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Significance of Intracranial Pressure Waveform Analysis After Head Injury

M. Czosnyka, E. Guazzo, M. Whitehouse, P. Smielewski, Z. Czosnyka, P. Kirkpatrick, S. Piechnik, and **J. D. Pickard**

MRC Cambridge Centre for Brain Repair and Academic Neurosurgical Unit, Addenbrooke's Hospital, University of Cambridge, U.K.

Summary

The authors have investigated the relationships between the amplitude of the ICP pulse wave, the mean values of ICP and CPP, and the outcome of 56 head injured ventilated patients.

The ICP was monitored continuously using a Camino transducer (35 patients) or subdural catheter (21 patients). The mean Glasgow Coma Score was 6 (range 3–13; 5 patients had a GCS > 8 after resuscitation). Patients were grouped according to their Glasgow Outcome Score assessed at 12 months after injury. The amplitude of ICP pulse waveform was assessed using the fundamental harmonic of the pulse waveform (AMP) to avoid distortion caused by different frequency responses of the pressure transducers used in the study. Statistical analysis revealed that in patients with fatal outcome the ICP pulse amplitude increased when the mean ICP increased to 25 mmHg and then began to decrease. The upper breakpoint of the AMP-ICP relationship was not present in patients with good/moderate outcome. The moving correlation coefficient between the fundamental harmonic of ICP pulse wave and the mean ICP (RAP: R-symbol of correlation between A-amplitude and P-pressure) was introduced to describe the time-dependent changes in correlation between amplitude and mean ICP. The RAP was significantly lower in patients who died or remained in the vegetative state.

In 7 patients who died from uncontrollable intracranial hypertension RAP was oscillating or decreased to 0 or negative values well before brain-stem herniation. The combination of an ICP above 20 mmHg for a period longer than 6 hours with low correlation between the amplitude and pressure (RAP < 0.5) was described as an predictive index of an unfavourable outcome.

Keywords: Head injury; intracranial pressure; monitoring; outcome; waveform analysis.

Introduction

Raised intracranial pressure (ICP) and reduced cerebral perfusion pressure (CPP) result in a worse outcome after severe head injury but is there further information within the ICP recording that might be of prognostic significance? An increase in ICP pulse waveform with rising mean ICP was observed in the early recordings made by Ryder in 1953 [26]. An interpretation of this phenomenon was suggested several years later by Langfitt [14], Lofgren [15] and Marmarou [16] who introduced the monoexponential model of cerebrospinal pressure-volume relationship. Classically, it was postulated that if an increase in cerebral blood volume during one heart contraction was constant, it would produce a higher pressure response at a higher ICP level. This model was accepted without substantial changes, only with slight modifications [2], although it was unclear which variable should be expressed on the x-axis of the pressure-volume curve: net intracranial volume, its absolute change (as Lofgren [15] and Marmarou [16] suggested), or the volume of one selected compartment?

Considerations about intracranial amplitude-pressure relationship may be even more complicated when the Monro-Kellie doctrine is taken as a starting point. Any changes in the three components of the intracranial space-brain, CSF or blood, contribute to the total and hypothetically constant intracranial volume. Can each pulsatile increase in cerebral blood volume be compensated for by reciprocal changes in CSF volume or brain tissue? The mean time needed to accomplish any pressure-volume process, as for example to provoke a stable increase in ICP by constant infusion of saline into a CSF container, ranges several minutes [10]. More than 30 minutes is needed for extra- or intracellular brain tissue change [24]. Pulsatile CSF flow through the foramen magnum to the more compliant lumbar subarachnoid space may provide a certain degree of compensatory reserve but the obstructed flow through this pathway in patients suffering from non-communicating hydrocephalus or in head injuries with compressed ventricles may alter

the gradient but does not change the linear character of the amplitude-pressure relationship [10]. Therefore, the rapid, pulse-related inflow of the arterial blood can be compensated for by an equivalent outflow of the venous blood [2]. Because of the different time profiles of arterial pulsatile inflow and the venous outflow, the temporal increase in total blood volume produces the pressure response observed as the amplitude of the ICP pulse wave. If, for example, the delay in venous outflow increases, the maximal rise in intracerebral blood volume also increases and the amplitude of ICP grows. Moreover, the recent studies on pulsatile blood supply using transcranial Doppler velocimetry [4, 17] have confirmed early experimental observations [2] that the amplitude of pulsatile blood inflow increases as the CPP decreases.

Therefore, the exponential shape of the pressure-volume relationship is not the only factor influencing the magnitude of ICP pulse wave in head injured patients [18]. Four simultaneously acting mechanisms may be listed:

(i) the gradient of the pressure-volume curve equivalent to the brain elasticity which increases with mean ICP; (ii) the pulsatile inflow of arterial blood that increases with falling CPP or changing arterial pulse pressure; (iii) the delay between arterial inflow and venous outflow profiles that varies with ICP; and (iv) the delay between arterial blood inflow and CSF outflow through the foramen magnum to the lumbar CSF space.

Each of these four phenomena can be studied independently. Mechanism (i) may be investigated using well established pressure-volume studies. Mechanism (ii) requires continuous monitoring of blood flow velocity in basal cerebral arteries. The third mechanism has not yet been fully described: the parallel recording of blood flow profiles in basal cerebral arteries and the straight sinus, reported by Aaslid *et al.* [1], may provide a suitable technique. To study the fourth mechanism, highly specialized dynamic magnetic resonance imaging is required.

It is difficult to monitor all these factors in parallel in patients with severe head injury. We have sought using computer supported bedside technology to establish firstly the time-dependent relationship between ICP pulse amplitude, mean ICP and CPP. Secondly, we have explored the possibility that such a relationship may be a useful additional tool for the prediction of outcome. We have been encouraged by the high statistical convergence of data obtained from a heterogeneous group of head injured patients.

Patients and Methods

56 patients were admitted to Addenbrooke's Hospital after severe head injury with a mean Glasgow Comma Scale 6 (range 3 to 13). Only 5 patients had an initial assessment of GCS after resuscitation greater than 8. There were 16 females and 40 males aged from 6 to 75 years (mean age 36 years). CT scans were examined giving the profile of brain lesions summarized in Table 1. 28 patients required surgery for haematoma removal. All were mechanically ventilated with the aim of achieving a $PaCO_2$ of 3.2–4.5 kPa. CPP was intended to be kept above 70 mmHg. Falls in ABP which reduced the CPP were managed with boluses of "colloid" solution followed by inotropic agents (Dopamine) to elevate the blood pressure. Boluses of mannitol were given when the brain oedema seen on CT was associated with an ICP rising above 20 mmHg.

Intracranial pressure was monitored continuously using a fibre-optic transducer (Camino Direct Pressure Monitor, US), inserted in an intradural location (33 cases) or a subdural catheter connected via a standard manometer line to the pressure transducer (19 cases). Arterial blood pressure (ABP) was measured directly from the radial or dorsalis pedis artery. The ABP (and also ICP in case of measurement using subdural catheter) was monitored using a bedside monitor (System 8000, S & W Vickers Ltd, U.K.). Analog outputs from the pressure monitors were connected to the analog-to-digital converter (DT 2814, Data Translation, USA) fitted into an IBM AT laptop computer (Amstrad ALT 386 SX, U.K.). Pur-

Table 1. *CT Findings in 56 Head Injured Patients*

A. Brain haematoma	
Type of haematoma	Number
Haematoma on initial CT	29
Haematoma present but not considered as significant and therefore not evacuated	11
Haematoma requiring surgery	18
– extradural	8
– subdural	7
– intracerebral	2
– combination of EDH/SDH	1
Haematoma on subsequent CT scan requiring surgery	10
Seen on previous scan	6
New	4
Extradural	1
Subdural	4
Intracerebral	5
B. Indicators of raised ICP on initial CT	
Midline shift	
– less or equal 0.5 cm	37
– shift greater than 0.5 cm	19
Appearance of basal cisterns	
– normal configuration	15
– compressed but present	30
– obliterated	11

pose-written software for continuous ICP and ABP analysis (ICM-M. Czosnyka, University of Cambridge and Warsaw University of Technology) was used for the signal on-line analysis and data recording. The program permits on-line analysis of up to 10 different signals with the sampling frequency programmable and the calculationl of ten different parameters including time averaging, event detection, spectral analysis, correlations between various signals or calculated parameters etc. The method of analysis, number of signals, and on-line computer screen display may be programmed readily. The program automatically stores the results on disk for further statistical evaluation.

For continuous ICP and CPP monitoring the following method of analysis was chosen. ICP and ABP waveforms were sampled with a frequency of 60 Hz. Four seconds long fragments were then subjected to signal processing. Mean values of ICP and ABP were calculated as an arithmetic mean of 256 consecutive data samples. CPP was determined as the difference between mean ABP and ICP. The power spectrum of the ICP signal in the bandwidth from 0 to 30 Hz was calculated using a FFT algorithm. The amplitude of the fundamental harmonics of ICP and ABP pulse waves (AMP and aABP respectively) and the heart rate (HR) were calculated as the interpolated height and position of the peak corresponding to the fundamental harmonic of the pulse waves. Using this algorithm, 15 subsequent values of ICP, ABP, AMP, aABP, and HR were calculated during a one-minute period. Then, the one minute mean values of these parameters were computed.

The pulsatility of the ICP waveform was assessed using its fundamental harmonic component, which is almost always lower than the peak-to-peak pulse amplitude, and usually better correlated with mean ICP [8]. Moreover, AMP is independent of the different frequency properties of pressure transducers used in the study. The linear correlation coefficient between thirty subsequent values of the four second mean ICP and AMP values was named RAP, after R-symbol of correlation, A-amplitude, P-pressure. The clinical significance of the index will be discussed later. Theoretically, the RAP index indicated how pulse amplitude of ICP correlates with the mean ICP over short periods of time (1–2 minutes). RAP close + 1 indicates that AMP varies according to changes in mean ICP. Negative RAP indicates that AMP decreases when mean ICP increases. RAP close to 0 indicates lack of synchronisation between fast changes in amplitude and mean ICP. The 'technical' advantages are that the coefficient has a normalised values from –1 to + 1. Therefore, any comparison between the patients is straightforward. As with AMP, the RAP coefficient is calculated using the fundamental harmonic of ICP pulse wave; therefore there is no need to use a pressure transducer with a wide bandwidth; a cheap subdural catheter connected to an external membrane transducer is adequate.

Four parameters: ICP, CPP, ABP, and HR were displayed on the screen of the bedside computer as time trends and together with the remaining calculated values were continuously stored on hard disk. Continuous data analysis was performed as long as ICP and ABP were monitored. However, in patients who died during intensive care data was excluded for the periods when the brain-stem death criteria were applicable. A total number of 138170 minute averages for each parameter were imported to statistical package Statgraphic 6 Plus (Statistical Data Corporation, USA) and analysed. The regressions between AMP, RAP and mean ICP level

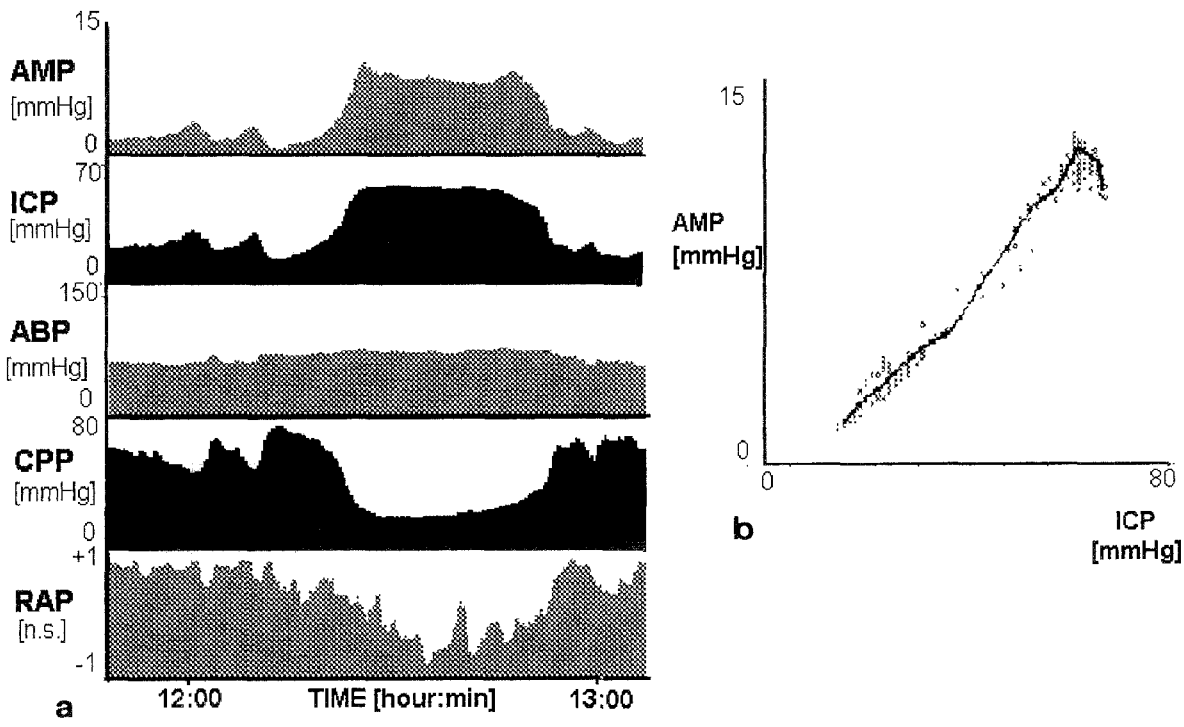

Fig. 1. (a) A typical recording of pulse amplitude of *ICP* (fundamental harmonic-AMP), mean ICP, mean blood pressure (*ABP*), mean cerebral perfusion pressure (*CPP*), and RAP coefficient during plateau wave. Note time-dependent fluctuation of RAP from positive to negative values recorded during plateau waves. X-axis: time, about two hours period. (b) Relationship between pulse wave amplitude and mean ICP from this period. The upper breakpoint is visible just above the mean ICP of 65 mmHg

were calculated. The influence of variation of the amplitude of ABP pulsations on amplitude of pulse waveform of ICP may be quite considerable because of the frequent use of inotropes to raise ABP. To investigate this influence the ratio of pulse amplitude of ICP and pulse amplitude of ABP (AMP/aABP, named 'transmission coefficient') was analysed. The ratio may be interpreted as an index of the arterial pulse transmission to the CSF compartment [20–22].

Patients' outcomes were assessed using the Glasgow Outcome Scale (from 1-good outcome to 5-death), at 12 months after the injury.

Results

1. Difference in ICP Pulsatility Recorded by Intracranial Fibreoptic Transducer and Subdural Catheter

None of the patients had ICP monitored using both a Camino transducer and a subdural catheter simultaneously. With the ICP measured using different transducers there was no statistically significant difference between ICP, CPP, and the RAP coefficient ($p > 0.05$). However, the pulse amplitude of ICP was statistically higher when measured with a Camino Transducer (3.4 mmHg mean with standard deviation 2.7 mmHg) than with a subdural catheter (2.2 mmHg mean, 1.7 mmHg standard deviation; $p < 0.001$). Histograms of pulse amplitude (first harmonic) and RAP evaluated with different transducers have similar shape, approximated best by a gamma distribution. Therefore, the analysis of the short-term correlation between changes in pulse amplitude (first harmonic) and mean ICP were not considered as being biased by the type of transducer.

2. Amplitude-Pressure Relationship in Patients with Different Outcome

All patients had their outcomes assessed using the Glasgow Outcome Scale at 12 months after injury. They were grouped as follows:

(i) Good recovery (1) or moderate disability (2) (n = 30); (ii) severe disability (3) (n = 13); (iii) persistent vegetative state (4) or death (5) (n = 13).

In individual patients, when the mean ICP increases, the linear correlation between AMP and mean ICP may be distored by an upper breakpoint, as seen in Fig. 1. This was always associated with a decrease in RAP coefficient from around + 1 to negative values.

To determine whether such phenomena were statistically significant in the whole group of patients the relationships between pulse amplitude of ICP versus mean ICP were evaluated for all recordings and presented in Fig. 2.

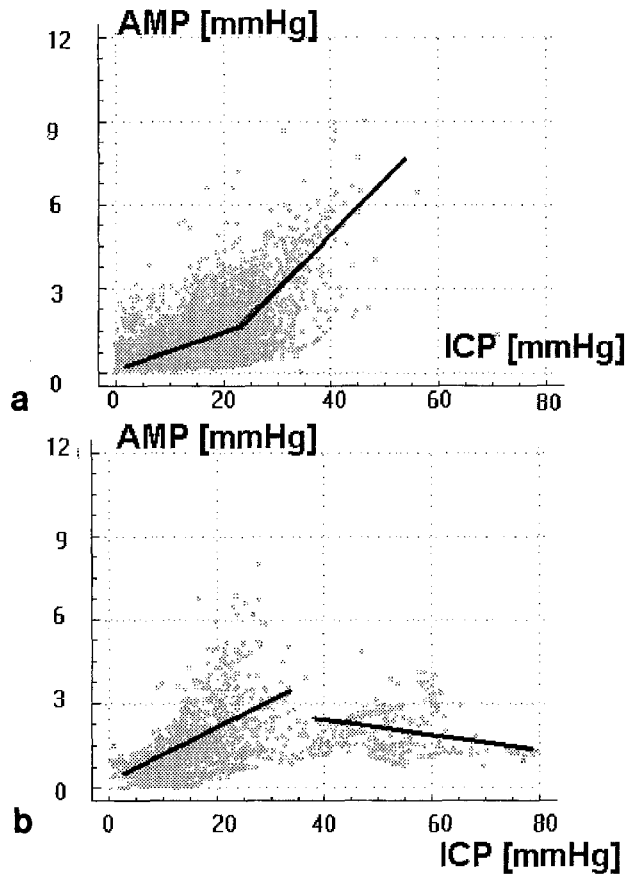

Fig. 2. Scatterplot of AMP versus mean ICP from all patients studied. Straight lines show section of consistent linear regression model. (a) Patients with good/moderate outcome. (b) Patients with fatal outcome (dead or persistent vegetative state)

The relationship between AMP and ICP in patients with good/moderate outcome (Fig. 2 a) demonstrated that AMP was increasing when ICP was increasing from around 5 mmHg to 25 mmHg (gradient = 0.124; Pearson correlation coefficient = 0.405). Above ICP of 25 mmHg the pulse amplitude increased faster when the mean ICP continued to increase (gradient = 0.36; Pearson correlation coefficient = 0.58).

The relationship between AMP and ICP in patients with fatal outcome (Persistent vegetative or dead – Fig. 2 b) demonstrated that AMP had a tendency to increase when ICP was increasing from 5 mmHg to about 30 mmHg (gradient = 0.19; Pearson correlation coefficient = 0.53). Above mean ICP of 40 mmHg the pulse amplitude was not increasing further when ICP continued to increase (gradient = – 0.07; Pearson correlation coefficient = – 0.358).

Individual observations (Fig. 3) showed that in pa-

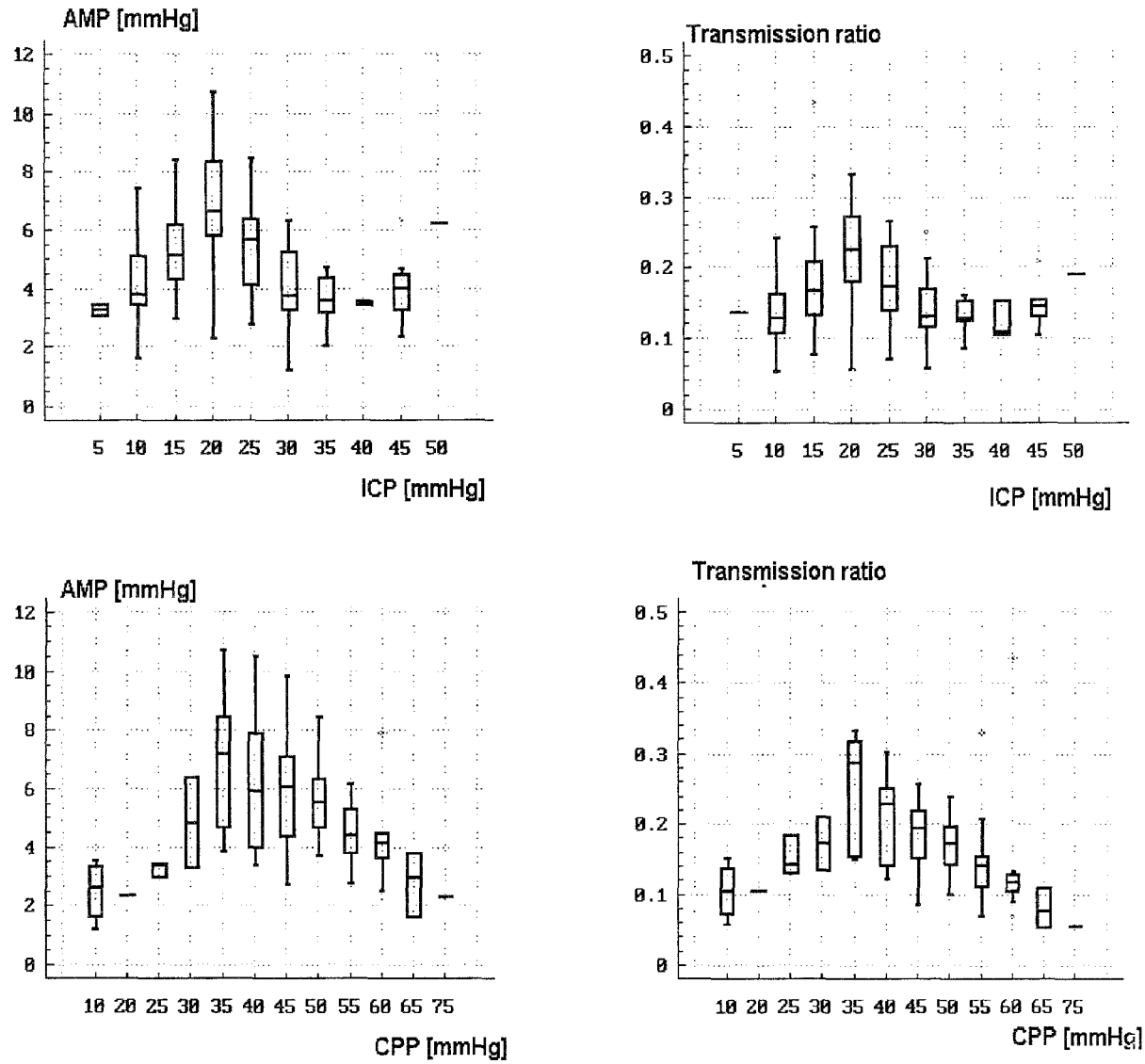

Fig. 3. Relationships (box- and wisker-plot) between AMP and transmission coefficient (ratio of AMP and amplitude of arterial pulse) versus ICP and CPP in patient who died from brain stem herniation. Breakpoints of AMP and the transmission ratio were detected at the same CPP and ICP levels

tients with fatal outcome the breakpoint of amplitude-pressure was seen in 9 cases (70%); this number includes all 7 patients who died because of uncontrollable intracranial hypertension (breakpoint was at mean ICP 25 mmHg, standard deviation 7 mmHg). Patients with good or moderate outcome had the breakpoint recorded only in 4 cases (13%) at mean ICP 45 mmHg (standard deviation 12 mmHg). The breakpoint was recorded during transitional periods of intracranial hypertension during first three days following head injury.

Transmission ratio (pulse amplitude of ICP divided by pulse amplitude of ABP) plotted against mean ICP in individual cases showed the same distribution of breakpoints (see Fig. 3). It is characteristic that the upper breakpoint of the amplitude-mean ICP curve corresponds to the lower breakpoint of amplitude of ICP- mean CPP curve at mean CPP of 40 mmHg (standard deviation 12 mmHg) in patients with fatal outcome.

3. Short-Term Correlation Between Pulse Amplitude (First Harmonic) and Mean ICP

The plot of the RAP index versus ICP in patients with good moderate outcome shows (Fig. 4 a) that for low ICP levels (less than 10 mmHg) the RAP was low

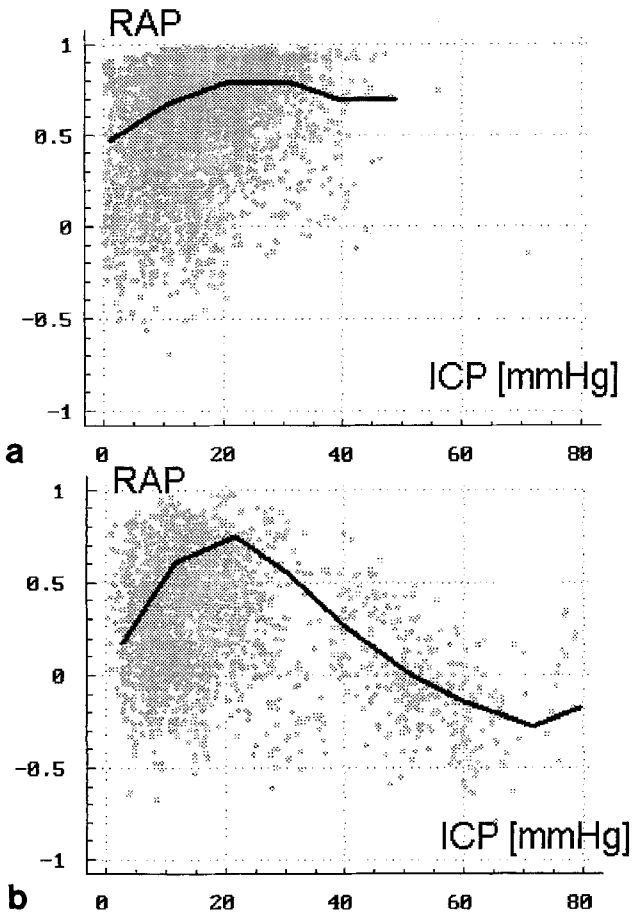

Fig. 4. Scatterplots of RAP versus ICP. Dark line shows empirical regression curve of RAP versus mean ICP. (a) Patients with good/moderate outcome. (b) Patients with fatal outcome (dead or persistent vegetative state)

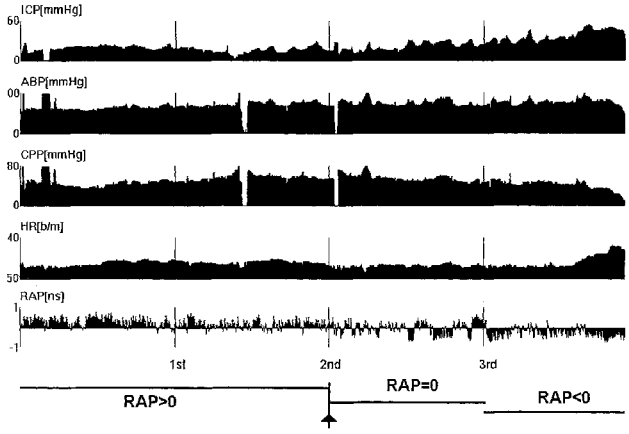

Fig. 5. Patient age 18, Glasgow Coma Score 3 on admission. Time average RAP decreased towards 0 on the 2nd day after admission, despite CPP > 65 mmHg. On the third day ICP was increasing steadily with strong vasogenic waves. Time average RAP became negative. Brain stem herniation was confirmed on 4th day after injury

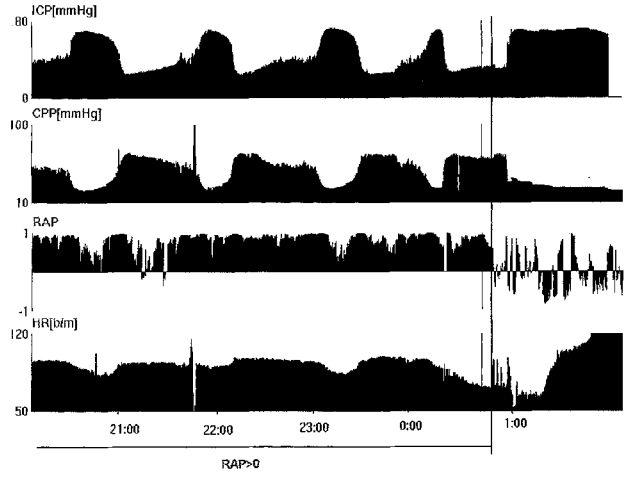

Fig. 6. 35-year-old male, admitted at GCS 3. Patient died 5 hours after Camino bolt was inserted. Several ICP plateau waves were recorded with temporal decreases of RAP from around + 1 to 0. Before the terminal ICP elevation (15 min) the RAP decreased to 0

Table 2. *Mean Values (Top in Box), Standard Errors (in Brackets) of Monitored Parameters and the Significance Levels of Differences Between Values in Different Outcome Groups*

	Moderate/good	Severe disability	PVS/dead
		$p < 0.05$	
	$p < 0.05$	n.s.	
ICP (mmHg)	16.2 (7.0)	22.6 (9.1)	19.5 (12)
		$p < 0.05$	
	n.s.	$p < 0.05$	
CPP (mmHg)	16.5 (14.1)	67 (13.2)	58 (8.2)
		$p < 0.05$	
	n.s.	$p < 0.05$	
ABP (mmHg)	82 (13.3)	89 (14.5)	77 (12.1)
		$p < 0.05$	
	n.s.	$p < 0.05$	
RAP	0.629 (0.14)	0.534 (0.12)	0.23 (0.16)

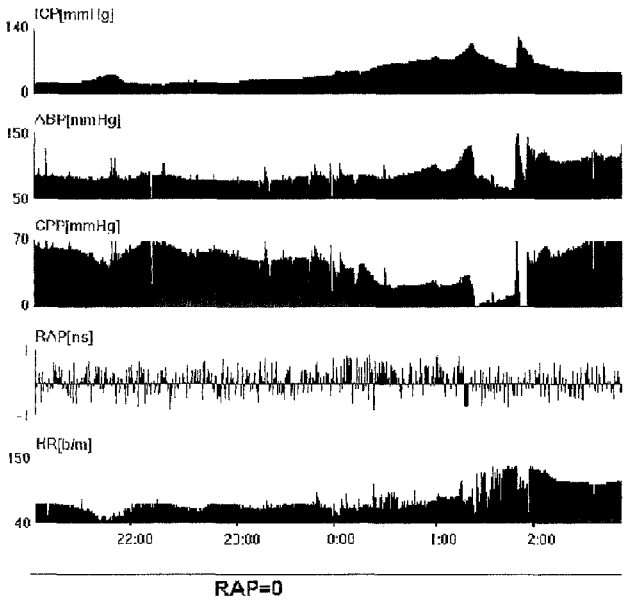

Fig. 7. Boy, age 15, GCS 3. The RAP coefficient was oscillating around 0 from the very beginning of monitoring, despite gross intracranial hypertension. Patient died around 1 a.m.

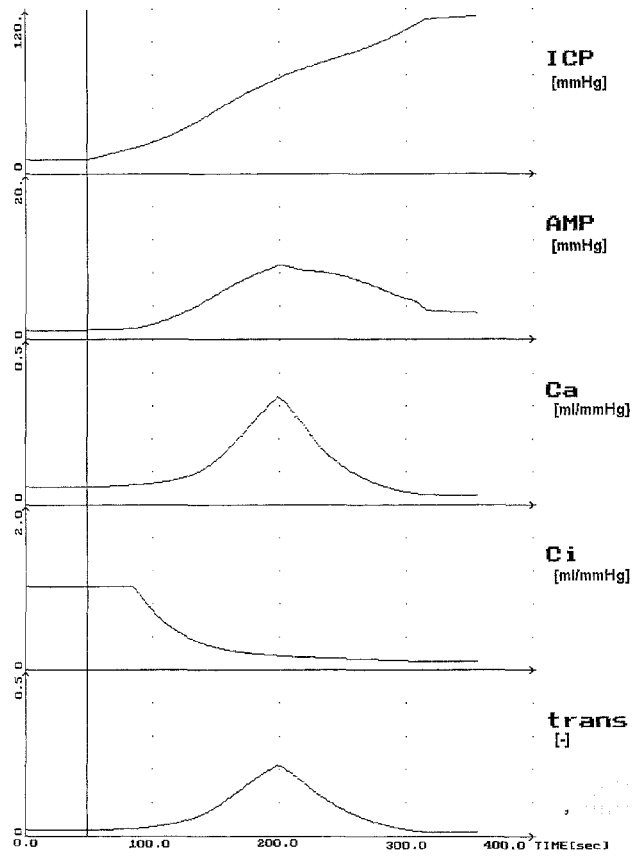

Fig. 8. Results of computer simulation of rising ICP, pulse amplitude of ICP (AMP), compliance of arterial bed (C_a), compliance of cerebrospinal fluid compartment (C_i) and transmission coefficient (trans). Note that the breakpoint of AMP coincides with the breakpoint of C_a and transmission coefficient between arterial to ICP pulse

with a tendency to increase towards + 1 when ICP increased.

In patients with fatal outcome (Fig. 4 b) mean RAP reached maximum at ICP about 20 mmHg. For higher ICPs the RAP started to decrease and negative mean RAP occurred for ICP above 50 mmHg ($p < 0.01$).

To demonstrate how RAP coefficient is helpful in time-analysis of the amplitude-pressure relationship we considered this parameter in all 7 patients who died from uncontrollable intracranial hypertension. In all 7 cases RAP either decreased from around + 1 to 0 or negative values from several minutes to one day before brain stem herniation or was permanently low in spite of ICP elevated above 20 mmHg. These three most typical scenarios are presented in Figs. 5–7.

4. Monitored Parameters in Patients with Different Outcome

The mean values of ICP, CPP, and RAP averaged over all monitoring period in each outcome group are presented in Table 2.

Because the mean values were averaged over the long period of monitoring, they did not reflect important differences between patients with different outcome. To allow for this, the following parameters were calculated and are presented in Table 3:

(i) % of time when ICP was elevated above 20 mmHg, which is accepted by consensus as a limit for post traumatic intracranial hypertension [5]; (ii) % of time when CPP was less than 55 mmHg. This limit was chosen in our group of patients because the previous preliminary study [6] showed disturbed blood supply in transcranial Doppler studies for CPP < 55 mmHg; (iii) % of time when mean ABP was less than 70 mmHg; this limit was chosen as a borderline for systemic hypotension [5]; (iv) % of time when there was close correlation between ICP pulse amplitude and mean ICP (RAP > 0.5); (v) time when RAP was less than 0.5 as a percent of time when ICP was greater than 20 mmHg.

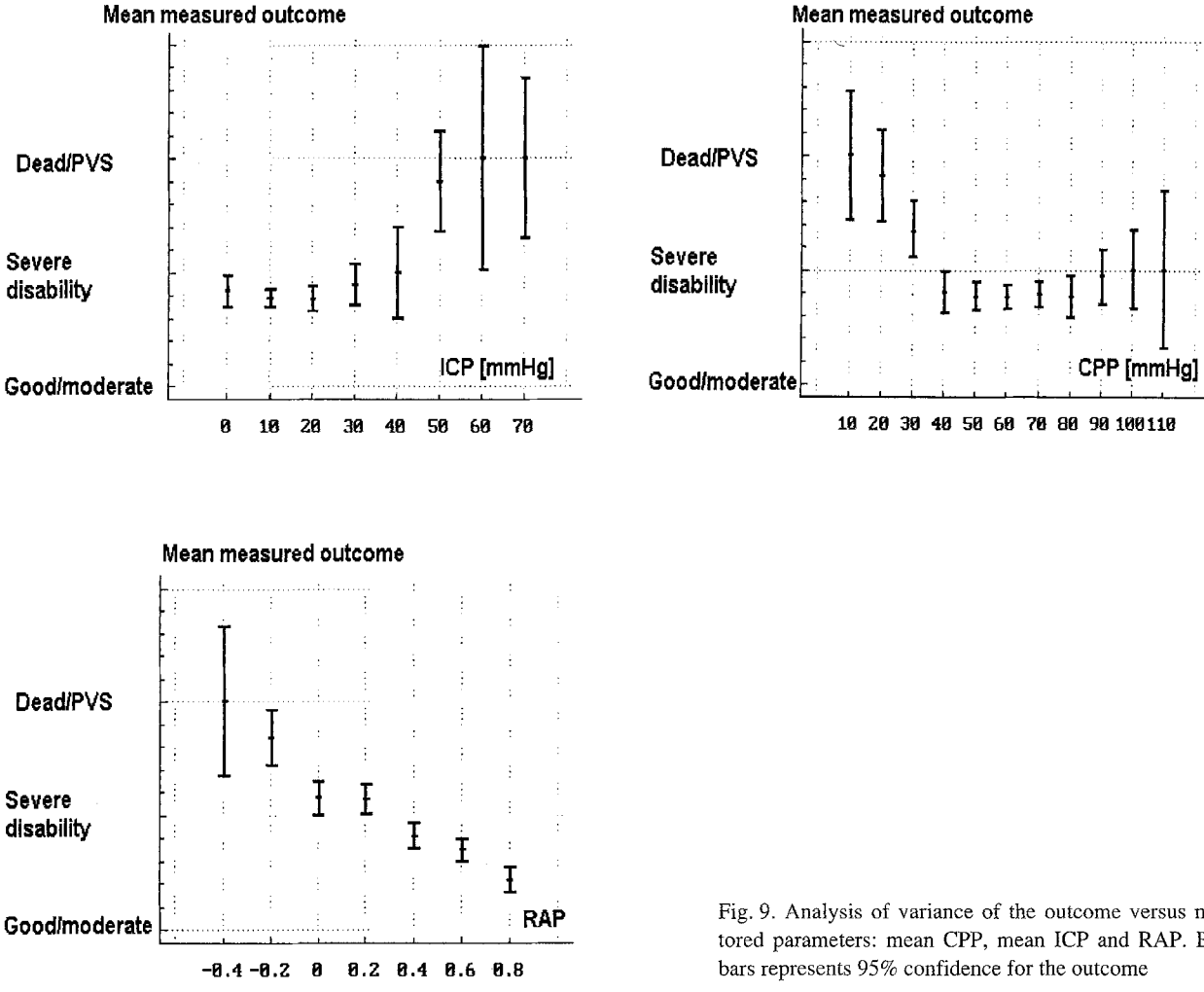

Fig. 9. Analysis of variance of the outcome versus monitored parameters: mean CPP, mean ICP and RAP. Black bars represents 95% confidence for the outcome

Discussion

Our preliminary results for 56 patients confirm that outcome following head injury is related to mean CPP and ICP but also depends in part on the relationship between ICP amplitude and mean ICP. Many more patients will need to be monitored before subgroup analysis can be performed of different pathologies and methods of therapy. However, we have been encouraged by the success of our initial statistical group analysis of 56 patients.

Upper Breakpoint of the Amplitude-Pressure Curve

An increase in the ICP pulse amplitude in parallel with the mean intracranial pressure can be seen in various clinical situations during continuous ICP monitoring [23] or during CSF infusion tests [6] with an upper breakpoint in the relationship readily observed in individual patients [7, 9, 11, 19, 23] (Fig. 1). In our group of 56 severely head injured patients the averaged relationship between the pulse amplitude and mean ICP was distored by such an upper breakpoint. However, our finding is substantially different to that reported in earlier experimental and clinical studies [2, 3, 12]. Avezaat and Ejindhoven [2] demonstrated a range of discontinuity, above 60–70 mmHg of ICP, in between regions of slow and fast linear rises in the amplitude with ICP. Within this range the amplitude may decrease as mean ICP increases. Experimentally, they observed a fast increase in the amplitude above ICP of 80–90 mmHg. Clinically, we did not recorded such high levels of ICP except terminally. Brawanski [3] presented a scatterplot of the amplitude versus mean ICP, recorded in head injured patients, which revealed a clear upper breakpoint, but he did not elaborate it further.

Table 3. *Percent of Time when Specific Condition was Detected in Continuous Monitoring of Patients with Different Outcome and the Significance Levels of Differences Between Values in Different Outcome Groups*

Condition	Moderate/good	Severe disability	PVS/dead
		$p < 0.05$	
	$p < 0.05$	n.s.	
ICP < 20 mmHg	29%	55%	53%
		n.s.	
	$p < 0.01$	$p < 0.01$	
ABP < 70 mmHg	18%	7%	17%
		$p < 0.01$	
	$p < 0.05$	$p < 0.05$	
CPP < 55 mmHg	21%	30%	43%
		$p < 0.01$	
	n.s.	$p < 0.05$	
RAP > 0.5	72%	62%	27%
		$p < 0.001$	
	$p < 0.01$	$p < 0.5$	
RAP < 0.5 as a per cent of time when ICP > 20 mmHg	14%	31%	75%

Modelling Interpretation

Classically [15] the increasing pulse amplitude of ICP was explained by the mono-exponential shape of the pressure-volume curve. Constant arterial blood volume load was suggested to produce greater pressure response when mean ICP increased. However, at the most elevated ICP, Lofgren *et al.* [15] demonstrated a decrease in elastance (i.e., gradient of the pressure-volume curve). This decrease theoretically may be responsible for the upper breakpoint of the amplitude-pressure relationship.

An alternative theoretical model of cerebral compensation taking into account the dynamic relationship between cerebral blood flow and cerebrospinal fluid circulation [9, 19] may be helpful in interpretation of this phenomenon. In this model the amplitude of the ICP pulse wave is dependent mainly on the transmission of the ABP pulse waveform to the cerebrospinal fluid compartment. The exact formulae expressing the amplitude of ICP related to ABP pulse waveform is complicated, but it can be approximated by a ratio of compartmental compliances:

$$\text{AMP} = \text{Transmission coefficient} \cdot \text{Amplitude of ABP} = \\ = \frac{C_a}{C_i + C_a} \cdot \text{Amplitude of ABP}$$

where C_a represents a compliance of the arterial walls and C_i is the net compliance of intracranial and lumbar CSF containers.

As the ICP increases the transmission coefficient is augmented by the increase in the compliance of arterial walls (as long as vasodilatory response to falling CPP is maintained) and the decrease in the compliance of the CSF space – see Fig. 8. However, when ICP is very high, causing a decrease in CPP below the threshold of autoregulation, the cerebral arteries cannot dilate more. Therefore, the compliance C_a cannot increase further and subsequently starts to decrease when the lumen of the cerebral arteries supplying blood to cortical and intraparenchymal vessels decreases passively due to falling transmural pressure. The transmission coefficient starts to decrease in modelling simulations when CPP is 10–15 mmHg below the lower limit of autoregulation of cerebral blood flow. Kontos *et al.* [13] reported that pial arterioles in cats continue to dilate below the threshold for decrease in cortical blood flow. This group found that the threshold of maximal vasodilation occurs at a CPP of 40 mmHg. It is tempting, with due care, to extrapolate such threshold values to man [25].

Influences of the Variability of the Arterial Blood Pressure Amplitude

The influence of the ABP pulse amplitude (aABP) on the amplitude of ICP has been found in this study and by previous investigators [20–22] to be limited. The amplitude of arterial blood pressure first decreased slightly with rising ICP and then rose significantly with severe intracranial hypertension (ICP > 40 mmHg). The ratio of amplitude of ICP divided by amplitude of ABP (fundamental harmonics of the heart rate) expressed as a function of ICP did not differ significantly from the amplitude-ICP relationship. The upper breakpoints of both curves are at the same

ICP levels. In practice, it is not fluctuation in magnitude of the arterial pulse pressure but characteristics of its transmission through the arterial walls to the intracranial compartments [20, 21] that determines the relationships between the amplitude of ICP, mean ICP and mean CPP.

Short-Term Correlation Coefficient Between ICP Pulse Amplitude and Mean ICP

The moving correlation coefficient between the amplitude of the ICP pulse wave and mean ICP, calculated for periods of 1 or 2 minutes, is a good index of the short time interdependence between amplitude and pressure [7, 23]. RAP reacts not only to temporary lack of correlation, immediately decreasing to zero or even negative values as seen in Fig. 1 or 6, but also describes the global relationship between amplitude and ICP over longer periods – as illustrated in Figs. 5–7.

The correlation between the amplitude of the pulse wave and mean ICP is a time-dependent phenomenon. Reversal of the correlation between ICP amplitude and mean ICP can almost always be seen on the top of plateau waves [3, 8, 23]. Using our model, this change in RAP can be interpreted as an index of maximal cerebral vasodilation. Rosner [25] suggested that plateau waves were the result of "vasodilatory cascade" with maximal vasodilatation on top. The detection of this phenomenon is not always possible by plotting an amplitude-mean ICP curve. During plateau waves where the vasodilatation is responsible for the rise of mean ICP [25], the upper breakpoint of the AMP–ICP relationship is hardly detectable because ICP rises only up to the level of maximal vasodilatation and never crosses this threshold. Therefore, the amplitude of ICP seldom starts to decrease significantly at the plateau of the wave – the recording as shown of Fig. 1 is very rare. In contrary, RAP always decreases significantly indicating the state of maximal vasodilatation (see Figs. 1 and 6).

When ICP is increasing steadily to very high values, the decrease of RAP from values close to + 1 to zero or negative often anticipates the final decrease of the ICP pulse amplitude and brain stem herniation.

Is ICP Pulsatility Correlated with the Outcome after Head Injury?

Our study has demonstrated a clear correlation between both the upper breakpoint of the amplitude-mean ICP relationship and the RAP coefficient with outcome after severe head injury. A poor outcome is characterized not only by high ICP and low mean CPP, but impaired tolerance to intracranial hypertension as determined by the lower value of time average RAP.

To investigate the relationship between the ICP, CPP, AMP, RAP and outcome assessed using simplified scoring. 1 for GOS 1 and 2, 2 for GOS 3, and 3 for GOS 4 and 5 the ANOVA of such a score versus selected parameter was considered. The 95% confidence intervals for mean outcome were plotted against mean CPP, ICP, and RAP (Fig. 9). The relationship between the mean expected outcome and CPP shows that the best outcome is expected when CPP lies between 60 to 80 mmHg. Outcome worsens significantly when ICP rises above 30 mmHg and when RAP is less than 0 (see Fig. 9).

The optimal linear model of the simplified outcome score versus measured parameters surprisingly does not contain either CPP or ABP ($p > 0.05$ for both parameters). Expected outcome (classified as previously from 1 to 3) is described by a formula:

$$\text{Expected Outcome Scoring (1–3)} = 2 + 0.01 \cdot \text{ICP–RAP}$$

where ICP and RAP are the 6–10 hour averages of the measured parameters. The correlation coefficient between the expected and real outcome is $r = 0.394$.

Mean CPP and AMP can be included in the prediction, but they do not improve the correlation coefficient between the real and expected outcome scoring. This formula has revealed that where there is not strong positive correlation between amplitude and mean ICP in intracranial hypertension, an unfavourable outcome is more probable.

An alternative analysis is to express the time when RAP lies within the given range as a percent of time when ICP is elevated above 20 mmHg (see Table 3). The greater percentage of time when RAP is close to zero or negative, indicates a low correlation between amplitude and pressure and increases the probability of a poor outcome. In the 13 patients in the group with a GOS of 4 or 5, five died resulting from brain stem herniation secondary to intracranial hypertension. In all these cases prior to herniation, the RAP coefficient was negative or approximately zero for greater than 85% of time that ICP was greater than 20 mmHg. None of the patients with a good outcome (GOS 1 or 2) had their RAP below 0.5 for more than 20% of time when ICP exceeded 20 mmHg.

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Comments

ICP monitoring is becoming more and more accepted as a useful and even indispensable tool in the management of patients with severe head injury. In clinical practice, as in most studies, only the actual level of ICP is taken into account. Some investigators, however, have, both experimentally and clinically, analyzed the pulsatile variations, synchronous with the cardiac cycle, of the ICP signal, with regard to both the amplitude and the waveform of these fluctuations. The reason for the interest in these parameters is that they provide information on both the compliance of the intracranial compartment and the state of the cerebral vascular bed. One of the problems is the methodology of how to extract this information

from the ICP-signal and another problem is that the ICP pulse is dependent on many clinical variables, both intracranial and extracranial. The advantage of this method is that it does not involve additional invasive procedures, as the information is contained within the ICP-signal itself. It is just a waste not to use it. Other methods for the assessment of the intracranial compliance usually require bolus injections or infusions into the CSF space. Methods for the assessment of the autoregulatory state of the cerebral vasculature require manipulation of the blood pressure. The present study describes one of the first attempts to apply this method in the clinical routine management of head injury. The authors have done previous research in this field and are well known in the "ICP community".

C. Avezaat

Correspondence: Marek Czosnyka, M.D., Academic Neurosurgical Unit, Addenbrooke's NHS Trust, P.O. Box 167, Hills Road, Cambridge CB2 2QQ, U.K.