Applications of Blood Flow Measurement in Neurovascular Care

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The case for advances in neurovascular care
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- Nutrition
- Fluids
- Ventilator controls
- Medications (infusion pumps)
- Head-of-bed angle
Very few metrics of brain health and perfusion!
A wish list of neurovascular measurements

- Brain perfusion
  - Brain oxygen consumption/demand

- Mechanical stress monitoring
  - Non/less-invasive intracranial pressure (ICP)
  - Continuous intracranial compliance (ICC)

- Autoregulation assessment
  - Cerebrovascular flow resistance (CVR)

- Neuronal activity interpretation, …

- Cerebral volumetric blood flow (Liters/min)
- Arterial blood pressure
Agenda

• Model-based ICP, ICC, and CVR estimation framework
• Framework validation in an animal model
• Clinical translation via ultrasound-based blood flow measurement
• Conclusion
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Cerebral blood flow (CBF) is driven by ABP – ICP not ABP – VBP.
Compartmental view of the cerebral space

Cerebrovascular resistance (CVR) = \( \frac{\text{ABP} - \text{ICP}}{\text{CBF}} \)

Intracranial compliance (ICC) = \( \frac{\Delta q}{\Delta p} \)

\( \Delta q \): Change in intracranial volume
\( \Delta p \): Change in ICP

ABP: Arterial blood pressure
ICP: Intracranial pressure
CBF: Cerebral blood flow

CVR and ICE measurements are rarely performed despite theoretical benefit
Model-based ICP, ICC, and CVR estimation

\( \dot{q}(t) \): Cerebral blood flow
\( p_a(t) \): Arterial blood pressure
\( p_i(t) \): Intracranial pressure
\( p_x \): DC operating point (after linearizing C2)

\( \overline{p}_i \): Mean intracranial pressure
\( \overline{p}_i(t) \): Intracranial pressure pulsatility
\( \overline{p}_a(t) \): Arterial blood pressure pulsatility

\[ R \] Cerebrovascular flow resistance
\( C_1 \): Vascular and brain compliance
\( C_2 \): Incremental dural compliance
\( C_e \): Effective compliance

\[ \dot{q}(t) \rightarrow p_a(t) \rightarrow R \rightarrow p_i(t) \]

\[ C_1 \]

\[ C_2 \]

\[ p_x \]

\[ \overline{p}_i = \gamma \overline{p}_a(t) \]

\[ \gamma = \frac{C_1}{C_1 + C_2} \]

\[ C_e = \frac{C_1 C_2}{C_1 + C_2} \]

Determine \( C_e \), \( R \), \( \overline{p}_i \), and \( \gamma \) using \( \dot{q}(t) \) and \( p_a(t) \)

\[ C_1 = \frac{C_e}{1 - \gamma} \quad \text{and} \quad C_2 = \frac{C_e}{\gamma} \]

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Validation in an animal model

• Rabbit model
  • Measure blood pressure and cerebral blood flow invasively
  • Raise ICP by inflatable balloon
  • Measure ICC by a second inflatable balloon
Validation in an animal model
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Clinical translation: ICP

Using pulsed-Doppler ultrasound for *cerebral blood velocity*

Boston Children’s Hospital

![Graph showing mean ICP comparison between estimate and reference](image)

- Bias = 2.4 mmHg, RMSE = 4.3 mmHg

Beth Israel Deaconess

![Graph showing mean ICP comparison between estimate and reference](image)

- Bias = 1.6 mmHg, RMSE = 5.0 mmHg


Mean ICP

- IP: Intraparenchymal
- VD: Ventricular drain

Clinical translation: ICP + ICC & CVR

Requires cerebral *volumetric* blood flow

Useful for estimating spatial gradients in ICP/CVR/ICC

Spatial resolution severely limited as low-frequency, skull-penetrating necessary

- Middle cerebral artery (MCA)
- Basilar artery
- Vertebral artery (VA)
- Internal carotid artery (ICA)
- Common carotid artery (CCA)

Higher frequencies enable higher spatial resolution

Simpler measurement for spot assessment

S. M. Imaduddin et al., *IEEE Trans Ultrason*, 2022

S. M. Imaduddin et al., *Int ICP Conf*, 2022
Cerebral blood flow measurement

Use of Butterfly iQ/iQ+ for neuromonitoring is considered off-label use

CF generally used for qualitative imaging
Here, we determine blood flow waveforms

Raw data acquired with the Butterfly iQ
Model validation: Healthy volunteers

**Upright position: ICP decreases in head-up position**
Qvarlander et al., *J Appl Physiol*, 2013

**Upright position: Cranial compliance expected to increase along with the total (spinal and cranial) compliance**

**CVR expected to decrease to sustain blood flow**
Model validation: ICP estimates

- Qvarlander et al., 2013, $n = 27$
- Petersen et al., 2016, $n = 9$
Model validation: ICC estimates
Clinical deployment

• Pediatric patients at Boston Children’s Hospital

• Three patients studied so far, and recruitment is ongoing
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Cerebral *volumetric* blood flow (Liters/min)
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Ongoing work and Future directions

• Extension to ophthalmic applications

• Unobtrusive blood pressure waveform estimation

• Improved blood flow measurement
  • Volumetric imaging
  • Higher frame rates

• Continuous monitoring instead of spot-assessment
  • Reducing transducer size and weight
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[Logos of MEDRC, Boston Children's Hospital, Analog Devices, and Butterfly]