SYSTEMS ANALYSIS APPLIED TO INTRACRANIAL PRESSURE WAVEFORMS AND CORRELATION WITH CLINICAL STATUS IN HEAD INJURED PATIENTS

E. S. LIN, W. POON, R. C. HUTCHINSON AND T. E. OH

SUMMARY

Intracranial pressure waveforms (ICPWF) in head injured patients vary with the nature and severity of injury. Clinical interpretation of ICPWF shape is not defined. Spectral analysis provides an objective method of measuring changes in waveform shape, but the indices most suitable for clinical use remain unknown. Spectral analysis has been applied to ICPWF recorded from 30 patients with head injury, classified on clinical grounds into good, poor and intermediate groups. Normalized indices derived from ratios of certain characteristics of the ICP waveform to those of the arterial pressure (AP) waveform, were different (P < 0.05) in all groups. A simple index examined was the harmonic count ratio \( (N_c : N_a) \) which decreased with increasing severity of injury. ICP/AP harmonic transfer functions were derived, and demonstrated a peaked response in the range 10-12 Hz. Increasing attenuation of this peaked response occurred with increasing severity of injury. These results suggest that transfer functions may be a clinically useful index of intracranial conditions.

KEY WORDS


Intracranial pressure (ICP) measurement remains the most commonly used technique for continuously monitoring intracranial conditions in neurosurgical patients. The mean ICP (MICP) is the usual variable monitored. However, clinical interpretation of increased MICP has some limitations. Although consistently increased MICP values (>40 mm Hg) correlate well with poor clinical status and outcome [1], this relationship is less predictable in patients with moderately increased values (20-30 mm Hg) [2]. In such cases, MICP measurements may fail to differentiate patients whose intracranial status is deteriorating from those who are stable or improving. The MICP may also prove unreliable by demonstrating a delayed response in the face of acute changes in intracranial conditions.

The pressure–volume relationship of the intracranial cavity has been investigated by some workers as a more useful index of intracranial status and prognosis. The intracranial elastance is represented by the slope of this curve \( \frac{dP}{dV} \). This may be determined by measuring the increase in ICP in response to a small volume challenge to the cerebrospinal fluid (CSF) space and may be referred to as the pressure–volume response (PVR). A pressure–volume index (PVI) also may be derived from a small injection into the CSF space. The PVI represents the volume of infusion required to increase the ICP 10 times and is calculated by assuming a logarithmic pressure–volume relationship [3, 4]. This improves predictive ability by locating the position of the intracranial cavity on the pressure–volume curve more accurately. However, such volume provocation tests are not suitable for repeated measurements because of their invasive nature, and cannot provide continuous monitoring.

A further alternative lies in the analysis of intracranial pressure waveforms (ICPW) which...
systems analysis and ICP waveforms

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MICP = 10 mm Hg
2.5 mm Hg

arterial pressure waves

intracranial cavity

intracranial pressure waves

MICP = 24 mm Hg
5 mm Hg

Fig. 2. Schematic diagram of intracranial cavity as a “black box” with arterial pressure waveform (APWF) as an input signal and ICPWF as the output signal.

MICP = 55 mm Hg
10 mm Hg

Fig. 1. Examples of varying intracranial pressure waveform (ICPWF) morphology recorded from different patients with head injury.

animal studies demonstrate that ICP/AP transfer functions can be derived for normal intracranial conditions and that changes in transfer function can be produced by artificially increasing intracranial pressure or by inducing hydrocephalus [8].

in this study we have attempted to determine which ICPWF spectral variables are likely to be clinically useful, by applying spectral analysis to ICP signals obtained in head injured patients. we have also derived ICP/AP transfer functions from these patients and examined these in relation to the neurological condition of the patients as assessed by Glasgow Coma Score (GCS).

patients and methods

following approval of the research ethics committee of the faculty of medicine, 32 head injured patients were studied in the intensive care unit (ICU) at the Prince of Wales Hospital. these patients were admitted after operation, having received neurosurgery (usually evacuation of a haematoma, contusionectomy, or both) which also included the insertion of an intraventricular catheter for ICP monitoring. in order to obtain spectral data in groups of patients with similar intracranial conditions, we grouped the patients, according to their GCS on admission to hospital, into “good” (GCS = 13–15), “intermediate” (GCS = 6–12) and “poor” (GCS = 3–5). the
patients were reassessed later, on discharge from the ICU after data collection was completed. Patients who underwent a marked change in neurological status so that initial and final GCS scores did not correspond were rejected. This ensured that the ICPWF recorded were grouped consistently according to GCS assessment over the period of data collection. Clinical assessment during this period was often difficult as patients were usually sedated and undergoing artificial ventilation.

The management of the patients in the ICU followed standard practice including sedation (morphine infusion with or without midazolam infusion) with and without neuromuscular block (atracurium), mechanical ventilation (maintaining $P_{aco_2}$, 3.5–4.5 kPa) for periods ranging from 12 h to several days, depending on severity of injury and clinical condition of the patient. Intra-arterial pressure monitoring (Deseret 8060 transducers) was routinely applied to all patients as part of normal management.

ICPWF were recorded (Hi-corder 8820, Hioki, Japan) initially on admission of each patient to the ICU and thereafter recordings were made at 12- or 24-h intervals. Simultaneous recordings were made of the radial APWF when ICPWF were recorded. Data were analysed on site using the built-in fast Fourier transform (FFT) facility of the recorder to provide an immediate hard copy of the APWF and ICPWF power spectra. In addition, derived power spectra were stored in an IBM-compatible microcomputer for further analysis and derivation of transfer functions.

**Signal processing**

ICP and AP signals were monitored using Deseret 8060 pressure transducers with a linear response over the range –50 to 300 mm Hg and a flat frequency response to 125 Hz. Signal conditioning was through the ICU monitoring system (Simonsen & Weel) with cut off filters set to 100 Hz and re-calibrated manometrically each morning before recordings were made.

The FFT routine used by the signal recorder stored 20-s signal epochs and performed 1024 sample FFT on the signal using Hanning windowing. These settings yielded spectra over a frequency range of 0–23.4 Hz.

Examples of ICPWF power spectra are illustrated in figure 4: this shows how the derived power spectra were composed of harmonic peaks or spikes. The power spectra for corresponding epochs of arterial pressure waveform consisted also of a fundamental component accompanied by harmonic spikes.

Spectral parameters derived from the ICPWF consisted of:

(i) a simple harmonic spike count ($N_c$), taken relative to a baseline 60 dB down from the maximum peak amplitude recorded in the power spectrum;
(ii) a spectral edge ($F_{90c}$) below which 90% of the power in the spectrum was contained;
(iii) the centroid frequency ($HFC_c$) of a “high frequency band” between 4 and 15 Hz as defined by Bray and colleagues [5].

Corresponding AP spectral parameters $N_a$, $F_{90a}$ and $HFC_a$ were determined also from the radial arterial pressure signals: “normalized” indices could then be calculated by taking the ratios $N_c:N_a$, $F_{90c}:F_{90a}$ and $HFC_c:HFC_a$.

In this way, a three-way comparison has been made between the standard monitoring indices of MICP and cerebral perfusion pressure (CPP), the spectral parameters obtained solely from the
ICPWF spectra, and the normalized spectral parameters derived from both ICPWF spectra and AP spectra. These sets of indices have been compared in their ability to distinguish between three groups of patients as defined by their presenting GCS.

The spectral analysis of the ICP and AP signals has been extended further by determining the amplitude transfer functions. These were obtained from the ratio of corresponding harmonic spike amplitudes in the individual power spectra. Ideally, a transfer function is a spectral response function which is continuous over the frequency range examined. However, if derived from periodic signals it may be approximated to by using the spectra of the “input” and “output” signals used as in this case.

Recordings have been analysed and spectral parameters averaged for each individual, with a total of more than 200 traces analysed. For each group, between subject SD were calculated, and statistical comparisons between patient groups were made with the Kruskal–Wallis test with an extension for multiple comparisons.

RESULTS

The mean duration of stay in the ICU for each of 32 patients was 4.1 (SD 3.7) days. A total of more than 200 ICPWF and APWF spectra were analysed.

Classification of the patients according to GCS on admission to hospital corresponded well with their grouping according to GCS on discharge from the ICU (table I). Two patients deteriorated markedly during admission to ICU and their recordings were rejected. Subsequent outcome in terms of clinical condition on discharge from the ward is shown also and it may be seen that correspondence between good and intermediate groups became poorer at this later stage.

Some examples of ICPWF power spectra obtained for patients from good (A), intermediate (B) and poor (C) groups are shown in figure 4. These demonstrate typical variations in spectral harmonics occurring between groups.

Simple spectral parameters derived solely from the ICPWF spectra, and relative indices derived from both ICPWF and APWF spectra are shown for the three groups in table II. Mean ICP and CPP values for the respective groups are included also. It may be seen that, while all indices produced significant differences between poor and intermediate groups, only the relative spectral indices differentiated between good and intermediate patients.

Correlations between harmonic count ratio (Nc:Na) and MICP and CPP were poor ($r = 0.27$, $P < 0.01$ and $r = 0.20$, $P < 0.05$, respectively).

The ICPWF/APWF harmonic transfer function obtained from the patients in the good group

| Table I. Grouping of 32 head injury patients according to Glasgow Coma Score (GCS) on admission to hospital, clinical condition on discharge from the Intensive Care Unit (ICU) and clinical condition on discharge from the ward, as defined according to a modified Glasgow Outcome Scale: good = potentially employable; intermediate = moderate or severe disability; poor = vegetative state or died during admission |
|-----------------|---|---|---|
| Admission GCS   | 7 | 16 | 9 |
| GCS on discharge from ICU | 6 | 15 | 11 |
| Condition on discharge from ward | 11 | 10 | 11 |
Table II. Intracranial pressure waveform (ICPWF) spectral indices (SD), mean intracranial pressure (MICP) and mean cerebral perfusion pressure (CPP) for good, intermediate and poor groups of head injury patients. n = Number of patients in group. *Significant difference (P < 0.05) from both other groups.

<table>
<thead>
<tr>
<th></th>
<th>Good (n = 6)</th>
<th>Intermediate (n = 14)</th>
<th>Poor (n = 10)</th>
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<tbody>
<tr>
<td>CPP</td>
<td>78.2 (16.0)</td>
<td>65.7 (13.1)</td>
<td>15.3 (36.4)*</td>
</tr>
<tr>
<td>MICP</td>
<td>13.0 (6.2)</td>
<td>16.5 (7.5)</td>
<td>46.4 (20.2)*</td>
</tr>
<tr>
<td>ICPWF spectral indices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nc</td>
<td>11.9 (1.7)</td>
<td>9.9 (2.2)</td>
<td>7.8 (1.8)*</td>
</tr>
<tr>
<td>F90c</td>
<td>12.6 (1.7)</td>
<td>11.6 (3.2)</td>
<td>7.8 (1.8)*</td>
</tr>
<tr>
<td>HFCc</td>
<td>8.0 (1.0)</td>
<td>7.2 (0.7)</td>
<td>6.6 (0.8)*</td>
</tr>
<tr>
<td>ICPWF/APWF normalized indices</td>
<td></td>
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<tr>
<td>Nc:Na</td>
<td>1.31 (0.29)*</td>
<td>0.97 (0.11)*</td>
<td>0.66 (0.15)*</td>
</tr>
<tr>
<td>F90c:F90a</td>
<td>1.36 (0.19)*</td>
<td>0.95 (0.18)*</td>
<td>0.64 (0.14)*</td>
</tr>
<tr>
<td>HFCc:HFCa</td>
<td>1.41 (0.24)*</td>
<td>0.98 (0.12)*</td>
<td>0.68 (0.13)*</td>
</tr>
</tbody>
</table>

Fig. 5. Effect of increasing severity of injury on transfer function in good (□), intermediate (■) and poor (○) patient groups.

The simple indices of Nc, HFCc, F90c, CPP and MICP provided non-significant differences between good and intermediate groups. However, the normalized indices (HFCc:HFCa, F90c:F90a and Nc:Na) derived from both ICPWF and APWF spectra did appear to be sensitive enough to distinguish between these groups. Thus normalization of spectral indices would appear to enhance their performance. Nc:Na was obtainable by simple inspection of the respective power spectra, whereas HFCc:HFCa and F90c:F90a required computation of areas under the spectral curves.

DISCUSSION

In this study, the patients were grouped according to clinical status in order to highlight spectral differences of clinical significance. Assessment of the patients has been performed before data recording (GCS on admission to hospital) and after recording was completed (GCS on discharge from ICU). In this way, we have tried to ensure that intracranial conditions retained a significant degree of consistency over the period of data collection.

Simple spectral parameters

Differentiating between the poor group patients and the remainder was effective with all indices, both spectrally and physiologically derived (CPP and ICP). This is of limited practical use because, even on clinical grounds, this does not often present a problem. However, differentiating between intermediate and good groups may be a clinical problem, particularly when patients are sedated and sometimes receiving neuromuscular blockers. It is often this intermediate group of patients in whom acute or sub-acute changes in intracranial conditions may occur, and in whom it is most desirable to detect such changes as early as possible.

The simple indices of Nc, HFCc, F90c, CPP and MICP provided non-significant differences between good and intermediate groups. However, the normalized indices (HFCc:HFCa, F90c:F90a and Nc:Na) derived from both ICPWF and APWF spectra did appear to be sensitive enough to distinguish between these groups. Thus normalization of spectral indices would appear to enhance their performance. Nc:Na was obtainable by simple inspection of the respective power spectra, whereas HFCc:HFCa and F90c:F90a required computation of areas under the spectral curves.
Transfer functions

Although the physiological and mechanical factors contributing to the transfer functions may be outlined (fig. 4), the relative importance of each component remains unknown. Thus interpretation of transfer function changes would be aided by further knowledge of how the pressure pulsations in the CSF originate. This question has been investigated by previous workers [9, 10]. The most attractive concept is that these waves are generated by the cerebral vessels and transmitted to the CSF spaces via the cerebral parenchyma and other tissues [11]. A further question arising is the relative contributions of arterial and venous vessels [12], although there is evidence to suggest that the ICPWF possesses components from both types of vessels [13]. In addition, because radial arterial pressure signals were used in these patients, the peripheral systemic vasculature also affects transfer function.

The mean transfer function obtained for patients in the good group (fig. 5) agrees with the general configuration obtained for the continuous extradural-carotid arterial transfer function derived for dogs with normal ICP [8]. As in the normal animal model, a peak is obtained (10–12 Hz) which is attributable to resonance in the response of the intracranial cavity.

Comparing this transfer function with those obtained in the intermediate and poor groups, significant changes may be noted with deteriorating clinical condition. Most prominently, there is increasing attenuation of the peak in the transfer function with increasing severity of injury. If these transfer functions are compared with the theoretical response of a simple damped mechanical oscillator (fig. 6), it may be seen that the effect of worsening clinical condition is analogous to increasing the mechanical damping in the second order system. In terms of intracranial contents, the mechanical damping or resistive factors represent the viscous and resistive tissue effects in cerebral parenchyma and vessel walls. Thus changes in these resistive factors may herald acute deterioration in intracranial conditions. This contrasts with the concept that intracranial compliance (or its reciprocal, elastance) is the most useful mechanical index clinically.

The application of transfer function monitoring in detecting acute changes in a patient's intracranial status would be particularly desirable in the intermediate group of patients, in whom the clinical course is most likely to change or be affected by therapeutic intervention (table I). An indication of potential performance was obtained from the records of selected patients from the intermediate outcome group, who were noted to improve during their ICU admission from GCS 6–7 on admission to 9–11 on discharge, and whose transfer functions also “improved” correspondingly. Serial transfer functions plotted on days 1, 3 and 8, for one such patient are shown in figure 7. However, further work is required to establish
if the response of transfer functions is consistent and rapid enough to be clinically useful in detecting acute changes in intracranial conditions.

REFERENCES


