Asymmetry of critical closing pressure following head injury

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Objective: Critical closing pressure (CCP) is the arterial pressure below which the vessels collapse. Hypothetically it is the sum of intracranial pressure (ICP) and vessel wall tension in the cerebral circulation. This study investigated transhemispherical asymmetry of CCP by studying its correlation with radiological findings on computed tomography (CT) scans in head injury patients.

Method: ICP, arterial blood pressure, and middle cerebral artery blood flow velocity were recorded daily in 119 ventilated patients. Waveforms were processed to calculate CCP. CT scans were analysed according to a system based on the Marshall classification.

Results: Left–right differences in CCP correlated with midline shift on the CT scan ($r=0.48$; $p<0.02$). Asymmetry of CCP also corresponded with the side of the head lesion ($p<0.007$) and the side of the craniotomy where it was performed ($p<0.006$). Absolute CCP weakly correlated with brain swelling ($r=-0.23$; $p<0.03$) and arterial pressure ($r=0.21$; $p<0.02$) but did not correlate with ICP. Cerebral perfusion pressure calculated as the difference between mean arterial pressure and CCP did not correlate with outcome, but “traditional” cerebral perfusion pressure (mean arterial pressure minus intracranial pressure) did.

Conclusions: Critical closing pressure is disturbed by localised brain lesions. Its asymmetry corresponds to asymmetrical findings on CT scans. CCP seems to describe vascular resistance better than ICP.

The critical closing pressure (CCP) of an artery is defined as the intraluminal pressure below which the artery collapses and flow ceases within that vessel. This concept was first formulated by Burton in 1951.¹ CCP for cerebral arteries represents the cumulative effect of the intracranial pressure (ICP) and the tension of arterial walls.² A method for calculating CCP using transcranial Doppler ultrasonography has been proposed by Aaslid³ so that CCP is becoming a physiological index rather than just a theoretical entity. It is specially attractive as it can be assessed purely non-invasively, and a number of neuroscientists have recently studied CCP in various scenarios.^{4–6}

The major determinants of outcome after serious head injury include systemic hypotension and intracranial hypertension. The cerebral perfusion pressure is reduced in either case and may result in a decrease in cerebral blood flow rendering the brain susceptible to secondary ischaemic insults. Therefore, the key to management is a cerebral perfusion pressure orientated strategy.⁷ When applied to the cerebral circulation, CCP may characterise the downstream resistance of the cerebral vascular bed more accurately than ICP alone and perhaps should be included in the estimation of cerebral perfusion pressure.⁸ This interesting hypothesis requires verification in clinical conditions.

With bilateral transcranial Doppler ultrasonography, CCP can be assessed independently for both hemispheres. Very little has been demonstrated with regard to the symmetry of CCP, with the exception of documented asymmetry in CCP and its correlation with asymmetry of vessel narrowing in patients with carotid artery stenotic disease.⁹ We investigated how the CCP is affected in patients with head injuries, paying particular interest to asymmetrical CCP patterns between the cerebral hemispheres and its relation to hemisphere swelling assessed by head computed tomography (CT) scanning.

PATIENTS AND METHODS

Patient population

A total of 119 patients (19 women, 100 men; mean age 36 years, range 16–76) with head injuries were included in

this study. The median initial Glasgow Coma Score was 7 (range 3–15). All patients were sedated, paralysed, and ventilated. They were treated in accordance with the neurocritical care unit protocol to optimise cerebral perfusion pressure.⁹ The patients were kept normothermic, ICP was maintained with boluses of mannitol, and arterial blood pressure (ABP) was maintained by volume expansion and dopamine.

Monitoring and data analysis

We measured the ABP directly from the radial artery and the ICP with a fiberoptic transducer inserted intraparenchymally into the right frontal region. We calculated the cerebral perfusion pressure as the difference between the mean ABP and mean ICP. In addition, we measured the cerebral blood flow velocities by the daily insonation of both the left and right middle cerebral artery for 20 minutes to two hours. The duration of recording conducted on the patients ranged from one to 11 days (median 3 days). Transcranial Doppler, ICP, and ABP measurements are conducted routinely for head injured patients.¹⁰ We retrospectively analysed routine clinical and brain monitoring data, prospectively collected and approved by the local multidisciplinary Neuro Critical Care Users group. No such data with which individuals could have been identified were included. At the time of data collection, the local ethical committee approval was not required. We assessed outcome using Glasgow Outcome Scale at six months after injury.

The analogue outputs from the transcranial Doppler unit and the pressure devices were fed into an analogue digital converter connected to a laptop computer. We calculated time-averaged values of ICP, ABP, and cerebral perfusion pressure from the saved data by integrating waveforms over five seconds. After removing artefacts, time-averaged values over the same five second periods were also calculated for the flow velocities (FV). The CCP was calculated according to formula⁶:

Abbreviations: ABP, arterial blood pressure; CCP, critical closing pressure; ICP, intracranial pressure; FV, flow velocity

$$CCP = ABP_{MEAN} - (\text{first harmonic of ABP pulse / first harmonic of FV pulse}) * FV_{MEAN}$$

We averaged the measured variables over the total time of monitoring so that every patient was represented by one set of results: left CCP, right CCP, the difference between left and right CCP, ICP, ABP, flow velocities for the left and right sides of the circulation, and cerebral perfusion pressure. Furthermore, CT findings were included in this data set and consisted of the extent of brain swelling, midline shift, and the side of the lesion. We estimated the cerebrovascular resistance as the ratio of cerebral perfusion pressure and mean flow velocity.

CT analysis

We selected the CT scans of the head injured patients that were closest to the date of transcranial Doppler recording for analysis and graded the abnormalities according to a simplified version¹¹ of the Marshall classification.¹² The extent of brain swelling was determined by evaluating the effacement of ventricles, disappearance of sulci, basal cistern compression, and a reduction in the delineation between grey and white matter. Based on the number of the above-mentioned features displayed in the scan, a score out of four (0 = no swelling, 4 = severe swelling) was assigned to each patient. We recorded the side of the major lesion as well as any midline shift.

Statistical analysis

Data in table 2 are presented as mean (SD). We analysed the correlation between different variables using linear regression and the calculation of Pearson's *r* (α level <0.05). Other statistical analyses were performed using the analysis of variance test. All other tests used are specified in the results.

RESULTS

Table 1 gives the location of the head injury lesions in the patients included in the study. There was a midline shift in 32 of the 119 cases (27%). The shift was from left to right in 20 patients and right to left in 12. Table 2 lists the mean (SD) of pressure, flow, and derived haemodynamic parameters.

The results show a significant correlation between differences in CCP across hemispheres and midline shift ($r = 0.48$; $p < 0.02$), indicating that a lower CCP can be seen at the side from which brain expands (fig 1). A similar picture was seen

Figure 1 Significant correlation between left-right difference in critical closing pressure (dCCP) and left-right midline shift (measured in cm from the CT scan). The relation indicates that on the side of brain expansion CCP is lower.

Figure 2 Difference between critical closing pressure (CCP) (means and 95% confidence bars) in contused hemisphere and uninjured hemisphere. CCP is lower at the side of contusion (paired signed rank test).

in patients with unilateral dominant contusion. CCP was lower at the side of contusion ($p < 0.007$; signed rank test) (fig 2). In patients with one-side craniotomy ($n = 16$) CCP was lower at the side of surgery ($p < 0.006$; signed rank test) (fig 3). CCP was not correlated with measured ICP ($p = 0.17$). The correlation between CCP and estimated cerebrovascular resistance was quite strong ($r = 0.50$; $p < 0.0001$) (fig 4), indicating greater CCP associated with greater vascular resistance. CCP correlated inversely with brain swelling ($r = -0.23$; $p < 0.03$). CCP did not correlate with outcome at six months after injury. In those individual cases where time related changes in ICP were recorded, good agreement can, anecdotally, be seen between dynamics of ICP and CCP (fig 5).

Figure 3 Differences in critical closing pressure (CCP) in 16 patients with one side craniotomy (mean values and 95% confidence bars). Analysis shows that that CCP is lower at the side of craniotomy (paired signed rank test).

Table 1 Side of lesion on computed tomography scans

Lesion type	No (%)
Right	44 (36)
Left	38 (32)
Bilateral	12 (10)
None	26 (22)

Table 2 Averaged haemodynamic indices

Index	Mean (SD)
Arterial blood pressure (mm Hg)	96.0 (9.5)
Intracranial pressure (mm Hg)	17.5 (7.3)
Cerebral perfusion pressure (mm Hg)	78.7 (8.9)
Blood flow velocity, left (cm/s)	58.7 (24.7)
Blood flow velocity, right (cm/s)	58.5 (26.2)
Critical closing pressure, left	19.29 (19.92)
Critical closing pressure, right	20.86 (19.73)

Figure 4 Relationship between CCP (averaged on left and right side) and estimator of cerebrovascular resistance (CVR). The correlation is highly significant.

To investigate what is the better measure for cerebral perfusion pressure: difference between ABP and ICP or difference between ABP and CCP, the analysis of outcome seems to be helpful, as greater mortality was historically always correlated with lower perfusion pressure. In those patients who died, “traditional” CPP (ABP–ICP) was significantly lower than in those who survived (died: 73.5 (14) mm Hg; survived: 79.5 (8.1) mm Hg; $p < 0.03$; Mann–Whitney test). Correspondingly, the difference in ABP–CCP in these two groups of patients was not significant (died: 77 (26) mm Hg; survived 74 (35) mm Hg).

DISCUSSION

In the present study we sought to determine how CCP was affected by one-sided head lesions and to what extent did changes in CCP reflect findings on CT scans. The results show that CCP was asymmetrical across the hemispheres. More than 15% of our patients had an absolute difference in left–right CCP greater than the 95% confidence limit evaluated in healthy volunteers (14 mm Hg¹³). In our material, the asymmetry of CCP was significantly correlated with midline shift, side of the original lesion, and side of the craniotomy. We found that CCP was lower on the side of the predominant hemisphere swelling and lower on both the side of the contusion and the craniotomy.

Absolute CCP had a significant (although weak) correlation with the extent of brain swelling, with a greater degree of swelling corresponding to a lower CCP. Conceptually, CCP has been compared to the sum of ICP and the tension of

arterial walls.² However in the relatively large group of the patients in the present study, the correlation between mean CCP and ICP was not significant. This, together with a lower CCP on the side of brain contusion or brain expansion in cases with visible midline shift, questions the role of CCP as a useful estimator of ICP.

On the other hand, if the cerebrovascular resistance can be simplistically expressed as the ratio: CPP/FV, CCP appears to correlate well with cerebrovascular resistance. However, the correlation may be artificial and result from the mathematical formulae rather than physiological associations. Furthermore, having CCP related to tone and therefore vascular resistance corresponds better to the CT findings than if it were related to ICP. The ICP will be higher on the side of the brain that expands in response to trauma as well as the side of the head that has sustained the dominant contusion and the therapeutic craniotomy. However, if the CCP is linked to the ICP, we would expect a raised CCP in those hemispheres that have sustained the injuries. Our results show that CCP was lower in these regions and that this difference may be due to damaged and dilated vessels which would have a lower vascular resistance than the vessels in the uninjured hemisphere.

Our results also cast a shadow on the interesting thesis that cerebral perfusion pressure can be expressed better by the difference between mean arterial pressure and CCP rather than by the difference of mean arterial pressure and ICP.⁸ CCP is undoubtedly an interesting variable with many possible clinical applications,¹⁴ however, the fact that vascular abnormalities (like vasospasm¹⁵) may alter its original interpretation,² is however disturbing. In our material, out of 119 patients, 16 had negative CCP without clear reason. Therefore, this index should be used with due care in clinical applications.

CONCLUSION

Critical closing pressure is a haemodynamic index that is affected in head injury patients. Side-to-side difference in CCP correlates with asymmetry of the injured brain. CCP is a poor estimator of mean intracranial pressure; it better describes cerebral vascular tone.

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Figure 5 Example of high dynamics of intracranial pressure (ICP) recorded during 30 minutes of TCD examination. ICP changed from 35 to 17 mm Hg and exhibited pattern of regular slow vasogenic waves of the period of around 2.5 minutes. Although the mean value of critical closing pressure (CCP) was strikingly different than mean value of ICP, changes in the CCP waveform did at times match the changes in ICP.

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