20. Cerebral Compartmental Compliances
Cerebral arterial blood volume ($C_{aBV}$)

\[
\Delta CBV = \int_{t_0}^{t} (CBF_a(t) - CBF_v(t)) dt
\]


Thanks to Dr. M. Kasprowicz
Cerebral arterial blood volume

Assumptions:
• Diameter of the MCA artery unchanged during the cardiac cycle
• Venous outflow constant during the cardiac cycle

Thanks to Dr. E.Carrera
Thanks to Dr. M. Kasprowicz
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
Thanks to Dr. E.Carrera
Is model with constant outflow the only model possible?

(baseline), 0.71 (-60) and 0.9 (0). Thus, there seems to be a strong decrease, but only little improvement during syncope.

Dear Christina and Magda, thank you for participating me in your research. I hope you are not disappointed by my comments and that we stay in discussion.

Sincerely,
Rolf
CVB1- CFF (continuous flow forward)
CVB3- PFF (pulsatile flow forward)
Compartmental compliances of brain

Cerebral arterial compliance \( (C_a) \)

\[
C_a = \frac{\text{Amp}_{CaBV}}{\text{Amp}_{ABP}}
\]

Cerebrospinal + venous compliance \( (C_i) \)

\[
C_i = \frac{\text{Amp}_{CaBV}}{\text{Amp}_{ICP}}
\]

Thanks to Dr. E.Carrera
Cerebrospinal compensation of pulsating cerebral blood volume in hydrocephalus

Dong-Joo Kim*, Emmanuel Carrera*, Marek Czosnyka*, Nicole Keong*, Peter Smielewski*, Olivier Balédent†, Michael P. F. Sutcliffe†, John D. Pickard* and Zofia Czosnyka*

Neurological Research 2010

D.-J. Kim et al. Cerebrospinal compensation of pulsating cerebral blood volume

Figure 2 Example of rising ICP during infusion study, change in pulse amplitude of ICP (AMP<sub>ICP</sub>), cerebral arterial blood velocity (CBFV<sub>a</sub>), relative change in pulse amplitudes of blood flow volume (AMP<sub>CaBV</sub>) and relative gradual decrease in cerebrospinal compliance index (C<sub>i</sub>)
Change of Cerebral Compliance (Ci) during infusion study

Thanks to Dr.DJ Kim
Clinical Investigative Study

Effect of Hyper- and Hypocapnia on Cerebral Arterial Compliance in Normal Subjects

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From the Department of Clinical Neurosciences, Addenbrooke’s Hospital, University of Cambridge, Cambridge, United Kingdom.
Thanks to Dr. E. Carrera
Cerebral arterial compliance in patients with internal carotid artery disease


Department of Clinical Neurosciences, Addenbrooke’s Hospital, University of Cambridge, Cambridge, UK

Cerebrovascular reactivity (CVR).
Cerebrovascular reactivity was defined as the relative change in CBFV per 1 mmHg change in CO₂:

\[
CVR(\%) = 100 \cdot \frac{CBFV(CO₂) - CBFV(Baseline)}{CBFV(Baseline)} \quad / \Delta(ETCO₂)
\]

Compliance reactivity was defined as the relative change in Ca per 1 mmHg change in CO₂:

\[
CaR(\%) = 100 \cdot \frac{Ca(CO₂) - Ca(Baseline)}{Ca(Baseline)} / \Delta(ETCO₂)
\]
Thanks to Dr. E. Carrera

**Reactivity of FV**

$R = -0.57; p = 0.023$

**Reactivity of Ca**

$R = -0.67; p = 0.016$
Figure 4  Correlation between degree of stenosis and asymmetry in cerebral arterial compliance (Ca). ($r = -0.35; P = 0.01$).
Stenotic disease - reaction to Diamox (Toulouse study)

ABP [mmHg]

FV [cm/s]

CVR [mmHg/(cm/s)]

Ca [cm/mmHg]

Thanks to Dr. N. Nasr
Thanks to Dr. N. Nasr
The monitoring of relative changes in compartmental compliances of brain

Dong-Joo Kim\textsuperscript{1,2}, Magdalena Kasprzycz\textsuperscript{3}, Emmanuel Carrera\textsuperscript{1}, Gianluca Castellani\textsuperscript{1}, Christian Zweifel\textsuperscript{1}, Andrea Lavinio\textsuperscript{1}, Peter Smielewski\textsuperscript{1}, Michael P F Sutcliffe\textsuperscript{2}, John D Pickard\textsuperscript{1} and Marek Czosnyka\textsuperscript{1,6}

Figure 3. Changes in primary values: mean ICP, arterial pressure (ABP) and cerebral blood flow velocity during a plateau wave. In this case, plateau waves were initiated at (A) when the compensation process to the initial ABP drop started. The plateau wave was stabilized and finally terminated (C, D and F) by a gradual increase (G) in ABP. ICP decreased back to the starting level (C) and beyond, due to the active vasoconstriction of autoregulation. Finally, all the signals recovered to their baseline values with the delay dictated by the inertia of the system. These events occur sequentially as a consequence of intact or mostly intact autoregulation, with a corresponding dependence on systemic circulation. (A) the starting point of plateau waves; (B) the starting point of the compensation of ABP; (C) the terminating point of the plateau wave; (D) the terminating point of the increase of CBF and (F) the gradual increase of ABP due to the increase of CBV.

Figure 4. Changes calculated in percentages of arterial compliance $C_a$ and intracranial compliance $C_i$ accompanying plateau waves from figure 3. Baseline values of $\text{AMP}_{\text{CBV}} C_a$ and $C_i$ were taken as 100%. The rest of the parameters are presented in absolute units. ICP during a wave is re-drawn from figure 3 for reference.
Compartmental compliances ($C_a, C_i$)

The monitoring of relative changes in compartmental compliances of brain

Table 1. Median values with 25th and 75th percentiles of variables and calculated indices before, during and after plateau waves. Significant $P_1$ and $P_2$ are calculated between periods during plateau-baseline and between periods during and after plateau waves, respectively.

<table>
<thead>
<tr>
<th>Status factor</th>
<th>Baseline</th>
<th>$P_1$ value</th>
<th>During</th>
<th>$P_2$ value</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABP (mmHg)</td>
<td>89.33 [85.02:92.19]</td>
<td>0.532</td>
<td>91.08 [86.51:94.33]</td>
<td>0.778</td>
<td>86.28 [83.81:97.61]</td>
</tr>
<tr>
<td>ICP (mmHg)</td>
<td>26.12 [17.84:34.47]</td>
<td>0.001</td>
<td>53.96 [51.45:56.98]</td>
<td>0.001</td>
<td>19.93 [19.92:12.54]</td>
</tr>
<tr>
<td>CPP (mmHg)</td>
<td>58.48 [55.90:65.25]</td>
<td>0.001</td>
<td>36.53 [31.94:42.39]</td>
<td>0.026</td>
<td>62.65 [60.83:73.28]</td>
</tr>
<tr>
<td>CBFv (cm s$^{-1}$)</td>
<td>41.18 [33.75:54.26]</td>
<td>0.001</td>
<td>33.62 [22.42:40.04]</td>
<td>0.002</td>
<td>41.43 [25.89:56.52]</td>
</tr>
<tr>
<td>AMP$_{ABP}$ (mmHg)</td>
<td>16.35 [13.47:20.38]</td>
<td>0.005</td>
<td>16.2 [12.27:19.26]</td>
<td>0.397</td>
<td>16.3 [15.07:18.55]</td>
</tr>
<tr>
<td>AMP$_{ICP}$ (mmHg)</td>
<td>2.04 [1.38:2.87]</td>
<td>0.001</td>
<td>5.99 [4.25:8.33]</td>
<td>0.001</td>
<td>1.82 [0.96:2.67]</td>
</tr>
<tr>
<td>AMP$_{CalW}$ (%)</td>
<td>100 [100:100]</td>
<td>0.001</td>
<td>125.8 [117.1:160]</td>
<td>0.000</td>
<td>93.63 [92.99:36]</td>
</tr>
<tr>
<td>$C_i$ (%)</td>
<td>100 [100:100]</td>
<td>0.000</td>
<td>51.1 [33.42:52.98]</td>
<td>0.000</td>
<td>115.7 [97.19:135.1]</td>
</tr>
<tr>
<td>$C_a$ (%)</td>
<td>100 [100:100]</td>
<td>0.0003</td>
<td>130 [117.9:176.9]</td>
<td>0.001</td>
<td>95.8 [84.48:100.4]</td>
</tr>
</tbody>
</table>

NB: Median (25th percentile: 75th percentile).

Abbreviations: ABP, arterial pressure; ICP, intracranial pressure; CPP, cerebral perfusion pressure; CBFv, blood velocity in the MCA (middle cerebro-artery); AMP$_{ABP}$, pulse amplitude of arterial pressure; AMP$_{ICP}$, pulse amplitude of intracranial pressure; AMP$_{CalW}$, pulse amplitude of blood velocity; AMP$_{CalW}$, percentage change of pulse amplitude of volume parameter (compared to the baseline); $C_i$, percentage change in compliance of CSF space; $C_a$, percentage change in compliance of the arterial bed.

Thanks to Dr. DJ Kim
Hypocapnia in TBI

Example: 18 yo woman GCS = 7

<table>
<thead>
<tr>
<th>Baseline characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39.5 ± 3.4</td>
</tr>
<tr>
<td>Gender (women)</td>
<td>6 (22%)</td>
</tr>
<tr>
<td>GCS</td>
<td>5 (3-8)</td>
</tr>
</tbody>
</table>

Physiological variables:

- ABP (mmHg) 97 ± 9
- ICP (mmHg) 18 ± 7
- CPP (mmHg) 79 ± 8
- PaCO₂ (mmHg) 38 ± 0.5

Thanks to Dr. E. Carrera
Results

“Sustained” hyperventilation

- CSF compartment
  - Re-increase in ICP (13.9 to 15.3 mmHg; p<0.001)
  - No significant change in Ci

- Arterial compartment
  - No changes in CBFV (63 vs 62 cm/s; p=0.3)
  - No significant change in Ca

Thanks to Dr. E. Carrera
Monro-Kellie doctrine

- **Definition**
  When the volume of one compartment increases, there must be a corresponding and compensatory decrease in the volume of the other compartment.
Algorithm to estimate ICC

Negative ICC
- Inverse relationship between $C_a\%$ and $C_i\%$
- Monro-Kellie doctrine is obeyed

Positive ICC
- Direct proportional relationship between $C_a\%$ and $C_i\%$
- Monro-Kellie doctrine is not followed
Observation II
Plateau waves (transient changes in cerebral blood volume)

Findings: $C_{a\%}$ and $C_{i\%}$ change in opposite directions, which makes ICC solidly negative
Observation I

Arterial hypertension (transient changes in arterial blood pressure)

Findings: $C_a\%$ and $C_i\%$ change in opposite directions, which makes ICC solidly negative.
Observation III
Intracranial hypertension (traumatic brain injury)

Findings: $C_{a\%}$ and $C_{i\%}$ change in same directions, which makes ICC positive
Outcome I
Distribution of ICC with different outcome cohorts

P (Kruskall-Wallis test) < 0.004
Outcome II
Change in ICC over time

ICC is significantly greater in patients who died, particularly over the first few days after head injury.

Thanks to Dr. DJ Kim
Correlation I
Relationship between ICC and ICP

Corr. R=0.65; p<0.001

Thanks to Dr. DJ Kim
Outcome III
Regression of ICC vs mortality rate

Intracranial hypertension (IH)
- Average ICP > 20 mmHg for entire NCCU stay

Thanks to Dr. DJ Kim
Messages to take home

- Relative changes in compartmental compliances may be assessed with TCD and ABP/ICP waveforms.
- Absolute values unknown- we do not know cross-sectional area of MCA.
- During plateau wave Ca increases and Ci decreases.
- During hyperventilation in TBI Ca decreases and Ci increases.
- Reactivity of Ca to change in PaCO2 is useful in carotid artery stenosis.
- Relative changes in Ca and Ci : monitoring of Monro-Kelly Doctrine?

All findings should be verified with PFF Model.