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ICM+: software for on-line analysis of bedside monitoring data after severe head trauma

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Summary

ICM software was developed in 1986 in Warsaw, Poland and has been in use at the University of Cambridge Neurocritical Care Unit for 10 years collecting data from bed-side monitors in nearly 600 severely head injured patients and calculating secondary indices describing cerebral autoregulation and pressure-volume compensation. The new software ICM+ includes a much extended calculation engine that allows easy configuration and on-line trending of complex parameters.

The program records raw signals, and calculates time trends of summary parameters. Configuration and analysis utilises arithmetic expressions of signal processing functions to calculate various statistical properties for each signal, frequency spectrums and derivatives, as well as correlations/cross-correlations between signals. The software allows configuration of several levels of analysis before calculating the final time trends. The final data are displayed in a variety of ways including simple time trends, as well as time window based histograms, cross histograms, correlations etc. All this allows complex information coming off the bed-side monitors to be summarized in a concise fashion and presented to medical and nursing staff in a simple way that alerts them to the development of various pathological processes.

The system provides a universal tool for clinical and academic purposes. Its flexibility and advanced signal processing is specialized for the needs of multidisciplinary brain monitoring.

Keywords: Brain monitoring; multimodal monitoring; on-line data analysis; cerebral autoregulation; head trauma; intensive care; neuro-monitoring.

Introduction

In an established environment of Clinical Neuroscience Department enormous quantities of data can be captured from bed-side monitors per each patient [5]. From that data information regarding cerebral autoregulation, cerebrospinal compensatory reserve, oxygenation, metabolite production and function can be obtained [1, 3, 6]. However, continuous assessment of changing cerebrovascular haemodynamics and oxygenation demands not only reliable monitoring techniques, but also sophisticated and time consuming signal analysis. This can be provided by dedicated computer support.

The intensive care multimodality monitoring system adopted in the Cambridge Neurosurgical Unit is based on software for a standard PC, equipped with a digital to analogue converter and RS232 serial interface, running Windows 2000/XP. First version of the software was introduced into clinical practice in Poland, Denmark and the UK in the middle 1980s and has subsequently been extended into a system for multimodal neuro-*i*ntensive *c*are *m*onitoring (ICM) and waveform analysis of intracranial pressure [1, 8] used in Cambridge, UK, and other centres in Europe (Goteborg, Toulouse) and United States (Detroit). Most data has been derived from head injured [3] and hydrocephalus patients [2]. However, the same or similar techniques are being increasingly applied to those suffering from severe stroke, subarachnoid haemorrhage, cerebral infections, encephalopathy, liver failure, benign intracranial hypertension, etc. In addition to monitoring of multiple variables describing dynamics of the studied pathology [5], some secondary indices have proved to be useful in clinical neurosciences [6]. The best known example is the cerebral perfusion pressure, calculated as a difference between mean arterial pressure and ICP. More sophisticated indices describing cerebrospinal compensatory reserve, pressure autoregulation and vascular reactivity were introduced to clinical practice recently and proved to be useful in head injury [3, 5] or poor grade subarachnoid haemorrhage. The aim of this paper was to present and discuss the concepts implemented in the new version of the monitoring soft-

ware ICM+ and to show its applications in research of Neurosurgical diseases and head traumas.

Methods

The ICM+ software extends the ideas included in the original ICM program for DOS [1] as well as in the cerebrovascular reactivity test analyser CVRTest [8] by the same authors. In particular, the principle of multistage analysis of the bed-side monitors signals has been carried through (Fig. 1). It has however been extended heavily based on the authors experience over the years of using the software in the neuro-intensive care unit in the Addenbrookes Hospital, Cambridge.

The software is composed of several modules of which the core are:

1. Sampler module – collects data from variety of sources including analogue/digital converter and RS232 serial port. Configuration of the analogue input involves specifying sampling frequency, actual analogue channel to be used for particular signal as well as the voltage amplifier gain and the voltage-signal units conversion. Configuration of the serial input involves communication protocol, specifying record and data field separators as well as the position of the particular data field in the data record. All the signals are provided to sampler clients as one list with their respective sampling rates, hiding the actual signals sources. There is also an off-line version of the sampler that uses a data file (several formats are supported) instead of directly reading the data from bed-side monitors.
2. On-line Data Analysis module – collects signal samples from the Sampler and processes them according to requested analysis configuration (Fig. 2) producing time trends of calculated parameters.
3. Display module – allows viewing of the time trends using a selection of various charts, data browsing and analysis tools.
4. Diagnostic manoeuvres analysis module – provides a mechanism for plugging in optional analysis tools for various intervention tests like for example transient hyperaemic response test, CO_2 reactivity test or cerebrospinal fluid infusion study [2, 4, 9].

Results

The software has been used in a variety of applications covering various neurological pathologies ranging from hydrocephalus, stroke to severe head injury. For the last two years it has been used routinely in the neuro-intensive care unit in the Addenbrookes Hospital, Cambridge, UK. Total number of 78 patients has been monitored/diagnosed using this software. Case studies exemplifying the software application in different neurological condition are presented in Figure 3. More examples of research and clinical applications of the software can be found on the web site http://www.neurosurg.cam.ac.uk/icmplus.

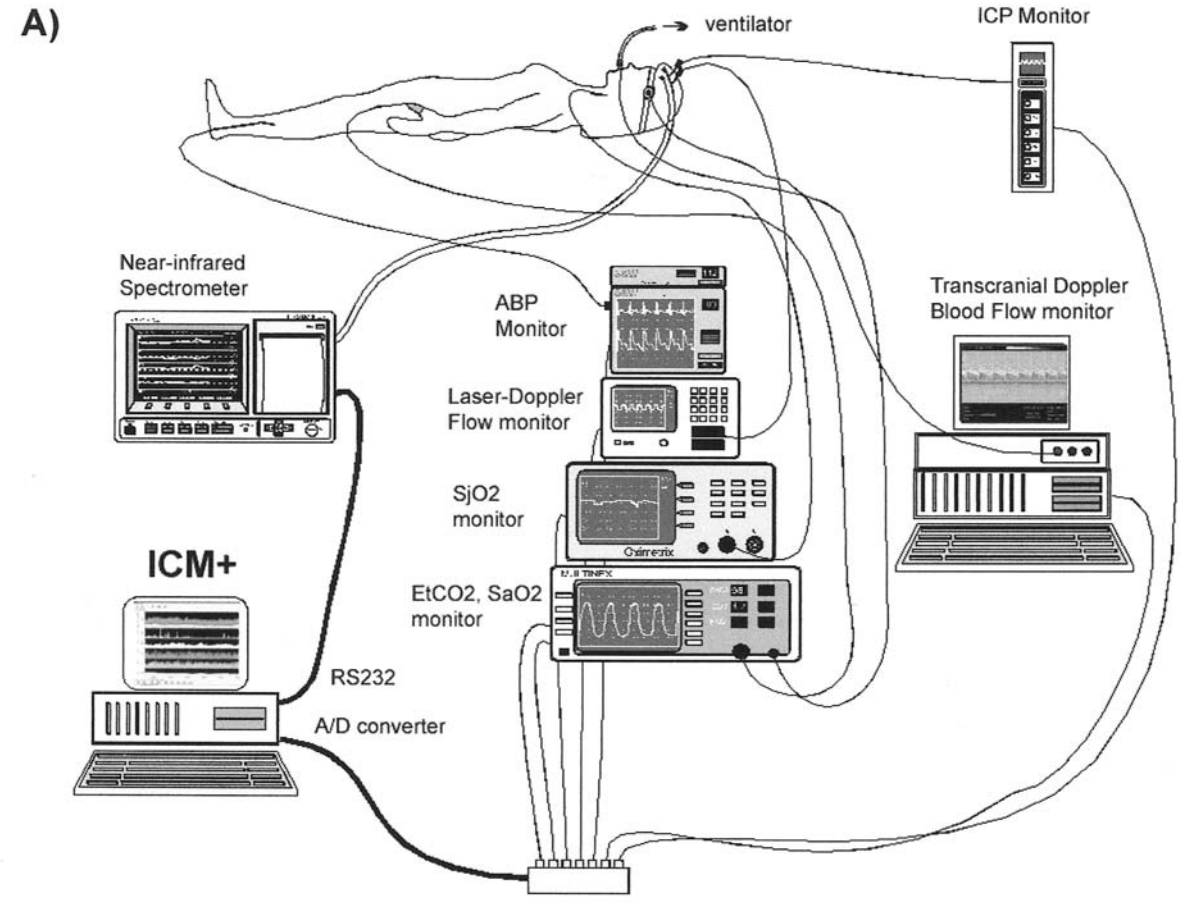
Discussion

Data from various monitoring equipment used in an intensive care unit contains a wealth of information about the patient's state. Some of the signals coming from the monitors are more complex than others, i.e. include complex waveforms. Instantaneous values of those signals are often difficult to interpret. Trends of minute by minute time averages travel far to aide in interpretation of the monitoring data but they completely dispose of information carried by the waveforms. Also, it is often the strength and character of association between different signals that provides extra information rather than the signals themselves.

The first specialised computer-based systems for neuro-intensive care were introduced at the beginning of the 1970s. Initially these systems were oriented to the monitoring of ICP and ABP allowing calculation of CPP and a basic analysis of the pulse waveform. In contrast, contemporary systems, like the one presented here, are highly sophisticated multi-channel digital trend recorders with built-in options for complex signal processing [1, 8]. The considerable flexibility of such systems allows almost unlimited signal analysis, which can generate a state of data chaos. Thus the modern user is faced with the problem of which parameters should be considered, and how the data should be interpreted. The information should then be presented in a manner that is comprehensible to medical and nursing staff. Decision on which calculated parameters are clinically most relevant should be made by the clinical stuff in collaboration with their research colleagues. Those carefully selected parameters, and only those, should then be presented continuously on the computer screen. Flexible configuration of data views implemented in ICM+ software allows for designing a clear summary view page for the clinically relevant parameters and additional, readily available pages containing all the other calculated parameters for more advanced clinical users or research fellows.

Multiple data sources

In a research orientated intensive care unit there may be several other monitors available in addition to the standard bed-side monitors of ABP and ICP. Those devices, e.g. TCD, Neurotrend, NIRS etc, are often used only during certain time periods rather than for the whole time of patient's stay in the ICU. Rather than creating new file with each configuration change ICM+ can accommodate those changes in its native file format and presents the whole patient data across different configuration as one time strip.



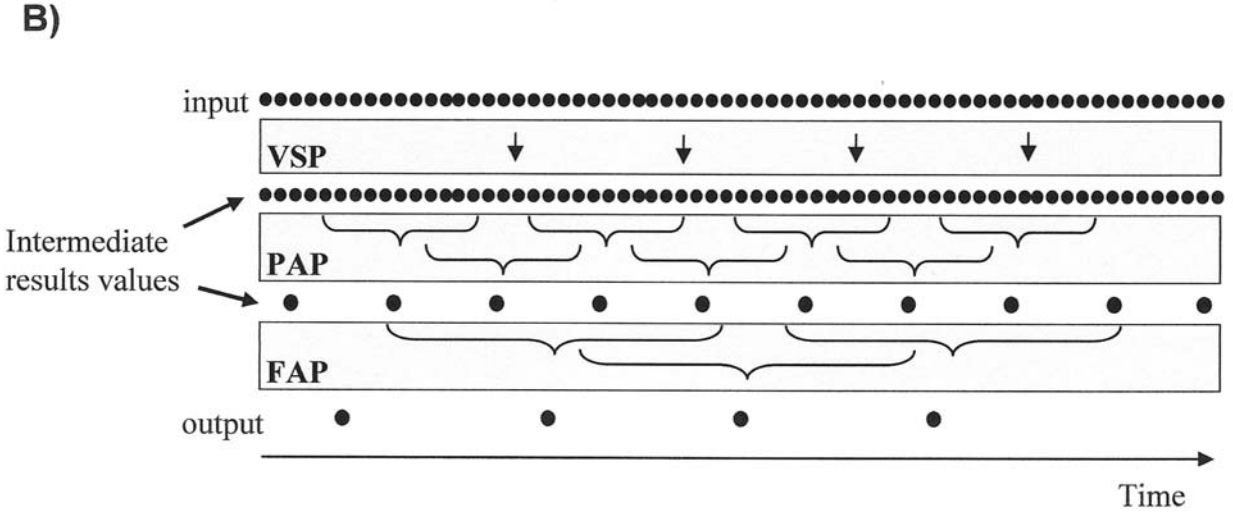
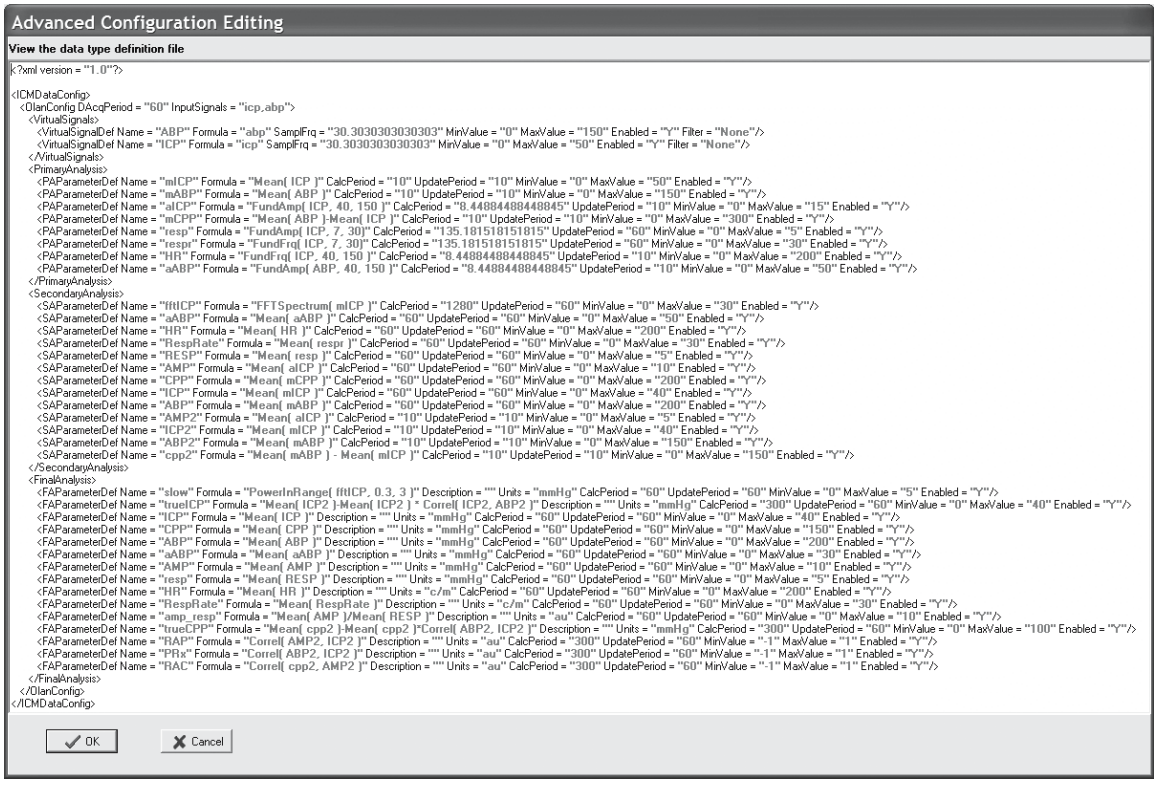


Fig. 1. (A) A symbolic diagram of a busy intensive care monitoring environment with various bed-side monitors hooked up to the data collection PC using either analogues or serial outputs. (B) A concept of multistage processing: raw data samples are first scaled using Virtual Signal Processor (*VSP*); the next stages (Primary Analysis Processor – *PAP* and Final Analysis Processor – *FAP*) operate on buffers of samples from the previous calculation stage – each buffer produces one intermediate result value at a time. The length of the buffer and how frequently the calculations are performed is fully configurable as are the calculation formulas

A)



B)

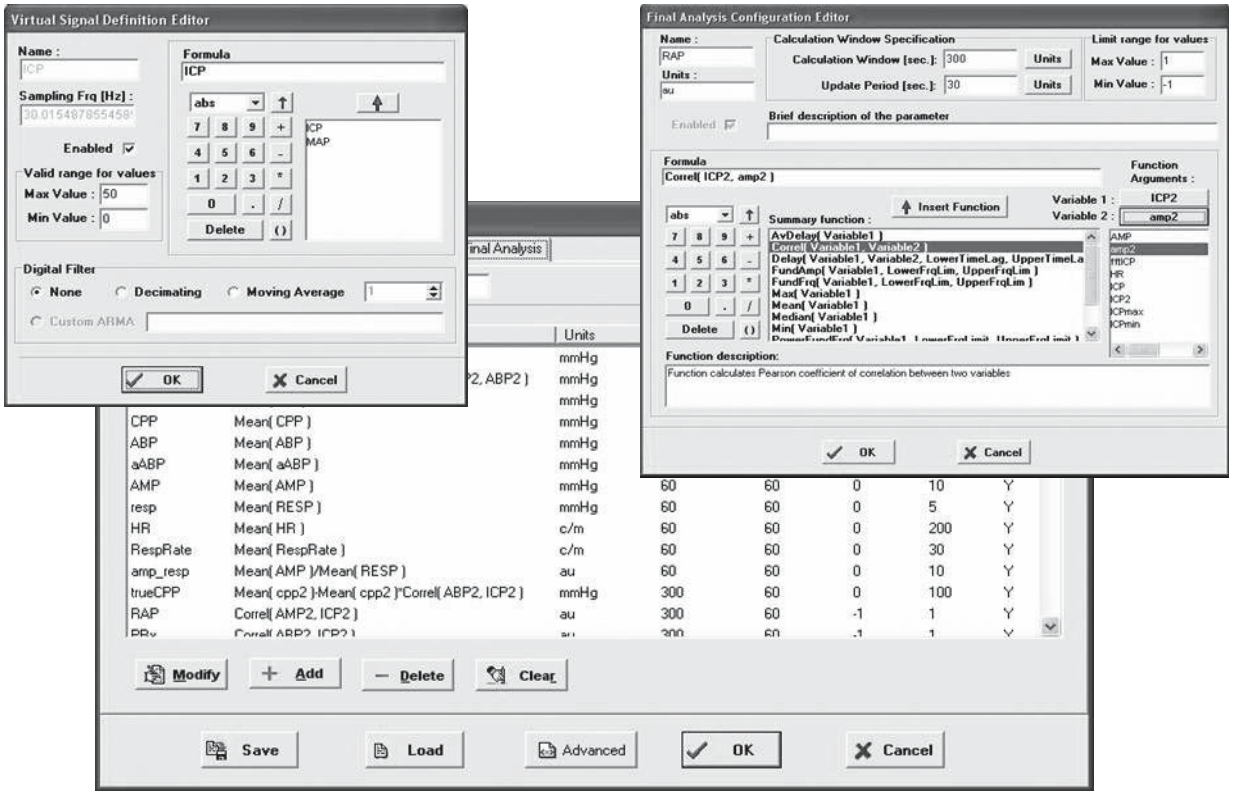


Fig. 2. Example of configuration of the on-line data analysis module. (A) The whole analysis prescription presented in its native XML format. (B) Snapshot of the graphical user interface for building up the analysis configuration

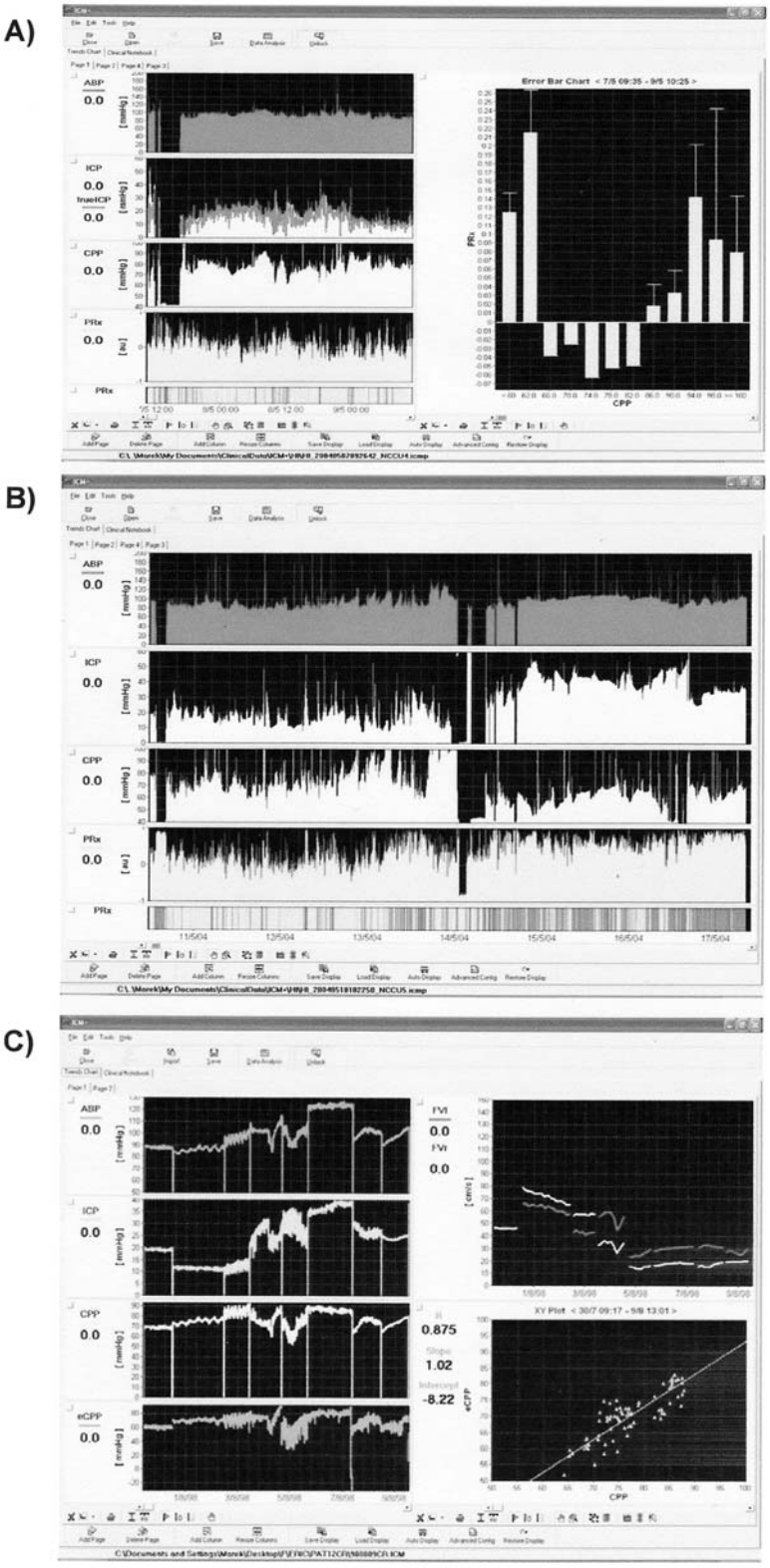


Fig. 3. Examples of ICP and ABP monitoring patients after head injury: (A) Patient admitted with GCS of 5. Initial ICP was around 40 mmHg and normalized after removal of large left subdural haematoma. Analysis of Pressure-reactivity (right panel) indicated 'optimal CPP' [10] for this patient of around 74 mm Hg; (B) Patient with multiple injuries. ICP was at first moderate but unstable, pressure-reactivity (*PRx*) was good. ICP deteriorated after abdominal surgery on the fourth day after accident. Pressure-reactivity index indicated permanent haemodynamic failure (see changing colour of bottom risk-chart: from green-light grey to red-dark grey). Patient died on day 6 after injury; (C) Day-by-day assessment of non-invasive CPP (*eCPP*) [7] after head injury. Correlation between non-invasive CPP and 'real' CPP is presented in right bottom corner

Clinical observations and comments

From the clinical research perspective the collected data is largely useless unless accompanied by the clinical picture of the patient. In order to decipher various episodes seen in the recorded time trends a scrupulous list of clinical observations should accompany the recording. Those observations can be recorded by the ICM+ software using three different methods: a notes tool, a system of user-definable events marking, and an annotation tool. The first two methods are used in an on-line mode with the event/note being stamped with the current time. Annotations are used off-line and get inserted at the point of time cursor, anywhere within the recording. These can be used to annotate the recording post-factum and can be modified/deleted at any time, unlike the notes and events which, once inserted, are read only.

Artefacts treatment

To ensure high quality of data analysis artefacts have to be dealt with. One cannot for example calculate mean value of ICP in the first 24 hours after injury without first taking out periods where ICP signal was lost or distorted. We feel strongly that rather than automatically substituting artefact periods with values predicted from the past and/or future history of the signal it is better to treat those as missing values. However in order to reduce influence of artefacts on the calculations they are divided into three categories depending on the where the fault occurred. Firstly there are global artefacts – i.e. reflected in all the signals. These are caused by events which involve temporary disconnection of the patient from all the monitoring devices and affect all the parameters. Then there are device related artefacts. These arise when a particular input device, like A/D converter, or a monitor using serial port for data transmission, gets temporarily disconnected, malfunctions or gets suspended. Here only parameters dependent on signals coming from the particular device will be affected. Other parameters will have valid values in those periods, unless of course affected by other overlapping source of artefact. And finally, there are artefacts that arise from temporary disturbance in measurement of individual signals. These can be for instance arterial line flushing, ICP calibration etc. As before, only parameters dependent on the particular signal are affected. The signal specific artefacts periods can be automatically detected and marked up during on-line analysis depending on the user configuration. Each of the calculation formula used in the analysis has a minimum and maximum value specified by the user. When the formula value falls outside of the specified region, signal(s) that contribute (directly or indirectly) to the calculations will have the period from which that value was calculated marked as an artefact. Such an automated processing will in no way cause data loss due to misclassification since it is only the artefact mark up that is being created. The data itself is recorded continuously and is not modified. The artefact mark up can later be modified manually, if necessary, in an off-line mode. Such an approach allows for cautious treatment of artefacts in the recording but yet provide a flexible tool for automated artefact recognition and treatment.

Optional diagnostic tools

In addition to continuous assessment provided by the calculated time trends of indices it is sometimes necessary to introduce external excitation to the measured system and quantify its response to it. This could be an increase of the ventilator rate to induce change in arterial CO2 content, brief compression of the common carotid artery to induce momentary drop in the cerebral perfusion pressure, or controlled infusion of saline into the cerebrospinal fluid space in order to challenge the compensatory reserve [2, 4, 9]. Such an intervention provides an opportunity for more accurate assessment of the queried system characteristics than the analysis of spontaneous fluctuations originated from it. Tools available on-line for assessment of these diagnostic tests help to gain additional insights into the developing pathology as well as allow for cross calibration of the continuous time trends.

Reuse of data

With the ongoing research on signal processing of data from the bed-side monitors it is important to build a data bank of raw signals for testing new hypothesis. The ICM+ software allows storing those in addition to time trends of calculated parameters. The raw signals can then be fed back into the software times and times again, with a different analysis configuration. This facilitates verification of new ideas for on-line data processing.

Data protection act

In order to comply with the Data Protection Act, all the data stored in the native ICM+ file format is strongly encrypted. In addition, the patient description data, i.e. information identifying the patient, is encrypted separately using a key individually selected by each research centre. That means that another centre will not be able to identify the patient without knowing the secret key but they will be able to browse the data and use it for the research purposes. That approach facilitates collaborative data exchange without worrying about violation of the Data Protection Act.

In conclusion, the system provides a universal tool for clinical and academic purposes. Its flexibility and advanced signal processing is specialized for the needs of multidisciplinary brain monitoring.

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