

Pulse and mean intracranial pressure analysis in pediatric traumatic brain injury*

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Summary

Objective. We investigated the relationship between the intracranial pulse pressure (ICP_{PP}) and the mean intracranial pressure (ICP_M) in pediatric patients with traumatic brain injury (TBI).

Methods. We screened ICP records of 42 patients admitted to the Pediatric Intensive Care Unit at Doernbecher Children's Hospital (OHSU) for segments in which the ICP_M varied at least 5 mmHg. We found 54 ICP segments in 9 pediatric TBI patients (ages 0.2–17.8 years, mean = 9.9). ICP was continuously monitored ($f_s = 125$ Hz). We used an automatic algorithm to detect ICP beat components. We then calculated the ICP_{PP} and ICP_M for each beat and created density plots of ICP_{PP} vs. ICP_M.

Results. The coefficient of linear correlation was $r > 0.70$ in 43/54 segments ($p < 0.01$). We found that an underlying linear relationship exists between ICP_{PP} and ICP_M in most 1-hour records of pediatric patients with TBI. This finding is consistent with the data in adult studies, suggesting that children with TBI demonstrate similar changes in brain compliance. However, density plots revealed that there are also nonlinear ICP_{PP}-ICP_M patterns present that are not captured by linear metrics.

Conclusion. Although there is an underlying linear relationship between ICP_{PP} and ICP_M, nonlinear patterns are also present. Further research is required to determine if specific nonlinear ICP_{PP}-ICP_M patterns correlate with clinically significant information.

Keywords: Intracranial hypertension; intracranial pressure; waveform analysis; pulse pressure.

Introduction

Traumatic brain injury (TBI) is the leading cause of death and disability in children in the United States [1]. Elevated intracranial pressure (ICP) following TBI may result in secondary injury due to decreased cere-

bral perfusion pressure (CPP) and cerebral ischemia. ICP monitoring and therapeutic interventions to control elevated ICP (>20 mmHg) have resulted in improved outcomes [9].

Several investigators and research groups have studied the relationship between the ICP pulse pressure (ICP_{PP}) and the mean ICP (ICP_M) in adult patients and dogs. Castel and Cohadon studied the ICP waveform in three groups of neurosurgical patients and noted that a linear relationship exists between ICP_{PP} and ICP_M [4]. Avezatt and Van Eijndoven examined this relationship in dogs and described a linear relationship between ICP_{PP} and ICP_M below a breakpoint where the slope changes, which they attributed to vasoparesis and failure of autoregulation [2]. They proposed to use the ratio ICP_{PP}-ICP_M as an index of brain compliance. The rationale behind this definition is that a change in this relationship during patient monitoring indicates a change either in the volume-pressure relationship or in the net volume change per cardiac cycle. Price defined the *pulse wave index* as the ratio of ICP_{PP} and ICP_M [10]. More recently, the correlation coefficient between ICP_{PP} and ICP_M has been termed the *pressure-volume compensatory reserve index* (RAP). This index measures the degree of correlation between ICP_{PP} and ICP_M over short periods of time, and indicates the relationship between ICP and changes in volume of the intracerebral space. In general, increased ICP_{PP} has been associated with decreasing intracranial compliance [3, 5–7].

Due to the unavailability of automatic ICP component detection algorithms, none of these previous studies calculated ICP_{PP} and ICP_M on a beat-by-beat

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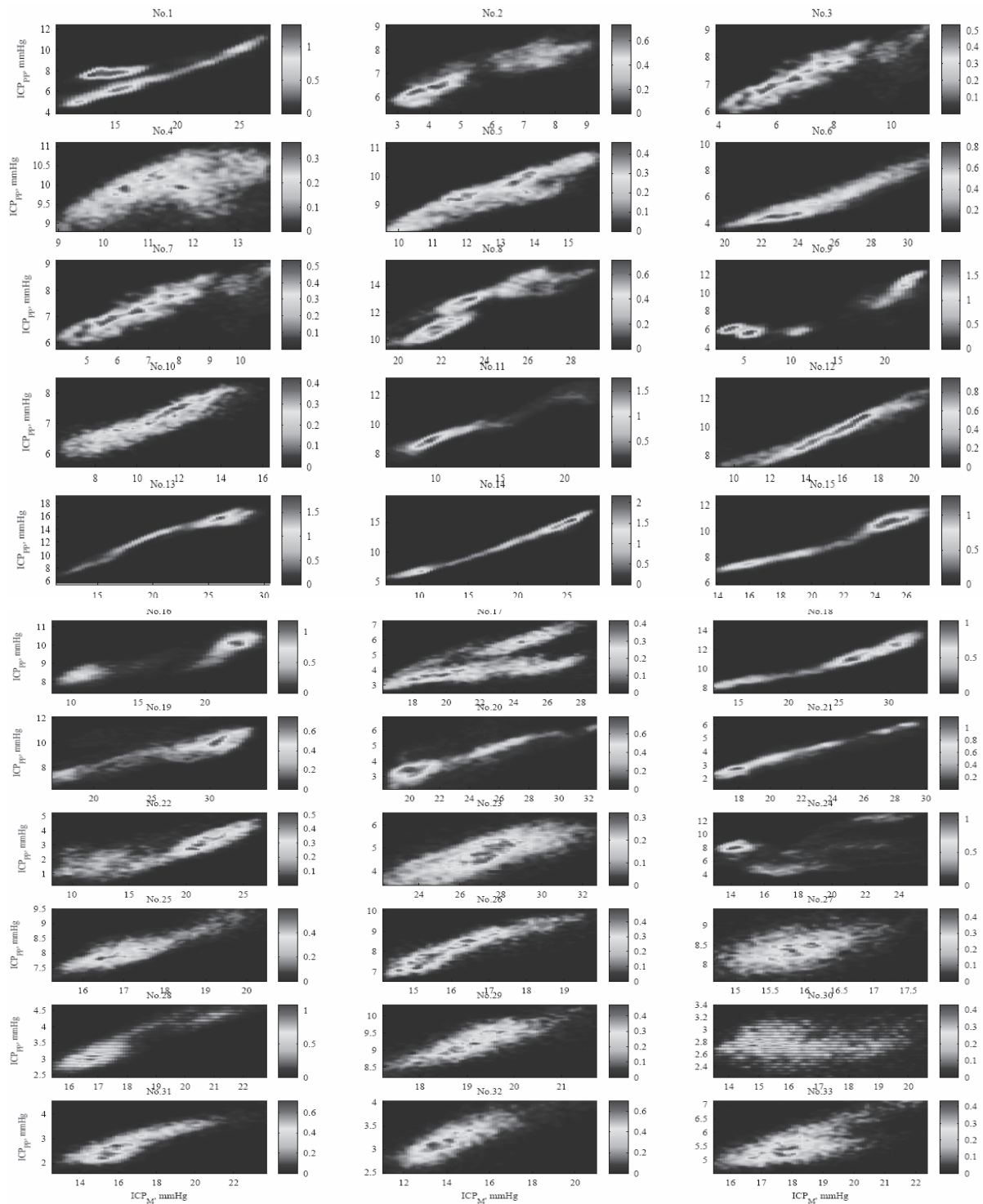


Fig. 1. Density plots showing the relationship between ICP_{PP} and ICP_M for 33 episodes

basis. Instead, ICP_{PP} and ICP_M are often estimated by indirect measures based on moving averages or frequency domain techniques. The most common methodology used to calculate the RAP index, for instance,

consists of estimating the ICP_{PP} as the squared root of the power of the fundamental harmonic component, and the ICP_M as the moving average mean ICP over specific time window length [6].

We investigated the relationship between ICP_{PP} and ICP_M in pediatric subjects with TBI. This study had three objectives: 1) to investigate the ICP relationship on a previously unstudied patient population, 2) to determine whether there is further information that can be derived from the relationship between ICP_{PP} - ICP_M that is not captured by linear metrics such as the coefficient of linear correlation, and 3) to describe a new methodology to calculate ICP_{PP} and ICP_M and visualize their relationship.

Materials and methods

Patient population and data acquisition

We examined ICP records of 42 patients admitted to the Pediatric Intensive Care Unit at Doernbecher Children's Hospital (Oregon Health and Science University, OHSU) for segments in which the ICP_M varied at least 5 mmHg over a 1-hour period. The study was reviewed and approved by the Institutional Review Board at OHSU, and the requirement of informed consent was waived. We found 54 1-hour ICP segments from 9 different subjects that met this condition (age range of 0.2 to 17.8, mean age 9.9 years).

ICP was monitored continuously using a ventricular catheter or parenchymal fiber-optic pressure transducer (Integra Neurocare, Integra LifeSciences, Plainsboro, NJ). The ICP monitor was connected to a Philips Merlin patient monitor (Philips, Best, Netherlands) that sampled the ICP signal at 125 Hz. An HPUX workstation automatically acquired these signals through a serial data network and stored them on CD-ROM [8].

Detection algorithm and ICP_{PP} / ICP_M definitions

An automatic beat detection algorithm was used to detect each ICP beat. The algorithm performs minima detection to identify the time location corresponding to the start of each beat a_k ,

$$\mathbf{a} = (a_1 \ a_2 \ \dots \ a_{k-1} \ a_k \ a_{k+1} \ \dots)^T. \quad (1)$$

Details of the beat detection process follow. The pressure signal is preprocessed by three bandpass elliptic filters with different cut-off frequencies. The output of the first bandpass filter is used to estimate the heart rate based on the estimated power spectral density (PSD). The estimated heart rate is then used to calculate the cutoff frequencies of the other two filters. Minima detection and the associated decision logic are performed based on rank-order (percentile-based) nonlinear filters, that incorporate relative amplitude and slope information to coarsely estimate the minima preceding each beat (a_k). A nearest neighbor algorithm is used to combine the information extracted from the relative amplitude and slope. Finally, an interbeat-interval stage uses this classification together with the estimated heart rate to make the final classification and detection of signal components. Since detection is made on the filtered signal, a second nearest neighbor algorithm is used to find the minima in the raw signal that are closest to the detected components.

The maximum in each ICP beat b_k was determined using the \mathbf{a} components identified by the beat detection algorithm in the previous step as follows,

$$b_k \triangleq \arg \max_{a_k \leq n \leq a_{k+1}} x(n) \\ \mathbf{b} = (b_1 \ b_2 \ \dots \ b_{k-1} \ b_k \ b_{k+1} \ \dots)^T \quad (2)$$

where $x(n)$ denotes the ICP signal. Based on these definitions, the ICP_M was calculated as the ICP beat mean \bar{x}_k , and ICP_{PP} was calculated as the beat pulse pressure p_k ,

$$\bar{x}_k \triangleq \frac{1}{a_{k+1} - a_k + 1} \sum_{k=a_k}^{a_{k+1}} x(k) \\ \bar{\mathbf{x}} = (\bar{x}_1 \ \bar{x}_2 \ \dots \ \bar{x}_{k-1} \ \bar{x}_k \ \bar{x}_{k+1} \ \dots)^T. \quad (3)$$

Analysis

We determined the ICP_M and ICP_{PP} for each beat in the dataset, created density plots ICP_{PP} vs. ICP_M using a Gaussian Kernel with width of 0.05 mmHg, performed least-squares linear regression, and calculated the coefficient of linear correlation. Statistical significance was assessed using the nonparametric binary sign test.

Results and discussion

We found that in 43 out of 54 segments ($p < 0.001$) the coefficients of correlation were greater than 0.70. This result indicates that in pediatric patients with TBI there is an underlying relationship with a significant linear component between ICP_{PP} and ICP_M . This finding is consistent with the results previously reported on adult subject population and dogs.

Visual inspection of the density plots reveals that even though there is an underlying linear component between ICP_{PP} and ICP_M , there are also other nonlinear phenomena present (Fig. 1). In some episodes we observed underlying linear relationships with nonlinear clusters (e.g., 1, 9, 24). Others exhibit two parallel close-to-linear relationships (e.g., 8, 17) and slope changes (e.g., 13, 15, 18).

These nonlinearities have not been previously described. This may be due to the fact the ICP_{PP} vs ICP_M relationship has been visualized primarily using simple scatter plots. Density plots are more informative since they have an extra dimension that provides information about the density of points. In fact, most of the episodes presented on Fig. 1 appear to be linear if visualized with scatter plots.

The detection of these nonlinearities may also be due to the methodological differences in the calculation of ICP_{PP} and ICP_M . In this study the ICP_{PP} and ICP_M were calculated exactly for each beat. This eliminates the correlation introduced by moving average or frequency domain techniques.

Further research on prospective clinically annotated data is required to determine if these nonlinear patterns contain clinically significant information.

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