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# Intracranial compliance and volumetry in patients with traumatic brain injury

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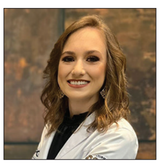

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## ABSTRACT

**Background:** Cerebral edema (CE) and intracranial hypertension (IHT) are complications of numerous neurological pathologies. However, the study of CE and noninvasive methods to predict IHT remains rudimentary. This study aims to identify in traumatic brain injury (TBI) patients the relationship between the volume of the lateral ventricles and the parameters of the noninvasive intracranial pressure waveform (nICPW).

**Methods:** This is an analytical, descriptive, and cross-sectional study with nonsurgical TBI patients. The monitoring of nICPW was performed with a mechanical strain gauge, and the volumetry of the lateral ventricles was calculated using the free 3D Slicer software, both during the acute phase of the injury. The linear model of fixed and random mixed effects with Gamma was used to calculate the influence of nICPW parameters (P2/P1 and time-to-peak [TTP]) values on volumetry.

**Results:** Considering only the fixed effects of the sample, there was $P = 0.727$ (95% CI [−0.653; 0.364]) for the relationship between P2/P1 and volumetry and 0.727 (95% CI [−1.657; 1.305]) for TTP and volumetry. Considering the fixed and random effects, there was $P = 8.5\text{e-}10$ (95% CI [−0.759; 0.355]) for the relationship between P2/P1 and volumetry and 8.5e-10 (95% CI [−2.001; 0.274]) for TTP and volumetry.

**Conclusion:** The present study with TBI patients found association between nICPW parameters and the volume of the lateral ventricles in the 1st days after injury.

**Keywords:** Computed tomography, Intracranial pressure, Traumatic brain injury

## INTRODUCTION

Intracranial hypertension (IHT) is an event that occurs in different neurological pathologies, either from traumatic events, metabolic disorders, intracranial neoplasms, or cerebrovascular diseases, as cerebral ischemia or intracranial hemorrhages. Although the neurological deficits observed in patients outcomes are secondary to cerebral ischemia,[4] the major cause of death and progressive neurological deterioration after any neurological event is related to cerebral edema (CE) and IHT development.[18,37] However, the prediction of CE and its management remains rudimentary.[14]

The traumatic brain-injured (TBI) patient requires close bedside monitoring for neurological deterioration,[13,20,34] with assessments to detect raised intracranial pressure (ICP) relying on the dependence of invasive procedures.[31] However, tomographic techniques may provide crucial information for the prediction of IHT, such as the cerebrospinal fluid (CSF) volumetry in the ventricles (CSFv) that reflects the direct physiological cerebral compensation in response to increased ICP,[30] and the measure of midline shift. Unfortunately, radiologic techniques present limitations especially regarding temporal resolution, since the midline shift only develops late in IHT, when space to compensate for the increased brain volume has been exhausted, mainly by displacement of blood and CSF. Furthermore, IHT can occur compartmentally, without a pressure gradient between the hemispheres, theoretically with a lower degree of IHT.[33]

Likewise, the relationship between intracranial volume and ICP is the determinants of intracranial compliance (ICC), which is possible to assess according to the dynamic changes in ICP pulse morphology or waveform (ICPW).[5,12] Recently, a noninvasive technique was developed for the acquisition of ICPW (nICPW) and validated in clinical settings such as the intensive care unit (ICU),[7,9] neuro-ICU[8,17,25] and children with hydrocephalus,[2] allowing a real tim1e of CSF in the lateral ventricles (obtained from tomographic images) and the dynamics parameters of the nICPW. CSFv by means of radiology and nICPW by means of physiology may be valuable for ICP dynamics monitoring of the TBI patient.

## MATERIALS AND METHODS

This is an analytical, descriptive, and cohort study carried out in the emergency department, wards, and ICU. The Local Ethics Committee approved this study under protocol number 3.361.003.

### Patients and design

Inclusion criteria were TBI patients without craniotomy, over 18 years of age. The patients had the first monitoring of cerebral compliance within 12 h after the admission computed tomography (CT) scan and the subsequent ones, 24, 48, 72, 96, and 120 h after the CT, totaling one to six monitoring lasting 10 min each, with follow-up interrupted according to the patient's discharge, death, or neurosurgery (the monitorization of patients submitted to decompressive craniectomy were performed only before the surgical procedure).

### Neuromonitoring

CT scans were obtained on the patient's admission and during the acute phase of the injury. Volumetry of the lateral ventricles was calculated using the free 3D Slicer software (Kitware, New York, United States). The left and right cerebral lateral ventricles were manually contoured, and based on the delineated areas, image density, and three-dimensional reconstruction, a volumetric estimation was performed by trained statisticians blinded to nICPW data.

A mechanical strain gauge (Braincare Corp. São Carlos, Brazil) subtype foil (diaphragm or SR-4) and an electronic data acquisition system with an analog-digital module connected to the sensor by an electrical wire were used for monitoring ICC. The strain gauge was applied to the temporoparietal bone, 1–1.5 cm above the ear, with engineering and technical information described elsewhere.[1] A P2 elevation was defined as a P2/P1 ratio ≥1.2.[6,25] The pulse slope (time to peak [TTP]) was calculated between the beginning of the wave increase and its highest point, resulting in an angle between the formed line and the pulse base.

### Statistical analysis

The arithmetic means of the relationships found in every monitoring minute were calculated. Qualitative data were presented as *n* (%). Quantitative data were presented as mean + standard deviation (SD). The linear model of fixed and random mixed effects with Gamma was used to calculate the influence of P2/P1 and TTP values on volumetry. A significant $P < 0.05$ was considered.

## RESULTS

### Data sample

The data from monitoring sessions in which P2/P1, TTP, and tomography data were analyzed simultaneously, excluding data from four patients (due to insufficient P2/P1 signal acquisition quality and TTP), keeping data from a total of 50 patients.

The mean age of the patients was 38.66 years (SD = 16.69; range from 19 to 83), and the male-to-female ratio was 4:1. The most common trauma mechanism was a motorcycle collision. Approximately 20% of patients had severe TBI, and the most common intracranial abnormalities were subarachnoid hemorrhage and intraparenchymal hematoma (34% each). During the monitorization, one patient presented with a small intraventricular hemorrhage without dilatation of the ventricular system and another with mild hydrocephalus and reduced brain volume. Two patients underwent decompressive craniotomy, whereas only one had external ventricular implantation and invasive ICP monitoring [Table 1]. The mean of the P2/P1 ratio in the first monitoring was 1.07 (SD = 0.27), and the TTP 0.204 (SD = 0.09), with 14 patients (28%) having P2/P1 >1.2 [Table 2].

### Relationship between volumetry, P2/P1, and TTP

Considering only the fixed effects of the sample (view of the entire population), there was $P$ = 0.727 (95% confidence interval (CI) [−0.653; 0.364]) for

**Table 1:** Demographic data.

| Variable | Total (%) |
|---|---|
| Number of patients | 50 (100%) |
| Age (years) | |
| Mean (variation) | 38,66 (19-83) |
| Gender | |
| Male | 41 (82%) |
| Female | 9 (18%) |
| Trauma mechanism | |
| Motorcycle | 16 (32%) |
| Vehicle | 15 (30%) |
| Falls | 9 (18%) |
| Assault | 7 (14%) |
| Others | 3 (6%) |
| Admission GCS | |
| Severe TBI (3 – 8) | 10 (20%) |
| Moderate TBI (9 – 12) | 3 (6%) |
| Mild TBI (13 – 15) | 37 (74%) |
| Tomographic abnormalities | |
| Subarachnoid hemorrhage | 17 (34%) |
| Intraparenquimal hematoma | 17 (34%) |
| Subdural hematoma | 14 (28%) |
| Epidural hematoma | 4 (8%) |
| Neurosurgical procedure | |
| Craniotomy | 2 (4%) |
| Ventriculostomy | 1 (2%) |

GCS: Glasgow coma scale, TBI: traumatic brain injury.

**Table 2:** Relationship between the variables according to lesion severity.

| Variables | Mild TBI | Moderate TBI | Severe TBI |
|---|---|---|---|
| P2/P1 of the first analysis | 1,04 | 1,05 | 1,18 |
| TTP of first analysis | 0,192 | 0,184 | 0,256 |

P2/P1: Peak 1/peak 2 ratio, TTP: Time to peak, TBI: Traumatic brain injury.

the relationship between P2/P1 and volumetry and a $P = 0.727$ (95% CI [−1.657; 1.305]) for the relationship between TTP and volumetry. On the other hand, considering the fixed and random effects (individual view of each patient), there was $P = 8.5\text{e-}10$ (estimate = −0.181; 95% CI [−0.759; 0.355]) for the relationship between P2/P1 and volumetry and a $P = 8.5\text{e-}10$ (estimate = −0.685; 95% CI [−2.001; 0.274]) for the relationship between TTP and volumetry [Figures 1 and 2].

## DISCUSSION

The Multidisciplinary Consensus Conference on Multimodal Monitoring in Neurocritical Care recently made a list of recommendations that included ICP monitoring.[32] Its use is mainly recommended for treating patients with acute brain injury. Despite this, the values that define when and how to intervene are still uncertain. In parallel to the absolutes, there are also ICP waveform (ICPw) analysis values.

ICPw is an early marker of impaired ICC. In recent years, it has been observed as its application of new studies that analyze the ICPw and its clinical application.[27] Under physical conditions, the ICPw is mainly defined by three distinct peaks: P1, P2, and P3. The P1 is the percussion wave in which the highest peak is produced by arterial contraction. The P2, a tidal wave, reflects the pressure pulse dissemination over the vascular and ventricular system. As cerebrovascular resistance is normally lower than other systems and organs, the tidal wave (P2) assumes a lower amplitude than P1. In raised ICP situations where the buffering mechanisms are exhausted, there is an ICPw modification with a P2 time amplitude greater than P1, a pyramidal format, and the interval between P1 and P2 becomes longer.[12,19,26]

The noninvasive method used in this study does not give results in millimeters of mercury as in the invasive ICP. Instead, it shows the amplitudes of peaks P1 and P2 of the ICP pulse waveform, allowing for the assessment changes in cerebrospinal compliance.[9] This technology was already validated by comparison with the invasive ICP monitoring method in animal models[17] and clinical settings.[1,2,8,25] Other situations where the method has been used include obesity,[6] COVID-19,[9] and hydrocephalus.[2] It has also received marketing authorization in Brazil (ANVISA) and the USA food and drug administration (FDA).

Until then, there is no literature on the relationship between the brain's lateral ventricles volume and the variables of the intracranial pressure curve, such as the P2/P1 ratio and the TTP. There was no statistically significant difference in our study when comparing the relationship between P2/P1, TTP, and volumetry, considering only the fixed effects. However, when considering the effect of each patient, the *P*-value proved to be extremely significant, demonstrating that as the values of P2/P1 and TTP increase, the volume of the lateral ventricles decreases, given the effect of CE, which is common in the acute phase of the injury after TBI.

Regarding the predictive capacity of CT, specifically evaluating the tomographic classification of Marshall *et al*.,[23] in the study by Lobato *et al*.,[21] the incidence of increased ICP was 3–4 times higher in patients with Diffuse injury III and IV, respectively, compared to Diffuse injury I and II. In 51.2% of the patients, significant changes in the control CT were observed. Gómez *et al*.[15] concluded that ICP elevation also had a higher incidence in patients classified as Diffuse injury IV. In the study by Martin *et al*.,[24] 69% of patients with IHT had Diffuse injury II, while the variables Diffuse injury III and IV were associated with IHT occurrence, with a positive predictive value of 100%. Another study showed that there are different times in days when patients develop

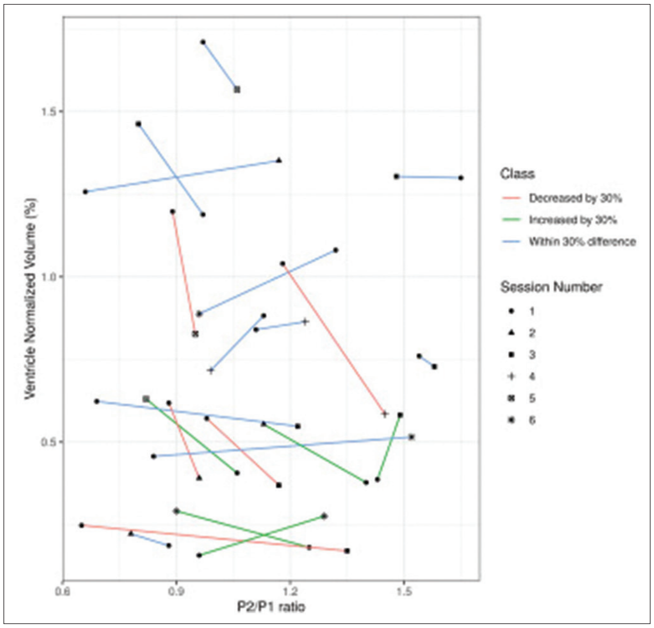


**Figure 1:** Visual analysis between P2/P1 and lateral ventricle volume.

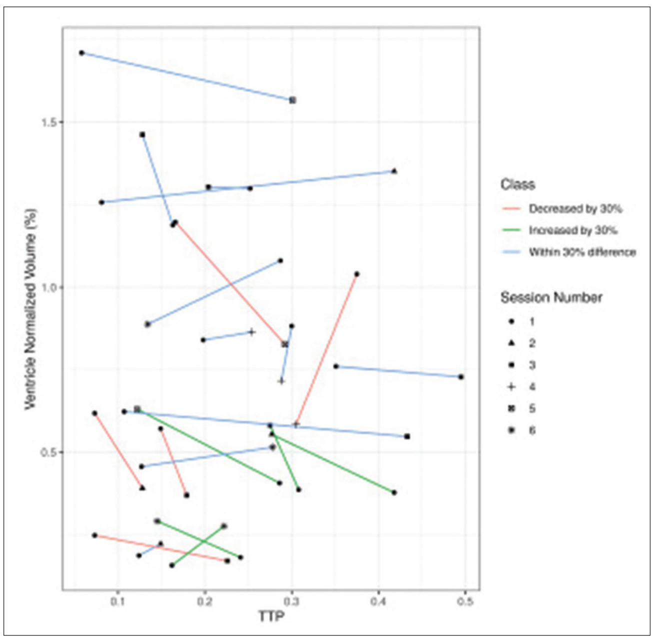


**Figure 2:** Visual analysis between TTP (time to peak) and lateral ventricle volume.

IHT, according to tomographic changes, with half of the patients with Diffuse injury II having ICP elevation later.[10]

In the Marshall III classification, the cisterns are compressed but without midline deviation, and in Marshall IV, there is a deviation of the midline structures (both without intraparenchymal hemorrhages >25 $cm^3$). It is well demonstrated that ventricular asymmetry is directly related to a worse prognosis, following the same reasoning as midline deviation. According to Toth *et al.*,[36] a lateral ventricular ratio of >1.67 as exposure yielded an OR of 7.56 ($P < 0.01$) and a risk ratio of 4.42 ($P < 0.01$) for midline shift development as an unfavorable outcome.

Although not described in the literature, the daily neurosurgical practice demonstrates that the ventricular volume is smaller in these patients. Despite some differences in results, these studies are in agreement in demonstrating that, as changes related to the onset of CE are present, and a reduction in the volume of the ventricles is expected due to the tumefactive effect, the occurrence of increased ICP is more likely, an event related to the impairment of ICC, in which an increase in the P2/P1 and TTP ratio is expected.

In other clinical conditions, such as hydrocephalus,[3,16] or even in patients with TBI,[35] as opposed to this study, an increase in the volume of the ventricles related to the increase in ICP can be observed, in these cases, by obstruction of the CSF drainage pathway. Furthermore, in later phases of TBI lesions, there may be an enlargement of the ventricles related to cerebral atrophy or obstruction of CSF drainage.[22,29]

In the study by Tabaddor *et al.*,[35] through the analysis of data from 36 patients with closed TBI and no lesions with surgical indication, ICP was classified as mild (when <20 mmHg), moderate (maintained below 20 mmHg with the use of medication), or severe (uncontrollable), ventricular compression was strongly associated with ICP level ($P < 0.025$), in agreement with our findings.

Almost all patients after a TBI have an impaired compensatory reserve. The extracranial subarachnoid space plays an important role in this mechanism by accommodating, through CSF deviation, acute variations in intracranial volume, and preventing or delaying significant increases in ICP. According to the study by Zeiler *et al.*,[39] tomographic classifications for TBI, midline deviation, and contusion volume fail to predict impaired compensatory reserve, measured through the correlation coefficient between changes in ICP pulse amplitude and mean ICP (RAP). At the same time, there is an important association between the compensatory reserve index and compression of the lateral ventricles.

The indication of the pressure-volume compensation status, through the RAP, can predict the future behavior of the ICP and hemodynamic instability, containing more information than just the monitoring of the mean ICP.[28] In a validation study, ICP weighted by a compensatory reserve (weighted by ICP), a variable that derives from the RAP, showed a greater association with outcomes than ICP alone,[11] highlighting the importance of monitoring compliance and compensatory reserve, especially in conditions where, although there is no significant increase in ICP, neurological dysfunction occurs.[38]

## CONCLUSION

We investigated alteration in ICPW in the 1st days after TBI, comparing it with the volume of the lateral ventricles and finding an association. Bedside monitoring of intracranial parameters in a noninvasive way can offer greater ease in the therapeutic decision process, especially in contexts where the availability of invasive and expensive technologies is more restricted. Their characterization concerning noninvasive methods is relevant and already used.

The relatively more accessible cost makes this method more practicable. Its characteristic of not being invasive allows access to information in patients with less severe injuries who would not have important parameters investigated due to the absence of a formal indication.

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### Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

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Nil.

### Conflicts of interest

Gustavo Frigieri declares that he has a conflict of interest with Braincare Desenvolvimento e Inovação Tecnológica SA - Brain4care, as he is a founder and Scientific Director.

Sérgio Brasil declares that he has a conflict of interest with Braincare Desenvolvimento e Inovação Tecnológica SA-Brain4care, as he is a scientific consultant.

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