23-Non-invasive ICP Assessment
Non-invasive ICP: Methods

- Ultrasound – Ophthalmic Artery A. Ragauskas (+/- 12 mm Hg)
- Skull movement (NASA, Mascarenhas)
- Tympanometry (R. Marchbank)
- MRI volume accounting (Alperin)
- Blood flow velocity in straight sinus (Schoser)
- EEG (Zhang) +/- 2 mm Hg
- Optic nerve sheath diameter
- Blood flow velocity in MCA arteries
Two optimistic cases:

95% confidence limit for predictors: +/- 2 mm Hg

Vascular

Transcranial Doppler Sonography Pulsatility Index (PI) Reflects Intracranial Pressure (ICP)

Johan Bellner, M.D.,† Bertil Romner, M.D., Ph.D.,† Peter Reinstrop, M.D., Ph.D.,* Karl-Axel Kristiansson, M.I.T.,† Erik Ryding, M.D., Ph.D.,† and Lennart Brandt, M.D., Ph.D.,†

*Department of Neurosurgery, Department of Anaesthesiology & Intensive Care and †Department of Neuroradiology, University Hospital of Lund, Lund, Sweden

Graph demonstrating a significant correlation between the ICP and the PI with a correlation coefficient of 0.058 (p < 0.001) and a correlation formula of $ICP = 10.927 + PI - 1.284$. The dotted lines are the 95% confidence intervals for the regression line, which can be significantly affected by outliers when PI is large.

95% confidence limit for predictors 5 mm Hg

ICP [mm Hg]
R=0.19; p<0.003; N=233
The impact of raised intracranial pressure on cerebral venous hemodynamics: a prospective venous transcranial Doppler ultrasonography study

BENEDIKT G. H. SCHÖSER, M.D., NILS RIEMENSCHNEIDER, AND H. CHRISTIAN HANSEN, M.D.

Department of Neurology, University Hospital Hamburg–Eppendorf, Hamburg, Germany

B. G. H. Schoser, N. Riemenschneider, and H. C. Hansen

R = 0.92 !!!

FIG. 4. Scatterplots showing the relationship between ICP and venous TCD values of the SS.
Implementation of non-invasive brain physiological monitoring concepts

Arminas Ragauskas, Gediminis Daubaris, Vytautas Ragaisis, Vytautas Petkus

* Kaunas University of Technology, Telematics Scientific Laboratory, Studentu 39 449, Kaunas 3031, Lithuania
* Neurosurgical Clinic, Medical University, Kaunas, Lithuania

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Fig. 5. The diagram of invasive and non-invasive brain physiological monitoring used for experimental studies.

Fig. 3. Relationships between ultrasound speed in cerebral parenchymal acoustic path and CBF, CPP, ICP, ABP, CVR and CBV.
Is non-invasive monitoring of intracranial pressure waveform analysis possible? Preliminary results of a comparative study of non-invasive vs. invasive intracranial slow-wave waveform analysis monitoring in patients with traumatic brain injury


1 Department of Neurosurgery, Medical Center of Central Georgia, Mercer University, School of Medicine, Macon, Georgia, USA
2 Department of Neurosurgery, Kaunas University, School of Medicine, Kaunas, Lithuania
3 Department of Neurosurgery, Medical Center of Central Georgia, Mercer University, School of Medicine, Macon, Georgia, USA
4 Telemedical Scientific Laboratory, Kaunas University of Technology, Kaunas, Lithuania

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Figure 1. Schematic diagram of the Vittamed device.

Figure 2. Simultaneous monitoring of cerebral auto-regulation estimating indices for 1-hour monitoring session.

Employed for all of our patients. Simultaneous monitoring of ICP, ABP and ΔCp/Cvo was performed, and the recorded data were used for the estimation of slow waves, slow trends, and selected indices (r(ΔCp/Cvo), r(ICP-ABP), and r(ΔCp/Cvo/ICP)) of the CA status (Figure 2).

Thirteen patients (8 males and 5 females) with severe traumatic brain injury (GCS-8) were simultaneously monitored invasively and non-invasively. The patients' mean age was
Two-depth Doppler ultrasound analysis of retinal artery with external pressure

The dual-depth Doppler ultrasound is positioned to monitor the pressure wave in both the intracranial and extracranial segments of the ophthalmic eye artery (IOA and EOA).

The pressure in the chamber is increased stepwise, and the two pressure waves are compared at each step.

When the pressure waveform from the IOA and EOA segments match in shape, the externally applied pressure must be equal to the intracranial pressure.

Thanks to P. Smielewski
Two-depth Doppler ultrasound analysis of retinal artery with external pressure

Figure 4: (A) The distribution of mean ICP values obtained from 62 patients, where MeanICP = 0.5(nICP + PCSF). There was a normal distribution (CI = 0.98). (B) Bland and Altman plot of the absolute difference (mmHg) between simultaneous invasive and non-invasive ICP measurements. The mean systemic error was 0.12 mmHg, which was not significantly different from zero (p =0.02). (C) Distribution of the random error was approximately uniform and nearly entirely contained within the 4 mmHg bounds.

Thanks to P. Smielewski
Optic nerve sheath diameter (ONSD)

Thanks to P. Smielewski

Figure 3A): ONSD with normal ICP (14). Figure 3B): ONSD with elevated ICP (14). Figure 3C): Linear correlation of invasive ICP to ONSD as measured by ultrasound (r=0.68, p=0.0002, 13).
The technique utilizes the acoustically stimulated stapedial reflex which causes the small stapedial muscle to pull on the tympanic membrane in response to a high intensity tone burst.

A short tone burst (300 milliseconds, 1000Hz) elicits the stapedial reflex that results in tympanic membrane displacement.

The stapedial reflex is thus quantified as the volume displacement over a period of 1.0 second in response to a 300 millisecond tone burst.

Thanks to P. Smielewski
Tympanic membrane displacement

TMD assessment of eight children with shunted hydrocephalus

Thanks to P. Smielewski
Skull displacement method - Prof. Sergio Mascarenhas

FIRST EXPERIMENT

AFTER 6 YEARS
Validation of a new minimally invasive intracranial pressure monitoring method by direct comparison with an invasive technique.
Singapore 2013
Is MCA, with its compliant walls, a sort of transmural pressure ‘transducer’? What is its linearity and calibration coefficient? Are they stable in time?
Non-invasive ICP assessment - basic model

FV \rightarrow TCD characteristics
\{ tcd_j \} j = 0, ..., m

regular updates

ABP \rightarrow ICP
\{ w_i \} i = 0, ..., n

nICP (non-invasively assessed ICP)

FV: flow velocity in middle cerebral artery.
ABP: arterial blood pressure
ICP: intracranial pressure
TCD: transcranial Doppler

Impulse Response: signal transformation, time correspondence to Transfer Function

Thanks to Dr. B. Schmidt
Control structure of basic model

TCD characteristics

A & B

Assumptions of Basic Model:
- Independence of Individual
- Time constant

ABP

Impulse Response Function

nICP

Thanks to Dr. B. Schmidt
Autoregulation is time-varying. Best example- plateau wave

Thanks to Dr.B.Schmidt
If model is independent on autoregulation, either plateau or baseline has a chance to be estimated less accurately.

Thanks to Dr.B.Schmidt
Control structure - extended model

TCD characteristics

A & B

Impulse Response Function

ABP

nICP

State of Autoregulation

Thanks to Dr. B. Schmidt
Example

Fixed model

Adaptive model

Thanks to Dr. B. Schmidt
diff = ICP - nICP

Std. abw. = 8,55
Mittel = ,7
N = 197,00
Adaptive nICP-assessment Study

- 145 patients with Traumatic Brain Injury or Stroke
- Age: 35 ± 18 years
- Adaptive model: $\Delta ICP = 6.9 \pm 5.4$ mm Hg
- Basic model: $\Delta ICP = 7.6 \pm 6.1$ mm Hg ($P < 0.005$)
- Increase of nICP dynamic
- Assessment of cerebral autoregulation
- Adaptive model less stable than basic model

Thanks to Dr. B. Schmidt

$\Delta ICP =$ absolute difference ($ICP-nICP$)
The list of functions in ICM+ can be extended by plugins. One such plugin already available for ICM+ enables non-invasive calculation of ICP from TCD FV and ABP signals in real time.
Non-Invasively Estimated ICP Pulse Amplitude Strongly Correlates with Outcome After TBI

Karol P. Budohoski, Bernhard Schmidt, Peter Smielewski, Magdalena Kasprowicz, Ronny Plontke, John D. Pickard, Jurgen Klingelhöfer, and Marek Czosnyka
Example 1
Example 2
Example 2
Example 4
73 patients after head injury with midline shift, 95% CI = 12 mm Hg
Model-Based Estimation of Intracranial Pressure and Cerebrovascular Autoregulation

FM Kashif, T Heldt, GC Verghese

Massachusetts Institute of Technology, Cambridge, MA, USA

Figure 1. The adapted cerebrovascular model.
\[ \hat{C}_a = \frac{\int_{t_b}^{t_s} q(t) \, dt}{p_a(t_s) - p_a(t_b)} \]

Fig. 4: Estimation of arterial compliance.

Thanks to Dr. F. Kashif
\[ q(t) = C_a \frac{dp_a(t)}{dt} + \frac{1}{R_{av}} [p_a(t) - p_{ic}(t)]. \] (1)

Thus the estimation task is reduced to only determining two parameters, \( C_a \) and \( R_{av} \) as well as the unknown node pressure \( p_{ic} \). We describe the estimation algorithm in the next section.

\[ \hat{q}_1(t) = q(t) - \hat{C}_a \frac{dp_a(t)}{dt}. \]

\[ \hat{R}_{av} = \frac{p_a(t_2) - p_a(t_1)}{\hat{q}_1(t_2) - \hat{q}_1(t_1)}. \]

\[ \hat{p}_{ic}(t) = p_a(t) - \hat{R}_{av}\hat{q}_1(t). \]

Figure 2. The simplified model.
Model-Based Noninvasive Estimation of Intracranial Pressure from Cerebral Blood Flow Velocity and Arterial Pressure

Faisal M. Kashif, 1, George C. Verghese, 1, Vera Novak, 2, Marek Czosnyka, 3, 4, Thomas Heldt 1*

Fig. 3. Comparison of measured and estimated ICP in four brain-injured patients. In (A), ICP was estimated on a sliding 60-beat data window. In (B) to (D), the estimates were obtained on 60-beat non-overlapping data windows. (A) Single plateau wave. (B) Severe progressive intracranial hypertension. (C) Two consecutive plateau waves. (D) Borderline normal ICP. All patient data are summarized in Table S2.
News from industry

**HeadSense Ltd**
- Acoustic propagation method
- No clinical data so far
- nICP in mm Hg

**Orsan Medical Technologies**

Impedance plethysmography method
New ideas...

From this formula, knowing PI, CPP can be calculated

\[ n_{CPP} = FV_m \cdot \frac{A_1}{F_1} \]

This is close to Aaslid’s formula
Messages to take home

• Bottom line for limit of agreement of nICP and ‘real’ ICP- probably 6 mmHg
• TCD based methods claim best confidence limit for predictors 12-17 mmHg
• Two possibilities Black-box (Schmidt) and physiological modelling (Kashif, Heldt et al.)
• Tympanometry and eye-ball compression- not suitable for monitoring
• Time-of-flight (Vittamed)- probably good for non-invasive PRx
• Straight sinus blood flow velocity- nobody replicated these results
• Pulsatility Index: awful absolute accuracy, but good for detection of deep intracranial hypertension: If at the bedside PI>2, ABP is normal and PaCO2 is >30 mm Hg- it is likely that ICP>25 mm Hg