Acta Neurochirurgica 32, 13—24 (1975)

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(Direktor: Prof. Dr. W. Grote)

The Relation between Intracranial Pressure, Mean Arterial Pressure and Cerebral Blood Flow in Patients with Severe Head Injury

By

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With 6 Figures

Summary

In patients with severe head injuries ICP, MAP and CBF were measured continuously. In most patients there was a positive vasopressor response to increasing ICP, but the ICP/MAP ratio varied considerably in individual cases.

CBF was diminished either by increasing ICP or by decreasing MAP. This effect was more marked with ICP above 40 mm Hg or MAP below 110 mm Hg. In terminal stages there was often a negative MAP/ICP ratio accompanied by massive cerebral hyperaemia.

Key words: Severe head injury—intracranial pressure—mean arterial pressure—cerebral blood flow—cerebral perfusion pressure—critical limit of ICP and CBF.

Abbreviations: ICP = intracranial pressure (mm Hg); CBF, Flow = cerebral blood flow (ml/min); MAP = mean arterial pressure (mm Hg); CPP = cerebral perfusion pressure (mm Hg) (difference between MAP and ICP); BP = blood pressure.

Cerebral oedema and disturbed central regulation are grave complications which can follow severe head injury. Various authors have tried to obtain information on the relation between intracranial pressure (ICP), mean arterial pressure (MAP) and cerebral blood flow (CBF) after acute cerebral trauma in experimental and clinical investigations! But the published results are not uniform. One important reason for this is the fact that, in animal experiments, different models were used to produce the increased ICP, and in clinical work the basic disease, and consequently the initial situation, was often not uniform.

In the present study, an attempt has now been made to investigate the relation between ICP, MAP and CBF in a homogeneous group of patients.

Method

Measurements taken from 52 patients with severe head injury were evaluated. ICP and MAP were monitored continuously, the measurements being made directly after admission and diagnostic or operative treatment. In 22 patients CBF was measured continuously. In this way, an attempt was made, as already mentioned, to evaluate the most homogeneous group possible. Only patients with severe closed head injuries were considered. In one case a subdural, and in another an epidural haematoma was removed. In all the others, a space occupying lesion was excluded angiographically. Clinically, all had primary unconsciousness. At least one pupil reacted to light. There was no reaction to speech, but there was a distinct reaction to pain.

The measurements of ICP and MAP were made for 9 days on an average, and of CBF for about 4 days. ICP was determined by means of an epidural miniature pressure transducer, as described in an earlier paper[7]. This new model allows recalibration in vivo, and consequently correct measurements can be carried out for a long time (up to 3 weeks).

CBF was measured continuously by means of an electromagnetic flowmeter. The flow probes were implanted operatively over the internal carotid artery on the same side as the ICP pressure gauge[8].

It is important to give attention to a few points for a correct measurement of flow: the flow probes must be implanted very close to the vessel. Haemoglobin and haematocrit readings should remain almost constant, otherwise errors of measurements are unavoidable. For this reason, these values must be checked and corrected at least every 4 hours. The flowmeters used (Statham 2202) permit a zero point calibration without occlusion of the vessel.

Blood pressure was measured in the femoral artery with a Statham 23 db transducer. All patients were on artificial respiration. An attempt was made to maintain the PCO^2 relatively constant (between 30 and 36 mm Hg) by regular checking of the blood gases. Blood pressure and intracranial pressure values are given as mean arterial and mean intracranial pressures.

Results

MAP and ICP

To obtain information on the relationship between changes in ICP and MAP, the individual values of the ICP were coordinated with the corresponding MAP values. For these values the regression line and the correlation coefficient were calculated in each case.

In 39 patients we found a positive correlation between ICP and MAP. This means that rising ICP was accompanied by an increase, and falling ICP by a decrease of MAP. But the relationship between MAP and ICP varied very greatly in different patients. Only in one case were changes

in ICP equivalent to those of MAP. In the rest of the cases, the increase in MAP was always less than the rise in ICP. Fig. 1 shows 8 typical examples.

In 6 patients, changes of ICP had no effect on the level of blood pressure. Of these, 2 patients had a marked arterial hypertension with MAP levels between 130 and 140 mm Hg, the remainder had normal blood pressures.

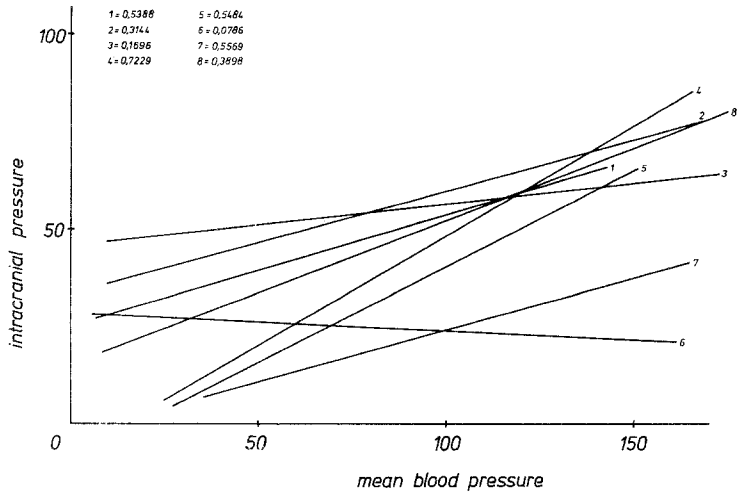

Fig. 1. Regression lines for the ICP/MAP ratio (examples for 8 patients). In most of the cases we found a positive correlation between changes of ICP and MAP. (MAP = mm Hg, ICP = mm Hg)

Seven other patients in the same clinical status developed no cerebral oedema during the period of observation. MAP changes between 90 and 140 mm Hg caused no significant ICP changes here.

Negative correlations between ICP and MAP were found exclusively in the pre-final stage with deterioration in general condition. Here, rises of ICP with falling MAP could frequently be observed.

ICP–MAP–CBF

Continuous measurement of CBF by an electromagnetic flowmeter allows no recording of regional CBF, but it gives complete information on total CBF during the whole time of observation. So 380 single values could be evaluated in this study. In order to obtain comparable measurements, mean value of CBF was calculated in 6 patients who survived, after their general conditions had improved (good reaction to speech) and the ICP and MAP had become normal. At an ICP below 20 mm Hg

and an MAP between 90 and 110 mm Hg a CBF value of 235 $\pm$ 11 ml/min was obtained. The remaining measurements were then converted into percentages of this value. As already stated, in most cases a rising ICP was accompanied by various increases in MAP (Fig. 2), consequently it is difficult to obtain information on the effect of the individual factors on the cerebral blood flow.

Fig. 3 shows how increasing cerebral pressure is compensated by a corresponding increase in MAP, so that no significant changes in the flow occur.

We therefore proceeded in such a way that at different, but always constant, degrees of ICP (20–40–50–75 mm Hg) mean values of MAP were coordinated with the measurement of cerebral blood flow. This was also carried out for ICP and CBF, this time at different, but also constant, degrees of MAP.

MAP and CBF

Fig. 4 shows the comparison of the measurements of MAP and flow at different, but constant, ICP levels. Shortly after trauma, cerebral blood flow is reduced by about 20%, with normal ICP (20 mm Hg) and MAP between 100 and 110 mm Hg. There was a distinct relation between flow and MAP changes. With a falling MAP the CBF decreased, and a rising MAP produced an increase in the CBF. In the blood pressure range below 110 mm Hg, this relationship is almost linear. This is underlined by the correlation coefficients given in Tab. 1.

Table 1. *Correlation Coefficients for the MAP/CBF Ratio, at Various ICP Levels*

There is a good and positive correlation between change in MAP and CBF, for MAP values under 110 mm Hg

ICP:	20	30	40	50	60	75	80 mm Hg
n:	14	25	33	49	48	29	25
r:	0,8855	0,8432	0,7975	0,7974	0,802	0,8679	0,9225

With MAP values above 110 mm Hg, however, the changes in flow are less marked. Thus, increases in MAP from 80 to 90 mm Hg produce a 12% increase in CBF. In contrast, increases in MAP from 120 to 130 mm Hg only produce a CBF increase of 4%. On the other hand, MAP values below 60 mm Hg are accompanied by extreme reductions of CBF, sometimes to 30% of control values.

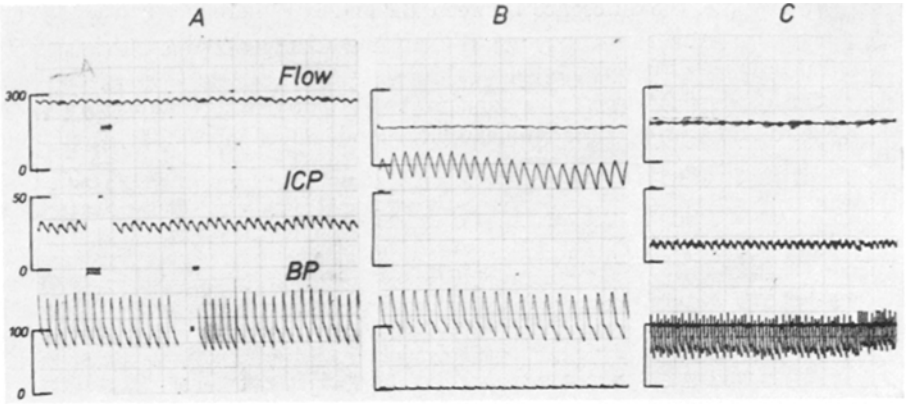

Fig. 2. CPP and therefore CBF is reduced at "B" by increasing ICP while BP remained unchanged, at "C" by decreasing BP without changing ICP. (Section from the original recordings)

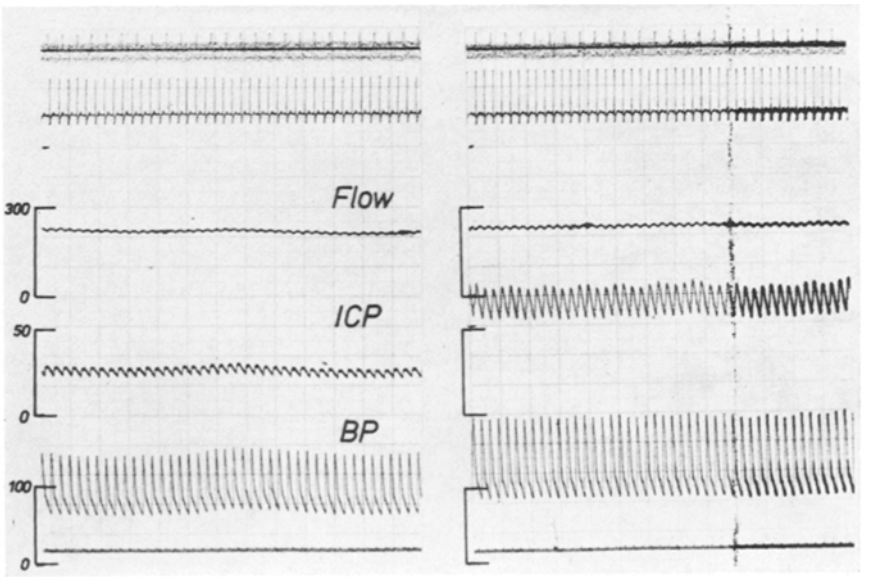

Fig. 3. A constant cerebral blood flow during rapid increase of ICP is upheld by a simultaneous increase of BP

If CPP (i.e. the difference between BP and ICP) is reduced to about 50 mm Hg both through rising ICP and also through falling BP, the blood flow falls to 50% of control values.

During deterioration in the general condition with flattening of the EEG and dilatation of the pupils, 5 patients developed extreme cerebral

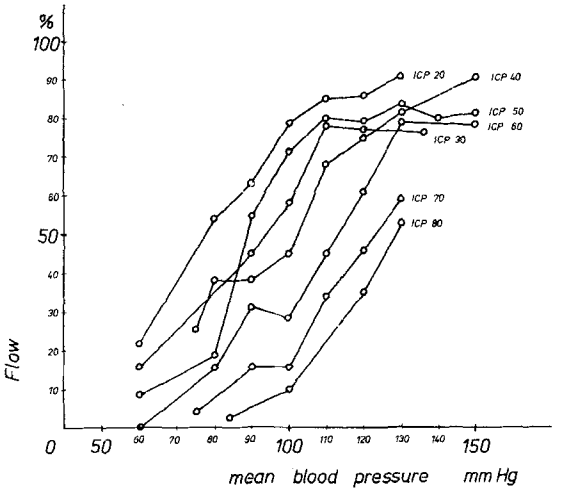

Fig. 4. Here the flow values are compared with MAP at different but always constant levels of ICP. (Open circles: mean values of all cases.) Below MAP at about 110 mm Hg CBF follows changes of MAP to a large extent passively

hyperaemia. Here, relation between CBF, ICP and MAP could no longer be observed. Fig. 5 shows an example of this.

The CBF increased greatly without changes of MAP and ICP, and finally, at 345 ml/min was far above normal values. In 3 other cases hyperaemia at about 320 ml/min was accompanied by a falling MAP and a constant ICP, and in another case by a falling MAP and a progressively rising ICP (from 40 to 110 mm Hg).

ICP and CBF

Fig. 6 shows the measurements of ICP and flow, this time compared at constant MAP levels. A good dependence of the blood flow on the level of the ICP can be seen. Increasing ICP without MAP change causes a decrease, whereas lowering the raised ICP effects a new rise in the reduced CBF. In the low range of ICP between 15 and 40 mm Hg, however, this tendency is not so marked as at higher ICP levels.

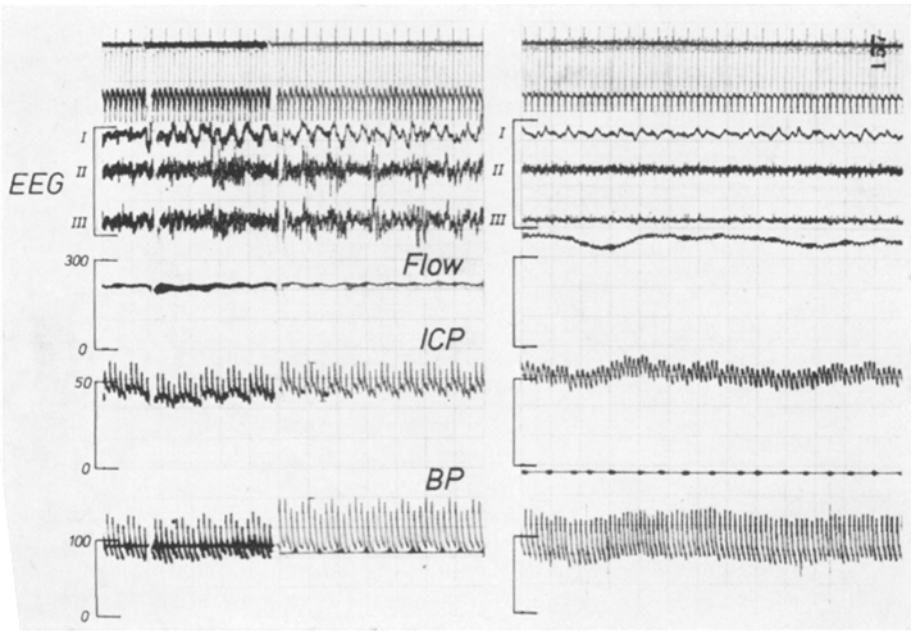

Fig. 5. During deterioriation of the clinical status and flattening of EEG these patients developed a massive hyperaemia up to 340 ml/min. This is far above the normal values (about 235 ml/min). ICP and BP remained unchanged

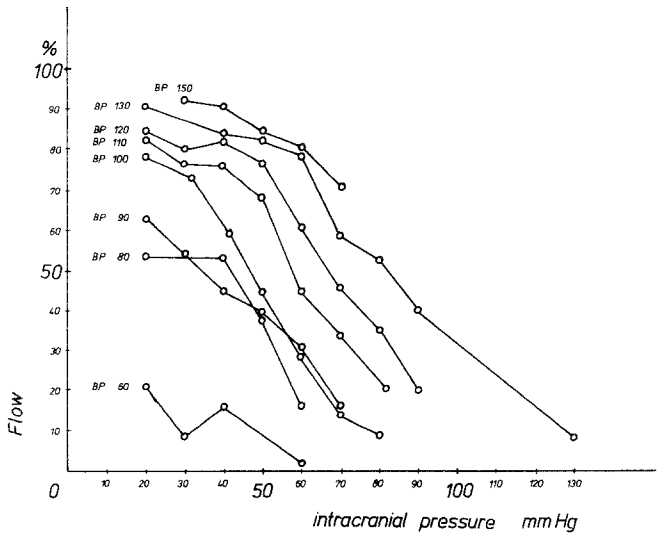

Fig. 6. Here the flow values are compared with ICP, this time at different levels of BP (MAP). Rising ICP causes a fall of CBF. This is more marked at ICP levels about 40 mm Hg. (Open circles: mean values of all patients)

In the ICP range between 40 and 110 mm Hg, this relation is almost linear. The regression lines calculated for this region underline the good correlation between ICP and flow. Tab. 2 gives the correlation coefficients.

Table 2. *Correlation Coefficients for the ICP/CBF Ratio at Various but Always Constant MAP Levels*

There is a good but negative correlation between ICP and CBF, when ICP exceeds 40 mm Hg

MAP:	130	120	110	100	90	80 mm Hg
n:	19	25	26	31	27	31
r:	—0,7841	—0,8321	—0,7891	—0,9226	—0,7496	—0,8232

For example, increase of ICP from 15 to 30 mm Hg cause a fall in flow of about 6%. If, on the other hand, the ICP increases from 60 to 75 mm Hg, the flow falls by almost 12% on average.

Discussion

ICP and MAP

80% of the patients investigated showed, as a reaction to increasing ICP, a simultaneous increase in MAP. But the MAP responses, with one exception, were always smaller than the ICP rises. Consequently the cerebral perfusion pressure is diminished with increasing ICP. Also the MAP/ICP ratio varied very greatly in the individual patients. In 6 patients rising ICP had no effect on the behaviour of the MAP.

Different blood pressure responses to ICP increase are also reported from animal experiments. Johnston[14] observed blood pressure increases even with slight changes of ICP. These could no longer be observed after transection of the cervical spinal cord. According to Weinstein[25] and Langfitt[16], however, the ICP/MAP ratio depends on type of anaesthesia and the appearance of pressure gradients between the supra and infratentorial spaces. McDowell[4] found MAP changes only when MAP reached the level of the intracranial pressure.

This same behaviour was observed in humans by Bowder[3] and Evan[6]. Here also MAP increases were only seen when ICP was equal to diastolic blood pressure. Greenfield[10] found no vasopressor response to acute increase in ICP. Troupp[27] was also unable to demonstrate any direct connection between ICP and BP changes in patients with severe head injury.

These observations are in good agreement with our results. There exists certainly a vasopressor response to ICP increases in the nature of the "Cushing reflex" in the majority of patients. This was sufficient to maintain a constant CPP, however, in only one case. But the ICP/MAP ratio varied so much that extrapolations from MAP to ICP were not possible.

It may consequently be assumed that a feedback exists between ICP and MAP, ICP being dominant. This is shown by observations on the 7 patients who developed no brain oedema. Here, MAP changes between 85 to 130 mm Hg had no effect on the level of the ICP.

ICP–MAP–CBF

The normal values coincided well with those of Greenfield[10] who also used electromagnetic flow probes, and of Lassen[18]. Like Hoyer[12], Fieschi[5], Seitz[24], and Arbus[1], we found CBF markedly diminished in the acute stage after trauma, even when ICP and MAP were normal. Subsequently, a completely intact autoregulation of cerebral blood flow could not be demonstrated in any patient. Both ICP and MAP changes had an effect on the CBF.

In animal experiments with rapidly expanding intracranial balloons Langfitt[17] described an immediately fall in CBF and a rise in ICP, but with a gradual increase in ICP, CBF reduction was minimal. Johnston[14] found a critical level of ICP beyond which loss of autoregulation appeared to be progressive.

Other authors emphasize the role of CPP. Zvetnov[26], Jennet[13], and Hamer[11] report that CPP must be lowered below 40 mm Hg before CBF is diminished significantly, whereas Matakas[19] found the figure for CPP to be 100 mm Hg.

Kety and Smith[15], and later Greenfield[10], saw in patients with brain tumour a reduction of CBF when ICP exceeded 40 mm Hg. Further increase of ICP to 70 mm Hg reduced CBF to below 75% of control levels. Bruce[2] and Overgaard[22] demonstrated that autoregulation was unpredictable in comatose patients. In the group without mass lesions Bruce[2] found a poor correlation between CBF and the other parameters measured (ICP, MAP, $CMRO_2$), whereas in the mass group there was a significant correlation between CPP and CBF.

According to our results 2 different phases of regulation must be differentiated. In both, an increase in ICP above 40 mm Hg independent of the level of MAP, and also a fall of MAP below 110 mm Hg independent of the relevant ICP, produce loss of autoregulation. In this range the CBF follows the change of ICP and MAP passively to a large extent. With increasing ICP or falling MAP, the cerebral blood flow is reduced.

In the cerebral pressure range below 40 mm Hg or with MAP above 110 mm Hg a similar dependence was shown. Therefore we are able to conclude that acute increases in the ICP, such as are observed after head injuries, lead to an increasing vasoparalysis, the critical limit being about 40 mm Hg.

On the other hand, the physiological lower limit for autoregulation of CBF seems to be raised from a mean arterial pressure of 60 mm Hg to about 110 mm Hg.

It must also be taken into account that our results are an evaluation of the mean values of all patients. In individual cases we found some where autoregulation was lost in the whole MAP range when tests with angiotensin or hyperventilation were applied. This was demonstrated in a preliminary report on patients who were in a worse clinical condition than the patients selected for this study. Here we found a good relation between flow and MAP changes over the whole MAP range in most cases (Gobiet[28]).

Complete dissociation of CBF from ICP or MAP values, just like the negative correlation between MAP and ICP, was only observed in the pre-final stage with rapid deterioration in the general condition. The massive cerebral hyperaemia phases recorded here perhaps signify the complete collapse of the central regulation. They accord with the results obtained by Overgaard[22] in patients with head injury and the CBF studies of Risberg[23] during plateau waves.

According to these results, the vasopressor responses to rises in ICP must be considerd as a safety device to maintain an adequate cerebral perfusion pressure and consequently CBF, in spite of increasing loss of autoregulation. This is in good accordance with the views of Miller[20], who found that autoregulation response to a fall of MAP is equal to the reaction to increased ICP. But this autoregulation was not adequate in most cases, as the comparison of ICP and MAP values had shown, because the CPP was constantly diminished with increasing ICP.

With regard to the cerebral haemodynamics after severe head injury, ICP must be maintained below 40 mm Hg and MAP between 100 and 120 mm Hg giving a cerebral perfusion pressure of 75 mm Hg (Gobiet[8, 9]). A further rise in MAP produces no significant change of CBF, but increases the danger of progressive brain oedema (Marshall[21]), whereas reduction of cerebral perfusion pressure below 50 mm Hg, either by increasing ICP or reducing MAP, brings the patient certainly into a critical phase of cerebral blood flow.

This work was supported in part by a grant from the „Deutsche Forschungsgemeinschaft".

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