Pulse waveform analysis of intracranial pressure: Spectral analysis, morphological methods, high frequency centroids?
Fig. 14. Computer analysis of ventricular fluid pressure (VFP) signal in combination with electrocardiogram (ECG). Sampling frequency of signal is 80 Hz. Mean VFP in N-th R-R interval of ECG (P_m(N)) is arithmetical average of samples. Due to fluctuation of mean VFP, pulse pressure (P_{max} - P_{min}) is different for ascending and descending slope of pulse. To overcome this problem pulse pressure for interval N (\Delta P(N)) is calculated according to:
\[ \Delta P(N) = \frac{1}{2} [2P_{max}(N) - P_{min}(N) - P_{min}^{(N+1)}]. \]
Fig. 9. Amplitude of CSF pulse (pulse pressure) increases with rising ICP in accordance with exponential shape of craniospinal volume-pressure curve. Magnitude of pulse pressure is determined by shape of curve and by amount of pulsatile change in cerebral blood volume ($\Delta V_b$).
Fig. 20. Computer plot of ventricular fluid pressure recording in 2 year old child with communicating hydrocephalus and malfunction of CSF shunt. Compare with Figure 19. Note that difference in $E_1$ is accurately reflected by difference in slope of relationship between CSF pulse pressure and VFP. This is because magnitude of $\Delta V_b$ is approximately the same in both patients.
Time-domain and frequency–domain calculations

Pulse analysis:
Time domain
(Avezaat & Ejindhoven), Eide (2000s)

Frequency domain
(short term FFT + interpolation)
Results of time domain analysis and spectral methods are similar.
In most cases AMP_P is linear (above $p_{opt}$; Sliwka et al 1985) and has positive slope
In some cases cases AMP_P ‘line’ may be non-linear
Change in a slope of AMP_P before, during and after plateau-wave
Pulse amplitude of ICP is positively related to pulse amplitude of blood flow velocity.

Relationship between pulse amplitude of ICP and pulse of ABP is much weaker.
AMP dramatically increases during ‘B waves’ of ICP detected during overnight monitoring.
During refractory intracranial hypertension, or during plateau waves of ICP amplitude-pressure line shows upper breakpoint.
Pictorial interpretation of the ‘upper breakpoint’

Thanks to Dr. K. Brady
Composite scattergram of AMP versus mean ICP monitored in patients after TBI:

a) Favourable outcome
b) Died
Analysis of the cerebrospinal fluid pulse wave in intracranial pressure


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Fig. 1. The cerebrospinal fluid (CSF) pulse wave has three main components: the percussion wave (P1), the tidal wave (P2), and the dicrotic wave (P3). The arrow indicates the dicrotic notch, between P2 and P3. It corresponds to the dicrotic notch of the arterial pulsation that originates the CSF pulse wave.

Fig. 2. The spontaneous increase in intracranial pressure (ICP) is accompanied by a disproportionate elevation of the cerebrospinal fluid pulse wave components P2 and P3, resulting in changes of the shape of the pulse wave. It first becomes rounded and, at higher ICP values, it acquires a pyramidal shape.

Results

Spontaneous Variations
What Shapes Pulse Amplitude of Intracranial Pressure?

Emmanuel Carrera, Dong-Joo Kim, Gianluca Castellani, Christian Zweifel, Zofia Czosnyka, Magdalena Kasparowicz, Peter Smielewski, John D. Pickard, and Marek Czosnyka
FIG. 5. Tracings in a patient with benign intracranial hypertension (BIH). The reduction in intracranial pressure caused by hyperventilation is accompanied by a decrease in the relative amplitude of $P_2$ and $P_3$ (upper tracing). The reverse is observed after hypoventilation (lower tracing).

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Brain Compliance proportional to $P_1/P_2$
Intracranial pressure pulse morphological features improved detection of decreased cerebral blood flow

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**Figure 1.** Block diagram of the Morphological Clustering and Analysis of Intracranial Pressure (MOCAIP) algorithm. The input to the algorithm is a segment of intracranial pressure and electrocardiogram signals and the output of the algorithm is a dominant intracranial pressure pulse representative of the majority of the pulses of the segment and designation of the three sub-peaks on this dominant pulse. The two shaded blocks in the diagram were recently improved since the publication of the original MOCAIP.

(This figure is in colour only in the electronic version)
Method

Morphological Clustering and Analysis of Intracranial Pressure

Thanks to Dr. M. Kasprowicz

MOCAIP Method

24 MOCAIP metrics (absolute and ratio values)

- Amplitude - 6 metrics
- Curvatures - 7 metrics
- Time interv. - 7 metrics
- Slope
- Decay time constant
- mean ICP
- diastolic ICP

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Thanks to Dr M Kasprowicz
Use of MOCAIP for analysis of slow waves in hydrocephalus (Dr. M. Kasprowicz)

NW – flat ICP recording
Thanks to Dr. M. Kasprowicz

SW – symmetrical ICP slow waves
AW – asymmetrical ICP slow waves

Thanks to Dr. M. Kasprowicz
PW – ICP slow waves with plateau phase
Systems analysis of cerebrovascular pressure transmission: an observational study in head-injured patients

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N. MARK DEARDEN, F.F.A.R.C.S., JAMES R. S. LEGGATE, F.R.C.S., AND
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Cerebrovascular pressure transmission in head-injured patients

**FIG. 1.** Systems analysis approach in which the blood pressure (BP) and intracranial pressure (ICP) waveforms (f(t) and g(t), respectively) are used as input and output functions to the cerebrovascular bed (CVB). These pressure waveforms can be transformed from the time domain (g(t)) to the frequency domain (G(\omega)) through Fourier transformation. Fourier analysis can represent a pressure waveform, as seen in the amplitude spectra, as a series of simpler sine waves consisting of a fundamental component frequency related to the heart rate and a series of higher harmonics at multiples of the fundamental component frequency. The system transfer function (H(\omega)), which consists of both amplitude and phase components, describes how the stimulus signals are transformed by the system into response signals and is calculated as the ratio of ICP and BP amplitude and phase values, taken from the amplitude spectra, at each of the measured cardiac component harmonics.
Fig. 2. Graphs depicting four classes of amplitude transfer function for the first six cardiac component harmonics, based on Fourier analysis of 100 pilot samples from a database of intracranial pressure and blood pressure waveforms collected from 30 head-injured patients. The amplitude transfer functions were calculated and found to cluster into four curve types: 1) those with an overall flat amplitude transfer function, 2) those with an elevated low-frequency response, 3) those with an elevated high-frequency response, and 4) those exhibiting both an elevated low- and high-frequency response.
Cerebrovascular pressure transmission in head-injured patients

Fig. 3. Graphs showing the results of Fourier analysis of the 1400 post-pilot samples from a database of intracranial pressure and blood pressure waveforms collected from 30 head-injured patients, and the amplitude transfer functions prospectively coded into one of four curve types (see legend to Fig. 2 for classification criteria). Data were averaged by amplitude transfer function curve type: curve type 1 = 382 samples, curve type 2 = 243, curve type 3 = 245, and curve type 4 = 202.

Fig. 4. Graphs showing the results of Fourier analysis of the 1400 post-pilot samples from a database of intracranial pressure and blood pressure waveforms collected from 30 head-injured patients and the phase transfer function data, averaged and classified by amplitude transfer function curve type (see legend to Fig. 2 for classification criteria). The first harmonic phase for curve type 3 shows a positive phase shift compared to the other curve types. Also associated particularly with phase transfer function curve type 3 is the presence of a phase cross-over from a positive to a negative phase. This phase cross-over was not seen with phase transfer function curve type 1. Phase transfer function is expressed in radians.

Cerebrovascular pressure transmission in head-injured patients

<table>
<thead>
<tr>
<th>Curve Type</th>
<th>No. of Samples</th>
<th>Mean ICP (mm Hg)</th>
<th>Mean BP (mm Hg)</th>
<th>Mean CVP (mm Hg)</th>
<th>Core Body Temperature (°C)</th>
<th>PaCO₂ (kPa)</th>
<th>PaO₂ (kPa)</th>
<th>pH (nmol/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>382</td>
<td>15 ± 9</td>
<td>90 ± 15</td>
<td>1.2 ± 2.8</td>
<td>37.2 ± 1.0</td>
<td>3.6 ± 0.7</td>
<td>18.8 ± 3.8</td>
<td>33.6 ± 3.7</td>
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<tr>
<td>2</td>
<td>243</td>
<td>24 ± 10</td>
<td>86 ± 10</td>
<td>2.7 ± 3.8</td>
<td>37.3 ± 0.6</td>
<td>3.3 ± 0.6</td>
<td>19.2 ± 3.9</td>
<td>31.5 ± 3.3</td>
</tr>
<tr>
<td>3</td>
<td>545</td>
<td>13 ± 10</td>
<td>85 ± 15</td>
<td>1.9 ± 2.9</td>
<td>37.4 ± 0.7</td>
<td>3.5 ± 0.6</td>
<td>18.1 ± 3.5</td>
<td>34.2 ± 4.5</td>
</tr>
<tr>
<td>4</td>
<td>202</td>
<td>30 ± 19</td>
<td>86 ± 10</td>
<td>1.6 ± 3.1</td>
<td>36.7 ± 1.3</td>
<td>3.6 ± 0.3</td>
<td>18.4 ± 3.2</td>
<td>34.0 ± 1.5</td>
</tr>
</tbody>
</table>

* Values are means ± standard deviations. ICP = intracranial pressure; BP = blood pressure; CVP = central venous pressure.
Waveform Analysis

Cerebrovascular Pressure Transmission Piper et al (J Neurosurg, 1990)

High Frequency Centroid (HFC) Robertson et al (J Neurosurg 1989)

HFC is Heart Rate Dependent Contant et al (ICP VIII)

Needs Validation against an independent measure of compliance

Thanks to DR. Ian Piper
Clinical experience with a continuous monitor of intracranial compliance

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Robert G. Grossman, M.D., Ziya L. Gokaslan, M.D., Rajesh Pahiwa, M.D.,
Pedro Caram, Jr., M.D., Robert S. Bray, Jr., M.D., and
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Fig. 2. Power shifts within the 4- to 15-Hz frequency range of the power density spectrum generated by the discrete Fourier transform (DFT) were found to occur with changes in intracranial compliance. To describe these frequency shifts, the power-weighted average frequency (or high-frequency centroid (HFC)) within the 4- to 15-Hz band is calculated. An HFC of 6.5 to 7.0 Hz indicates a normal intracranial compliance, while an HFC of 9.0 Hz occurs with reduction in pressure-volume index to approximately 13 ml.
Fig. 5. Clinical course of a patient who had a slightly increased high-frequency centroid (HFC) for the first 2 days after head injury. Abruptly at 49 hours after injury, the HFC increased from 7.0 to greater than 8.5 Hz over a 1-hour period. Within another hour, the patient had a sudden increase in intracranial pressure (ICP) accompanied by clinical signs of herniation. A computerized tomography (CT) scan showed a delayed intracerebral hematoma in the temporal lobe.

Fig. 6. Clinical course of a patient who developed cerebral edema associated with a contusion. The high-frequency centroid (HFC) gradually increased from 7.6 to 9.2 Hz over about 36 hours. At the peak of the HFC increase, the intracranial pressure (ICP) became uncontrollable and barbiturate coma was necessary. Computerized tomography showed an increase in cerebral edema surrounding the contusion. The patient eventually required a frontal lobectomy.
Cerebrospinal fluid pulse pressure waveform analysis in hydrocephalic children

Fig. 1 Increase in CSFP (a) during lumbar infusion test is commonly followed by decrease in HFC (b). *Horizontal axis* time (total duration 35 min)
Clinical Article
Intracranial pressure parameters in idiopathic normal pressure hydrocephalus patients treated with ventriculo-peritoneal shunts

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Fig. 1. A continuous ICP signal of 30 seconds (a) highlighting one single 6-second time window (b)

Fig. 2. The difference between patients groups with change in NPH Score of either -4 to 0, 1 to 2, 3 to 4, or >5 twelve months after shunt surgery concerning (a) mean ICP, (b) mean ICP wave latency and (c) mean ICP wave amplitude
Metrological issue: AMP is a great marker of transducer failure
Metrological issue: pulse amplitude from lumbar puncture is slightly lower than measured from ventricles

AMP [mm Hg]

2.8 60:61; p=0.061
2.6
2.4
2.2
2
1.8
1.6

Ventricles Lumbar
AMP seems to increase with age

AMP [mm Hg]  R=0.31; p<0.0001

Age [years]
Messages to take home

Pulse waveform includes information about:
• Cerebral blood stroke volume
• Cerebral compliance
• Probably a compliance of cerebral arteries (this concept will be followed later)

Measurement principle: no pulse, no ICP!
1st harmonic and peak-to-peak amplitude are linearly associated

• High Frequency centroid - descriptor of compliance?
• P1/P2 – descriptor of cerebrospinal compliance
• Peak-to-peak ICP amplitude correlates with outcome after shunting in NPH?