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Double jeopardy: The aortic-diaphragmatic injury complex

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ABSTRACT

Objective: Concurrent traumatic diaphragmatic hernia (TDH) and blunt thoracic aortic injury (BTAI) are rare but critical injury complexes that result from high-energy trauma mechanisms. This study analyzed the epidemiology, diagnostic approaches, risk factors, and outcomes of concurrent TDH and BTAI and proposed a structured treatment algorithm.

Material and Methods: A retrospective analysis was performed using trauma records from a level 1 trauma center (2004-2024). Four male patients with confirmed concurrent TDH and BTAI were included in the study. Data on demographics, injury characteristics, diagnostic methods, treatment, and outcomes were collected. Statistical analyses were conducted using appropriate tests.

Results: All injuries were caused by high-energy traumas. Mean injury severity score was 38 and the revised trauma score was 6.58. A massive transfusion protocol was activated in 75.0% of cases. Diagnostic imaging showed varying accuracies, with computed tomography demonstrating superior sensitivity for both injuries. All TDH were left-sided posterolateral and BTAI predominantly involved the isthmus. Management followed a sequential approach, with 75.0% of diaphragmatic repairs preceding the aortic intervention. Mean hospital stay was 33 days, with complications including infections, deep vein thrombosis, and atelectasis. Despite the high severity of the injury, all patients survived.

Conclusion: Concurrent TDH and BTAI are rare, but critical injury complexes. Early recognition through structured diagnostic protocols and sequential management guided by institutional capabilities can achieve favorable outcomes despite high injury severity.

Keywords: Wounds and injuries, diaphragmatic hernia, traumatic, abdominal injuries, aortic rupture, thoracic injuries

INTRODUCTION

Traumatic diaphragmatic hernia (TDH) and blunt thoracic aortic injury (BTAI) present unique challenges in trauma management. Diaphragmatic herniation following blunt trauma occurs in a small proportion of cases, predominantly affecting the left hemidiaphragm, whereas BTAI, although uncommon, has a devastating immediate mortality rate (1,2). Although both injuries have been extensively studied individually, their concurrent occurrence has been infrequently discussed in the literature. This injury complex has gained increasing recognition with the advent of high-speed vehicular crashes, improved pre-hospital care systems, and enhanced diagnostic capabilities. Patients with TDH have a six-fold increased risk of BTAI, reflecting shared high-energy injury mechanisms, primarily motor vehicle collisions. Despite their clinical significance, there is limited literature examining these concurrent injuries, with the last major series reporting only seven cases (3). Although TDH and BTAI have been extensively studied as independent entities, their concurrent presentations remain poorly understood. We hypothesize that this injury complex occurs more frequently than is recognized in high-energy trauma, is followed by predictable injury patterns, and that outcomes can be improved through standardized diagnostic and treatment protocols.

This study aimed to analyze the epidemiology, diagnostic approaches, and outcomes of concurrent TDH and BTAI, focusing of developing an evidence-based treatment algorithm based on institutional capabilities.

MATERIAL and METHODS

A descriptive retrospective analysis was performed using the medical records from the trauma database of the Division of Trauma Surgery at the University of

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Campinas, covering the years 2004 to 2023. The facility serves as a level 1 trauma center for a metropolitan area of 3.9 million inhabitants, featuring a dedicated 16-bed trauma floor and 10-bed trauma intensive care unit (ICU). Of the 40 cases of blunt TDH and 47 cases of BTAI, we only included patients with confirmed concurrent injuries. The exclusion criteria were grade I diaphragmatic injuries, congenital defects, deaths before imaging, and incomplete medical records.

Data collection included demographics, trauma bay presentation, injury characteristics (diaphragmatic grade/location and aortic classification/position), herniated organs, and associated injuries. Injury severity score (ISS) and revised trauma score (RTS) were calculated for all patients.

Prior to 2008, whole-body computed tomography (CT) scanning was strictly limited to selected cases, with most trauma patients undergoing selective radiography or segmental CT. Since then, our diagnostic protocol has standardized contrast-enhanced whole-body CT scanning for all hemodynamically stable patients with high-energy trauma mechanisms, when immediate surgery is not indicated.

Treatment documentation covered diagnostic methods, surgical timing, approach selection, and repair techniques. Our protocol for diaphragmatic injuries favors laparotomy or laparoscopy using interrupted non-absorbable sutures with chest drainage. Aortic repair primarily employs endovascular approaches when anatomically suitable, with open repair reserved for specific indications. The timing of aortic intervention was determined based on the associated injuries, patient stability, and prosthesis logistics.

Injuries were classified using standardized criteria. The American Association for the Surgery of Trauma organ injury scale (4) was used for diaphragmatic injuries (grades II-V) and the Society for Vascular Surgery (5) grading system was used for aortic injuries (grades I-IV). Postoperative care followed a standardized protocol, including routine imaging and appropriate anticoagulation therapy. Outcome measures included length of hospital stay, complications, reinterventions, mortality, and follow-up data.

Statistical Analysis

To address the limitations of our small sample size (n=4), statistical analysis included descriptive statistics with median and range for continuous variables.

Fisher's exact test was used for categorical data, and bootstrap resampling was used for confidence intervals. Detailed individual case analyses were performed to strengthen clinical correlations. The analysis was performed using SPSS (version 25.0; IBM Corp., Armonk, NY, USA) was considered statistically significant at $p<0.05$. The study received approval from the Ethics in Research Committee of University of Campinas (CAAE: 78780517.4.0000.5404 and 66498422.9.0000.5453).

RESULTS

Four male patients with concurrent TDH and BTAI were analyzed. The mean age was 32.0±8.4 years. All injuries were caused by high-energy trauma mechanisms. Initial assessment revealed hemodynamic instability in 75.0% of patients, with a mean ISS of 38.0±9.8 and a mean RTS of 6.58±1.2. Glasgow Coma scale scores were distributed bimodally: 50.0% severe and 50.0% mild. Epidemiological data are shown in Table 1.

Table 1. Epidemiological and clinical characteristics of trauma patients

Parameters	Patient 1	Patient 2	Patient 3	Patient 4	Mean ± SD (range)
Trauma severity scores					
ISS	38	38	50	26	38.0±9.8 (26-50)
RTS	4.95	7.84	5.68	7.84	6.58±1.2 (4.95-7.84)
Pre-hospital					
Rescue type	Ground	Ground	Ground	Air	-
Trauma mechanism					
Mechanism	Collision	Rollover	Struck	Rollover	-
Vehicle type	Motorcycle	Car	Car	Car	-
Position	Driver	Passenger	Pedestrian	Driver	-
Safety device	Helmet	No seatbelt	Out of lane	Seatbelt	-
Injury grade					
TDH grade	IV	IV	IV	IV	-
BTAI grade	III	III	III	III	-
Clinical course					
Positive blood culture	Y	Y	Y	Y	100.0%
Length of stay (days)	40	40	42	12	33.0±8.4 (12-42)
ICU stay (days)	34	20	22	9	21.0±6.8 (9-34)
Rehabilitation (days)	90	120	150	100	128.0±24.6 (90-150)

ISS: Injury severity score, RTS: Revised trauma score, TDH: Trauma diaphragmatic hernia, BTAI: Blunt traumatic aortic injury, ICU: Intensive care unit, SD: Standard deviation

Most patients (75.0%) required massive transfusion protocol (MTP) activation, receiving an average of 4 units of packed red blood cells, 4 units of fresh frozen plasma or cryoprecipitate (1 U/10 kg), and 1 g of tranexamic acid. Microperfusion parameters showed significant derangements, with initial lactate levels >6.0 mmol/L and base excess <-5 mmol/L, indicating 100% sensitivity for the MTP requirement. The microperfusion parameters showed significant derangements, and are expressed in Table 2.

Diagnostic imaging has shown varying accuracies. Chest radiography (CXR) demonstrated 50.0% and 75.0% sensitivity for TDH and BTAI, respectively. CT angiography achieved 100% sensitivity and specificity for BTAI, whereas contrast-enhanced CT showed a sensitivity of 75.0% for TDH. Table 3 and 4, Figures 1-3.

Three cases were diagnosed within 2 hours of admission, with one TDH diagnosed at 47 days. All patients with TDH had left-

Table 2. Hemodynamic and microperfusion status in trauma room

Parameters	Patient 1	Patient 2	Patient 3	Patient 4
Vital signs				
SBP <90 mmHg	Y	Y	Y	N
HR >120 bpm	Y	Y	Y	N
RR >20 rpm	Y	Y	Y	Y
Shock index	2.0	1.5	1.5	0.8
Laboratory values				
Base excess (mmol/L)	-12.1	-14.3	-8.9	-2.1
Lactate (mmol/L)	6.8	7.6	6.5	3.6
Ionic calcium (mmol/L)	0.90	0.95	1.1	1.2
Other parameters				
Massive transfusion protocol	Y	Y	Y	N
FAST	Pos	Pos	Neg	Neg
Urine output <1.5 mL/kg/h	Y	Y	Y	N
Tranexamic acid	Y	Y	Y	Y

SBP: Systolic blood pressure, HR: Heart rate, RR: Respiratory rate, FAST: Focused assessment with sonography in trauma

Table 3. Initial chest X-ray findings in trauma patients

Findings	Patient 1	Patient 2	Patient 3	Patient 4
Mediastinal				
Mediastinal widening	Y	Y	Y	Y
Obscured aortic contour	Y	Y	Y	Y
Pleural/rib/parenchymal				
Left hemothorax	Y	Y	N	Y
Left rib fractures	Y	Y	N	Y
Pulmonary opacity	Y	Y	Y	N
Additional				
Right tracheal deviation	Y	Y	Y	Y
Intrathoracic bowel loop	N	Y	N	N
Left main bronchus depression	N	N	Y	Y
Blurring of the diaphragm contour	Y	Y	Y	Y
Atelectasis	N	Y	Y	Y

Table 4. Initial chest CT findings in trauma patients

Findings	Patient 1	Patient 2	Patient 3	Patient 4
Vascular/mediastinal				
Pseudoaneurysm	Y	Y	Y	Y
Mediastinal hematoma	Y	N	N	N
Pneumothorax left	Y	Y	N	Y
Pneumothorax right	N	N	N	Y
Hemothorax left	Y	Y	Y	Y
Hemothorax right	Y	Y	N	N
Pulmonary				
Pulmonary contusion left	Y	Y	N	Y
Pulmonary contusion right	Y	N	N	N
Left rib fractures	Y (1-8)	Y (2-5)	N	Y (1-10)
Right rib fractures	N	N	N	Y (3-7)
Clavicle fracture left	Y	N	N	N
Intrathoracic structure	Y	Y	Y	N
Pneumomediastinum	Y	N	N	N
Atelectasis	Y	Y	Y	Y
Subcutaneous emphysema	Y	Y	N	Y

CT: Computed tomography

sided posterolateral injuries. Herniated organs included the isolated stomach (50.0%), transverse colon with spleen (25.0%), and liver with stomach (25.0%). BTAI predominantly involved the isthmus (75.0%), with one case affecting the anterior wall of the descending aorta (25.0%). The associated injuries are listed in Table 5.

Management followed a sequential approach, with 75.0% of diaphragmatic repairs preceding aortic intervention. Most diaphragmatic repairs (75.0%) were performed via laparotomy, with one laparoscopic repair in a case of delayed diagnosis. All aortic injuries underwent endovascular repair between 3 and 28 days post-injury.

The mean hospital stay was 33.0±8.4 days, with a median ICU stay of 20 days. Early complications included bloodstream infections

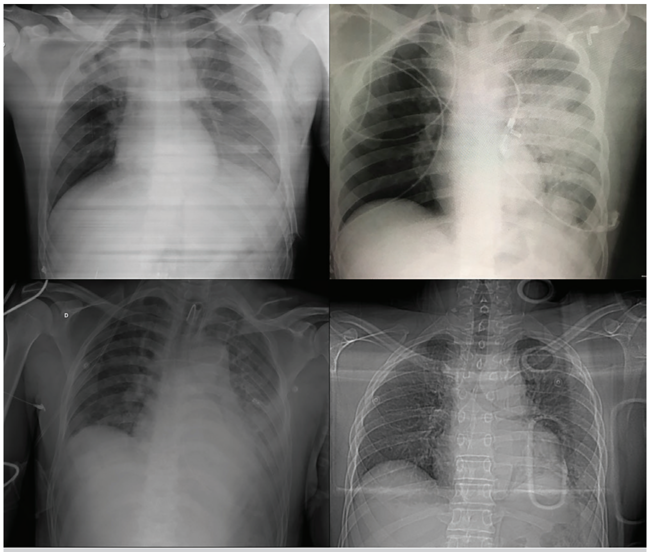

Figure 1. CXR demonstrating mediastinal widening and blurred diaphragmatic contour in patients 1-4, suggestive of BTAI and TDH.

CXR: Chest radiography, BTAI: Blunt thoracic aortic injury, TDH: Traumatic diaphragmatic hernia

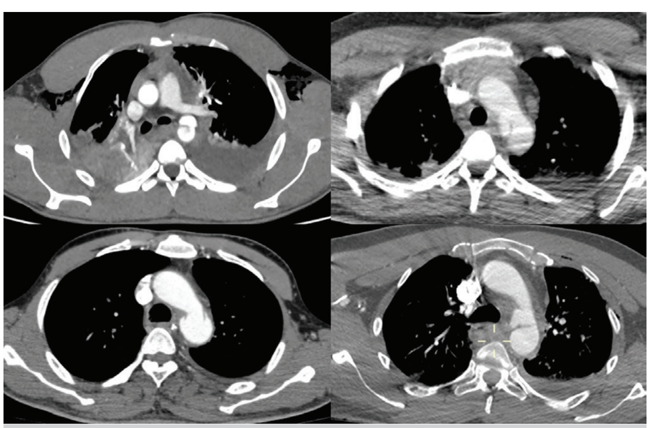

Figure 2. Axial CT angiography showing BTAI grade III in patients 1-4.

CT: Computed tomography, BTAI: Blunt thoracic aortic injury

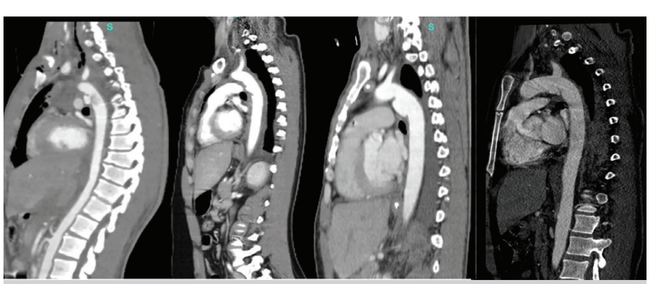

Figure 3. Sagittal CT angiography showing BTAI grade III in patients 1-4.

CT: Computed tomography, BTAI: Blunt thoracic aortic injury

Table 5. Associated injuries in trauma patients

Body region/ injuries	Patient 1	Patient 2	Patient 3	Patient 4
Thoracic				
Pneumothorax	Y	Y	N	Y
Hemothorax	Y	Y	Y	Y
Rib fractures	Y	Y	N	Y
Clavicle fracture	Y	N	N	N
Pulmonary contusion	Y	Y	N	Y
Abdominal				
High-grade liver laceration	Y	N	N	N
Low-grade liver laceration	N	Y	N	N
Low-grade kidney injury	Y	N	N	N
Abdominal wall hematoma	Y	N	N	N
Extraperitoneal bladder injury	N	Y	N	Y
Head				
Subarachnoid hemorrhage	Y	N	Y	N
Subdural hematoma	Y	N	Y	N
Skull fracture	Y	N	N	N
Spine				
Unstable fractures	N	N	N	N
Stable fractures	Y	N	N	N
Long bones				
Open fracture lower limb	Y	N	Y	N
Open fracture upper limb	N	Y	N	N
Pelvis				
Ischio-pubic fracture	N	Y	N	Y
Open book fracture	N	N	N	N
Sacral fracture	N	Y	N	Y

(100%), pneumonia (75.0%), deep vein thrombosis (50.0%), and atelectasis requiring prolonged ventilation (25.0%). Procedure-related complications included femoral artery pseudoaneurysms following thoracic endovascular aortic repair (TEVAR). Long-term follow-up (1-5 years) demonstrated favorable outcomes in three patients with no endoleak, migration, or graft-related complications. One patient required reintervention at six months for stent graft migration, causing partial left subclavian artery occlusion, which was successfully managed with secondary stent deployment. All the patients achieved complete functional recovery and returned to their previous activities. Annual CT angiography surveillance confirmed stable graft positions.

Analysis revealed that a shock index >1.4 correlated to longer ICU stay (25 vs. 9 days) and increased hospital length of stay (40 vs. 12 days). ISS was correlated with length of stay. Despite the high injury severity, all patients survived and returned to work after rehabilitation [mean 128.0±24.6 days (90, 150)].

DISCUSSION

Over the past two decades, trauma surgeons have encountered an increasing incidence of complex injury patterns. This evolution reflects multiple factors: higher-energy vehicular crashes, improved pre-hospital care systems, and enhanced trauma center capabilities. Advancements in diagnostic technologies, particularly the widespread implementation of computed tomography as a screening tool, combined with structured trauma training programs, have significantly improved injury detection rates.

Diaphragmatic injuries, particularly blunt ruptures which are rare, are now more frequently diagnosed (3). Blunt thoracic aortic injuries, although uncommon, have shown high detection rates. This parallel increase in TDH and BTAI appears to be linked to shared injury mechanisms during high-energy trauma (6,7). Both conditions, although historically underdiagnosed, are being identified with increasing frequency in modern trauma practice, highlighting the importance of early recognition and standardized protocols.

Teixeira et al. (8) demonstrated that BTAI is present in one-third of motor vehicle crash fatalities and remains the second most common cause of death following blunt mechanisms. Fox et al. (9) reported that 80.0% of BTAI patients die before reaching a trauma center, with an additional 50.0% mortality within 24 hours of hospital arrivals, largely due to severely associated injuries. While our experience at Campinas confirmed the substantial injury burden, with a mean ISS of 38±9.8 (range 26-50), our series demonstrated markedly improved early survival outcomes.

The predominance of motor vehicle collisions (MVC) in concurrent TDH and BTAI has been consistently documented over the past three decades. For TDH, the authors (10-12) reported MVC rates of 63.0% and 65.0%, respectively, which are consistent with the National Data Bank (1) showing 63.0% MVC and 17.0% motorcycle crashes. Regarding BTAI, the multicenter study by the Aortic Trauma Foundation (13) demonstrated a 72.8% prevalence of MVC, with additional injury mechanisms including motorcycle collisions (14.0%) and pedestrian injuries (9.0%). Similarly, Fox et al. (9) found a 70.0% association with MVC. Notably, in the only previous series of concurrent TDH/BTAI, Rizoli et al. (3) reported that all seven cases resulted from MVC. Our series demonstrated a comparable distribution, with 75.0% of cases involving MVC. The specific mechanisms include two frontal fixed-object collisions with a subsequent rollover and one pedestrian struck. Although motorcycle collisions were underrepresented in our study, the increasing prevalence of motorcycle accidents in Brazil warrants particular attention from surgeons.

There is a lack of literature regarding the impact of safety devices on these injuries. In our series, 50.0% of the vehicle occupants were unrestrained by seatbelts. Although safe device use did not appear to affect mortality or injury grade, restrained victims demonstrated lower ISS and RTS scores, reduced length of stay in the ICU, and no activation of the MTP, suggesting a potential mitigating effect.

In our series, 75.0% of the patients presented with shock on admission, requiring MTP activation. This rate is notably higher than that previously reported for isolated TDH, in which Boulanger et al. (6) found a 34.0% overall incidence of shock admissions, with right-sided injuries showing a higher prevalence (56.0% vs. 22.0%). Other investigators have reported admission hypotension rates ranging from 30 to 66.0% in cases of TDH, while DuBose et al. (13) observed an incidence of isolated BTAI at 14.7% (10-15).

Our experience suggests that hemodynamic instability on admission is primarily caused by associated injuries rather than by TDH or BTAI alone. This observation aligns with that of Shah et al. (16), who found that early mortality in TDH predominantly results from associated injuries. All patients with a shock index >1.4 in our series demonstrated significant associated injuries. Two patients presented with similar injury patterns: Both had liver lacerations, hemothorax (>500 mL), and open fractures, with one additionally sustaining pelvic and renal injuries and the other experiencing extraperitoneal bladder injury. Interestingly, patient three presented with shock despite the absence of abdominal bleeding. In this case, we hypothesized that shock resulted from a combination of significant blood loss from open fractures and hemothorax, with hypotensive effects of sedative medications administered for emergency intubation (Glasgow Coma scale score <8 at the scene).

MTP activation in our series followed two distinct patterns: Patients 1 and 2 met the traditional assessment of blood consumption score triggers (systolic blood pressure <90 mmHg, heart rate >120, positive FAST) (17), whereas Patient 3's activation was based on metabolic derangement (base excess -8.9 mmol/L) and surgeon experience. Notably, we observed that a combination of lactate >5.0 mmol/L and calcium consumption demonstrated 100% sensitivity for massive transfusion requirements. Our findings expand upon those of Meyers and McCabe (10), who identified TDH as a marker of serious occult injuries. We observed an average of 4.2 associated injuries per patient, including concurrent injuries, suggesting that both TDH and BTAI may serve as markers of severe multisystem trauma.

Gelman et al. (18) reported distinct differences in CXR sensitivity between left (64%) and right (17.0%) diaphragmatic injuries. Common findings included an elevated hemidiaphragm (61.0%) and intrathoracic air-containing viscera (45.0%). In our TDH cases, CXR demonstrated limited diagnostic reliability with 25.0% sensitivity: Detecting intrathoracic viscera in only one case and missing three others. Diagnostic optimization strategies include pre-imaging nasogastric tube placement and serial radiographic examination. The most sensitive and specific finding in our series was the blurring of the diaphragmatic contour present in all cases. We consider this sign to be the most reliable early indicator of TDH because anatomical disruption of the diaphragmatic outline invariably precedes visceral herniation. While the intrathoracic hollow viscus is traditionally emphasized, this sign may be absent in early presentations. Therefore, trauma surgeons should maintain a high suspicion of TDH when encountering diaphragmatic contour irregularity, even in the absence of obvious herniation.

Despite the relatively low reported sensitivity of 41.0% for BTAI (19), several valuable radiographic findings warrant attention. While classical findings include mediastinal widening, aortic knob obliteration, deviation of the trachea to the right side, and apical pleural cap, these signs often lack specificity. Moreover, in patients with concurrent TDH, these findings can be obscured by pulmonary contusions, herniated viscera, hemothorax, pneumothorax, or atelectasis. Mediastinal widening [mean 8.75±0.5 cm (8.5-9.6)] and right tracheal deviation were present in all cases. Additional findings included an obscured aortic contour, left hemothorax (75.0%), and left main bronchus depression in two patients. These observations reinforce that CXR serves as an important initial screening tool but is insufficient for a definitive diagnosis.

Contrast-enhanced CT (CECT) demonstrated superior diagnostic capability for delineating injury patterns in both TDH and BTAI. Our institutional experience with whole-body CT revealed 100% sensitivity and specificity for BTAI and 75.0% sensitivity for TDH, showing a complete correlation with the intraoperative findings. These results align with those of previous studies that reported sensitivities of 61-100% and specificities of 76-99.0% (20,21). CT features proved particularly valuable, demonstrating higher sensitivity for left-sided injuries, enhanced diagnostic accuracy with coronal and sagittal reformations, and specific signs including the collar sign, dangling diaphragm, and intrathoracic visceral herniation.

For BTAI, CT angiography (CTA) has emerged as the primary diagnostic tool, demonstrating 98-100% sensitivity and specificity with near-perfect negative predictive value (22,23). Our cases showed 100% diagnostic accuracy, with CTA precisely characterizing the type and extent of vascular injury, identifying pseudoaneurysm in all cases, and associated periaortic hematoma in one case. CTA also provides superior detection of associated thoracic injuries, including hemopneumothorax, pneumomediastinum, and rib fractures. Although conventional angiography remains a potential diagnostic modality, it has been largely superseded by CTA. Our findings highlight two critical considerations in trauma imaging assessments. CXR and CECT should not be viewed as competing modalities. Although CECT offers superior diagnostic details, CXR plays an essential role as a screening tool. These imaging approaches are complementary, rather than substitutive. Second, CECT interpretation requires a broader perspective beyond identifying single injuries. Trauma surgeons must actively search for associated injuries that often require more urgent attention than initially suspected.

All BTAI cases and three TDH cases were diagnosed within 2 hours post-trauma, with one notable exception: A TDH case diagnosed at 47 days. This delayed diagnosis occurred in a patient with complex thoracic trauma including multiple bilateral rib fractures, atelectasis, hemothorax (>500 mL), pneumothorax, and splenic herniation. Overlapping injuries create a challenging radiological picture that compromises the sensitivity of CT imaging. Early diagnosis and surgical repair are crucial to prevent catastrophic outcomes in patients with TDH. This case highlights one of the three potential diagnostic pitfalls cited by Kruger et al. (11): Misinterpretation of initial imaging.

A high index of suspicion is mandatory for trauma surgeons, focusing on trauma mechanisms. Reiff et al. (24) demonstrated that combining specific crash parameters (frontal/near-side lateral compartment intrusion ≥30 cm, or delta-V ≥40 kph) with associated organ injuries provides high sensitivity (68-89.0%) for TDH prediction (Figure 4). Notably, BTAI showed a strong association with TDH (odds ratio 5.2, 95.0% confidence interval 2.2-12.5), exhibiting high specificity (96.6%) despite low sensitivity (15.4%). This suggests that although aortic injury strongly indicates potential TDH, its absence does not exclude the diagnosis. All the patients in our series had posterolateral left-sided grade IV TDH. Left-sided injuries predominate in hospital settings owing to three factors: Anatomical weakness at the left posterolateral embryonic fusion point, protective effect of the

Figure 4. High-energy trauma mechanism: (Top) Fixed barrier impact with severe deformation before rollover; (Bottom) lateral impact against barrier followed by rollover, resulting in extensive structural damage.

liver on the right hemidiaphragm, and detection bias. This bias becomes evident when comparing clinical and autopsy findings. While hospital studies show left-side predominance, autopsy studies reveal a more balanced distribution (right-sided injuries: 50.0% in autopsy vs. 14.0% in hospitalized patients), suggesting that right-sided TDH carries higher pre-hospital mortality (25).

Nikolic et al. (26) described two distinct patterns of BTAI mechanisms. Drivers sustain injury through thoracoabdominal compression during steering wheel impact, whereas front passengers experience aortic injury through hyperextension when sudden deceleration causes opposing forces between the forward-moving carotid vessels and fixed intercostal arteries. The aortic isthmus, anatomically located at the ligamentum arteriosum, represents the most vulnerable segment, accounting for 60.0 - 66.0% of injuries in the literature and 75.0% of cases in our series (8,9,13,26). This predominance is explained by the distortion of the aorta and vertebral column during rapid deceleration in frontal collisions (27). BTAI manifests as a spectrum of lesions, with Grade III injuries (pseudoaneurysm) representing the most prevalent form, both in the literature and in our four cases (8,13).

Our cases demonstrated distinct mechanisms of injury. The driver (Patient 4) showed extensive thoracic injuries from steering wheel compression during deceleration, whereas the front passenger (Patient 2) presented with fewer thoracic injuries but a significant hematoma near the left subclavian artery, reflecting the typical passenger injury pattern of caudorostral hyperextension.

TDH requires more urgent surgical management than BTAI because of the associated injuries that can cause hemodynamic shock or ventilatory impairment. Patients who required laparotomy demonstrated a higher ISS (42 vs. 26). In our series, except for one missed diagnosis, all patients underwent laparotomy with diaphragmatic repair before aortic intervention. The timing of diagnosis and repair was consistently less than 4 hours. In contrast, TEVAR procedures were significantly delayed (3-28 days post-injury). This timing differs from contemporary literature: In 2008, Demetriades et al. (28) reported a mean intervention time of 67 h; DuBose et al. (13) recently demonstrated shorter intervals from admission to repair of 36 h (within 6 h, 49.1%; within 24 h, 78.7%; within 48 h, 80.3%). Our extended timeline reflects several challenges: The need for custom endografts in young trauma patients with smaller, non-atherosclerotic aortas, public healthcare system constraints, the institutional learning curve, and complex team coordination. However, improved endograft availability, established supply chains, and streamlined team protocols have significantly reduced the treatment intervals in recent cases.

The management of BTAI has undergone changes over the last two decades, primarily driven by the development of minimally invasive endovascular techniques. The current treatment strategy begins with impulse control (IC). Multiple studies have validated beta-blocker-based anti-impulse therapy with additional agents to achieve target parameters. Jacob-Brassard et al. (29) meta-analysis of 8,606 patients confirmed the safety and feasibility of medical management, while recent studies by Arbabi et al. (30), established the following specific targets: systolic blood pressure <120 mmHg and HR 60-80 bpm.

DuBose et al. (31) recommend expectant management with blood pressure control for grade I lesions, as most heal spontaneously. Anti-impulse therapy dramatically reduced the risk of rupture from 12.0% to 1.5%. TEVAR has emerged as the dominant therapeutic approach for higher-grade injuries, accounting for 76.4% of cases in the largest multicenter analysis (32). While SVS guidelines (23) recommend urgent repair (<24 h), evidence suggests that delayed intervention may improve outcomes, with one study showing that delayed repair (>24 h) of BTAI is associated with improved survival (33). In our series, none of the patients presented with low-grade BTAI, which would have been suitable for non-operative management. All patients were admitted to the ICU with strict IC until endograft placement, managed with esmolol, with two cases additionally requiring nitroprusside. All four BTAI cases were treated with TEVAR by cardiac surgeons, whereas three TDH cases underwent exploratory laparotomy with reduction of herniated contents and diaphragmatic repair. One case of TDH was laparoscopically managed (Figure 5). This patient had a delayed diagnosis, was beyond the acute trauma phase, and lacked associated intra-

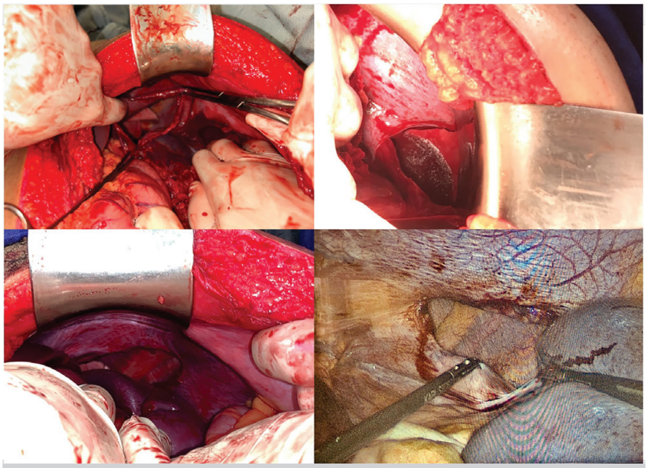

Figure 5. Intraoperative findings during TDH repair: 1-3: Direct visualization of diaphragmatic rupture 4: Laparoscopy view during diaphragmatic repair.

TDH: Traumatic diaphragmatic hernia

abdominal injuries or hemodynamic instability, supporting the suitability of a minimally invasive approach. Although most surgeons in our series were more experienced in open surgery, this case highlights the potential role of minimally invasive techniques in selected TDH cases, but success depends on surgeon expertise and patient stability.

Teixeira et al. (8) demonstrated that BTAI significantly increased the risk of concurrent injuries compared to patients without BTAI, particularly affecting solid organs such as the liver (55.0% vs. 34.0%, p<0.001), spleen (36.0% vs. 22.0%, p=0.009), and kidneys (18.0% vs. 9.0%, p=0.023). They also noted increased rates of thoracic trauma, including rib fractures, hemothorax, (86.0% vs. 56.0%, p<0.001), and pelvic fractures (40.0% vs. 26.0%, p=0.014). A landmark study (10) on diaphragmatic rupture revealed similar patterns, with high rates of musculoskeletal injuries (pelvic 52.0% and long bone fractures 48.0%) and solid organ trauma (splenic injury 48.0% and hepatic lacerations 16.0%). Their series also documented significant thoracic involvement, including rib fractures (52.0%), pulmonary contusions (20.0%), BTAI (8.0%), and cardiac contusions (4.0%). Studies have reported concurrent injury rates ranging from 3.0% to 14.0% (8,12).

Our findings align with this pattern; specifically, all cases presented with thoracic injuries including hemothorax, pulmonary contusion, and rib fractures. Abdominal injuries followed a distribution similar to that of common liver and pelvic injuries. Notably, both patients with pelvic trauma had extraperitoneal bladder injury. In our TDH cases, the stomach was the most herniated organ, consistent with the literature.

Demetriades (32) reviewed 125 patients and reported 43.5% systemic complications, including paraplegia (1.7%), pneumonia (30.7%), acute respiratory distress (16.1%), sepsis (12.4%), urinary tract infection (17.9%), deep vein thrombosis (4.5%), and renal failure (4.5%). TEVAR-specific complications occurred in 18.4% of cases, predominantly endoleaks (13.6%). More recently, lower rates of endovascular complications have been observed, as reported in (13), including endograft malposition (3.0%), endoleaks (2.5%), paralysis (0.5%), and stroke (1.0%).

Respiratory complications have historically been dominant in patients with blunt TDH. Rodriguez-Morales et al. (14) reported atelectasis in 65.0% of patients, whereas pneumonia rates varied from 32.0% in the Boulanger series (6) to 14.8% in the Fair analysis (12). Beyond respiratory issues, infectious complications significantly impact outcomes, with Boulanger reporting intra-abdominal abscess in 32% and Rodriguez-Morales et al. (14) documenting systemic sepsis in 28.0% of cases (6,12).

In our series, complications were predominantly related to prolonged hospitalization (mean, 33 days) and ICU stay (21 days for the first three cases), rather than directly linked to TDH or BTAI repair. Systemic complications included DVT requiring anticoagulation in two patients and pneumonia with septic complications in three patients. Procedure-related complications occurred in two cases: endograft malposition causing partial left subclavian artery occlusion requiring secondary stent graft deployment, and a femoral artery pseudoaneurysm after puncture. Three patients required tracheostomy due to prolonged ICU stay and extended mechanical ventilation requirements. Notably, no cases of paralysis, myocardial infarction, renal failure requiring hemodialysis, multiple organ failure, or chest tube complications were observed. Our experience suggests that complications are primarily associated with the severity of the associated injuries rather than with TDH or BTAI. Experts (34) have recommended lifelong imaging surveillance after endovascular repair. Our follow-up CTA results at six months are shown in Figure 6.

Compared to the Rizoli et al. (3) series, which reported 14.0% mortality in seven cases, our four patients survived, although recovery time was significantly impacted in our cases.

Study Limitations

Our study had several important limitations that warrant caution. This retrospective study has inherent limitations in terms of data collection and analysis. More significantly, despite our status as a high-volume trauma center, we identified and treated only four cases over the past 20 years. This small sample size severely limits our statistical power and ability to draw robust conclusions. Nevertheless, given the extreme rarity of combined BTAI and TDH injuries, with the last report published over 30 years ago, which was reporting only seven cases, we believe our detailed case series adds valuable information to the current literature.

Based on our institutional experience and literature review, we propose a structured treatment algorithm for concurrent TDH and BTAI, according to institutional capabilities. For centers without surgical capabilities, immediate transfer to tertiary trauma centers is recommended. For institutions with surgical but lacking endovascular resources, we suggest first addressing TDH and associated injuries, maintaining strict IC, and then transferring the patient to an endovascular-capable facility. For fully capable trauma centers, we recommend initial TDH repair and any associated injuries, followed by a TEVAR procedure within the first 3-5 days, allowing for patient stabilization and custom endograft availability. For suspected TDH with negative initial imaging, follow-up CT at 5-7 days with nasogastric tube, thin-slice acquisition, and multiplanar reconstruction is recommended. In concurrent BTAI cases, TEVAR is performed before chest drainage to minimize complications with post-drainage CT follow-up. For a retained hemothorax, video-assisted thoracoscopy enables both diaphragmatic inspection and evacuation (Figure 7).

Given the rarity of these concurrent injuries, establishing a global trauma registry is recommended, as even high-volume trauma centers encounter too few cases to generate robust evidence-based recommendations.

CONCLUSION

Concurrent TDH and BTAI present a challenging injury complex that requires a structured diagnostic and therapeutic approach. Sequential management through diaphragmatic repair and endovascular intervention guided by institutional capabilities can achieve favorable outcomes despite high injury severity. A global trauma registry is essential to develop evidence-based protocols for these rare injuries.

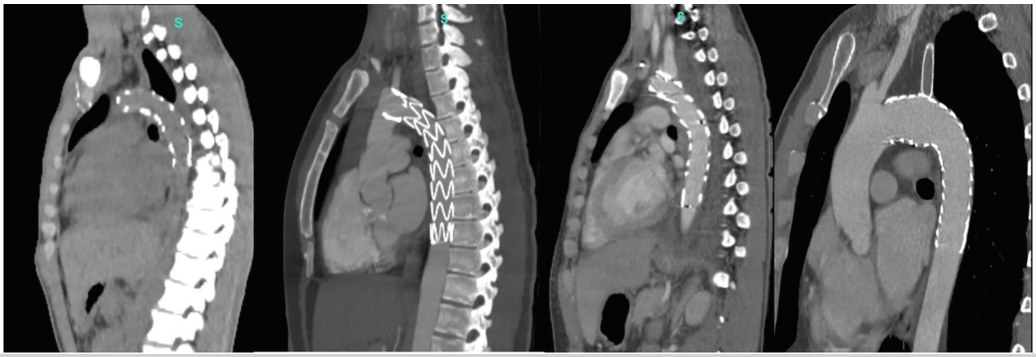

Figure 6. Sagittal CT angiography showing grade III BTAI post-TEVAR in patients 1-4.
CT: Computed tomography, BTAI: Blunt thoracic aortic injury, TEVAR: Thoracic endovascular aortic repair

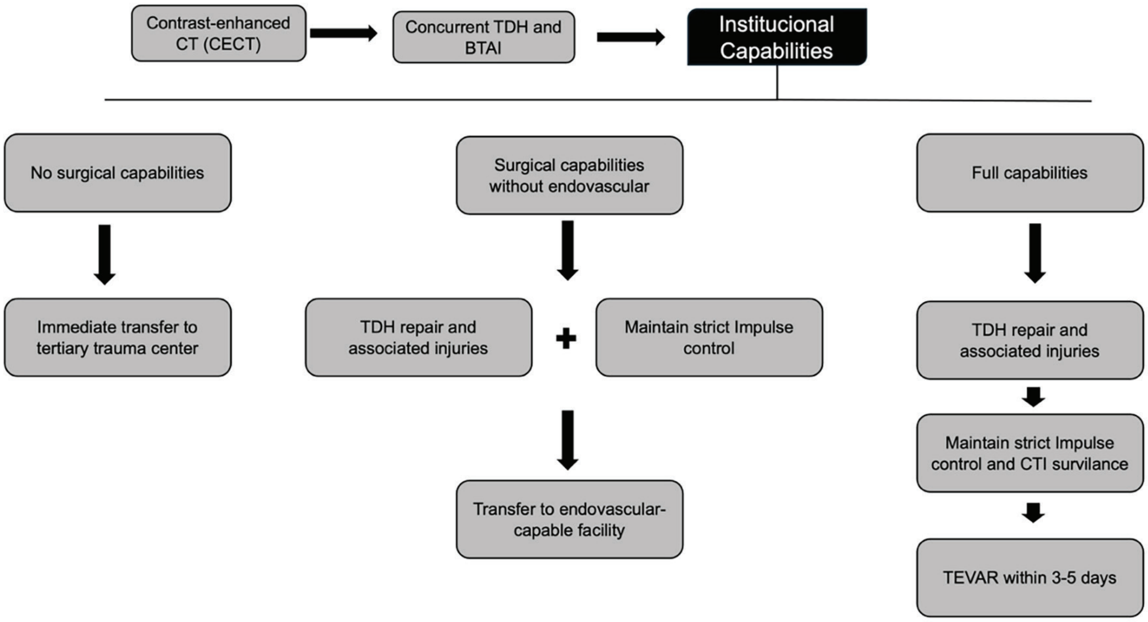

Figure 7. Treatment algorithm for concurrent TDH and BTAI, according to institutional capabilities.
CT: Computed tomography, BTAI: Blunt thoracic aortic injury, TEVAR: Thoracic endovascular aortic repair, TDH: Traumatic diaphragmatic hernia

Ethics

Ethics Committee Approval: The study received approval from the Ethics in Research Committee of University of Campinas (CAAE: 78780517.4.0000.5404 and 66498422.9.0000.5453).

Informed Consent: Retrospective study.

Footnotes

Author Contributions

Concept - V.F.K., C.J.M.; Design - V.F.K., G.P.F.; Supervision - V.F.K.; Data Collection or Processing - M.L.L., C.J.M.; Literature Search - V.F.K.; Writing - V.F.K., G.P.F.

Conflict of Interest: No conflict of interest was declared by the authors.

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