Systemic vascular responses to increased intracranial pressure

3 Effects of individual balloon inflations on intracranial pressure and the systemic circulation

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SUMMARY The effects of discrete increases in the volume of an artificial space-occupying lesion on intracranial pressures and the systemic circulation were studied in six anaesthetised and artificially ventilated dogs. Each increase in volume, accompanied by an increase in supratentorial intracranial pressure, a decrease in supratentorial perfusion pressure, and an increase in transtentorial pressure gradient, induced alterations in the systemic circulation. There were a decrease in heart rate, marked alterations in the arrhythmia index, and increases in stroke volume and systemic vascular resistance. A period of transient systemic hypertension was noted to accompany each discrete increase in intracranial pressure.

The application of mechanical pressure to the surface of the cerebrum (Cooper, 1824) has been shown to produce alterations in conscious level and in the systemic circulation. In particular, bradycardia and systemic hypertension were noted to follow the application of such pressure. In previous communications, Fitch and McDowall (1977) and Fitch *et al.* (1977) reported the changes in intracranial pressure (both in the supratentorial and infratentorial compartments) and on the systemic circulation which were produced by increases in the volume of an artificial intracranial space-occupying lesion. During these studies it was noted that, in addition to the alterations which resulted from the cumulative effects of the increasing balloon volume, changes were induced in the systemic circulation each time fluid was added to the balloon—that is, by each *individual* balloon inflation. The present study attempts to investigate these changes and to augment certain results published previously (Fitch *et al.*, 1970).

Methods

As details of the methods used have been published previously (Fitch and McDowall, 1977), only a brief description of the technique used is given here.

In six mongrel dogs anaesthesia was induced with thiopentone and maintained with nitrous oxide in oxygen, halothane being added during the surgical preparation of the animals. Intramuscular suxamethonium was given at 30 min intervals to produce muscular relaxation, and ventilation was controlled, the minute volume of ventilation being adjusted to produce normocapnia. In addition, the inspired oxygen tension was adjusted as necessary to produce arterial oxygen tensions within the normal range.

An artificial space-occupying lesion was created in each animal by inserting a balloon into the extradural space overlying one cerebral hemisphere. This artificial mass lesion was inflated with 1 ml increments of fluid, each increment being added over 2 min and being separated from the succeeding increment by approximately 30 min (Fig. 1). On the opposite side of the skull, a thin-walled loose balloon inserted into the subarachnoid space was used for the measurement of subarachnoid pressure in the supratentorial com-

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partment. In two animals, a catheter was inserted into the cisterna magna, and from this catheter measurements of infratentorial (posterior fossa) pressure were obtained. During each investigation, intracranial and systemic arterial pressures were monitored continuously, and cardiac output was determined intermittently by dye dilution (indocyanine green). Arterial pressure was measured via a catheter inserted into a femoral artery. Lead 2 of the electrocardiograph was monitored, and the QRS complex was used to trigger an instantaneous heart rate meter from which measurements of mean heart rate and of the absolute arrhythmia were obtained.

In addition to the indices described above which were measured, stroke volume, systemic vascular resistance, pulse pressure, supratentorial and infratentorial perfusion pressures, transtentorial pressure gradient, and the arrhythmia index were calculated as described previously (Fitch and McDowall, 1977).

The protocol of each experiment was such that all measurements, including those of cardiac output, were made according to the pattern depicted diagrammatically in Fig. 1. A measurement of each variable under study was taken 3 min before the start of each balloon inflation (A^1), at the end of the period of actual balloon inflation (B), and again 5 min after the end of the balloon inflation (C). Finally, some 20 min later, another series of measurements was made (A^2) which served not only as the final series of measurements for any one change in balloon volume, but also as the first (preinflation or baseline) set of measurements for the subsequent balloon inflation. This experimental protocol was repeated throughout each investigation, and to ensure reproducibility, the times for each step were given on a continuously running, tape recorded commentary. In this way, the vol-

ume of the extradural balloon was increased by 1 ml fluid every 30 min, although it should be emphasised that the actual change in balloon volume took place rapidly (over 2 min).

Results

The results to be presented are the averaged changes in the various indices produced by 40 individual balloon inflations made in six animals and include the additions to the balloon volume which took place from the start of each investigation up to the commencement of the systemic hypertensive response (SHR). The rapid changes which took place during the SHR—changes which took place often within the duration of a single balloon inflation—were considered to invalidate results during this particular phase. The preinflation or baseline value for each change in balloon volume (A^1 , A^2 , A^3 , and so on) has been given the value 100%, and the values obtained at points B , C , and A (where A is taken as the final value for one inflation) are presented as percentages of the baseline value. Mean blood pressures have been calculated as the diastolic pressure plus one-third of pulse pressure, and the values have been presented as the mean $\pm$ SEM. Probability values have been determined using Student's t test for paired data.

The alterations in the intracranial indices and the cardiovascular indices are presented in Tables 1 (intracranial indices) and 2 (cardiovascular indices).

INTRACRANIAL INDICES

As a consequence of the addition of each 1 ml fluid to the intracranial balloon, mean supratentorial pressure increased acutely and significantly to almost three times the preinflation value. Once

Fig. 1 Diagrammatic presentation of experimental protocol.

Table 1 *Changes (mean±SEM) produced in supratentorial pressure, supratentorial perfusion pressure, infratentorial pressure, infratentorial perfusion pressure, and transtentorial pressure gradient by the addition of 1 ml fluid to the extradural balloon. The results for supratentorial pressure and supratentorial perfusion pressure were obtained from 40 individual balloon inflations in six animals. The results for the other indices were obtained from 15 individual balloon inflations in two animals*

Intracranial indices	A ¹	B	C	A ²
Mean supratentorial pressure (%)	100	280±28***	199±24***	154±15***
Supratentorial perfusion pressure (%)	100	72±3***	72±3***	86±3***
Mean infratentorial pressure (%)	100	279±46**	180±17***	150±28
Infratentorial perfusion pressure (%)	100	94±4	87±3	92±3*
Transtentorial pressure gradient (%)	100	417±89**	309±48***	211±42*

Significant differences: *P<0.05; **P<0.01; ***P<0.001.

the actual addition of fluid to the balloon had stopped, mean supratentorial pressure decreased gradually towards the baseline, although by the start of the next balloon inflation it was still significantly greater than the preinflation or baseline value (Fig. 2). Although mean arterial pressure was increased also at the peak of the balloon inflation, the change in mean supratentorial pressure was the greater of the two, so that there was a significant decrease in supratentorial perfusion pressure to 72% of the baseline value. The supratentorial perfusion pressure recovered only partially so that, as the investigation progressed, mean supratentorial perfusion pressure decreased steadily with each increase in balloon volume.

Although the percentage changes in supratentorial and infratentorial perfusion pressure were similar, the alterations in absolute values differed such that at the end of the balloon inflation (point B) mean supratentorial pressure had increased by an average of 36 mmHg±2 (SE) with each increase in balloon volume, whereas the mean infratentorial pressure had increased by 19 mmHg±3. As a result, there were marked and significant increases in the transtentorial pressure gradient in these animals at the peak of the balloon inflation (Fig. 2).

CARDIOVASCULAR INDICES

Each balloon inflation caused an acute increase in arterial pressure which was evident even although the intracranial pressure was low and still well below mean arterial pressure. This was certainly the case during the early balloon inflations,

Fig. 2 *Effects produced on the intracranial indices by the addition of 1 ml fluid to the extradural balloon. The results for supratentorial pressure and supratentorial perfusion pressure are the averaged results from 40 individual balloon inflations from six animals. The results for infratentorial pressure, infratentorial perfusion pressure and transtentorial pressure gradient are the averaged results from 15 individual balloon inflations in two animals.*

and even in the later inflations mean supratentorial pressures above 80 mmHg were recorded on only a few occasions. This hypertensive phase was transient, and was succeeded by a hypotensive response which was present at the 5 min point after the balloon inflation (point C). The hypotensive response was the result of an increase in systemic vascular resistance since this index increased sig-

Table 2 *Changes (mean±SEM) produced in the cardiovascular indices by the addition of 1 ml fluid to the extradural balloon. The results were obtained from 40 individual balloon inflations in six animals*

Cardiovascular indices	A ¹	B	C	A ²
Heart rate (%)	100	87±2***	87±2***	90±2***
Mean arterial pressure (%)	100	107±1***	94±1***	98±1
Pulse pressure (%)	100	110±7**	106±5	98±5
Cardiac output (%)	100	98±2	101±3	97±3
Stroke volume (%)	100	115±4***	117±3***	109±3**
Systemic vascular resistance (%)	100	111±3***	97±3	104±3
Arrhythmia index (%)	100	226±13***	152±13***	123±3***

Significant differences: **P<0.01; ***P<0.001.

nificantly (11%) at point B, while cardiac output did not change significantly (Fig. 3).

With each balloon inflation the heart rate decreased significantly and showed no tendency to recover over the 30 min period to the next balloon inflation (Fig. 3). The decrease in heart rate was largely compensated for by an increase in stroke volume so that cardiac output decreased only slightly and not significantly. In addition to the heart rate changes, the arrhythmia index increased two-fold. After the peak of the balloon inflation, this index tended to decrease towards baseline values but did not return to the preinflation value by the start of the next inflation.

Discussion

The results show quite clearly that a vasopressor response to the presence of a space-occupying lesion may occur whatever the level of the supratentorial pressure, and certainly without the intracranial pressure reaching the level of the diastolic, systolic, or mean arterial pressures. This vasopressor response is shortlasting and repeatable, and is not a terminal event. As a result it can be distinguished from the hypertensive response of the typical "Cushing" response to increased intracranial pressure which has been shown to be a terminal, nonrepeatable event (Fitch *et al.*, 1977). The hypertensive response observed in this investigation was similar to that noted by Johnston and

colleagues (1973) and was elicited under conditions in which the global supratentorial perfusion pressure and the infratentorial perfusion pressure, although decreased, were adequate. The arterial pressure level is clearly not related to the supratentorial pressure directly, because at the 5 min postinflation point (point C) arterial pressure was less than baseline while the mean supratentorial pressure was still elevated significantly.

These results support two possible hypotheses for the development of the systemic hypertension. In the first place, they would support the suggestion of Thompson and Malina (1959) that the systemic hypertension seen with space-occupying lesions is produced by acute distortion of the brainstem, especially if pressure gradients develop between the supratentorial and the infratentorial compartments. In the present study gradients have been observed in the two animals in which measurements were made. One could postulate from the present observations that immediately after inflating the balloon, the subsequent brain displacement caused a degree of cerebral compression at the tentorium such that a pressure gradient developed between the two intracranial compartments. This tentorial compression would be associated with brainstem compression and distortion. Over the next five minutes, pressure equalisation occurred across the tentorium with a resultant reduction in the compression of the brainstem. As a result, arterial pressure decreased to below baseline values and, indeed, probably reflected the effects of an accumulation of tissue metabolites in the periphery during the preceding vasoconstrictive phase. Furthermore, it has been established that the arterial pressure increase was entirely the consequence of peripheral vasoconstriction, cardiac output not changing significantly although, if anything, decreasing slightly with each balloon inflation.

In the second hypothesis, the hypertensive response could be a result of local cerebral compression. It has been shown previously that mechanical pressure on the surface of the cerebrum would produce increase in arterial pressure, and similarly mechanical pressure on the spinal cord can result in an increase in arterial pressure (Alexander and Kerr, 1964). In the context of the present discussion, global perfusion, as conventionally defined, was obviously adequate. However, local compression may have produced local ischaemia with effects on the sympathetic system which could have triggered the hypertensive response (Hoff and Reis, 1969, 1970).

The heart rate changes noted must be mediated by a quite different mechanism from those medi-

Fig. 3 Effects produced on the cardiovascular indices by the addition of 1 ml fluid to the extradural balloon. The results are averaged from 40 individual balloon inflations in six animals.

ing the arterial pressor response since the heart rate was decreased by approximately 10% with each balloon inflation and remained depressed until the beginning of the next balloon inflation. In other words, the heart rate changes appeared to correlate most closely with the volume of the extradural mass lesion. On the other hand, the sinus arrhythmia appeared to follow the level of the supratentorial pressure. The arrhythmia index doubled with the balloon inflation and then decreased slowly over the next 30 min, in parallel with the changes in supratentorial pressure.

Conclusions

The findings of this study have shown that the changes occurring due to an acute increase in balloon volume were (1) transient hypertension followed by transient hypotension, (2) a decrease in heart rate, (3) an increase in stroke volume, (4) an increase in systemic vascular resistance, (5) marked alterations in the arrhythmia index, (6) a decrease in supratentorial perfusion pressure, and (7) an increase in transtentorial pressure gradient.

It is pertinent to note that these findings were obtained in animals which were paralysed and ventilated artificially. Previously, it has been shown (Fitch *et al.*, 1977) that certain indices, in particular the heart rate and the arrhythmia index, may be of value in predicting the development of intracranial hypertension in such animals. The results of the present study are similar, but the changes were induced by more modest alterations in intracranial pressure (mean ($\pm$ SE) increase in supratentorial pressure 36 ± 2 mmHg) and, as such, may be sensitive indicators of changing intracranial pressure. However, the findings were obtained in dogs and extrapolation to other animal species or to man may be unwarranted without further studies.

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