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Use of ICM+ software for on-line analysis of intracranial and arterial pressures in head-injured patients

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Summary

Objective. To summarize our experience from the first 2 years of use of the ICM+ software in our Neurocritical Care Unit (NCCU).

Materials and methods. Ninety-five head-injured patients (74 males, 21 females), average age 36 years, were managed in the NCCU. Intracranial pressure (ICP) was monitored using Codman intraparenchymal probes and arterial blood pressure (ABP) was measured from the radial artery. Signals were monitored by ICM+ software calculating mean values of ICP, ABP, cerebral perfusion pressure (CPP) and various indices describing pressure reactivity, compensation and vascular waveforms of ICP (pulse amplitude, respiratory, and slow waves), etc.

Results. Mean ICP was 17 mmHg, mean CPP was 73 mmHg. Seven patients showed permanent disturbance of cerebral autoregulation (mean pressure reactivity index above 0.3). Pressure reactivity index demonstrated significant U-shape relationship with CPP, suggesting loss of pressure reactivity at too low (CPP < 55 mmHg) and too high CPPs (CPP > 95 mmHg). Mean ICP was inversely correlated with respiratory rate ($R = 0.46$; $p < 0.0001$; reciprocal model).

Conclusion. The new version of ICM+ software proved to be useful clinically in the NCCU. It allows continuous monitoring of pressure reactivity and exploratory analysis of factors implicating intracranial hypertension.

Keywords: Head injury; intracranial pressure; cerebral perfusion pressure; autoregulation; computer monitoring.

Introduction

Major improvements in outcome after traumatic brain injury (TBI) over the past 20 years have been achieved, not only because of new drugs and therapies, but also through the identification and monitoring of secondary brain insults [12]. Within the first few days after injury, vital mechanisms to match the blood supply of the brain to its energy demands are often impaired [7, 9]. This leaves the brain vulnerable to relatively minor insults such as transient falls in arterial blood pressure (ABP) or arterial oxygen saturation with profound effects on outcome. The new generation of brain sensors (intracranial pressure [ICP], tissue oxygen, pH, temperature, intracerebral microdialysis, transcranial Doppler, laser Doppler, near-infrared spectroscopy) enables on-line acquisition of vital information on cerebral metabolism and blood supply and function, enabling clinicians to recognize secondary insults and optimize management [10, 11]. However, to process and analyze on-line the large amount of data generated continuously by bedside monitors in order to facilitate decision-making is a complex task. The problems of data filtration, integration, appropriate analysis and prognostic interpretation await a satisfactory solution, which has been only partly addressed in previous studies [4, 8, 13].

The first specialized computer-based systems for neurointensive care were introduced in the early 1970's. Initially, these systems were aimed at monitoring ICP and ABP, allowing calculation of CPP and a basic analysis of the pulsatile ICP waveform. In contrast, contemporary systems are sophisticated, multichannel, digital trend recorders with built-in options for complex signal processing [13].

The intensive care multimodality monitoring system adopted in our Cambridge Neurosurgical Unit is based on software for the standard IBM-compatible personal computer, equipped with a digital to analogue converter and RS232 serial interface. The first version of the software was introduced into clinical practice in Poland, Denmark, and the United Kingdom in the middle 1980's and has been extended into a system for multimodal neuro-*i*ntensive *c*are *m*onitoring (ICM) and waveform analysis ICP [4] used in Cambridge, UK, and other centers in Europe and the United States. Most data has been derived from head-injured [5, 14] and hydrocephalus patients [1, 6]. However, the same or similar techniques are being increasingly applied to those suffering from severe stroke, subarachnoid hemorrhage, cerebral infections, encephalopathy, liver failure, idiopathic intracranial hypertension.

Over past 2 years, new software called ICM+, has been introduced into clinical practice. We summarize our clinical experience from use of the software in the management of patients after TBI.

Materials and methods

Following head injuries of various etiology, 95 patients (74 males, 21 females) with an average age of 36 years were managed in the Neurocritical Care Unit (NCCU) between 2003 and 2005. Median admission Glasgow Coma Scale (GCS) score was 6 (range 3 to 14), with 23% of patients having a GCS of 9 or greater, but deteriorating later. ICP was monitored using Codman intraparenchymal probes and ABP was measured from a peripheral artery. Signals were captured by personal computers running ICM+ software, calculating mean values of ICP, ABP, cerebral perfusion pressure (CPP) and various indices describing pressure reactivity, compensation, and vascular waveforms of ICP.

The software reads analog signals through the analog-to-digital converter (Data Translation 9800 USB box) with the sampling frequency of 50 Hz. Data were processed (processing is fully programmable) and, for TBI patients, configuration was set to calculate average values of the following variables every minute:

ABP	mean arterial blood pressure
aABP	pulse amplitude of arterial blood pressure
AMP	pulse amplitude of ICP waveform
CPP	mean cerebral perfusion pressure
HR	mean heart rate
ICP	mean intracranial pressure
PRx	pressure reactivity index
RAC	index describing moving correlation between pulse waveform of ICP and mean CPP
RAP	index describing pressure-volume compensatory reserve
Resp	amplitude of respiratory waveform
RespRate	mean respiratory rate
Slow	slow waves of ICP (equivalent time periods from 20 seconds to 3 minutes)

Particular care was paid to organization of the front page display, which shows time trends of ABP, ICP, CPP, and pressure reactivity. For clarity, the pressure reactivity index (PRx) is also displayed at the bottom of the screen as risk-graph, converting information about reactivity to colors: green = good; red = impaired (Fig. 1). Optimal CPP [14] was also calculated on-line (Fig. 2).

Results

Artifact-free time of signal recording, which provided good quality output suitable for data analysis, was around 92% of the time our patients spent in the NCCU.

Averaged values of monitored variables and their standard deviations are given in Table 1. PRx plotted as a function of CPP showed a significant relationship (ANOVA: $p < 0.023$) indicating loss of cerebral pressure-reactivity for low CPP ($CPP < 55$ mmHg) and for high CPPs ($CPP > 95$ mmHg). This averaged trend (Fig. 2b) emphasizes the validity of individual methodology for tracing optimal CPP (Fig. 2a) using finite-time (3 to 6 hours) plots of PRx versus CPP.

In total, 10% of patients had permanently impaired cerebral autoregulation ($PRx > 0.2$). The software was helpful in analyzing ICP respiratory waves. Respiratory amplitude was not associated with any other parameters characterizing intracranial hypertension or cerebral perfusion. But, respiratory rate demonstrated a strong inverse relationship to ICP ($R = 0.46$; $p < 0.0001$) indicating that lower mean ICP is present with higher frequency ventilation (20 to 25 cycles per minute).

Discussion

In the established environment of a clinical neuroscience department, enormous quantities of data can be captured, from which information regarding cerebral autoregulation, cerebrospinal compensatory reserve, oxygenation, metabolite production and function can be obtained. Recognition of changing cerebrovascular hemodynamics and oxygenation demands can result from reliable monitoring techniques, as well as sophisticated and time-consuming signal analysis provided by dedicated computer support [4, 8, 13].

The flexibility of such systems allows wide-range signal analysis, which can generate data chaos. Thus, the modern user must decide which parameters should be considered and how the data should be interpreted. This information must be presented in a manner that is comprehensible to medical and nursing staff. Although personal computers with designated software are portable, they have yet to gain widespread clinical acceptance as an intensive care tool. They are seen as stand-alone instruments requiring specialized skills for their operation, and occupying precious space. In contrast, a commercial hardware system with a cus-

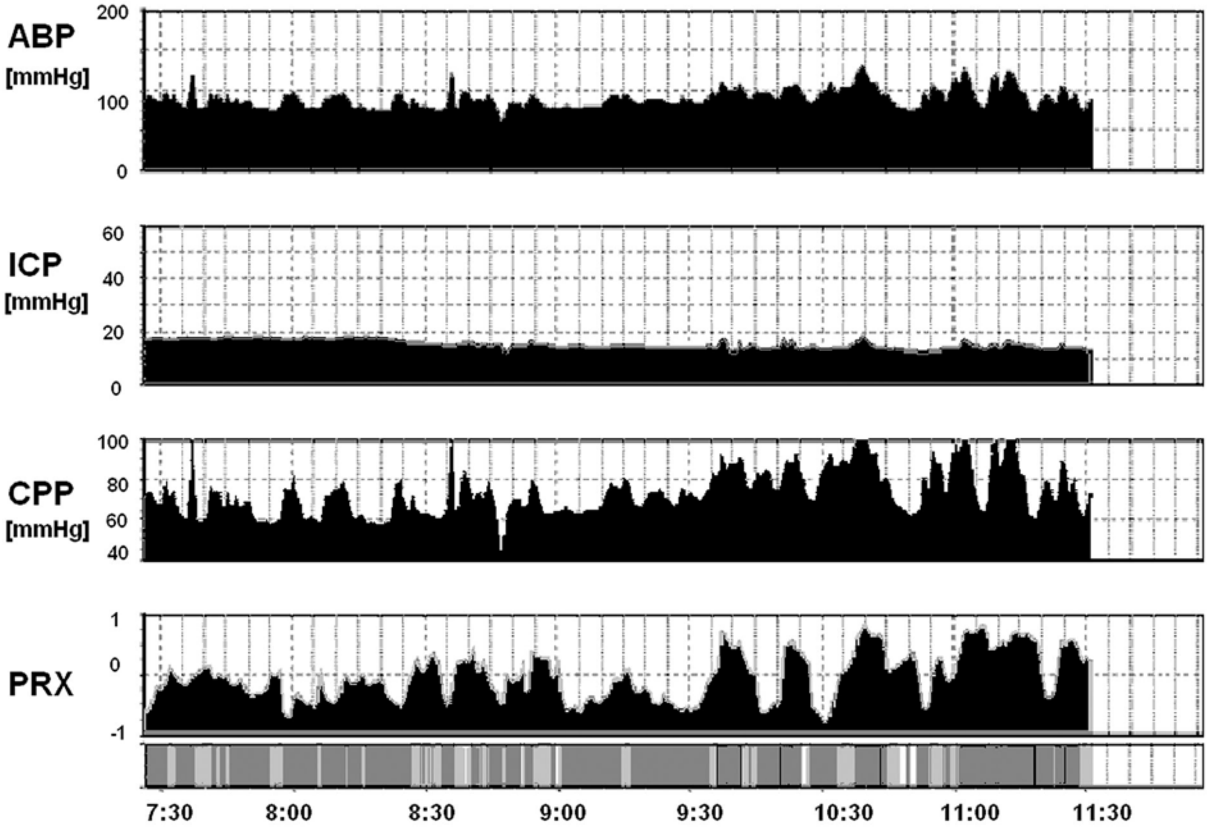


Fig. 1. Example of the 'front page' of the software. Standard display shows mean ABP, ICP, and CPP. PRx is displayed both as time trend and color graph (here reduced to grey-scale). White indicates good autoregulation and black indicates poor pressure-reactivity. In this example, ICP was quite stable but PRx deteriorated in the second half of the recording, probably due to elevated CPP

tomized console can be more user-friendly, but less flexible and more expensive.

PRx – global index of cerebrovascular reactivity

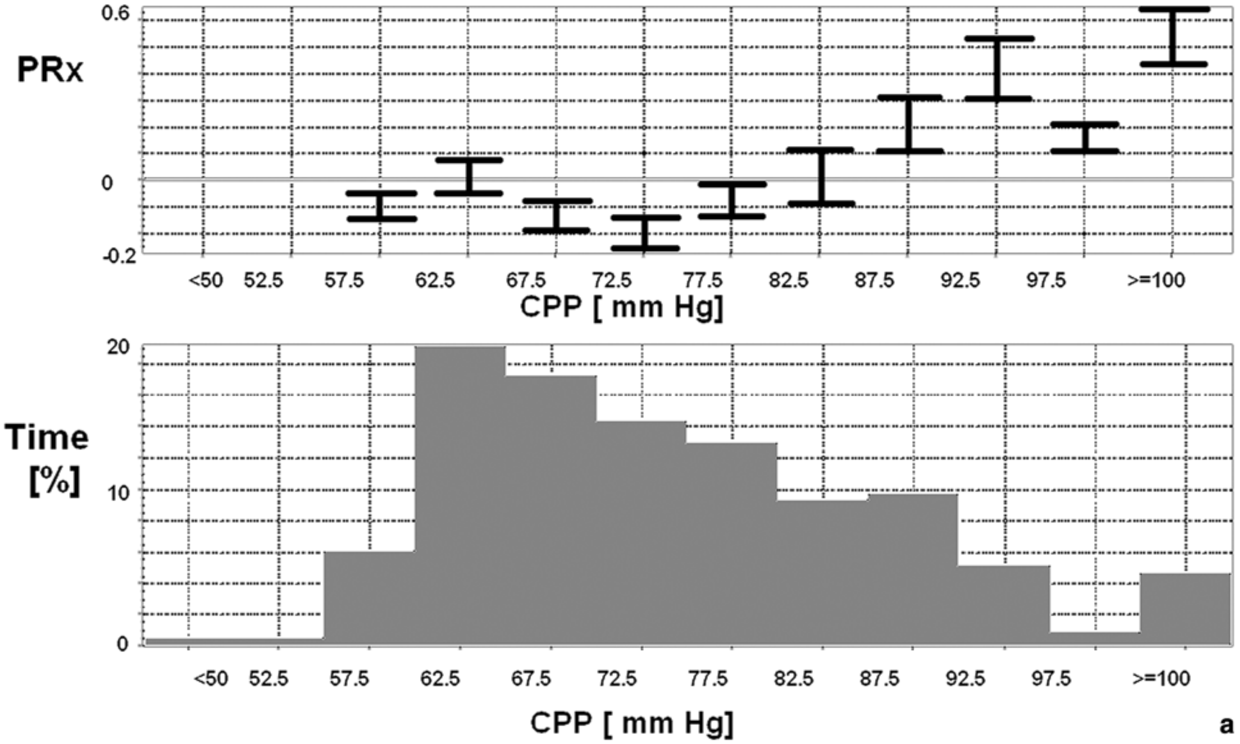
Useful ICP-derived variable is the PRx, based on assessing the response of ICP to spontaneous fluctuations in ABP [5]. Using computational methods, PRx is determined by calculating the correlation coefficient between 40 consecutive, time-averaged data points (over 6- to 10-second periods) of ICP and ABP. A positive PRx signifies a positive gradient of the regression line between the slow components of ABP and ICP, which has been shown to be associated with passive behavior of a non-reactive vascular bed. A negative value of PRx reflects normal reactive cerebral vessels, as ABP waves provoke inversely correlated waves in ICP.

Earlier work has shown a correlation between PRx and outcome [14]. Our results show that the PRx/CPP plot replicates a U-shape curve often seen in individual cases: pressure reactivity is disturbed by both too low and too high CPPs.

Optimization of CPP

Many attempts have been made to find an optimal value for CPP; however, there is no method available currently that is accurate enough to be clinically useful.

In a group of retrospectively-evaluated patients, the greater the distance between current and "optimal" CPP, the worse the outcome [14]. This potentially useful parameter attempts to refine CPP-directed therapy. Both, too low CPP (indicating ischemia) and too high CPP (indicating hyperemia) are detrimental. Hence, it has been suggested that CPP should be optimized online to maintain cerebral perfusion in the most favorable state (Fig. 2).



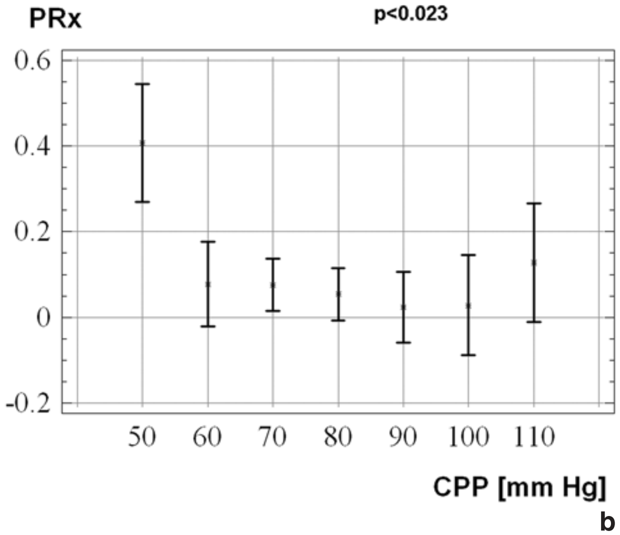


Fig. 2. (a) Individual plot of PRx versus CPP (upper panel) and histogram of CPP, used to analyze on-line optimal CPP. This is a value of CPP corresponding to the lowest PRx (i.e., the best PRx) updated on-line using past 3-hour trends of PRx and CPP. (b) Averaged plot of PRx versus CPP in a group of 95 patients. The plot replicates U-shape often seen in individual cases: PRx is disturbed by too low and too high CPP (ANOVA; $p < 0.023$)

Relationship between ICP and respiratory rate

Head trauma is a significant cause of death and disability, especially in young males, and is associated with raised ICP. Raised ICP is defined as pressure greater than 20 mmHg, and appears most commonly in about 50 to 75% of patients with serve head injury who remain comatose after resuscitation [3, 11]. In the past, raised ICP has been found to be associated with a poorer outcome from injury. Higher ICP, particularly higher peak ICP levels, correlate with mortality and morbidity [2, 12].

It is difficult to establish a universal “normal value” for ICP because it depends on age, body position, and

Table 1. *Mean values and standard deviations of the monitored variables.*

Variables	Units	Average	Standard deviation
ABP (arterial blood pressure)	mmHg	90.7	17.1
aABP (pulse amplitude of ABP)	mmHg	20.1	6.2
AMP (pulse amplitude of ICP waveform)	mmHg	4.78	7.98
CPP (cerebral perfusion pressure)	mmHg	73.4	20.8
HR (heart rate)	Beats/minute	72.8	17.5
ICP (intracranial pressure)	mmHg	17.3	20.3
PRx (pressure reactivity index)		0.0558	0.1639
RAC (index describing moving correlation between pulse waveform ICP and mean CPP)		1.11	9.22
RAP (index describing pressure-volume compensator reserve)		0.148	0.174
Resp (amplitude of respiratory waveform)	mmHg	0.515	0.450
RespRate (respiratory rate)	Cycles/minute	14.44	3.39
Slow (slow waves of ICP)	mmHg	5.97	7.28

clinical conditions. Our results show an inverse relationship between respiratory rate and mean ICP, i.e., a high respiratory rate signifies low ICP.

However, several questions need to be addressed to determine the mechanistic and clinical significance of this relationship. While the association of respiratory rate and ICP is intriguing, these data do not provide a complete explanation for the underlying pathophysiology, because higher frequency ventilation may control intracranial hypertension. And, higher respiratory rate leads to a lower arterial CO_2 with vasoconstriction of the cerebral blood vessels, causing ICP to fall.

Optional diagnostic tools

Program monitors gather input variables in the preprogrammed manner and analyzes them according to the programmed configuration, saving the output data in 2 separate files. First file contains time trends of the analyzed signals, and all calculations as well as comments and remarks introduced during monitoring. The second file contains raw data (input signals defined by the user). This file may be viewed and analyzed using various spectral analysis methods, or processed directly on-line.

Software also enables off-line data analysis, including files from the old ICM software, text files, and cerebrovascular laboratory software known also as BioSAn, i.e. 'text files'.

The software enables modification of existing methods of brain monitoring and development of new algorithms through extensive programming of signal analysis. It aids the integration of physiological monitoring with clinical observations.

In addition to continuous assessment provided by the time trends of indices, it is sometimes necessary to introduce external excitation to the measured system and to quantify its response. Examples are an increase in the ventilator rate to induce a change in arterial CO_2 content, brief compression of the common carotid artery to induce a momentary drop in CPP, or controlled infusion of saline into the cerebrospinal fluid space in order to challenge the compensatory reserve. Such an intervention provides an opportunity for more accurate assessment of the queried system characteristics than analysis of spontaneous fluctuations originating from it. On-line tools available to assess these diagnostic tests help gain additional insight into the developing pathology as well as allow for cross-calibration of continuous time trends.

Conclusion

ICM+ software proved to be useful in the management of patients after TBI. The study revealed that respiratory rate and mean ICP were inversely related. Therefore, higher frequency ventilation may be helpful to control intracranial hypertension.

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ICM+ software is licensed by University of Cambridge, Cambridge Enterprise (www.nerosurg.cam.ac.uk/icmplus). PS and MC have a financial interest in a fraction of the licensing fee.

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