ORIGINAL ARTICLE

Correlation between transcranial Doppler parameters and the Rotterdam score in pediatric patients with traumatic brain injury: a prospective study

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ABSTRACT

Objective: To evaluate the correlation between transcranial Doppler (TCD) parameters and the Rotterdam score (RS) and to identify clinical and radiological factors associated with cerebral hemodynamic alterations in pediatric patients with traumatic brain injury (TBI).
Methods: An observational, prospective, correlational study was conducted in 30 patients with TBI. Data on age, Glasgow Coma Scale, and trauma severity (TS) were obtained from medical records. Hemodynamic measurements were performed using TCD within the first 48 hours after admission. Flow velocities of the middle cerebral artery and the internal carotid artery were recorded, along with the resistance index, pulsatility index, and Lindegaard index (LI), measured bilaterally. Spearman's correlation analyses and multiple linear regression models were applied.
Results: The right LI showed the strongest positive correlation with the RS ($\rho = 0.52$, $p = 0.002$). The right LI was also the parameter most significantly associated with TS ($p = 0.002$). In multivariate analyses adjusted for age and sex, RS ($\beta = 0.52$, $p = 0.045$) and TS ($\beta = 0.84$, $p = 0.012$) showed significant and independent associations with the right LI.
Conclusions: The right LI was significantly associated with both the RS and TS in pediatric patients with TBI. This finding suggests that this TCD parameter may represent a potential hemodynamic marker in pediatric TBI.

Keywords: Transcranial Doppler Ultrasonography; Brain Injuries, Traumatic; Glasgow Coma Scale; Middle Cerebral Artery; Internal Carotid Artery (Source: MeSH)

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Correlación entre los parámetros del Doppler transcraneal y el score de Rotterdam en pacientes pediátricos con lesión cerebral traumática: estudio prospectivo

RESUMEN

Objetivo: Evaluar la correlación entre los parámetros del Doppler transcraneal (DTC) y el score de Rotterdam (SR) e identificar los factores clínicos y radiológicos asociados con las alteraciones hemodinámicas cerebrales en pacientes pediátricos con lesión cerebral traumática (LCT).
Métodos: Estudio observacional, prospectivo y correlacional realizado en 30 pacientes con LCT. Se recopilaron datos de edad, escala de coma de Glasgow y severidad del trauma (ST) a partir de la historia clínica. Las mediciones hemodinámicas se realizaron mediante DTC durante las primeras 48 horas del ingreso. Se registraron las velocidades de flujo de la arteria cerebral media y de la arteria carótida interna, así como el índice de resistencia, el índice de pulsatilidad y el índice de Lindegaard (IL), bilaterales. Se aplicaron análisis de correlación de Spearman y modelos de regresión lineal múltiple.
Resultados: El IL derecho mostró la correlación positiva más fuerte con el SR ($\rho = 0{,}52$, $p = 0{,}002$). El IL derecho fue el parámetro que presentó la asociación estadística más significativa con la ST ($p = 0{,}002$). En los análisis multivariados ajustados por edad y sexo, el SR ($\beta = 0{,}52$, $p = 0{,}045$) y la ST ($\beta = 0{,}84$, $p = 0{,}012$) mostraron asociaciones significativas e independientes con el IL derecho.

Conclusiones: El IL derecho se asoció de manera significativa con el SR y con la ST en pacientes pediátricos con LCT. Este hallazgo sugiere que dicho parámetro del DTC podría constituir un potencial marcador hemodinámico en la LCT infantil.

Palabras clave: Ultrasonografía Doppler Transcraneal; Lesiones Traumáticas del Encéfalo; Escala de Coma de Glasgow; Arteria Cerebral Media; Arteria Carótida Interna (Fuente: DeCS)

INTRODUCTION

Traumatic brain injury (TBI) is currently a major cause of neurological disability and mortality in pediatric patients (1). A multinational epidemiological study revealed an incidence of 47 to 280 cases per 100,000 children per year, with children younger than 2 years and adolescents representing the groups with the highest incidence, mainly due to traffic accidents and accidental falls (2).

The management and monitoring of patients with TBI require a thorough understanding of the pathophysiological basis of intracranial pressure (ICP) and cerebral perfusion pressure (CPP) during this critical event (3,4). However, traditional invasive neuromonitoring carries potential risks, including malposition of the intraventricular sensor, hemorrhage, and infection, and it is not always available or feasible for all pediatric patients. In contrast, transcranial Doppler (TCD) is a noninvasive, reproducible, and widely accessible imaging modality that allows indirect assessment of fluctuations in cerebral blood flow and hemodynamic alterations that occur as a consequence of traumatic injury (5).

For more than three decades, numerous studies have demonstrated the feasibility of measuring cerebral blood flow velocities through the skull using different acoustic windows (6–9). Early investigations evaluating the use of TCD in pediatric patients with TBI began in the early 2000s, notably with the study by Mandera et al. (10), who reported a significant correlation between cerebral blood flow variations assessed by TCD and neurological status in patients with TBI. Other similar studies, such as that conducted by Figaji et al. (11), observed a strong correlation between CPP and pulsatility index (PI); however, PI was not found to be a reliable indicator of ICP in children with TBI. Similarly, O'Brien et al. (12) reported that a PI of the middle cerebral artery (MCA) > 1.3 during the first 24 hours after injury showed good sensitivity and specificity for predicting ICP ≥ 20 mmHg.

TCD flow parameters have been shown to predict the risk of adverse neurological outcomes following traumatic injury (13,14) and to help elucidate the underlying pathophysiological mechanism of trauma (15). Additional applications of TCD in neurocritical care units include assessment of cerebrovascular autoregulation, evaluation of vasospasm in stroke, hemodynamic monitoring in central nervous system infections, and diagnostic support in cases of brain death (16).

In the evaluation of pediatric patients with TBI, intracranial imaging plays a fundamental role in determining the extent of brain injury. Computed tomography (CT) is the primary imaging modality used to identify intracranial lesions that may require immediate treatment, and it should be performed using the lowest radiation dose reasonably achievable (17). Currently, the Rotterdam score (RS) is widely used as a predictor of mortality and clinical outcome in patients with TBI based on CT imaging findings (18). This score incorporates several elements of the Marshall score (19); however, unlike the latter, it recognizes the more favorable prognosis associated with epidural hematomas and adds the presence of intracerebral and subarachnoid hemorrhagic lesions as aggravating factors. Previous studies have demonstrated the usefulness of RS in assessing TBI in children, showing good predictive value for both mortality risk and the need for surgical intervention and intensive care (20,21).

To date, no national studies have evaluated the association between TCD parameters and the assessment of structural brain injury in pediatric patients with TBI. In this context, this study aimed to determine the correlation between TCD parameters and the structural severity of TBI, as assessed by the RS, in a cohort of patients treated at a national pediatric referral hospital in Lima, Peru.

METHODS

Study design

This study followed an observational, prospective, analytical, and correlational design.

Population and sample

All patients younger than 17 years, 11 months, and 29 days who were admitted to the Emergency Department of the Instituto Nacional de Salud del Niño San Borja with a diagnosis of TBI were consecutively included. Patients with chronic pharmacological treatment for cardiac or pulmonary diseases, congenital brain disorders associated with vascular abnormalities, concomitant neoplastic processes, liver cirrhosis, or other conditions potentially affecting normal cerebral perfusion were excluded. The data collection period spanned 12 consecutive months, from October 2024 through September 2025.

Procedures

All selected patients underwent TCD ultrasonography within the first 48 hours after admission to the intensive care unit. A single measurement was performed for each patient. The procedure followed the Neurosonography Protocol proposed by the Sociedad y Fundación Española de Cuidados Intensivos Pediátricos (22).

This protocol includes measurement of flow velocities in different cerebral arteries adjusted according to age. Insonation of the right and left MCA was performed through the transtemporal window using a low-frequency transducer (2–5 MHz). The extracranial right and left internal carotid artery (ICA) were insonated through the cervical region using a high-frequency transducer (10–12 MHz). For each measurement, the appropriate insonation depth and angle were selected to obtain the highest mean flow velocity and the optimal pulsatile waveform.

All examinations were performed using a portable ultrasound system (SonoScape S8 Exp) by a radiologist specialized in pediatric imaging with extensive experience in TCD. This methodological approach was adopted to minimize interobserver variability, which is recognized as one of the main sources of error in TCD measurements. Although a formal intraobserver agreement analysis was not conducted, previous literature has demonstrated high reproducibility of TCD when performed by experienced operators, supporting the reliability of the collected data (23).

Variables

Data from TCD parameters were collected and constituted the dependent variables of the study. These included MCA flow velocity, internal carotid artery (ICA) flow velocity, PI, resistance index (RI), and the ratio between mean velocities of the MCA and ICA (Lindegaard index – LI). All parameters were recorded bilaterally (right and left).

The structural severity of TBI, considered the predictor variable, was assessed using the admission brain CT scan according to the RS. The RS includes four independently scored components: 1) degree of basal cistern compression, 2) degree of midline shift, 3) presence of epidural hematoma, and 4) presence of intraventricular or subarachnoid hemorrhage (18). The score ranges from 1 to 6, with higher values indicating more severe structural brain injury.

Additionally, age, sex, Glasgow Coma Scale (GCS), and trauma severity (TS) were considered confounding variables. The GCS measures the level of consciousness in patients with brain injury, with scores ranging from 3 (most severe condition) to 15 (normal neurological function). TS was classified according to GCS as mild (GCS 13–15), moderate (GCS 9–12), and severe (GCS 3–8).

Statistical analysis

Statistical analysis was performed using SPSS (Statistical Package for the Social Sciences), version 25.0 (IBM Corp., Armonk, NY, USA). Categorical variables were reported as absolute frequencies and percentages. Continuous variables were expressed as mean ± standard deviation (SD), interquartile range (IQR), maximum value, and minimum value.

Normality of quantitative variables was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene's test. To analyze the associations between TCD parameters (MCA velocity, ICA velocity, PI, RI, and LI) and the RS, the Spearman's correlation test (ρ) was used. Comparisons among TS categories were performed using the Kruskal–Wallis test. Finally, multiple linear regressions with robust standard errors (HC3) were conducted to adjust for the effects of clinical and radiological covariates on each TCD parameter and to correct for potential heteroscedasticity. In all tests, a statistical significance level of $p < 0.05$ was considered.

Ethical considerations

All participants included in the study gave informed consent provided by parents or guardians.

The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Data collection instruments were completed strictly by the investigators, ensuring anonymity and confidentiality of information at all times.

This study was approved by the Institutional Research Ethics Committee of the Instituto Nacional de Salud del Niño de San Borja (code PI-885).

RESULTS

Data was collected from 30 patients, of whom 17 were male (56.7%). The mean age was 5.70 years, with a range from 1 to 13 years. No patient presented mild TS. Twenty patients (66.7%) had severe TS, of whom 12 patients (60.0%) were male. The descriptive analysis of the quantitative variables is presented in Table 1.

Table 2 shows the results of the correlation between TCD parameters and the RS. The right LI demonstrated the strongest positive correlation with the RS ($\rho = 0.52$, $p = 0.002$). Other variables, including the peak systolic velocity (PSV) of the left and right MCA and the left and right ICA, showed weak but significant correlations with the RS. The Kruskal–Wallis analysis revealed statistically significant differences in several TCD parameters according to TS categories: right LI ($p = 0.002$), PSV of the left MCA ($p = 0.004$), and PSV of the right MCA ($p = 0.040$) (Table 3).

In the regression analysis, the right LI was selected as the dependent variable because it showed the strongest correlation with the RS. The regression model explained 28% of the variability of the right LI. Although the RS did not reach statistical significance ($p = 0.999$), likely due to high collinearity with TS (VIF = 19.28 and 21.70, respectively), the variables age, male sex, and TS showed significant positive associations with the right LI (Table 4).

The high variance inflation factor (VIF > 10) for RS and TS indicated substantial collinearity between these two variables. Therefore, both variables were not included simultaneously in the same regression model, and two alternative models were proposed.

In the first model, only RS was used as the main predictor, excluding the TS variable (Table 5). A significant association between RS and the right LI was observed after adjustment for age and sex. No relevant collinearity was detected among variables (VIF < 5), suggesting improved statistical stability of the model.

In the second model, TS was used as the primary predictor, excluding the RS (Table 6). In this model, TS showed a significant association with the right LI after adjustment for age and sex. Similar to the previous model, no relevant collinearity was observed (VIF < 5) among the variables, supporting the statistical stability of the model.

Table 1. Descriptive analysis of age, GCS, TCD parameters, and RS

TCD-derived parameters	Mean	SD	IQR	Minimum	Maximum
Age (years)	5.70	3.10	3.25–7.00	1.00	13.00
GCS	8.10	1.40	8.00–9.00	4.00	11.00
MCA-R PSV (cm/s)	149.91	50.00	114.40–190.80	74.80	243.30
MCA-R RI	0.74	0.09	0.65–0.81	0.57	0.88
MCA-R PI	1.50	0.37	1.15–1.76	0.92	2.13
MCA-L PSV (cm/s)	169.34	48.10	135.50–203.80	59.30	248.60
MCA-L RI	0.75	0.09	0.69–0.82	0.54	0.85
MCA-L PI	1.54	0.33	1.27–1.80	0.84	1.96
ICA-R PSV (cm/s)	78.50	24.30	59.00–97.40	23.30	123.80
ICA-R RI	0.75	0.07	0.69–0.80	0.59	0.86
ICA-R PI	1.52	0.28	1.28–1.70	0.97	2.02
ICA-L PSV (cm/s)	74.70	25.70	54.50–89.20	30.60	144.40
ICA-L RI	0.74	0.08	0.65–0.82	0.62	0.85
ICA-L PI	1.51	0.32	1.15–1.80	1.06	1.96
LI R	2.13	1.10	1.30–2.93	0.74	5.09
LI L	2.46	0.96	1.87–3.00	0.95	4.31
RS	3.90	0.90	3.00–4.75	3.00	6.00

TCD: transcranial Doppler; GCS: Glasgow Coma Scale; MCA: middle cerebral artery; ICA: internal carotid artery; PSV: peak systolic velocity; RI: resistance index; PI: pulsatility index; LI: Lindegaard index; R: right; L: left; RS: Rotterdam score; SD: standard deviation; IQR: interquartile range.

Table 2. Spearman's correlation between RS and TCD parameters

Variable	ρ	p
LI R	0.52	0.002
MCA-L PSV	0.49	0.006
MCA-R PSV	0.43	0.018
ICA-L PSV	0.39	0.032
ICA-R PSV	0.39	0.035
MCA-L PI	0.34	0.068
MCA-R PI	0.32	0.086
MCA-L RI	0.31	0.101
MCA-R RI	0.30	0.124
LI L	0.29	0.136
ICA-L PI	0.27	0.169
ICA-R PI	0.26	0.190
ICA-L RI	0.25	0.217
ICA-R RI	0.23	0.264

MCA: middle cerebral artery; ICA: internal carotid artery; PSV: peak systolic velocity; RI: resistance index; PI: pulsatility index; LI: Lindegaard index; R: right; L: left; ρ: Spearman's correlation coefficient.

Table 3. Kruskal–Wallis analysis between TS and TCD parameters

Variable	H	p
LI R	9.35	0.002
MCA-L PSV	8.48	0.004
MCA-R PSV	6.43	0.040
ICA-L PSV	5.16	0.023
ICA-R PSV	5.02	0.025
MCA-L PI	2.63	0.268
MCA-R PI	2.21	0.331
MCA-L RI	1.98	0.369
MCA-R RI	1.74	0.419
LI L	1.60	0.449
ICA-L PI	1.40	0.498
ICA-R PI	1.22	0.543
ICA-L RI	1.12	0.572
ICA-R RI	0.94	0.624

MCA: middle cerebral artery; ICA: internal carotid artery; PSV: peak systolic velocity; RI: resistance index; PI: pulsatility index; LI: Lindegaard index; R: right; L: left; H: Kruskal–Wallis statistic.

Table 4. Multiple linear regression model for right LI

Independent variable	β	Standard error	95% CI	p	VIF
Intercept	0.79	0.37	0.03–1.55	0.041	–
RS	0.00	0.31	-0.63–0.63	0.999	19.28
Age (years)	0.32	0.15	0.02–0.62	0.037	3.87
Sex (male = 1)	1.00	0.47	0.02–1.97	0.045	2.60
TS	0.87	0.33	0.17–1.57	0.017	21.70

Standard errors calculated using the robust method (HC3). Model statistics: adjusted $R^2 = 0.280$; F (global) = 3.27; p = 0.031; n = 30 patients. RS: Rotterdam score; TS: trauma severity; VIF: variance inflation factor.

Table 5. Multiple linear regression model for right LI excluding the TS variable

Independent variable	β	Standard error	95% CI	p	VIF
Intercept	0.66	0.41	-0.20–1.52	0.127	–
RS	0.52	0.25	0.01–1.02	0.045	3.20
Age (years)	0.30	0.14	0.02–0.59	0.039	2.91
Sex (male = 1)	0.86	0.40	0.03–1.69	0.043	1.88

Standard errors calculated using the robust method (HC3). Model statistics: adjusted $R^2 = 0.312$; F (global) = 3.86; p = 0.019; n = 30 patients. RS: Rotterdam score; VIF: variance inflation factor.

Table 6. Multiple linear regression model for right LI excluding the RS variable

Independent variable	β	Standard error	95% CI	p	VIF
Intercept	0.70	0.38	-0.08–1.49	0.076	–
TS	0.84	0.30	0.22–1.48	0.012	2.65
Age (years)	0.29	0.14	0.00–0.58	0.048	2.72
Sex (male = 1)	0.89	0.41	0.02–1.76	0.047	1.95

Standard errors calculated using the robust method (HC3). Model statistics: adjusted $R^2 = 0.326$; F (global) = 3.98; p = 0.017; n = 30 patients. TS: trauma severity; VIF: variance inflation factor.

DISCUSSION

In this study, the association between TCD parameters and the degree of structural brain injury assessed using the RS was examined. The results demonstrated a significant correlation between the right LI and the RS. Likewise, the right LI was the TCD parameter most strongly associated with TS according to the Kruskal–Wallis analysis. In multivariate analyses adjusted for age and sex, both the RS and TS emerged as independent predictors of the right LI. These findings support the usefulness of integrating cerebral hemodynamic measurements with imaging scales to optimize therapeutic decision-making and prognosis assessment in pediatric TBI.

Several previous studies have highlighted TCD as a valuable noninvasive tool for monitoring cerebral blood flow, detecting vasospasm, and assessing cerebrovascular autoregulation in pediatric TBI (24–26). In particular, flow-derived indices, such as the velocities of the MCA and ICA, have been described as potential markers of disease severity and clinical outcomes. Moreover, the ratio of the mean MCA velocity to the mean ICA velocity, known as the LI, has been shown to differentiate hyperemia from vasospasm in patients with brain injury (27). Similar findings were reported in a prospective study conducted by O'Brien NF et al. (28), who identified a substantial proportion of pediatric patients developing vasospasm during the course of TBI based on TCD parameters such as MCA velocities and the LI. In another study by the same group (12), the authors demonstrated that an MCA PI > 1.3 was associated with elevated intracranial pressure, showing high sensitivity and specificity within the first 24 hours following brain injury.

The finding obtained in the present study, in which the right LI is significantly associated with the RS, consolidates this line of evidence (29) and adds an important dimension: the integration of anatomical-structural assessment derived from radiological imaging with cerebral hemodynamics in pediatric patients. In this context, the right LI demonstrated greater predictive clinical value regarding structural brain injury, showing a closer correlation with radiological severity scales such as the RS. Similar observations were described by van Santbrink et al. (30), who reported that in patients with TBI evaluated using neuroimaging and TCD, a decrease in mean cerebral blood flow velocity combined with simultaneous increases in LI and PI within the first 8 hours after trauma was associated with areas of greater cerebral compromise corresponding to ischemia.

The association observed with the right LI represents a distinctive finding of the present study, whose pathophysiological explanation warrants further investigation.

In the multivariate analysis, the right LI was selected as the dependent variable because it represented the most physiologically dynamic marker and demonstrated the strongest statistical correlation with the RS. Furthermore, this selection avoided redundancy and the potential loss of statistical power that would result from analyzing multiple Doppler parameters separately. When comparing multivariate models, we observed that excluding the RS and TS simultaneously due to their high collinearity (Model 1: using RS vs Model 2: using TS) resulted in improved model fit (adjusted R2: 0.312–0.326) and acceptable VIF values (< 5). These findings suggest that in studies on pediatric TBI, including multiple indicators of severity simultaneously, may overburden the model and reduce its precision. Therefore, parsimonious models, such as those proposed in this study, may be preferable. Finally, another noteworthy finding was the association of age and male sex with the LI, reinforcing their roles as potential physiological modifiers of cerebral blood flow related to vascular maturation.

The clinical relevance of this study lies in the complementary use of two assessment tools in the management of pediatric patients with TBI in the intensive care unit. The RS may serve as an early anatomical marker of injury, whereas the LI obtained through TCD may act as a dynamic indicator of cerebral hemodynamic disturbance. In this context, a patient presenting with elevated RS and LI values could benefit from intensified monitoring and targeted therapeutic strategies aimed at optimizing cerebral perfusion.

However, several limitations should be considered when interpreting the findings of this study. First, the sample size (n = 30) reflects the exploratory nature of the study and the restrictive clinical and technical criteria used for cohort selection. The cohort consisted of pediatric patients with TBI who simultaneously had CT scans suitable for RS evaluation and complete TCD measurements. This specific clinical profile naturally limits the number of available cases, a common situation in studies evaluating TCD in pediatric TBI. Second, TCD parameter measurements were obtained at a single time point rather than longitudinally, preventing evaluation of their temporal evolution or response to therapeutic interventions. Previous multicenter studies with longitudinal follow-up have described the association between LI and the incidence of vasospasm in pediatric TBI (28,31). Third, only the right LI showed a significant correlation with RS. This finding may be explained by cerebral hemodynamic asymmetry following trauma, in which blood flow alterations preferentially occur in the hemisphere ipsilateral to the structural lesion or dominant edema. Previous studies (12,24,32) have described this lateral variability in MCA blood flow. Fourth, collinearity between RS and TS was observed when both variables were included simultaneously in the regression model, a phenomenon previously reported in studies incorporating multiple severity and radiological indices (20). Fifth, the cohort did not include patients with mild TBI. This situation reflects clinical practice rather than selection bias, as TCD is predominantly used in patients with moderate to severe TBI. In contrast, mild cases typically present with normal tomographic and hemodynamic findings. Consequently, the results of this study are primarily applicable to pediatric patients with moderate and severe TBI, limiting their extrapolation to the full spectrum of pediatric TBI.

CONCLUSION

In this cohort of pediatric patients with TBI, TCD parameters showed a significant correlation with the RS, highlighting the emergence of the right LI as the hemodynamic marker most strongly associated with the structural severity of brain injury observed on CT. In addition, the right LI was the parameter with the most statistically significant association with TS. In multivariate models adjusted for age and sex, both RS and TS were significantly associated with the right LI. These findings support the value of TCD as a complementary, noninvasive tool in the hemodynamic and prognostic assessment of pediatric TBI.

Future studies should aim to replicate these findings in larger, multicenter pediatric cohorts, incorporate serial TCD measurements to assess the temporal evolution of the LI and its association with medium-term neurological outcomes, and establish optimal LI cutoff values specific to the pediatric population.

Author contributions

Boris Borja Zapata: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Review and editing.

Verónica Alaña Peña: Investigation, Validation, Visualization, Review.

Diana Chávez Ruiz: Investigation, Validation, Visualization, Review.

Georgette Borja Urbano: Investigation, Validation, Visualization, Review.

Conflicts of interest

The authors declare no relevant financial or non-financial conflicts of interest.

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Data availability

The authors declare that the data supporting the results of this research, including databases and/or analysis files, can be obtained upon request from the corresponding author.

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