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Trauma

Slope of the intracranial pressure waveform after traumatic brain injury

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Abstract

Background: The measurement and treatment of ICP within the management of TBI generally focuses on keeping the mean ICP to less than 20 mm Hg. More sophisticated analysis of the intracranial pressure waveform has yielded important relationships, but those methods have not gained widespread use. Prior analysis of the slope of the ICP waveform during inspiration and expiration in patients with hydrocephalus has provided valuable information that has never been applied to patients with TBI. This study used digital methods to examine ICP and the slope of the ICP waveform in relation to the respiratory cycle in subjects with TBI.

Methods: Intracranial pressure was monitored in 6 randomly selected patients admitted with acute TBI. In the first 3 subjects, a single 5-minute recording was analyzed. In 3 subsequent subjects, 4 nonsequential 5-minute epochs were analyzed during periods of varying ICP. The systolic slope of the ICP waveform was compared during inspiration and expiration, and then evaluated in relation to simultaneous mean ICP.

Results: The slope of the systolic ICP waveform was significantly greater during inspiration than during expiration ($P < .0001$ for 5 subjects and $P < .03$ for 1 subject). Within each subject, the ICP slope was positively correlated with simultaneous ICP ($P < .0001$ in all 6 cases).

Conclusion: Greater systolic ICP waveform slope during inspiration has not been described previously after TBI and is consistent with prior observations in subjects with hydrocephalus. The strong correlation between ICP slope and simultaneous mean ICP suggests that increasing ICP slope might indicate loss of intracranial compliance after TBI.

Keywords: Intracranial pressure; Traumatic brain injury; Brain compliance; Intracranial pressure waveform analysis

1. Introduction

Intracranial pressure monitoring and treatment has become common practice in the management of many neurologic disorders, including severe TBI, spontaneous intracerebral hemorrhage, and subarachnoid hemorrhage. Despite multiple sophisticated analyses of the ICP waveform for prognostication and management of increased ICP, lack of clinical utility and difficulty of use have hampered widespread adoption of those methods of analysis [1-3,7,8]. We developed a pilot study to examine the slope of the ICP waveform during inspiration and expiration in patients with severe TBI. This objective is an expansion of approaches first introduced for the evaluation and categorization of hydrocephalus [5,6].

Foltz et al examined the slope of the systolic CSF pulse waveform during inspiration and expiration in patients with hydrocephalus of various causes and durations. They demonstrated an inverse relationship between the I/E ratio of slopes and the mean ICP so that a normal I/E ratio is between 2.0 and 3.0, whereas an I/E approaching 1.0 is

Abbreviations: AC, assist control; CNS, central nervous system; CSF, cerebrospinal fluid; E, expiration; EDH, epidural hematoma; GCS, Glasgow Coma Scale; GOS, Glasgow Outcome Scale; I, inspiration; ICP, intracranial pressure; ICU, intensive care unit; IMV, intermittent mandatory ventilation; MPM-1, Multi-Parameter Monitoring System 1; MVA, motor vehicle accident; PC, pressure control; PEEP, positive end-expiratory pressure; SAH, subarachnoid hemorrhage; SDH, subdural hematoma; TBI, traumatic brain injury.

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associated with higher mean ICP. They then postulated that the normal systolic CSF pulse wave is damped by venous venting that changes during inspiration and expiration. When intracranial venous volume is exhausted, intracranial compliance is lost and the I/E ratio approaches 1.0 [6].

Based on this, the current study hypothesized that in patients with TBI, the slope of the systolic ICP waveform would be greater during inspiration than during expiration. This hypothesis was tested using a new method to digitally acquire and analyze ICP waveform values and slopes. The slope of the ICP waveform was calculated according to the same principle used by Foltz and Aine [5] using the minimum to the maximum amplitude of the systolic ICP pulse waveform.

2. Methods

2.1. Subjects

This study consisted of analysis of ICP waveforms recorded in patients with TBI and was approved by the institutional review board of the University of California, Irvine. Informed consent was obtained from a surrogate. All patients were treated by a standard protocol that consisted of head elevation, placement of ICP monitors for GCS score of less than 9, early surgical evacuation of intracranial hematomas, controlled positive-pressure ventilation (see Table 2), and aggressive treatment to keep ICP to less than 20 mm Hg and cerebral perfusion pressure to higher than 60 mm Hg. Routine medications included narcotic analgesics, sedatives, neuromuscular blockage, vasopressors, and phenytoin. Patients whose ICP measurements exceeded 20 mm Hg were treated with CSF drainage, sedation, paralysis, mannitol, and barbiturates if necessary.

Table 1
Summary of patient demographics, clinical conditions, and procedures

Subject no.	Age	GCS score on admission	GOS on discharge	Operative procedures	Intracranial pathology
1	20	7	4	Left decompressive hemicraniectomy	Skull fractures Cerebral contusion EDH, SAH
2	22	14	3	Right decompressive hemicraniectomy	Skull fracture Frontal/occipital contusion SAH
3	32	3	5		Cerebral contusion
4	59	8	5	Left craniotomy for EDH evacuation	Skull fracture Cerebral contusion SAH, SDH
5	41	5	4		Cerebral contusion
6	25	3	3		Skull fracture Cerebral contusion SAH/SDH

Table 2
Summary of values for subjects with TBI

Subject	Average slope (mm Hg/s)	Ave ICP (mm Hg)	I/E ratio	Time epoch (days after admission)	Ventilation mode/ pressure support/ PEEP
1	7.0	46	1.2	10	IMV/10/5
2	12.8	22	1.1	8	IMV/8/5
3	13.9	26	1.2	18	IMV/10/5
4	11.2	8	1.0	1	IMV/10/8
	17.9	19	1.3	4	IMV/10/7
	14.4	25	1.4	4	IMV/10/7
	16.0	14	1.2	4	IMV/10/7
5	15.8	9	1.1	1	AC/0/5
	16.9	12	1.1	1	AC/0/5
	21.0	6	1.1	3	IMV/10/5
	28.7	16	1.1	3	IMV/10/5
6	12.7	8	1.0	1	AC/0/5
	38.0	34	1.0	3	AC/0/5
	9.9	15	1.2	4	AC/0/5
	7.7	7	1.2	13	AC/0/5

Increased ICP refractory to maximal nonoperative therapy was treated with a decompressive hemicraniectomy. Intracranial pressure was monitored in all patients with a Camino® intraparenchymal transducer (Integra Neurosciences, Plainsboro, NJ) and the waveform was digitally recorded. The ICP monitor was zeroed and calibrated at the time of insertion of the transducer.

Intracranial pressure waveforms were analyzed in 6 male adult patients, aged 20 to 59 years, admitted to the ICU for acute TBI between December 2004 and May 2006. The patients' ICP was measured for an average of 7 days. The cause of TBI, age, GCS score on admission, GOS on discharge, operative procedures, and intracranial pathology are summarized in Table 1. All patients experienced closed head injury with cerebral contusions; 4 (66%) had skull fractures. Three were involved in motor vehicle collisions, including 2 who were struck by cars. Two had TBI from assault. One patient had TBI when his motorcycle struck a wall.

The current study consists of an initial pilot analysis of a small sample of ICP waveform data in patients with TBI to determine whether further large-scale analysis would be beneficial. Intracranial pressure waveform recordings were started as soon as surrogate consent was obtained, usually within 6 to 24 hours after admission and continued for as long as ICP monitoring was clinically indicated. In the first 3 patients studied (subjects 1-3), a single 5-minute epoch was analyzed. This group of patients all had severely increased ICP and was being treated with maximal medical therapy. Their ICPs were recorded for several days, and epochs were chosen for analysis by selecting an interval during increased ICP that demonstrated good ICP waveform variability of inspiration to expiration with minimal noise. In 3 additional patients (subjects 4-6), four 5-minute epochs were recorded during a time interval during which there were minimal management changes (such as change of medication, etc), and the ICP waveform was also recorded over a 5-minute period. These epochs were selected randomly during episodes of variable ICP. Table 2 lists the hospitalization day during which each epoch was recorded.

2.2. Data collection

Intracranial pressure was digitally recorded with the Camino® intraparenchymal transducer (Integra Neurosciences) using an MPM-1 software at 167samples per second. These data were then imported into Chart 5™ (ADInstruments, Inc, Colorado Springs, Colo) for waveform analysis.

2.3. Data processing

Waveforms were smoothed in Chart 5™ using a 1/4-second window (using the "triangular" [Bartlett] window). Waveform patterns were each assigned to inspiration or expiration based on respiratory variability (Fig. 1). The upslope of each systolic ICP waveform, from nadir to peak, was then determined. The mean ICP across each waveform was also determined. Slopes were then averaged for each epoch during inspiration, expiration, and combined.

2.4. Statistics

Bivariate analysis was used to compare the ICP slope with respiratory phase (inspiration vs expiration), separately for each subject, using a 2-tailed *t* test assuming unequal variances. Also separately for each subject, regression analysis was used to compare ICP slope with simultaneous ICP, across all ICP systolic waveforms.

3. Results

The number of waveforms analyzed per subject ranged from 248 to 291 (subjects 1-3) and from 1043 to 1098 (subjects 4-6).

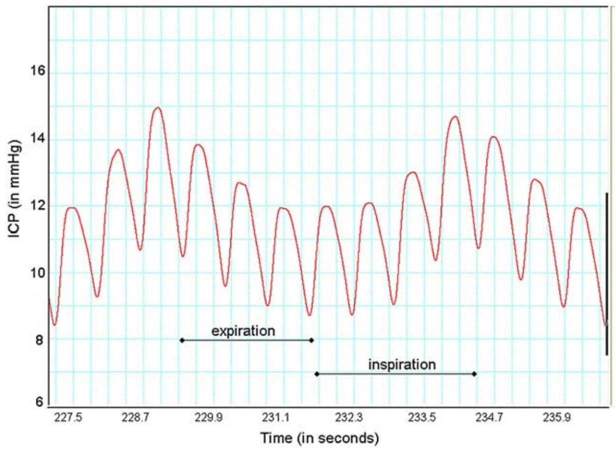

Fig. 1. Representative systolic ICP waveforms, with inspiration and expiration phases labeled.

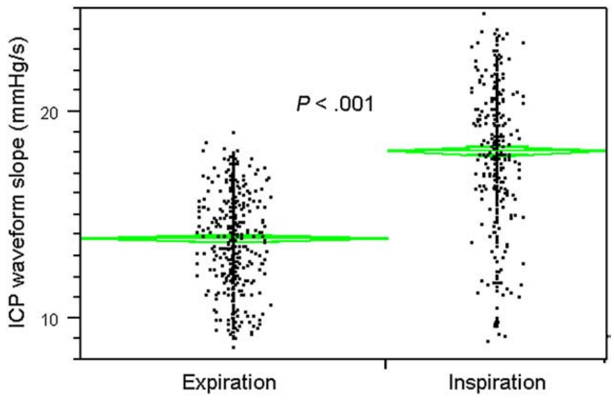

Fig. 2. One-way analysis of ICP over a point in respiratory cycle. For all patients, ICP slope during inspiration was significantly ($P < .0001$) greater than during expiration. Data are shown for patient 4. Diamonds superimposed on scatterplots indicate mean ± 95% confidence interval.

The slope of systolic ICP waveforms varied in relation to a point in respiratory cycle. The slope of systolic ICP waveforms during inspiration was significantly increased over the slope during expiration ($P < .0001$ for 5 subjects and $P < .03$ for 1 subject). Representative data from subject 4 (Fig. 2) demonstrate a significantly higher ICP slope during inspiration as compared to expiration.

All subjects in this study had I/E ratios that were less than 1.5, with an average ratio of 1.1, ranging from 1.0 to 1.4. There was no statistically significant relationship between the average ICP and the I/E ratio between subjects.

The slope of systolic ICP waveforms also varied in relation to mean ICP. When all ICP slopes (inspiration and expiration combined) were analyzed within each subject, there was a strong positive correlation between ICP slope and simultaneous ICP ($P < .0001$ in all 6 cases). Fig. 3A to F shows this relationship for each subject.

4. Discussion

This pilot study set out to determine whether the systolic slope of the ICP waveform is greater during inspiration than during expiration. The results confirm that the slope of systolic ICP waveforms during inspiration was significantly greater than the slope during expiration ($P < .0001$ for 5 subjects and $P < .03$ for 1 subject), which is consistent with previous observations in patients with hydrocephalus [5,6].

Like the study of hydrocephalus by Foltz et al [6] in which the I/E ratio approaches 1.0 as mean ICP increases, all patients with TBI in our study had I/E ratios that were less than 1.5, ranging from 1.0 to 1.4. However, whereas all patients with TBI in this study had low I/E ratios, the relationship between mean ICP and I/E ratio did not show a clear trend between subjects. This may be due to the fact that because only 5-minute epochs were used, either once or 4 times, the sample size is too small to reveal between-subject trends across larger periods.

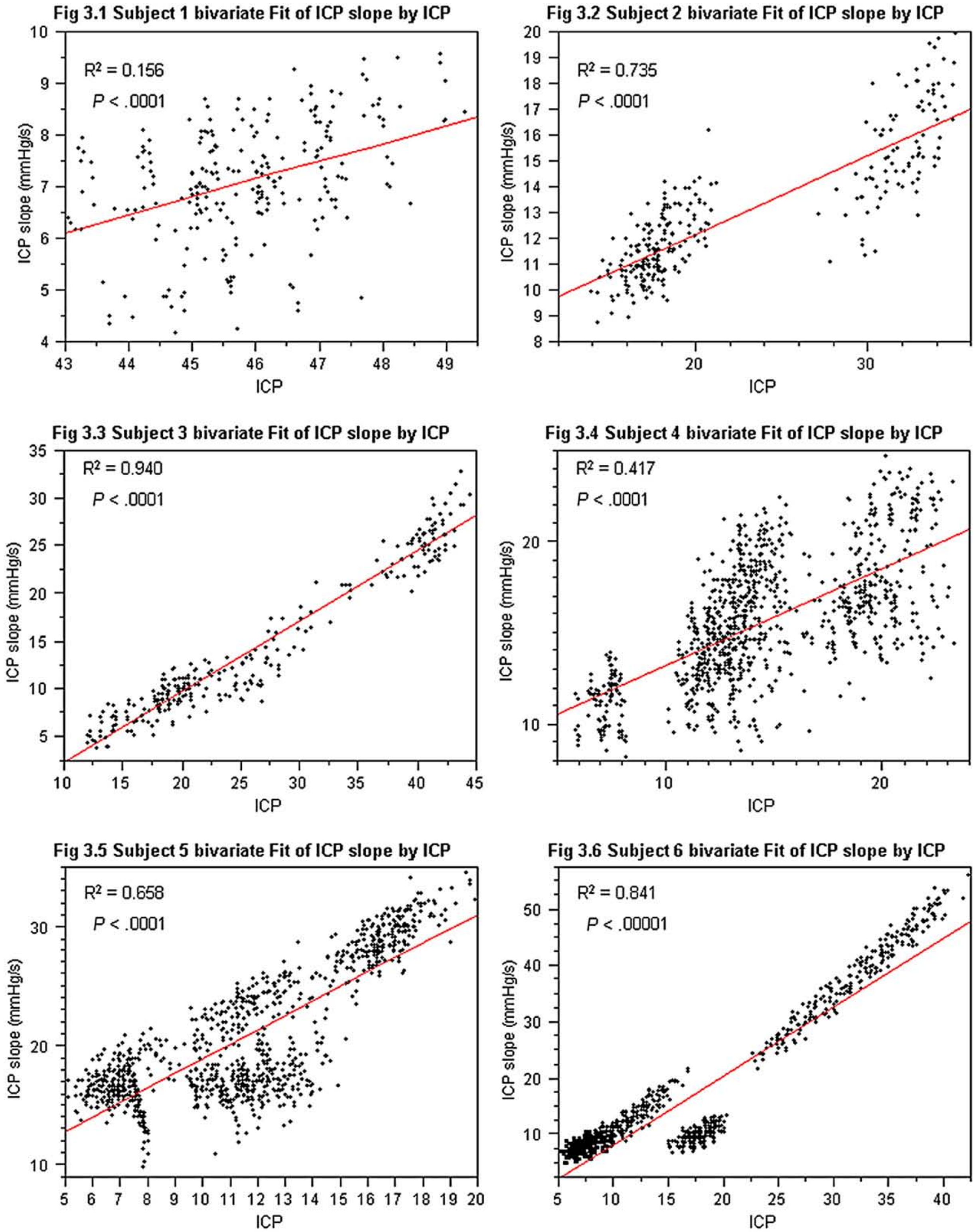

Fig. 3. Intracranial pressure slope is plotted in relation to simultaneous ICP. As ICP increases, the slope of each ICP waveform also increases.

This study also showed a strong positive correlation between simultaneous mean ICP and ICP slope within each subject, a finding that was not mentioned in the studies by Foltz et al [5,6]. Another study examined this relationship by developing a computer-based method that enables continuous analysis of each pulse of the ICP wave. They found in 9 patients with head injury that the gradient (slope) of the single ICP pulse wave increased linearly with rising ICP [7]. However, they did not examine the respiratory variability of the waveforms nor did they apply any statistical analysis to their results. Dubin et al [4] measured the respiratory variability of the ICP waveform slope in 6 minipigs and found a positive correlation; however, it was not statistically significant.

This pilot study in patients with TBI confirms that the slope of the ICP waveform is greater in inspiration than in expiration, similar to patients with hydrocephalus. This relationship holds although the patients in the current study were all on positive-pressure ventilation and the patients in the prior study were all breathing spontaneously. The overall effect of mechanical ventilation is to reduce venous return to the heart; however, further data are needed to determine whether significant differences exist between inspiration and expiration slopes in mechanically ventilated patients vs those breathing spontaneously.

It is hoped that further analysis of I/E ICP slopes in patients with TBI may have predictive value, either for changes in mean ICP or in patient outcome. Ongoing studies will correlate predictive value of I/E with outcome variables.

5. Conclusion

This pilot study of the respiratory variability of ICP waveform slope in patients with TBI reveals that the ICP slope is greater during inspiration than during expiration, consistent with prior studies in hydrocephalus. This has not been demonstrated previously in patients with TBI. The lack of correlation between I/E ratio and mean ICP between subjects, previously demonstrated in hydrocephalus, may be because of the small sample size. Our finding that increasing mean ICP strongly corresponds to an increase in the ICP slope suggests that increasing the ICP slope may be an indicator of loss of intracranial compliance in TBI. Further analysis of longer epochs of ICP waveforms is ongoing and should permit clarification of the relationship between I/E and mean ICP.

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Commentary

The authors describe their experience with ICP waveform analysis among patients with TBI in this small prospective study. They find that ICP waveform slope correlates with mean ICP and, furthermore, suggest that these observations are likely due to exhausted venous venting and poor brain compliance.

This study builds nicely on concepts pioneered by Foltz and colleagues [1] who described the benefits of waveform analysis in a predictive model for hydrocephalus. Although it is interesting that the physiologic variance of inspiratory and expiratory waveform slopes applies to patients with severe TBI, the clinical utility of this finding has yet to be developed. To establish their hypothesis, the authors studied a cohort of severely injured patients with refractory ICP elevations in which application of these methods adds minimally to the understanding of brain compliance. Application of a similar analysis to less severely injured patients with TBI may prove to be more revealing. One would expect even greater discrepancies in I/E ratios and perhaps interesting correlations with ventricuostomy weaning and shunting requirements.

This study provokes many questions regarding the hemodynamics of elevated ICP. In particular, it is surprising that the inspiratory and expiratory waveforms in this cohort resemble those described by Foltz despite the presence of positive pressure ventilation. The authors are to be applauded for their insights into this common and devastating complication of TBI. I look forward to their innovative future work in hopes that ICP waveform analysis might be used in real-time patient management.

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