to the criticism that bleeding occurs from an opening in a previously normal vessel, as opposed to the pathological vessel at the site of a ruptured berry aneurysm.

The production of a spectrum of clinical grades in our model, with neurological deficits that vary in site and severity, suggests that such posterior communicating artery transection is a reasonable approximation to aneurysm rupture.

The detection of hyperaemic flow at 30 minutes and 48 hours post-bleed in the less severely ill animals compared with subnormal flows in the more seriously affected could be useful in human prognosis. Similar findings of hyperaemia in the post-operative phase of aneurysmal SAH gave some correlation with post-operative course in the human CBF studies of Merory et al.

The focal reduction in rCBF found in both hemipar-

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Autoregulatory Impairment Following SAH. Autoregulation Changes Expressed as: Slope = Change in CBF (corrected for Pa CO₂) in ml/100 g brain/min. Change in a BP in mm Hg</th>
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<tr>
<td></td>
<td>Prior to SAH</td>
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</table>

FIGURE 6. a) Changes in opercular (Area A) CBF in Grade III animal. b) Changes in right opercular (Area A) CBF in relation to the flow in rest of the brain in Grade IV animal.

FIGURE 7. Impairment of autoregulation in relation to clinical grading of the animals following SAH.
etic animals (Grade III and IV) correlated well with their neurological deficits, and confirms the findings that have been suggested by studies of CBF in patients.26

The measurements of autoregulation gave a result prior to SAH very similar to the values found in primates by other authors.27, 28 The observed disturbances of autoregulatory capacity to systemic hypertension after haemorrhage were both marked and prolonged, and more so in the animals with significant neurological deficit.

The persistence of autoregulatory impairment in the Grade IV animal over a month from SAH compares with the prolonged vasomotor paralysis in patients with severe neurological deficits after aneurysmal SAH.29

This observation implies that CPP needs to be maintained following SAH, and NP should not be allowed to fall because of hypovolaemia or through administration of hypotensive drugs. Particularly in patients with neurological deficit, hypotension should be avoided if possible. The prolonged period over which autoregulatory impairment has been observed implies that BP may remain critical up to at least a month after SAH.

The pre-bleed value for CO2 reactivity compares with values found in this laboratory and elsewhere.31-33 Unlike autoregulation, reactivity was unaffected by SAH in the animals without deficits (Grade I & II) and was focally impaired only in the damaged hemisphere of the Grade III animal. In the Grade IV animal, reactivity became negative in the most damaged region, the right Sylvian operculum, the phenomenon of intracerebral steal.3

Depressed reactivity is a documented consequence of ischaemia,3, 34 and the most dense ischaemia was found in the areas of impaired reactivity in these experiments. The reactivity changes were short lived compared with autoregulatory impairment, and all areas except the right operculum in the Grade IV animal had recovered reactivity by 48 hours post-bleed.

If similar changes can be impaired in humans with post SAH clinical deficits, the importance of controlling arterial carbon dioxide tension is clear. If PaCO2 rises, flow in damaged brain with impaired reactivity will not be greatly increased. If reactivity is negative (as was the case in the right operculum of the Grade IV animal) a rise in PaCO2 will directly reduce flow in the damaged area in the phenomenon of intracerebral steal.34

The reactivity changes are maximal within the first 48 hours, and use might be made of this finding by maintaining hypocapnia during early interventional surgery. Early surgery allows evacuation of blood clot from the basal cisterns, known to influence prognosis.35, 36 In addition, hypertensive therapy37 if needed in

### Table 5 Changes in CO2 Reactivity in Relation to Clinical Grading of the Animals Following SAH

<table>
<thead>
<tr>
<th>CBF reactivity per torr change in PaCO2 in Grade 1 &amp; 2 animals (controls) and Grade 3 &amp; 4 animals</th>
<th>% per torr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to SAH 2 hours 2 days</td>
<td></td>
</tr>
<tr>
<td>Grade 1 &amp; 2 Mean Reactivity</td>
<td>2.43 ± 0.55</td>
</tr>
<tr>
<td>[5]</td>
<td>[3]</td>
</tr>
<tr>
<td>Grade 3 Right Operculum</td>
<td>2.43</td>
</tr>
<tr>
<td>Grade 3 Left Operculum</td>
<td>2.43</td>
</tr>
<tr>
<td>Grade 4 Right Operculum</td>
<td>2.43</td>
</tr>
<tr>
<td>Grade 4 Left Operculum</td>
<td>2.43</td>
</tr>
<tr>
<td>Grade 4 Rest of Brain</td>
<td>[ ]</td>
</tr>
</tbody>
</table>
the early post-operative phase might be beneficially combined with hypocapnic ventilation.

The measurements of central conduction time correlated well with both the clinical grading of the animals and with the two patterns of change in cerebral blood flow (fig. 7a, b). This is in some agreement with preliminary clinical\(^\text{30}\) and experimental\(^\text{38}\) observations that changes in CCT could be an indicator of ischaemia. The fact that both blood flow changes and central conduction time were most marked around two days following subarachnoid haemorrhage may have prognostic value in the decision for aneurysmal surgery, particularly in Grade III patients.

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A primate model of subarachnoid hemorrhage: change in regional cerebral blood flow, autoregulation carbon dioxide reactivity, and central conduction time.

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