Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Helmet type predicts outcomes following road traffic-related traumatic brain injury: A cohort study from regional Colombia

Marlon E Tafur
marlon.tafur@utp.edu.co
Technological University of Pereira
Laura M Loaiza
Technological University of Pereira
Jhon A Alvarez
Technological University of Pereira
Jacobo Pulido
Technological University of Pereira
Diana V Cardona
Technological University of Pereira
Federico Loaiza
Technological University of Pereira
Oscar F Suarez
Technological University of Pereira
Adriana M Paez
Technological University of Pereira
Victor M. Lu
University of Miami

Research Article

Keywords: traumatic brain injury, helmet, fracture, Latin America, Colombia

Posted Date: August 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10049854/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background

Helmets reduce head injury in road traffic accidents, but the differential protective effect of helmet type remains poorly characterized, particularly in low- and middle-income countries. We evaluated how increasing cranial protection by helmet type affects outcomes following traffic-related traumatic brain injury (TBI) in regional Colombia.

Methods

Prospective observational cohort study of 211 patients with TBI from road traffic accidents admitted to Hospital Universitario San Jorge de Pereira (Risaralda, Colombia). Helmet exposure was characterized as binary (use vs. no use), categorical (no helmet, open-face, half, full-face), and ordinal (0–3). Outcomes were modeled using logistic regression adjusting for age, sex, substance use, polytrauma, and vehicle type.

Results

Median age was 30 years (IQR 22–42), 84.4% were male, and 138 (65.4%) wore helmets: 23 open-face, 35 half, and 80 full-face. A clear dose-response gradient was observed for in-hospital mortality (16.4%, 4.4%, 5.7%, 1.3%; adjusted odds ratio [aOR] per level 0.43, p = 0.002), facial fracture (35.6%, 39.1%, 31.4%, 13.8%; aOR per level 0.67, p = 0.003), composite cranial-or-facial fracture (aOR per level 0.74, p = 0.013), and unfavorable functional outcome at 6 months (aOR per level 0.61, p = 0.010). Full-face helmet conferred the greatest specific protection against facial fracture (aOR 0.28, p = 0.001). In contrast, no dose-response was observed for any intracranial lesion on CT (aOR per level 0.92, p = 0.52).

Conclusions

Helmets provide graded, dose-response protection against mortality, skeletal craniofacial injury, and 6-month functional outcome, with the strongest protection conferred by full-face helmets. These findings support public health policies favoring full-face helmets and underscore the inadequacy of partial-coverage designs.

Introduction

Traumatic brain injury (TBI) is a critical global challenge, affecting over 20 million people in 2021 [1], with road traffic incidents serving as the primary cause of TBI-related mortality [2]. Road traffic injuries are the leading cause of death among children and young adults worldwide, and remain a major global health challenge, with an estimated 1.19 million deaths in 2021. Notably, nine in ten deaths occur in low and middle-income countries (LMICs), which account for only 50% of the world's registered vehicles, reflecting a disproportionate burden in LMIC settings [3].

Helmets have been associated with reductions in both the occurrence and severity of TBI across a range of activities, including motorcycling, bicycling, and recreational sports [4–7], and have similarly been associated with lower TBI-related mortality[8] and functional outcomes at discharge [9, 10]. The mechanical function of a helmet is direct skeletal protection through impact attenuation: the outer shell distributes force, and the inner liner absorbs and dissipates kinetic energy [10].

However, there are many different helmet types that have not been explored in the setting of TBI prevention. A protection gradient derived from anatomical coverage, ranging from cranial vault coverage in open face helmets to complete maxillofacial coverage in full-face designs has been theorized [5] and consequently, this dose-response relationship would be most evident in outcomes dependent on cumulative mechanical trauma, such as overall mortality. However, prior work has been limited to often binary comparisons (helmet vs no helmet or full-face vs. half-face) [8, 9], missing the mechanistic gradient between no helmet, open-face, half, and full-face designs that differ in anatomical coverage[5].

Furthermore, evidence of TBI protection from helmets in LMIC settings such as our primary institution in regional Colombia, where helmet quality, enforcement, and clinical pathways differ from high-income countries, remains scarce [9, 11]. In this study, we prospectively tested these predictions using a cohort of 211 patients with road traffic-related TBI admitted to a regional teaching hospital in Risaralda, Colombia. We characterized helmet exposure as binary, categorical (four protection levels), and ordinal (continuous gradation), and examined dose-response associations with skeletal, clinical, and radiological outcomes.

Methods

Study design and cohort

This was a prospective cohort study of patients with TBI from road traffic accidents admitted to Hospital Universitario San Jorge (HUSJ) in Pereira, Risaralda, Colombia, between July 2024 and January 2025. HUSJ is a regional referral center serving the central western Colombian coffee region (estimated population 972.000)[12]. Eligible patients were individuals ≥ 16 years of age with clinically defined TBI, confirmed by head computed-tomography (CT) when indicated. Patients were excluded if helmet status or accident mechanism could not be reliably established from interviews or medical records.

Data collection

Data were collected prospectively at admission through a structured interview with the patient or a family member, complemented by review of the electronic medical record throughout the hospital stay. Variables included demographics (age, sex), injury details (mechanism, vehicle type, helmet use and type), clinical status at admission (Glasgow Coma Scale, pupillary reactivity, polytrauma status, alcohol or substance use), radiological findings from admission head CT (cranial and facial fractures, cervical spine fractures, extra-axial and intra-axial hemorrhages, contusions, diffuse axonal injury, intraventricular hemorrhage), and hospital course (neurosurgical intervention, intensive care admission, discharge status). Functional outcomes were assessed at six months post-injury via structured telephone follow-up, during which the Glasgow Outcome Scale-Extended (GOSE) was administered to the patient or a primary caregiver.

Helmet type and covariates.

We categorized helmet use and type based on the World Health Organization (WHO) 2023 road safety manual: binary, helmet (yes/no); categorical: no helmet (reference), open-face, half-coverage, and full-face. Open-face helmets cover the cranium with no chin or face protection; half-coverage helmets cover cranium and partial frontal/lateral face; full-face helmets cover cranium, face, and chin via integrated chin guard and visor (1) [Figure 1]. Covariates identified a priori were age (16–19, 20–39 [reference], 40–59, ≥ 60 years), sex, substance use at injury (alcohol or illicit drugs), polytrauma status, and vehicle type (motorcycle vs. bicycle). Glasgow Coma Scale at admission was excluded from primary models as a potential mediator of helmet protection.

Figure 1. **Helmet Classification by cranial and facial coverage.** Helmets were classified by cranial and facial coverage based on the classification used by the WHO in the 2023 road safety helmet manual: No helmet; Half-coverage helmet; Open-face helmet; Full-face helmet. Cranial and facial coverage levels were used to generate an ordinal scale (0 to 3, respectively) of increasing protection. This ordinal level is used as the exposure variable in subsequent dose-response analyses.

Statistical analysis

The primary outcome was composite cranial-or-facial fracture, defined as any cranial vault and/or facial bone fracture confirmed on admission CT. Secondary outcomes included cranial fracture alone and facial fracture alone, analyzed separately to test differential helmet-type protection by anatomical site; moderate-to-severe TBI (admission GCS ≤ 12); in-hospital mortality; and unfavorable functional outcome at 6 months, defined as GOS-E 1–4 versus 5–8, with in-hospital deaths assigned a GOS-E of 1. Any intracranial lesion on CT was an exploratory outcome.

Continuous variables were summarized as median (IQR) and compared using the Mann-Whitney U test; categorical variables using Pearson chi-square or Fisher exact test. The Cochran-Armitage trend test assessed crude trends across protection categories. Multivariable analyses used Firth-penalized logistic regression to address separation and small-sample bias. For each outcome we estimated three models: helmet use as binary; helmet type as four-level categorical (reference: no helmet); and protection level as an ordinal continuous variable yielding a single odds ratio per one-step increase, our principal dose-response test. All adjusted models included age category, sex, substance use, polytrauma, and vehicle type.

Three patients (1.4%) did not undergo admission head CT and were excluded from imaging-based analyses but retained for analyses not requiring imaging; their distribution across helmet use ($p = 0.96$), helmet type ($p = 0.68$), GCS severity ($p = 1.00$), and mortality ($p = 1.00$) did not differ from imaged patients. Events-per-variable was assessed to ensure model stability (target ≥ 10 events per predictor); for mortality, given 16 events, a reduced model adjusted for age, substance use, and polytrauma was used. For the 6-month GOS-E outcome, complete-case analysis was used (follow-up available for 165 of 211 patients, 78.2%). All analyses were performed in Stata 18 (StataCorp, College Station, TX). Two-sided $p < 0.05$ was considered significant. Following dose-response convention, no multiple-comparison correction was applied; consistency of effect direction and gradient across related outcomes was used to evaluate robustness.

Results

Cohort characteristics

A total of 211 patients met all selection criteria. The cohort was predominantly male (84.4%, n = 178) with median age 30 years (IQR 22–42); 91.9% (n = 194) were involved in motorcycle accidents and 8.1% (n = 17) in bicycle accidents. Helmet use at the time of injury was documented in 138 patients (65.4%): 23 wore open-face (10.9%), 35 wore half (16.6%), and 80 wore full-face helmets (37.9%). Polytrauma was present in 74.9% of patients.

Compared with helmeted patients, unhelmeted patients were younger (median 26 vs. 31.5 years), more likely to be 16–19 years old (24.7% vs. 8.7%, $p = 0.014$), more likely to have used illicit substances at injury (20.6% vs. 6.5%), and presented with worse neurological status (GCS 3–8: 23.3% vs. 14.5%; abnormal pupillary reactivity: 16.4% vs. 5.1 [Table 1] [Figure 2].

Table 1. Demographic and clinical characteristics of TBI patients stratified by helmet use and type of helmet.

Characteristic	Cohort (*N* = 211)	No Helmet (*N* = 73)	Open Face Helmet (*N* = 23)	Half Coverage Helmet (*N* = 35)	Full Face Helmet (*N* = 80)
Demographics					
Age (years), median (IQR)	30 (22-42)	26 (20–38)	26 (23-43)	36 (25-54)	31 (24-38.5)
Female n(%)	33 (15.6%)	9 (12.3%)	3 (13.0%)	6 (17.1%)	15 (18.8%)
Male sex, n (%)	178 (84.4%)	64 (87.7%)	20 (87.0%)	29 (82.9%)	65 (81.3%)
Age Category, n (%)					
16–19 years	30 (14.2%)	18 (24.7%)	4 (17.4%)	3 (8.6%)	5 (6.3%)
20–39 years	124 (58.8%)	38 (52.1%)	10 (43.5%)	17 (48.6%)	59 (73.8%)
40–59 years	38 (18.0%)	10 (13.7%)	8 (34.8%)	9 (25.7%)	11 (13.8%)
≥60 years	19 (9.0%)	7 (9.6%)	1 (4.4%)	6 (17.1%)	5 (6.3%)
Accident Profile					
Vehicle type: Motorcycle, n (%)	194 (91.9%)	60 (82.2%)	21 (91.3%)	34 (97.1%)	79 (98.8%)
Vehicle type: Bicycle, n (%)	17 (8.1%)	13 (17.8%)	2 (8.7%)	1 (2.9%)	1 (1.2%)
Alcohol use at admission, n (%)	57 (27.0%)	21 (28.8%)	7 (30.4%)	9 (25.7%)	20 (25.0%)
Illicit drug use, n (%)	24 (11.4%)	15 (20.6%)	2 (8.7%)	0	7 (8.8%)
Associated polytrauma, n (%)	158 (74.9%)	57 (78.1%)	15 (65.2%)	25 (71.4%)	61 (76.3%)
Initial Severity and Injuries					
Initial GCS Severity, n (%)					
Mild (13–15)	156 (73.9%)	46 (63.0%)	19 (82.6%)	28 (80.0%)	63 (78.8%)
Moderate (9–12)	18 (8.5%)	10 (13.7%)	1 (4.4%)	4 (11.4%)	3 (3.8%)
Severe (3–8)	37 (17.5%)	17 (23.3%)	3 (13.0%)	3 (8.6%)	14 (17.5%)
Abnormal pupillary reactivity*, n (%)	19 (9.0%)	12 (16.4%)	1 (4.4%)	1 (2.9%)	5 (6.3%)
Intra cranial Lesions on CT					
Patients with CT	208 (98.6%)	72 (98.6%)	23 (100%)	35 (100%)	78 (97.5%)
Patients with at least one lesion on CT, n (%)	62 (29.4%)	25 (34.2%)	8 (34.8%)	9 (25.7%)	20 (25.0%)
Epidural Hematoma, n (%)	16 (7.6%)	8 (11.0%)	1 (4.4%)	2 (5.7%)	5 (6.3%)
Subdural Hematoma, n (%)	18 (8.5%)	9 (12.3%)	1 (4.4%)	1 (2.9%)	7 (8.8%)
Subarachnoid Hemorrhage, n(%)	34 (16.1%)	12 (16.4%)	4 (17.4%)	5 (14.3%)	13 (16.3%)
Contusions, n(%)	40 (19%)	19 (26.0%)	5 (21.7%)	6 (17.1%)	10 (12.5%)
Intracerebral Hemorrhage, n (%)	6 (2.8%)	1 (1.4%)	2 (8.7%)	1 (2.9%)	2 (2.5%)
Intraventricular Hemorrhage, n (%)	5 (2.4%)	1 (1.4%)	0 (0%)	2 (5.7%)	2 (2.5%)
Collapsed Basal Cisterns, n (%)	9 (4.3%)	3 (4.1%)	0 (0%)	1 (2.9%)	5 (6.3%)
Midline Shift >5 mm, n (%)	8 (3.8%)	3 (4.1%)	0 (0%)	1 (2.9%)	4 (5.0%)
Bone fractures					
Skull Fracture, n (%)	32 (15.2%)	16 (21.9%)	5 (21.7%)	1 (2.9%)	10 (12.5%)
Facial Fracture, n(%)	57 (27.0%)	26 (35.6%)	9 (39.1%)	11 (31.4%)	11 (13.8%)
Cervical Fracture, n(%)	10 (4.7%)	3 (4.1%)	2 (8.7%)	0	5 (6.3%)
Outcomes					
ICU admission	67 (31.8%)	26 (35.6%)	6 (26.1%)	10 (28.6%)	25 (31.3%)
Need of Neurosurgical Intervention	6 (2.8%)	2 (2.7%)	0 (0%)	1 (2.9%)	3 (3.8%)
In-Hospital Mortality	16 (7.6%)	12 (16.4%)	1 (4.4%)	2 (5.7%)	1 (1.2%)

Unfavorable GOS-E at six months	25 (11.8%)	13 (17.8%)	2 (8.7%)	3 (8.6%)	7 (8.8%)

Figure 2. **Characterization of helmet types in a cohort of 211 TBI patients.** Data collected at the Hospital Universitario San Jorge (Pereira, Colombia) shows that while full-face helmets were the most frequent (37.9%), a significant portion of the population (34.6%) was unhelmeted at the time of the trauma. The "Cranial protection level" axis reflects an ordinal scale of increasing protective surface area. TBI: Traumatic Brain Injury.

Helmet use and primary outcome: composite cranial-or-facial fracture

The crude prevalence of cranial-or-facial fracture decreased from 47.2% in unhelmeted patients to 30.9% in helmeted patients (crude OR 0.50, 95% CI 0.27–0.94, p = 0.020). After adjustment for age category, sex, substance use, polytrauma, and vehicle type, helmet use was associated with a non-significant reduction (adjusted OR 0.58, 95% CI 0.30–1.10, p = 0.10) [Tables 2, 3].

Table 2. Adjusted multivariable model for the primary outcome (composite cranial-or-facial fracture): Firth-penalized logistic regression with helmet use

Variable	Odds Ratio	Std. Error	z	p-value	95% CI (Lower –
Helmet use (yes vs no)	**0.58**	0.192	−1.64	0.101	0.31 – 1.11
Age category (Ref: 20–39)					
16–19 years	1.75	0.765	1.27	0.203	0.74 – 4.12
40–59 years	0.98	0.402	−0.04	0.966	0.44 – 2.19
≥60 years	1.48	0.826	0.70	0.484	0.49 – 4.42
Sex (Female)	0.43	0.209	−1.73	0.083	0.17 – 1.12
Substance use at injury	1.57	0.510	1.38	0.169	0.83 – 2.96
Polytrauma	2.06	0.751	1.99	0.047*	1.01 – 4.21
Vehicle (Bicycle)	0.63	0.372	−0.78	0.434	0.20 – 2.00
Constant	0.42	0.196	−1.86	0.063	0.17 – 1.05

Abbreviations: CI, confidence interval; Ref, reference category.

Notes: *p<0.05. Reference categories: no helmet for helmet use; 20–39 years for age; male for sex; motorcycle for vehicle type. Three patients without admi (n=208 of 211). Wald $\chi^2(8) = 15.97$, p=0.043.

Table 3. Binary Helmet effect across all outcomes

Clinical Outcome	n	Adjusted Odds Ratio (95% CI)	p-value
Survival and Function			
In-hospital Mortality	211	0.145 (0.045 – 0.463)	0.001
Unfavorable Outcome (6 months)	165	0.240 (0.088 – 0.655)	0.005
Neurological and Structural Injury			
Mod-to-Severe TBI (GCS <12)	211	0.465 (0.231 – 0.935)	0.032
Any Intracranial Lesion (CT)	208	0.854 (0.434 – 1.677)	0.646
Craniofacial Fractures			
Facial Fracture	211	0.525 (0.266 – 1.036)	0.063
Cranial Fracture (Alone)	208	0.545 (0.241 – 1.231)	0.144
Composite Craniofacial Fracture	208	0.585 (0.307 – 1.111)	0.101

Table 3. Association between binary helmet use and clinical outcomes. Data are presented as adjusted Odds Ratios (aOR) with 95% confidence intervals (CI). All models were conducted using Firth-penalized logistic regression to account for sparse data and ensure stable estimates. Adjustments: The mortality model was adjusted for age, substance use, and polytrauma. All other clinical outcomes were adjusted for age, sex, substance use, polytrauma, and vehicle type. An aOR < 1.0 indicates a protective effect associated with helmet use. Bold values signify statistical significance ($p < 0.05$). TBI: Traumatic Brain Injury; GCS: Glasgow Coma Scale; CT: Computed Tomography.

When helmet was modeled by type, only full-face helmet showed significant protection compared with no helmet (adjusted OR 0.41, 95% CI 0.19–0.86, p = 0.019). The dose-response model treating protection level as ordinal demonstrated a graded reduction of 26% in odds per one-step increase in protection (adjusted OR 0.74, 95% CI 0.58–0.94, p = 0.013). [Table 4]

Table 4
Adjusted dose-response model for the primary outcome (composite cranial-or-facial fracture): Firth-penalized logistic regression with protection level as an ordinal exposure (n = 208).

Variable	Odds Ratio	Std. Error	z	p-value	95% CI (Lower – Upper)
Protection level (ordinal, 0–3)	**0.74**	0.091	−2.48	**0.013***	0.58–0.94
Age category (Ref: 20–39)					
16–19 years	1.55	0.686	0.98	0.326	0.65–3.69
40–59 years	0.91	0.376	−0.22	0.826	0.41–2.05
≥60 years	1.42	0.804	0.62	0.533	0.47–4.31
Sex (Female)	0.42	0.208	−1.75	0.080	0.16–1.11
Substance use at injury	1.52	0.500	1.29	0.199	0.80–2.90
Polytrauma	2.11	0.773	2.04	**0.042***	1.03–4.33
Vehicle (Bicycle)	0.56	0.331	−0.98	0.329	0.18–1.78
Constant	0.49	0.222	−1.57	0.116	0.20–1.19

Abbreviations: CI, confidence interval; Ref, reference category. **Notes**: *p < 0.05. Reference categories: no helmet for protection level (entered as ordinal continuous, 0 = no helmet, 1 = open-face, 2 = half, 3 = full-face); 20–39 years for age; male for sex; motorcycle for vehicle type. Each one-step increase in protection level corresponds to a 26% reduction in the adjusted odds of composite cranial-or-facial fracture. N = 208; 3 patients excluded due to absence of admission head CT.

Differential helmet-type protection by anatomical site

The mechanical prediction of differential helmet-type protection by anatomical site was supported by the data. For cranial vault fracture, all helmet types showed numerically protective effects without a clear graded pattern (open-face: 21.7%; half: 2.9%; full-face: 12.8%; adjusted OR per level 0.79, 95% CI 0.57–1.08, p = 0.13). In contrast, facial fracture showed a clear dose-response: 35.6% (no helmet), 39.1% (open-face), 31.4% (half), and 13.8% (full-face) (Fisher p = 0.005; adjusted OR per level 0.67, 95% CI 0.51–0.87, p = 0.003). The full-face helmet specifically conferred a 72% reduction in odds of facial fracture compared with all other categories combined (adjusted OR 0.28, 95% CI 0.13–0.59, p = 0.001). **[**Figure 3**]**

Figure 3. **Helmet-type protection differs by anatomical site. (**A) Facial fracture prevalence shows a graded dose-response across protection levels (adjusted OR per level 0.67, 95% CI 0.51–0.87, p = 0.003). (B) Cranial fracture shows no gradient (adjusted OR per level 0.79, 95% CI 0.57–1.08, p = 0.13). Denominators shown beneath each bar. Models adjusted for age, sex, substance use, polytrauma, and vehicle type using Firth-penalized logistic regression. Cranial fracture analysis n = 208 (3 patients without head CT excluded).

Clinical correlate: moderate-to-severe TBI

Helmet use was associated with lower odds of moderate-to-severe TBI on admission in the binary helmet/no helmet model (adjusted OR 0.47, 95% CI 0.23–0.94, p = 0.032) [Table 3]. The ordinal dose-response model showed a directionally consistent but weaker effect (adjusted OR per level 0.80, 95% CI 0.62–1.04, p = 0.093), suggesting that the effect on neurological severity operates principally through helmet use itself rather than through type-specific protection. Polytrauma was the strongest concurrent predictor of moderate-to-severe TBI (adjusted OR 3.56, 95% CI 1.45–8.73, p = 0.005).

In-hospital mortality

In-hospital mortality declined steeply across protection levels: 16.4% (12/73) in unhelmeted patients, 4.4% (1/23) in open-face, 5.7% (2/35) in half, and 1.3% (1/80) in full-face helmet wearers (Cochran-Armitage trend test z=-3.45, p = 0.0006; test of departure from linear trend p = 0.50). In the adjusted dose-response model (reduced for low event rate), each one-step increase in protection level was associated with a 57% reduction in odds of in-hospital mortality (adjusted OR per level 0.43, 95% CI 0.26–0.73, p = 0.002). The full-face helmet, compared with no helmet, conferred a 91% reduction in odds of mortality in unadjusted analysis (OR 0.09, 95% CI 0.02–0.52, p = 0.007). [Figure 4]

Figure 4. **Dose-response relationship between cranial protection level and in-hospital mortality.** Bar heights represent the mortality rate (%) within each category of helmet protection, with absolute mortality ratios (deaths/n) displayed on the x-axis. A significant downward trend in mortality is observed as the level of structural coverage increases (p = 0.0006, Cochran-Armitage trend test; test of departure from linear trend, p = 0.50). In the adjusted dose-response model, each one-step increase in protection level (from no helmet through to full-face) was associated with a 57% reduction in the odds of in-hospital mortality (aOR per level 0.43; 95% CI 0.26–0.73; p = 0.002). Notably, the use of a full-face helmet conferred a 91% reduction in the odds of mortality compared to being unhelmeted (OR 0.09; 95% CI 0.02–0.52; p = 0.007). aOR: adjusted Odds Ratio; CI: Confidence Interval; n: number of patients; OR: Odds Ratio; TBI: Traumatic Brain Injury.

Functional outcome at 6 months

Six-month GOS-E follow-up was completed in 165 of 211 patients (78.2%). Baseline characteristics did not differ between followed and lost-to-follow-up patients, except for higher substance use among those lost to follow-up (47.8% vs 29.1%, p = 0.021). All 16 in-hospital deaths were captured as GOS-E = 1;

attrition was confined to discharged survivors.

Unfavorable functional outcome (GOS-E 1–4) occurred in 25 of 165 followed patients (15.2%): 16 in-hospital deaths and 9 survivors with severe disability. After adjustment for age, sex, substance use, polytrauma, and vehicle type, helmet use was associated with reduced odds of unfavorable functional outcome (adjusted OR 0.24, 95% CI 0.09–0.65, p = 0.005) [Table 3]. The dose-response model showed a 39% reduction in odds per one-step increase in protection level (adjusted OR 0.61, 95% CI 0.42–0.89, p = 0.010). Full-face helmet conferred the strongest protective association compared with no helmet (adjusted OR 0.23, 95% CI 0.08–0.70, p = 0.010), with non-significant estimates for open-face (aOR 0.38, 95% CI 0.08–1.81) and half helmet (aOR 0.24, 95% CI 0.05–1.18). Figure 5 illustrates the dose-response relationship across clinical outcomes.

Figure 5. **Dose-response relationship between cranial protection levels and clinical outcomes.** The forest plot displays adjusted Odds Ratios (aOR) and 95% confidence intervals (CI) for each one-step increase in the protection scale (No helmet; Open-face; Half-face; Full-face). Analyses were performed using Firth-penalized logistic regression to ensure robust estimates. Models were adjusted for age, sex, toxicology, polytrauma, and vehicle type. Black markers represent statistically significant findings ($p < 0.05$), while gray markers indicate non-significant trends. An aOR < 1.0 indicates a reduction in the odds of the outcome as helmet protection increases. TBI: Traumatic Brain Injury; GCS: Glasgow Coma Scale; CT: Computed Tomography.

Discussion

In this single-center prospective cohort of 211 patients with road traffic-related TBI in regional Colombia, increasing cranial protection produced a clear dose-response gradient across skeletal craniofacial injury, neurological severity, in-hospital mortality, and unfavorable 6-month functional outcome. This gradient was absent for intracranial parenchymal lesions, supporting a mechanistic interpretation in which helmet protection operates through bony envelope attenuation, while parenchymal injury depends on acceleration-deceleration forces inadequately neutralized by current designs [13, 14]. These findings extend prior literature by quantifying the type-specific gradient in an LMIC setting [2, 15].

The differential protection observed for cranial versus facial fractures supports the anatomical specificity hypothesis. Cranial vault fractures were reduced without a graded pattern across types, consistent with all designs providing some cranial coverage [13, 15].

Facial fractures, by contrast, showed a clear dose-response with strongest protection from full-face helmets (adjusted OR 0.28, 95% CI 0.13–0.59, p = 0.001 against all other categories combined), attributable to the chin guard and visor unique to this design[16]. This aligns with Urrechaga et al. (> 37,000 subjects), who reported similar facial fracture reduction (OR 0.26) with full-face designs[17] and reinforces this position in a Latin American setting where partial-coverage designs remain prevalent for climate-related comfort [11, 13].

The steep mortality gradient was the most clinically dramatic finding, declining from 16.4% in unhelmeted patients to 1.3% in full-face wearers (aOR per level 0.43, 95% CI 0.26–0.73, p = 0.002), exceeding prior meta-analyses that estimated 42% mortality reduction with binary helmet exposure[18] and and 57% reduction in head and neck injuries with full-face designs [16].

The parallel reduction in 6-month unfavorable outcome (aOR per level 0.61, 95% CI 0.42–0.89, p = 0.010) is consistent, given that in-hospital deaths constitute the worst GOS-E category. The larger-than-expected effect may reflect severe primary injuries among unhelmeted riders in LMIC settings with limited prehospital capacity [2, 9], and type-specific protection components (chin coverage, full visor) that binary models cannot resolve [5, 8, 9]. Both strengthen the rationale for promoting full-face helmets specifically in Latin American countries, where motorcycle taxis and commercial fleets don't comply certification standards [3, 11].

The absence of dose-response for parenchymal outcomes was expected. Acute parenchymal injury depends on rotational acceleration, brain stem strain, and vascular tearing, mechanisms operating independently of the linear impact attenuation helmets provide. Empirical testing shows linear and rotational risks are not strongly correlated; rotational-management technologies reduce rotational kinematics (PRA, PRV, BrIC) without corresponding reductions in peak linear acceleration. Because standard helmets are optimized for linear thresholds preventing skull fracture, they may fail to neutralize the rotational forces driving intracranial injury [14, 15, 19]. Our findings converge with Ryalino et al., who in the BRAIN-PROTECT cohort (n = 499) demonstrated helmet-associated reductions in epidural mass lesion (OR 0.25) and skull fracture (OR 0.37), but no association with intraventricular hemorrhage, basal cistern compression, or midline shift after correction [8]. Both studies converge on the same principle: helmets attenuate linear contact forces producing skeletal injury but do not reduce diffuse parenchymal injury following rotational kinematics [19–21].

Our study advances prior work in three directions. First, compared with the largest helmet-type-stratified cohort to date (Seo et al., n = 1,910), we used radiologically confirmed outcomes rather than AIS-based composites, enabling differentiation between skeletal and parenchymal pathways [5]. Second, the LMIC focus complements the predominantly high-income evidence base [4, 5, 7], addressing the disproportionate global TBI burden found in these settings [3, 13, 15]; compared with Gupta et al. (n = 491, binary exposure only), our four-level model shows that binary contrasts miss clinically relevant differences between partial- and full-coverage designs [9]. Third, our 6-month functional follow-up addresses a known gap in helmet effectiveness research [8].

Strengths include detailed radiological characterization allowing anatomical differentiation, complete helmet-type ascertainment, dose-response framework, Firth-penalized regression to mitigate small-sample bias, and 78.2% follow-up completeness. Limitations include a single hospital-based cohort that does not capture prehospital deaths, potentially biasing the mortality association if prehospital survival differs by helmet status; a sample size (n = 211) that limits precision, particularly for mortality (16 events); helmet type obtained from clinical and witness records, introducing possible non-differential misclassification; inclusion of 17 cyclists, whose exposure differs from motorcyclists[6] without sensitivity analyses; and unavailable confounders (speed, quantified blood alcohol, helmet age, certification standard) limiting attribution of the gradient to design-specific properties [8, 11]. Although the single-center design limits generalizability, HUSJ's regional referral pattern extends coverage beyond the metropolitan area.

These findings support three implications. First, public health messaging in LMICs should emphasize full-face helmets specifically; the WHO helmet manual notes their greater effectiveness against cranial and cervical injuries, and our data support this for Latin American contexts [13, 17]. Second, certification and import standards should prioritize chin and full-face coverage, particularly for commercial fleets with high exposure intensity. Third, helmet use does not eliminate parenchymal injury risk; surveillance, neurorehabilitation, and follow-up should not be reduced based on helmet use alone, converging with Ryalino et al.'s conclusion that helmeted riders with severe TBI warrant equal vigilance at initial assessment [8].

Conclusions

In this prospective cohort of 211 patients with road traffic-related TBI in regional Colombia, increasing cranial protection produced a clear dose-response gradient in mortality (57% reduction per level), facial fracture (33% per level), and composite craniofacial fracture (26% per level), with a 39% reduction per level in unfavorable 6-month functional outcome. Full-face helmets conferred specific protection against facial fracture not seen with partial-coverage designs. No dose-response was observed for parenchymal intracranial lesions, consistent with helmets operating through skeletal protection rather than direct prevention of brain injury. These findings, aligned with biomechanical evidence and recent prospective European data, support efforts to prioritize full-face helmet adoption.

Statement and declarations

Funding and Disclures: The authors received no funding for the conduct of this study or preparation of this manuscript. All authors declare no financial or personal conflicts of interest related to the content of this manuscript.

Acknowledgements: The authors thank the staff of the Emergency Department, Neurosurgery Service, Intensive Care Unit, and Medical Records Department at San Jorge University Hospital (Pereira, Colombia) for their support in patient identification and data collection. We are also grateful to the patients and their families for their participation and trust. We acknowledge the support of the Neurosurgery Research Group of the Technological University of Pereira for facilitating the conduct of this study.

The authors acknowledge the use of OpenAI's ChatGPT (OpenAI, San Francisco, CA, USA) to assist in the generation of the graphical illustration presented as Figure 1. The authors developed the original concept, provided the prompts and specifications, critically reviewed the generated content, and assume full responsibility for the accuracy, interpretation, and final presentation of the figure.

Authorship Confirmation and Author Contributions (CRediT): All authors meet the authorship criteria established by the International Committee of Medical Journal Editors (ICMJE). All authors contributed substantially to the work, revised the manuscript critically for important intellectual content, approved the final version to be published, and agree to be accountable for all aspects of the work.

CRediT Author Statement

Marlon E. Tafur: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Visualization; Writing original draft; Writing review & editing; Project administration.

Laura M. Loaiza: Investigation; Data curation; Validation; Writing review & editing.

Jhon A. Alvarez: Investigation; Data curation; Writing review & editing.

Jacobo Pulido: Investigation; Data curation; Writing review & editing.

Diana V. Cardona: Investigation; Data curation; Writing review & editing.

Federico Loaiza: Investigation; Data curation; Writing review & editing.

Oscar F. Suarez: Methodology; Supervision; Validation; Writing review & editing.

Adriana M. Paez: Methodology; Supervision; Validation; Writing review & editing.

Victor M. Lu: Conceptualization; Methodology; Supervision; Formal analysis; Writing review & editing.

All authors have read and approved the final manuscript.

Patient Follow-up Consent

Written informed consent was obtained from all participants aged 18 and older; for patients with GCS ≤8, consent was provided by legal representatives, while minors provided assent in the presence of a legal guardian.

Ethics and Approvals

The study protocol was approved by the Research Ethics Committee of the Technological University of Pereira (CEI-UTP; code: 21-040324) and the Institutional Ethics Committee of the E.S.E. San Jorge University Hospital of Pereira. Classified as "minimal risk research" under Colombian Ministry of Health Resolution 8430 of 1993, the study strictly adhered to the Declaration of Helsinki.

Clinical trial number

Not applicable.

Data Availability Statement

The datasets analyzed in this study are available from the corresponding author upon reasonable request, subject to institutional ethical guidelines and approval.

References

1. Global, regional, and national burden of traumatic brain injury and spinal cord injury, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet Neurol. 20181126th ed. 2019;18(1):56–87. doi:10.1016/s1474-4422(18)30415-0 PubMed PMID: 30497965.
2. Dewan MC, Rattani A, Gupta S, Baticulon RE, Hung YC, Punchak M, et al. Estimating the global incidence of traumatic brain injury. J Neurosurg. 20180427th ed. 2019;130(4):1080–97. doi:10.3171/2017.10.Jns17352 PubMed PMID: 29701556.
3. World Health Organization. Global status report on road safety 2023: summary [Internet]. Geneva: World Health Organization; 2023. Available from: https://www.who.int/publications/i/item/9789240086456
4. Bailly N, Laporte JD, Afquir S, Masson C, Donnadieu T, Delay JB, et al. Effect of Helmet Use on Traumatic Brain Injuries and Other Head Injuries in Alpine Sport. Wilderness Environ Med. 20180204th ed. 2018;29(2):151–8. doi:10.1016/j.wem.2017.11.007 PubMed PMID: 29397300.
5. Seo S, Yeom SR, Park SW, Wang IJ, Cho SJ, Yang WT, et al. Effect of use and type of helmet on occurrence of traumatic brain injuries in motorcycle riders in Korea: a retrospective cohort study. J Trauma Inj. 20221209th ed. 2023;36(2):87–97. doi:10.20408/jti.2022.0029 PubMed PMID: 39380699.
6. Næss I, Døving M, Galteland P, Skaga NO, Eken T, Helseth E, et al. Bicycle helmets are associated with fewer and less severe head injuries and fewer neurosurgical procedures. Acta Neurochir (Wien). 20241009th ed. 2024;166(1):398. doi:10.1007/s00701-024-06294-6 PubMed PMID: 39379615.
7. Troy BM, Fraser Doh K, Linden AF, Xiang Y, Gillespie S, Agarwal M. Changes in pediatric injuries sustained while engaged in activities where helmet usage is recommended during the COVID-19 pandemic. Inj Epidemiol. 20230801st ed. 2023;10(Suppl 1):38. doi:10.1186/s40621-023-00449-2 PubMed PMID: 37525250.
8. Ryalino C, van der Naalt J, Bossers SM, Bloemers FW, Den Hartog D, Van Lieshout EMM, et al. Helmet use in patients with severe traumatic brain injury: associations with Rotterdam CT score components, skull fractures, and cervical fractures. Brain Inj. 20251105th ed. 2026;40(2):107–16. doi:10.1080/02699052.2025.2585488 PubMed PMID: 41190725.
9. Gupta S, Klaric K, Sam N, Din V, Juschkewitz T, Iv V, et al. Impact of helmet use on traumatic brain injury from road traffic accidents in Cambodia. Traffic Inj Prev. 20170712th ed. 2018;19(1):66–70. doi:10.1080/15389588.2017.1342821 PubMed PMID: 28699848.
10. Wang F, Wu J, Hu L, Yu C, Wang B, Huang X, et al. Evaluation of the head protection effectiveness of cyclist helmets using full-scale computational biomechanics modelling of cycling accidents. J Safety Res. 20211201st ed. 2022;80:109–34. doi:10.1016/j.jsr.2021.11.005 PubMed PMID: 35249593.
11. Guzman LA, Ortiz AI V, Mesa VG, Camargo JP, Allen KA, Hyder AA. The relationships between correct helmet use, enforcement presence, and mortality in a Latin-America city: The case study of Bogotá, Colombia. Traffic Inj Prev. 20200821st ed. 2020;21(7):500–5. doi:10.1080/15389588.2020.1805737 PubMed PMID: 32822246.
12. Data Commons. Demographics of Pereira, Colombia [Internet]. Google Data Commons; 2026. Available from: https://datacommons.org/place/wikidataId/Q13993?category=Demographics&hl=es
13. World Health Organization. Helmets: a road safety manual for decision-makers and practitioners, second edition [Internet]. Organization WH, editor. Geneva: World Health Organization; 2023. Available from: https://www.who.int/publications/i/item/9789240069824
14. Baker CE, Martin P, Wilson MH, Ghajari M, Sharp DJ. The relationship between road traffic collision dynamics and traumatic brain injury pathology. Brain Commun. 20220212th ed. 2022;4(2):fcac033. doi:10.1093/braincomms/fcac033 PubMed PMID: 35291690.
15. Young L, Rule GT, Bocchieri RT, Walilko TJ, Burns JM, Ling G. When physics meets biology: low and high-velocity penetration, blunt impact, and blast injuries to the brain. Front Neurol. 20150507th ed. 2015;6:89. doi:10.3389/fneur.2015.00089 PubMed PMID: 25999910.
16. Tabary M, Ahmadi S, Amirzade-Iranaq MH, Shojaei M, Sohrabi Asl M, Ghodsi Z, et al. The effectiveness of different types of motorcycle helmets - A scoping review. Accid Anal Prev. 20210306th ed. 2021;154:106065. doi:10.1016/j.aap.2021.106065 PubMed PMID: 33689958.
17. Chaichan S, Asawalertsaeng T, Veerapongtongchai P, Chattakul P, Khamsai S, Pongkulkiat P, et al. Are full-face helmets the most effective in preventing head and neck injury in motorcycle accidents? A meta-analysis. Prev Med Rep. 20200513th ed. 2020;19:101118. doi:10.1016/j.pmedr.2020.101118 PubMed PMID: 32509508.
18. Urréchaga EM, Kodadek LM, Bugaev N, Bauman ZM, Shah KH, Abdel Aziz H, et al. Full-face motorcycle helmets to reduce injury and death: A systematic review, meta-analysis, and practice management guideline from the Eastern Association for the Surgery of Trauma. Am J Surg. 20220707th ed. 2022;224(5):1238–46. doi:10.1016/j.amjsurg.2022.06.018 PubMed PMID: 35821175.
19. Baker CE, Yu X, Lovell B, Tan R, Patel S, Ghajari M. How Well Do Popular Bicycle Helmets Protect from Different Types of Head Injury? Ann Biomed Eng. 20240919th ed. 2024;52(12):3326–64. doi:10.1007/s10439-024-03589-8 PubMed PMID: 39294466.
20. Abderezaei J, Rezayaraghi F, Kain B, Menichetti A, Kurt M. An Overview of the Effectiveness of Bicycle Helmet Designs in Impact Testing. Front Bioeng Biotechnol. 20210927th ed. 2021;9:718407. doi:10.3389/fbioe.2021.718407 PubMed PMID: 34646816.
21. Crompton JG, Bone C, Oyetunji T, Pollack KM, Bolorunduro O, Villegas C, et al. Motorcycle helmets associated with lower risk of cervical spine injury: debunking the myth. J Am Coll Surg. 20110112th ed. 2011;212(3):295–300. doi:10.1016/j.jamcollsurg.2010.09.032 PubMed PMID: 21227720.

Figures

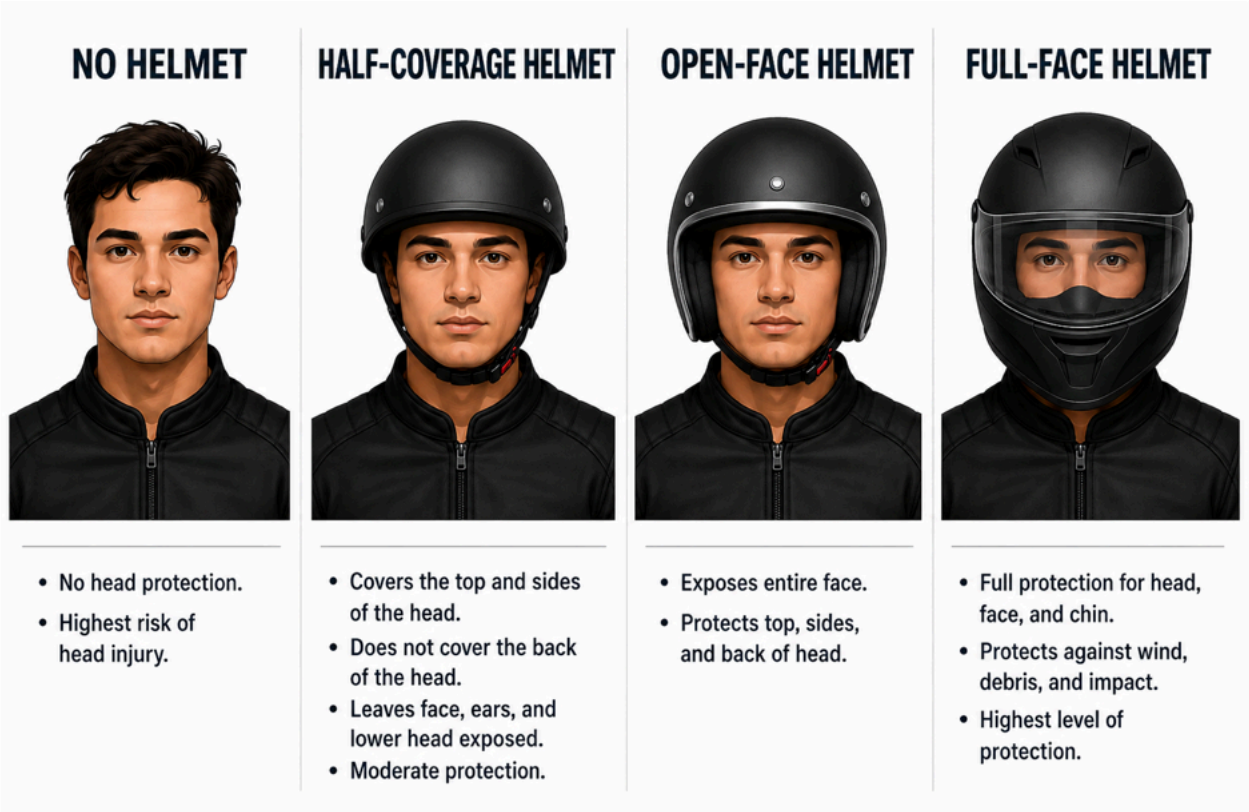


Figure 1

Helmet Classification by cranial and facial coverage. Helmets were classified by cranial and facial coverage based on the classification used by the WHO in the 2023 road safety helmet manual: No helmet; Half-coverage helmet; Open-face helmet; Full-face helmet. Cranial and facial coverage levels were used to generate an ordinal scale (0 to 3, respectively) of increasing protection. This ordinal level is used as the exposure variable in subsequent dose-response analyses.

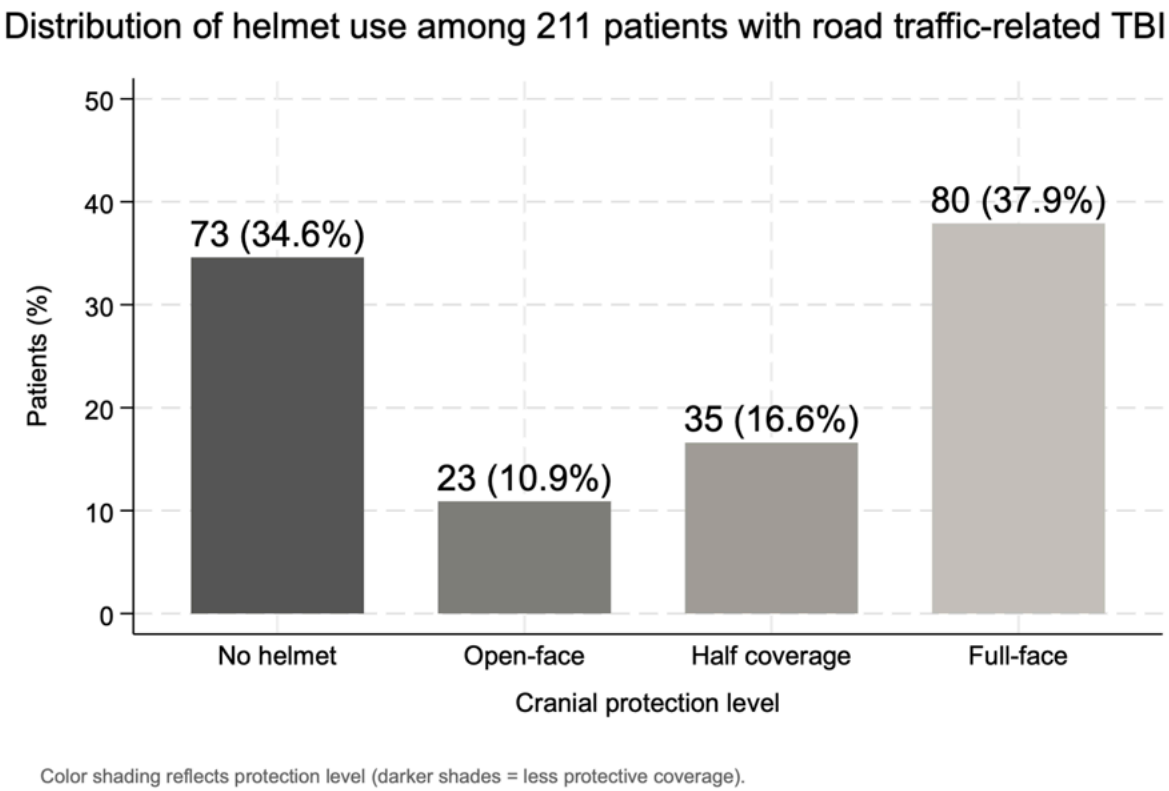


Figure 2

Characterization of helmet types in a cohort of 211 TBI patients. Data collected at the Hospital Universitario San Jorge (Pereira, Colombia) shows that while full-face helmets were the most frequent (37.9%), a significant portion of the population (34.6%) was unhelmeted at the time of the trauma. The "Cranial protection level" axis reflects an ordinal scale of increasing protective surface area. TBI: Traumatic Brain Injury.

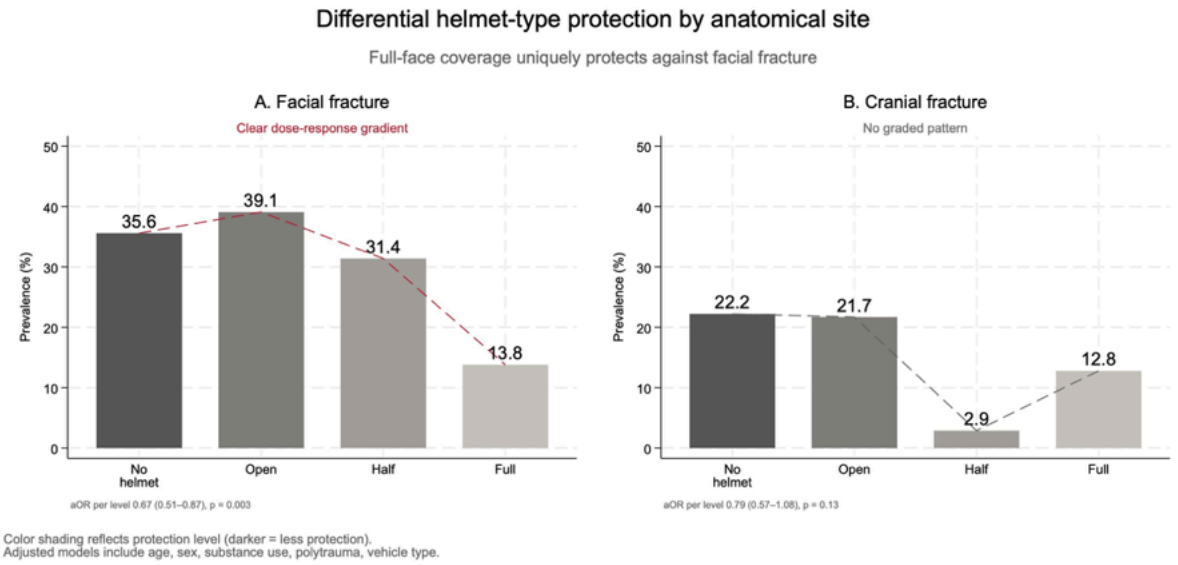


Figure 3

Helmet-type protection differs by anatomical site. (A) Facial fracture prevalence shows a graded dose-response across protection levels (adjusted OR per level 0.67, 95% CI 0.51–0.87, p=0.003). (B) Cranial fracture shows no gradient (adjusted OR per level 0.79, 95% CI 0.57–1.08, p=0.13). Denominators shown

beneath each bar. Models adjusted for age, sex, substance use, polytrauma, and vehicle type using Firth-penalized logistic regression. Cranial fracture analysis n=208 (3 patients without head CT excluded).

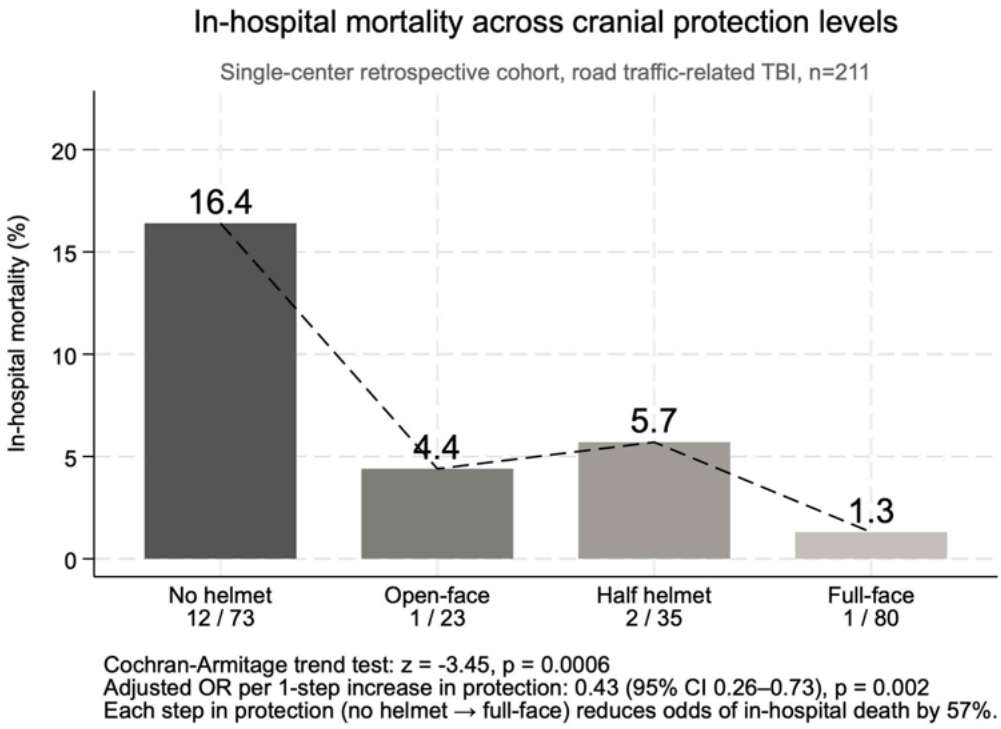


Figure 4

Dose-response relationship between cranial protection level and in-hospital mortality. Bar heights represent the mortality rate (%) within each category of helmet protection, with absolute mortality ratios (deaths/n) displayed on the x-axis. A significant downward trend in mortality is observed as the level of structural coverage increases (p = 0.0006, Cochran-Armitage trend test; test of departure from linear trend, p = 0.50). In the adjusted dose-response model, each one-step increase in protection level (from no helmet through to full-face) was associated with a 57% reduction in the odds of in-hospital mortality (aOR per level 0.43; 95% CI 0.26–0.73; p = 0.002). Notably, the use of a full-face helmet conferred a 91% reduction in the odds of mortality compared to being unhelmeted (OR 0.09; 95% CI 0.02–0.52; p = 0.007). aOR: adjusted Odds Ratio; CI: Confidence Interval; n: number of patients; OR: Odds Ratio; TBI: Traumatic Brain Injury.

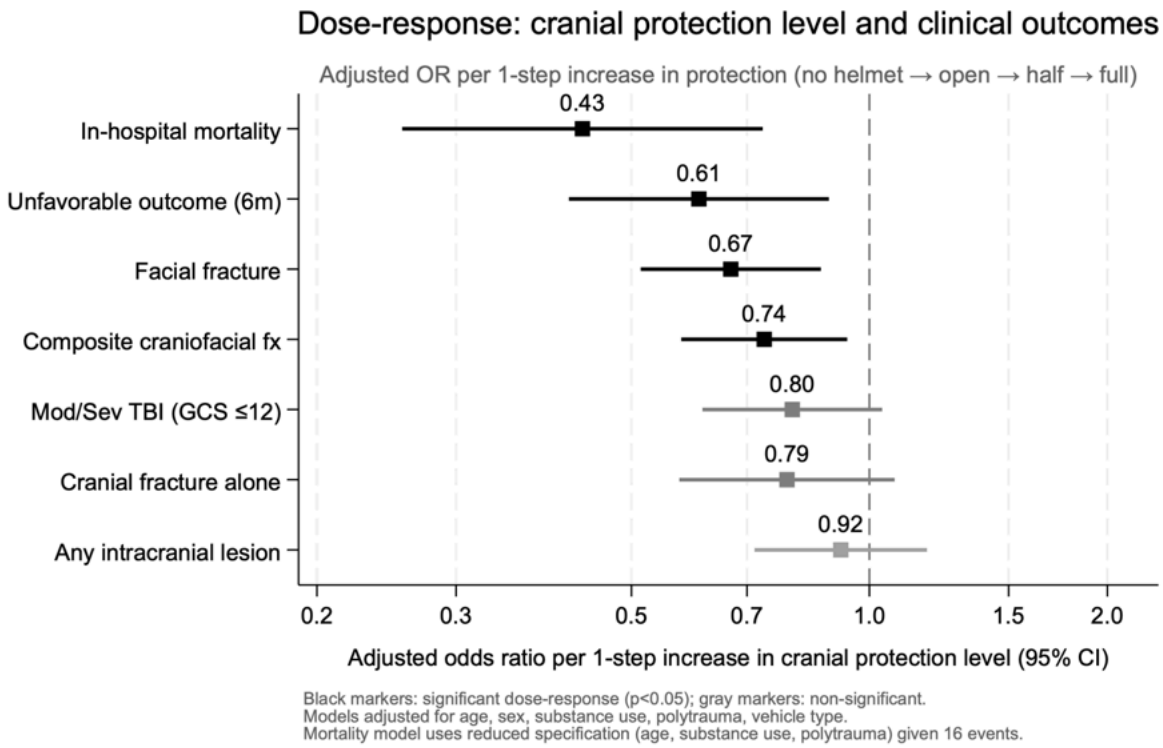


Figure 5

Dose-response relationship between cranial protection levels and clinical outcomes. The forest plot displays adjusted Odds Ratios (aOR) and 95% confidence intervals (CI) for each one-step increase in the protection scale (No helmet; Open-face; Half-face; Full-face). Analyses were performed using Firth-penalized logistic regression to ensure robust estimates. Models were adjusted for age, sex, toxicology, polytrauma, and vehicle type. Black markers represent statistically significant findings ($p < 0.05$), while gray markers indicate non-significant trends. An aOR < 1.0 indicates a reduction in the odds of the outcome as helmet protection increases. TBI: Traumatic Brain Injury; GCS: Glasgow Coma Scale; CT: Computed Tomography.