A New Visualization Technique for Intracranial Pressure Pulse Waveform Morphology

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Introduction: Physiology

- Traumatic brain injury (TBI) is the leading cause of death among children and infants
- TBI damage: secondary injury resulting from loss or impairment of cerebral autoregulation (CAR):
  a. CAR regulates intracranial pressure (ICP)
  b. Diminished CAR capacity $\rightarrow$ elevated ICP
  c. Elevated ICP $\rightarrow$ brain blood supply interrupted
  d. Brain cells die
Introduction: Physiology

- Elevated ICP requires swift intervention
- Monitoring and interpreting intracranial pressure is essential
- Mean ICP is standard measure
Introduction: Pulse Wave Morphology

- Normal vs. abnormal
- Correspondence to mean ICP
- Several indices based on pulse morphology exist
- Impractical to examine in time domain
  → Difficult to gain new insight
Objective

- Develop visualization technique that displays morphology versus signal metrics
- Turn ICP signals into 2-D color map of individual pulses:
  - Color indicating pulse amplitude
  - Pulses oriented vertically and sorted horizontally based on index of interest
Significance

• Only intuitive morphology visualization analysis tool
• Allow researchers to explore the efficacy of examining pulse morphology
  ➔ Effect new insights in underlying physiological mechanisms
  ➔ Potential for creation of new indices
Algorithm Block Diagram

1. Resample
2. Calculate mean ICP
3. Detect beat minima
4. High-pass filter
5. Smooth pulse amplitudes
6. Display colormap
7. Calculate average pulse length
Algorithm Overview

- **Beat minima**
  - automatic detection algorithm
  - manual detection
- **Beat-by-beat ICP mean and heart rate**
- **High-pass filter**
- **With beat-by-beat index of interest:**
  - Smooth pulse amplitudes
  - Display colormap
Smoothing

- Make morphogram robust
  - Missed detections
  - Artifacts
  - Regions of sparse data
- Smooth amplitudes at each step along average pulse length
- Specific implementation:
  - MATLAB
  - Gaussian kernel smoothing
  - Metric range determines kernel width
Smoothing: Implementation

Time = 40% of pulse length
Smoothing: Result
Assessment Methodology

- Residual distribution
- Pulse wave distribution
- Pulse wave snapshots
- Residual scatter snapshots
- Histogram
Results: Original Signal
Results Continued: Morphogram with Mean ICP
Results Continued: Morphogram with Heart Rate
Results Continued: Morphogram with Time
Results Continued: Signal Two
Results Continued: Signal Three
Results Continued: Signal Four
Results Continued: Signal Five
Discussion

- Assessment visualizations indicate good performance
- Expected rounding of pulse morphology with increased mean ICP
- Interesting residual scatter observation
Conclusion

• Project meets objective
  ➔ Morphogram accurately and intuitively reveals pulse morphology

• Need to examine more signals
  ➔ Will try to analyze 96 GB of ICP data
  ➔ Existence of counter examples would be significant

• Morphogram will be a valuable analysis tool
(Appendix) Algorithm: Signal Processing

ICP signal $x$

1. Resample $x$ from $f_s = 125$ to $f_s = 500$ Hz

2. Apply high-pass filter ($f_c = 0.5$ Hz) to obtain $x_h$

3. Calculate beat minima
   
   $b = [b_0, b_1, \ldots b_n]$

   using BSP Toolbox PressureDetect and EditAnnotations functions
(Appendix) Algorithm: Signal Processing

4. Calculate average pulse length, $p_l$

$$p_l = \frac{1}{n-1} \sum_{i=1}^{n-1} b_{i+1} - b_i$$

5. Calculate mean ICP $a = [a_0, a_1, \ldots, a_n]$

$$a_k = \frac{1}{b_{k+1} - b_k + 1} \sum_{k=b_k}^{b_{k+1}} x(k)$$
(Appendix) Algorithm: Signal Processing

6. Calculate heart rate vector, \( h = [h_0, h_1, \ldots, h_n] \)

\[
h_k = \frac{f_s}{b_{k+1} - b_k}
\]

7. Use beat-by-beat index measure for calculations; in this example, taken to be mean ICP
(Appendix) Algorithm: Smoothing

8. Create vectors of amplitudes at each step $i$ along $p_l$
   
   $$y_i = [y_{i,0}, y_{i,1}, \ldots, y_{i,n}]^T$$
   
   $$y_{i,k} = x_h(b_k + i)$$

9. Employ (kernel) smoothing over scattered data

   $$\hat{y}_{i,k} = \frac{\sum_{j=1}^{n} y_{i,j} w_\sigma \left( | a_1 + \frac{a_n - a_1}{\hat{n}} k - a_j | \right)}{\sum_{j=i}^{n} w_\sigma \left( | a_1 + \frac{a_n - a_1}{\hat{n}} k - a_j | \right)}$$

   $$w_\sigma = ce^{-u^2}$$
10. Create image matrix, \( Y \), using smoothed amplitude vectors

\[
\hat{y}_i = [\hat{y}_{i,0}, \hat{y}_{i,1}, \ldots, \hat{y}_{i,\hat{n}}]^T
\]

\[
Y = [\hat{y}_0, \hat{y}_1, \ldots, \hat{y}_{p_1}]
\]

\( \hat{n} \) = user-specified length of evenly-spaced evaluations

\[ \rightarrow \] Kernel width determined by minimizing leave-one-out CVE using several indices and signals

\[ \rightarrow \] Kernel type should make little difference

11. Display image matrix, \( Y \), using imagesc function