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Integration of a Hybrid Operating Room for the Management of Severe Traumatic Brain Injury: A Combined Approach with Real-Time Xper-CT Imaging and Neurointervention

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ABSTRACT

AIM: To evaluate the safety and efficacy of the hybrid operating room (HOR) approach in the management of severe traumatic brain injury (sTBI) using Xper-computed tomography (CT)-guided imaging and neurointerventional techniques

MATERIAL and METHODS: A retrospective analysis was conducted on 154 patients with TBI treated surgically between February 2020 and December 2023. Among these, 26 patients with sTBI were managed in an HOR equipped with an Allura Xper FD 20® system. Intraoperative interventions included Xper-CT confirmation, real-time imaging-guided hematoma aspiration or catheter placement, and combined neurointerventional procedures. Clinical outcomes were assessed using the Glasgow Outcome Scale-Extended (GOS-E) at 6 months, and procedural morbidity and mortality rates were documented.

RESULTS: The 26 patients with sTBI had a mean age of 45.3 ± 12.0 years, with 60.4% being male. Xper-CT was used in all cases (mean: 1.7 scans/patient) for confirmation and in 11 cases (42.3%) for real-time guidance, enabling precise interventions such as parenchymal hematoma aspiration (30.8%) and external ventricular drainage (11.5%). Vascular injuries were managed with N-butyl cyanoacrylate glue or polyvinyl alcohol particle embolization (15.4%) and endovascular coiling for pseudoaneurysms (11.5%), with intraoperative angiography performed in 7.7% of cases. No HOR-related complications or reoperations were noted. Favorable outcomes (GOS-E≥4) were observed in 42.3% of patients at 6 months, whereas the 28-day mortality rate was 19.2%, primarily owing to initial trauma (n=3) and pneumonia or sepsis (n=2).

CONCLUSION: The HOR approach represents a significant advancement in the management of sTBI and potentially improves the overall quality of emergency neurosurgical care.

KEYWORDS: Cerebrovascular trauma, Craniocerebral trauma, Subdural hematoma, Traumatic brain injury

ABBREVIATIONS: CT: Computed tomography, **ED:** Emergency department, **EDH:** Epidural, **EVD:** External ventricular drainage, **GCS:** Glasgow Coma Scale, **GOS-E:** Glasgow Outcome Scale-Extended, **HOR:** Hybrid operating room, **ICP:** Increased intracranial pressure, **SDH:** Subdural hemorrhage, **sTBI:** Severe traumatic brain injury, **T-ICH:** Traumatic intracerebral hemorrhage

INTRODUCTION

Traumatic brain injury (TBI) is a global health burden and one of the leading causes of death and disability worldwide (11). TBI is characterized by an abrupt disruption in brain function owing to external mechanical forces and presents considerable clinical challenges, especially in the context of emergency neurosurgery (7). Long-term studies of patients with TBI have revealed that more than half of them have some

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form of disability and a high mortality rate (24,28). The presence of complex hemorrhages, multiple fractures, and rapid evolution of symptoms often necessitate immediate and precise interventions (27).

The traditional neurosurgical management of TBI typically involves sequential procedures across various settings, requiring separate stages for imaging, neurointervention, and surgical treatment. In cases with cerebrovascular injury, the diagnostic and treatment procedures can become even more complex (3,26). This segmented approach can lead to delays in care, which may affect patient outcomes (12,27,33). The advent of hybrid operating rooms (HORs) offers a promising solution for streamlining TBI management. HORs are specially designed surgical suites that integrate advanced imaging capabilities, such as Xper computed tomography (CT), with interventional and surgical tools in a single environment (8,21,22). This setup enables real-time imaging and allows surgeons to perform both diagnostic and therapeutic procedures without relocating the patient, thereby reducing treatment delays and enhancing procedural accuracy.

By examining patient outcomes in cases of severe traumatic brain injury (sTBI) treated using HORs, we aimed to determine their potential to improve the efficiency and quality of emergency neurosurgical care.

MATERIAL and METHODS

Patient Selection

All procedures involving human participants were conducted in accordance with institutional and national ethical standards, as well as the 1964 Declaration of Helsinki and its later amendments. This study followed the STrengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. This retrospective study was approved by the local institutional review board (Approval number: 2025-01-013, Approval date: 05 Feb 2025).

This study retrospectively analyzed patients who underwent surgical management for TBI between February 2020 and December 2023. Of the 154 patients treated surgically for TBI, 26 (16.9%) were specifically classified as having sTBI and managed within an HOR. sTBI was classified based on institutional standards and specific clinical indicators, including the Glasgow Coma Scale (GCS) score, acute neurological and systemic signs, and neuroimaging findings (35).

The criteria for defining sTBI in this study included:

1. **Glasgow Coma Scale:** An initial GCS score of 8 or less within the first 24 h post-injury was used to identify severe impairment (36). Persistent scores of 8 or less beyond the acute phase indicated prolonged sTBI, necessitating intensive monitoring and management
2. **Acute neurological and systemic signs:** Indicators such as non-reactive pupils, hemiparesis, abnormal posturing, and irregular vital signs suggestive of brainstem dysfunction (e.g., Cushing's reflex) were considered significant markers.
3. **Neuroimaging findings:** Evidence of substantial structural brain damage on imaging, such as intracranial hemorrhages (subdural, epidural, or intraparenchymal), diffuse axonal injury, traumatic intracerebral hemorrhage (T-ICH), or significant brain edema, was a critical component of classification. Additionally, detection of blunt cerebrovascular injury using imaging modalities such as CT angiography or magnetic resonance angiography was included (26,32). Common blunt cerebrovascular injury findings encompassed arterial dissections, pseudoaneurysms, and vessel occlusions, which informed the need for targeted surgical or interventional management.

HOR

The HOR was equipped with the Allura Xper FD 20® system (Philips, Best, The Netherlands), a ceiling-mounted monoplane flat-panel detector seamlessly integrated with a three-dimensional rotational angiography workstation. This system enabled intraoperative imaging modalities such as Xper-CT® and three-dimensional rotational angiography without requiring patient movement or repositioning, ensuring efficient workflow. Although the flat panel CT resolution for brain tissue is inferior to that of standard CT, the system provides critical advantages for managing sTBI, including real-time imaging confirmation, guided interventions, and the integration of endovascular and open surgical techniques. Based on these capabilities, we utilized it for accurate intraoperative decision-making and effective planning of strategic interventions, implementing three primary approaches for sTBI management in the HOR.

1. **Xper-CT confirmation:** Intraoperative Xper-CT imaging was used to confirm the successful evacuation of intracranial hemorrhages and to monitor the development of new lesions. This imaging approach was crucial for ensuring complete removal of hematomas and maintaining real-time surveillance of the intracranial status, thereby reducing the risk of postoperative complications.
2. **Xper-CT guidance:** Xper-CT provided real-time imaging guidance for targeted interventions, such as hematoma aspiration and external ventricular drainage (EVD) placement. Using a 240° scan trajectory, the system captured 600 frames over a 20 s period at a rate of 30 frames/s, enabling high-resolution visualization. The 30×40 cm detector format allowed for detailed imaging of critical anatomical landmarks. The acquired source images were transferred to a workstation where a volumetric dataset was reconstructed within 1 min. This rapid feedback facilitated precise procedural execution and enhanced the accuracy of interventions within the hybrid setting.
3. **Combined neurointervention:** This approach incorporated neurointerventional techniques, including glue embolization, and angiography, primarily aimed at stabilizing and controlling vascular injuries associated with TBI. By achieving immediate hemostasis, these procedures minimized intraoperative bleeding risks and improved patient safety, especially in complex cases requiring both surgical and endovascular management.

Clinical Outcomes

Clinical outcomes were evaluated to assess the effectiveness and safety of the HOR treatments. Functional outcomes were measured using the Glasgow Outcome Scale-Extended (GOS-E) 6 months post-injury, categorizing the results into unfavorable outcomes (scores 1–3: death, vegetative state, or severe disability) and favorable outcomes (scores 4–8: moderate to low disability or good recovery). Assessments were conducted through neurosurgical evaluations of hospitalized patients, reviews of referral documents for transferred patients, and structured telephone interviews of discharged patients. Procedural outcomes included procedure-related morbidity and complications directly linked to systematically recorded HOR interventions. Mortality rates at 28 days and 6 months post-injury were documented, with the causes analyzed and attributed to the initial trauma, increased intracranial pressure (ICP), or other factors. Additionally, reoperation rates were tracked to assess the need for subsequent surgical interventions after the initial procedures in the HOR.

Statistical Analysis

All statistical analyses were performed using IBM SPSS version 28.0 (IBM Corp, Armonk, NY). All categorical variables are presented as percentages and 95% confidence intervals. All continuous variables are presented as means ± standard deviations.

RESULTS

A total of 26 patients with sTBI were treated at our HOR (Table I). This cohort included 16 men (60.4%) and 10 women (39.6%) with a mean age of 45.3 ± 12.0 years. The primary trauma causes included falls (n=14, 53.8%), car accidents (n=5, 19.2%), bicycle accidents (n=4, 15.4%), pedestrian injuries (n=2, 7.7%), and motorcycle accidents (n=1, 3.8%). Skull fractures were identified in all patients, including depressed (n=6; 23.1%), basilar (n=5; 19.2%), compound (n=11; 42.3%), and linear (n=4; 15.4%) fractures. Radiographic findings revealed epidural hemorrhage (EDH) in two (7.7%) patients, EDH with subdural hemorrhage (SDH) and traumatic intracerebral hemorrhage (T-ICH) in four (15.4%) patients, SDH with T-ICH in 12 (46.2%) patients, and SDH with T-ICH and intraventricular hemorrhage and traumatic subarachnoid hemorrhage in eight (30.8%) patients.

Table I: Demographics of the 26 Patients with Severe TBI Treated in the Hybrid Operating Room

Characteristic	Value
Age, mean ± SD (range), years	45.3 ± 12.0 (21–78)
Gender	**n (%)**
Male	16 (61.5)
Female	10 (38.5)
Trauma Cause	**n (%)**
Fall	14 (53.8)
Car	5 (19.2)
Bicycle	4 (15.4)
Pedestrian	2 (7.7)
Motorcycle	1 (3.8)
Initial GCS (mean)	6 (3.8)
Type of Skull Fracture	**n (%)**
Depressed	6 (23.1)
Basilar	5 (19.2)
Compound	11 (42.3)
Linear	4 (15.4)
Classification of Hemorrhage	**n (%)**
EDH	2 (7.7)
EDH + SDH + T-ICH	4 (15.4)
SDH + T-ICH	12 (46.2)
SDH + T-ICH + IVH + T-SAH	8 (30.8)

***EDH:** Epidural hemorrhage, **GCS:** Glasgow Coma Scale, **IVH:** Intraventricular hemorrhage, **SDH:** Subdural hemorrhage, **TBI:** Traumatic brain injury, **T-ICH:** Traumatic intracerebral hemorrhage, **T-SAH:** Traumatic subarachnoid hemorrhage.*

Table II presents the types of surgical procedures, applications of the HOR, and clinical outcomes in our cohort. The initial surgical approach was determined based on preoperative imaging and clinical status. Most patients underwent decompressive craniectomy and hematoma evacuation (n=23, 88.5%). In cases where the extent of injury allowed for a less invasive approach, craniotomy and hematoma evacuation were performed in three patients (11.5%). However, intraoperative Xper-CT, performed at an average of 7.5 ± 4 minutes (min) after the initial operation, identified additional findings in 10 patients (38.4%), necessitating immediate surgical modifications. Among these, contralateral craniectomy and hematoma evacuation were performed in five patients (19.2%) owing to newly detected hematoma expansion, whereas in three patients (11.5%), contralateral craniotomy and hematoma evacuation were required to address developing mass effects on the opposite side. Additionally, ipsilateral extended craniectomy was performed in two patients (7.7%) to manage rapid brain swelling requiring further decompression. All patients underwent intraoperative Xper-CT confirmation at an average of 1.7 times per patient. The mean interval from neurointervention to surgery was 14.5 ± 7 min. Xper-CT guidance was used in 11 patients (42.3%), primarily for hematoma evacuation and EVD placement. Among the surgical interventions, parenchymal hematoma aspiration was performed in eight patients (30.8%), whereas EVD placement for ICP control and monitoring was conducted in three patients (11.5%). For hemostatic control in patients with basilar skull fractures, N-butyl cyanoacrylate was used in three patients (11.5%) and polyvinyl alcohol particles in one patient (3.8%). Additionally, coil embolization was performed in three patients (11.5%) to treat pseudoaneurysms associated with traumatic vascular injuries, and intraoperative angiography was conducted in two

Table II: Surgical Procedures and Outcomes via Hybrid Operating Room

Surgical Procedures and Outcomes	n (%)
Decompressive craniectomy and hematoma evacuation	23 (88.5)
Craniotomy and hematoma evacuation	3 (11.5)
Type of application	
Xper CT confirmations	26 (100.0)
Contralateral craniectomy & hematoma evacuation	5 (19.2)
Contralateral craniotomy & hematoma evacuation	3 (11.5)
Ipsilateral extended craniectomy	2 (7.7)
Xper CT guidance	11 (42.3)
Aspiration of parenchymal hemorrhage	8 (30.8)
EVD	3 (11.5)
Combined with neurointervention	9 (34.6)
Embolization with nBCA or PVA	4 (15.4)
Coil embolization for traumatic pseudo-aneurysm	3 (11.5)
Angiography for evaluation of vessel injury	2 (7.7)
Time interval from operation to Xper CT (minutes)	7.5 ± 4
Time interval from intervention to operation (mean ± SD) (minutes)	14.5 ± 7
Re-operation after use of HOR	0 (0.0)
GOS-E at 6 months	
Good recovery	11 (42.3)
Moderate disability	9 (34.6)
Severe disability/vegetative state/death	6 (23.0)
Mean ICU stay / total hospitalization (mean ± SD) (days)	22.5±3.5 / 35.7±4.6
HOR-related morbidity	0 (0.0)
Mortality at 28 days	4 (15.4%; 95% CI, 6.2–33.5%)

***CT:** Computed tomography, **EVD:** External ventricular drainage, **GOS-E:** Glasgow Outcome Scale-Extended, **HOR:** Hybrid operating room, **ICU:** Intensive care unit, **nBCA:** N-butyl cyanoacrylate, **PVA:** Polyvinyl alcohol, **95% CI:** 95% confidence interval.*

patients (7.7%) to evaluate arterial and venous injuries. Notably, none of the 26 patients required immediate reoperation after HOR-assisted treatment. Furthermore, no HOR-related morbidities, such as surgical site infections, femoral puncture site complications, procedural rebleeding, cerebral infarction, or acute hydrocephalus requiring additional intervention, were observed. At discharge, favorable GOS-E was observed in nine patients (34.6%); however, 17 (65.4%) had unfavorable outcomes. By 6 months post-injury, the proportion of patients with good recovery, defined as a GOS-E score between 4 and 8, increased to 11 (42.3%), with moderate disability reported in nine patients (34.6%) and severe disability, vegetative state, or death occurring in six (23.0%). The mean intensive care unit stay was 22.5 ± 3.5 days, and the mean total hospitalization duration was 35.7 ± 4.6 days, reflecting the intensive care needs and prolonged recovery period in sTBI management. The 28-day mortality rate was four (15.4%), with one death (7.7%) attributed to the initial traumatic injury, two (7.7%) to increased ICP, and one (3.8%) from secondary complications, such as sepsis and pneumonia.

Illustrative Cases

Case 1 (Figure 1)

A 37-year-old male construction worker was admitted to the emergency department (ED) with altered mental status (initial GCS score: 7) following a fall from a height at a construction site. The initial brain CT revealed a sagittal skull fracture with extensive EDH, SDH, and T-ICH in the frontal lobe. The patient underwent emergency bilateral decompressive craniectomy with hematoma evacuation in the HOR. Intraoper-

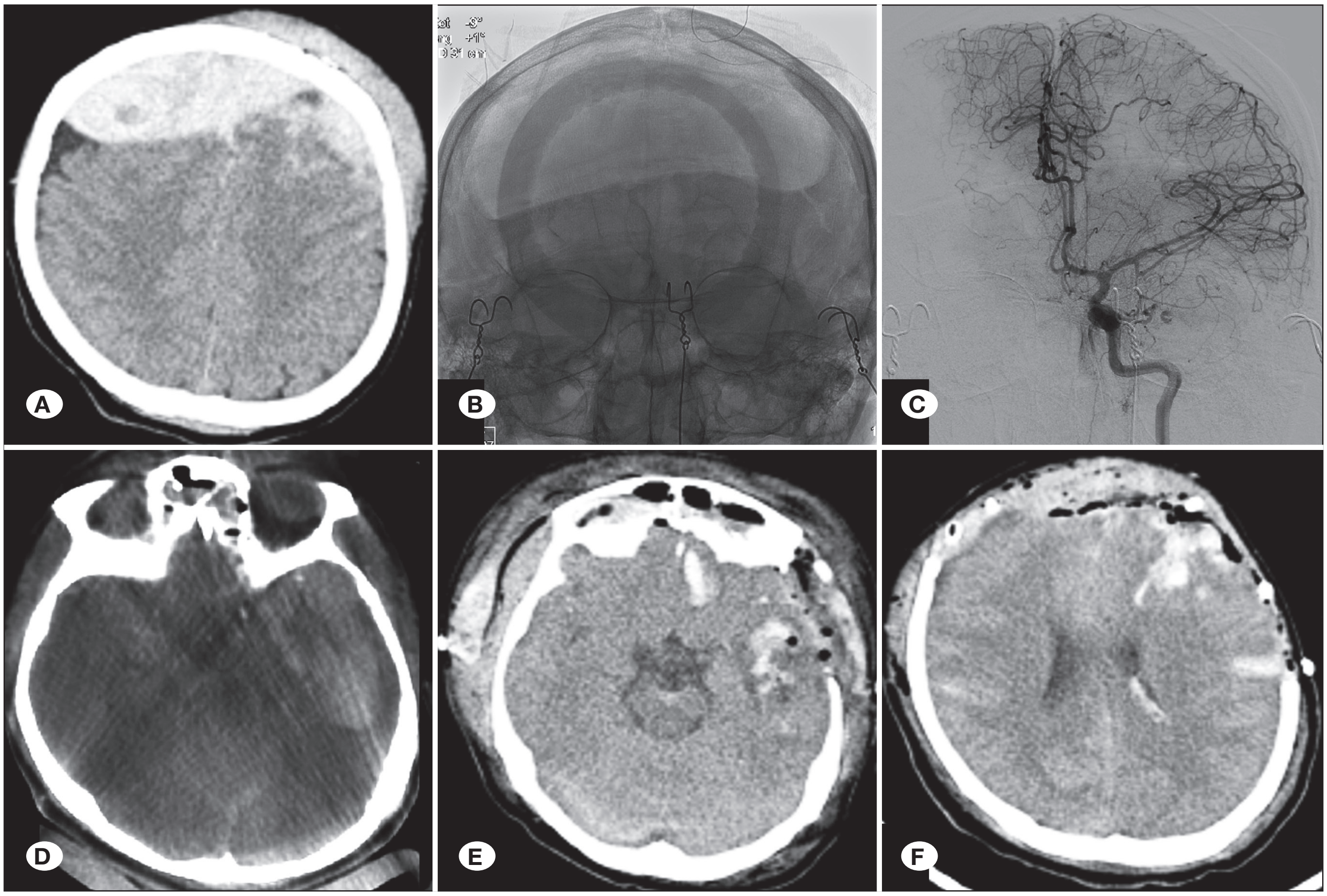

Figure 1: Illustrative case 1. **A)** Brain CT showing an epidural hematoma and subdural hematoma. **B)** Intraoperative fluoroscopic image demonstrating the extent of bifrontal decompressive craniectomy. **C)** Displaced bone fragment causing injury to the sagittal sinus and underlying dura, with cerebral angiography performed to evaluate for additional vascular injury. **D)** Intraoperative Xper CT showing a left temporal traumatic intracerebral hemorrhage. **E, F)** Postoperative CT scans showing complete evacuation of the primary hematoma and secondary evolved lesions. **CT:** computed tomography.

ative exploration revealed a sagittal sinus laceration caused by displaced bone fragments, leading to further evaluation via cerebral angiography for associated vascular injuries. Intraoperative Xper-CT revealed newly increased T-ICH levels in the left frontal and temporal regions, likely secondary to evolving parenchymal damage and venous congestion, necessitating additional hematoma evacuation. Postoperative CT confirmed the complete clearance of all traumatic hematomas. During the subsequent 2-week neurocritical care course, the patient demonstrated rapid neurological improvement, including ICP normalization, improved consciousness, and resolution of focal deficits. He was discharged for home-based rehabilitation with a GOS-E score of 7, indicating good recovery with minor neurological sequelae.

Case 2 (Figure 2)

A 36-year-old male construction worker was brought to the ED in a semi-comatose state following blunt head trauma from falling construction material and a concurrent fall of approximately 3 m. He had severe maxillofacial crush injuries and emergency decompressive craniectomy with hematoma evacuation was performed in the HOR. Intraoperative Xper-CT revealed diffuse cerebral edema without new hemorrhage but with persistent ICP elevation, indicating secondary brain injury. To manage the acute-phase ICP, EVD was performed under Xper-CT guidance to ensure accurate ventricular targeting and real-time monitoring. With aggressive neurocritical care, including ICP control and sedation, the patient's condition gradually stabilized. The patient was weaned off mechanical ventilation on postoperative day 14 and underwent tracheostomy decannulation at week 4. Eight weeks after the injury, the patient was discharged to a neurorehabilitation facility with a GOS-E score of 4, indicating moderate disability.

Case 3 (Figure 3)

A 20-year-old male was brought to the ED with altered consciousness, left-sided mydriasis, and active oral and nasal bleeding after a motorcycle accident. Brain CT revealed a large EDH, along with facial bone and basal skull fractures. Urgent glue embolization of the external carotid artery branches at the active bleeding site was performed, followed by evacuation of the EDH. The patient recovered rapidly postoperatively

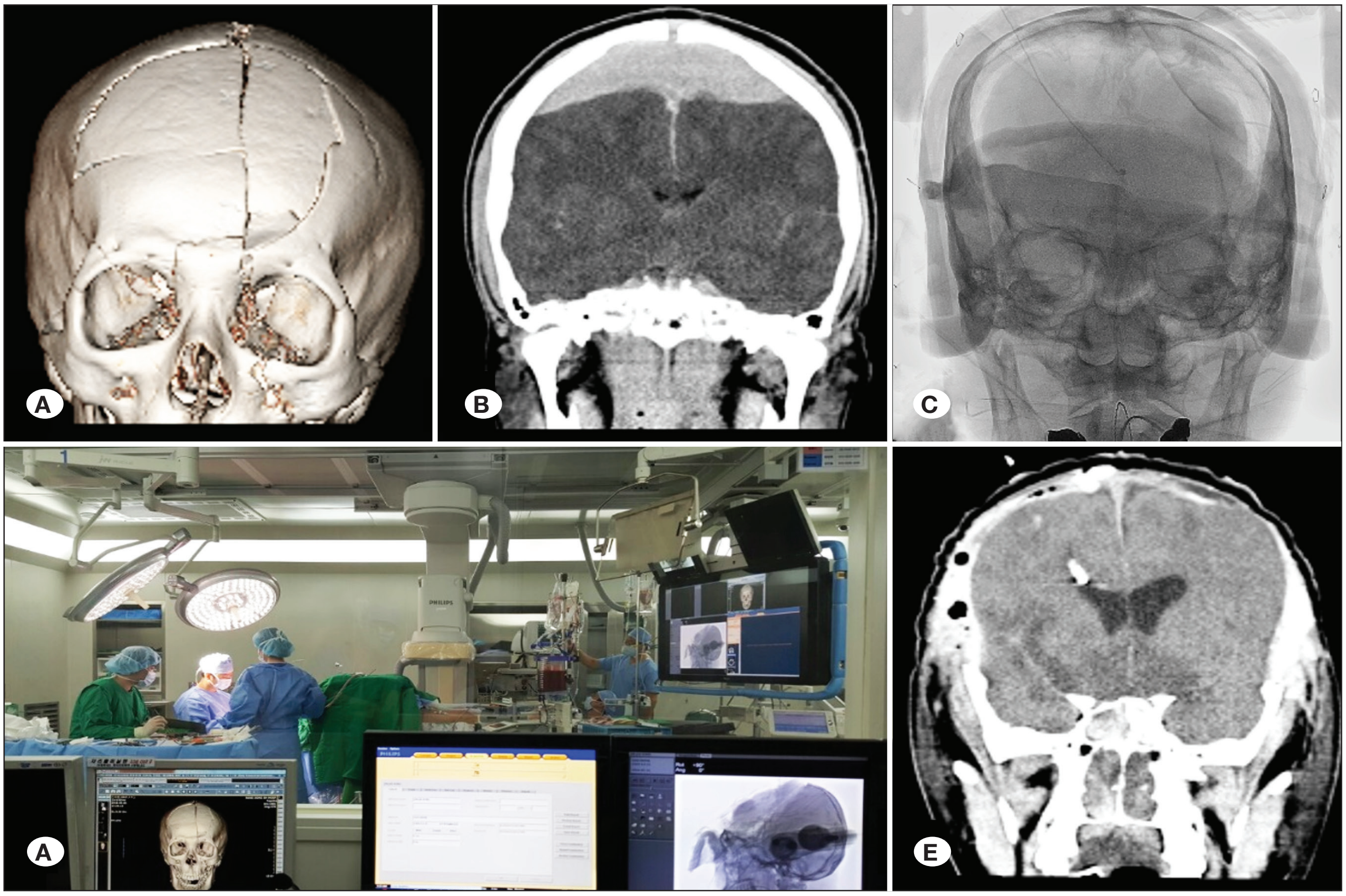

Figure 2: Illustrative case 2. **A)** 3D reconstructed CT showing a large depressed fracture of the frontal bone with a diastatic fracture along the sagittal suture. **B)** Brain CT demonstrating a subdural hematoma at the vertex and signs of IICP. **C)** Intraoperative fluoroscopic image showing the extent of bifrontal decompressive craniectomy and Xper CT-guided EVD insertion for IICP control. Intraoperative photograph in the hybrid operating room showing the actual setup, including positions of anesthesiology staff and imaging equipment. **D)** Intraoperative view of hybrid operating room. **E)** Postoperative CT showing the evacuated hematoma, inserted EVD, and ischemic injury in the basal area caused by IICP. **CT:** Computed tomography; **IICP:** Increased intracranial pressure; **EVD:** External ventricular drainage.

without complications and was discharged on postoperative day 28 without neurological deficits.

DISCUSSION

The management of sTBI requires a rapid, multidisciplinary approach to minimize secondary injuries and improve outcomes. Traditional neurosurgical workflows often involve staged interventions that require multiple imaging sessions, reoperation for delayed hemorrhage, and separate neurovascular procedures. Frequent patient transfers between the CT suite, operating room, and neurointerventional suite delay treatment and increase the risk of secondary ischemia and transport-related complications, which can worsen patient outcomes (2,18,19,23). The HOR enhances workflow efficiency by integrating intraoperative imaging, Xper-CT guided hematoma evacuation or cerebrospinal fluid drainage, and real-time neurovascular interventions within a single setting. This setup eliminates unnecessary patient transfers, enables immediate reassessment of evolving hemorrhages, and facilitates timely intervention without workflow disruptions.

Expedited management is a key determinant of TBI outcomes as delays in hematoma evacuation and neurovascular stabilization are directly linked to increased mortality (12,33). Prior studies have shown that conventional hospital workflows result in an average delay of 45 ± 12 min for initial imaging and 65 ± 18 min for neurointervention (2,12,33). In contrast, intraoperative Xper-CT in the HOR reduced these delays by 60% and 57%, respectively, enabling immediate confirmation of hematoma clearance and vessel integrity (8,22). Furthermore, the time from admission to definitive surgical intervention improved by 38%, decreasing from 120 ± 30 min to 75 ± 15 min, which is significant given that each 30-min delay in TBI intervention increases mortality risk by 20–25% (12,33). In our HOR setting, intraoperative imaging to confirm surgical results required an average of 7.5 ± 4 min, and the interval between neurointervention procedures and craniotomy was approxi-

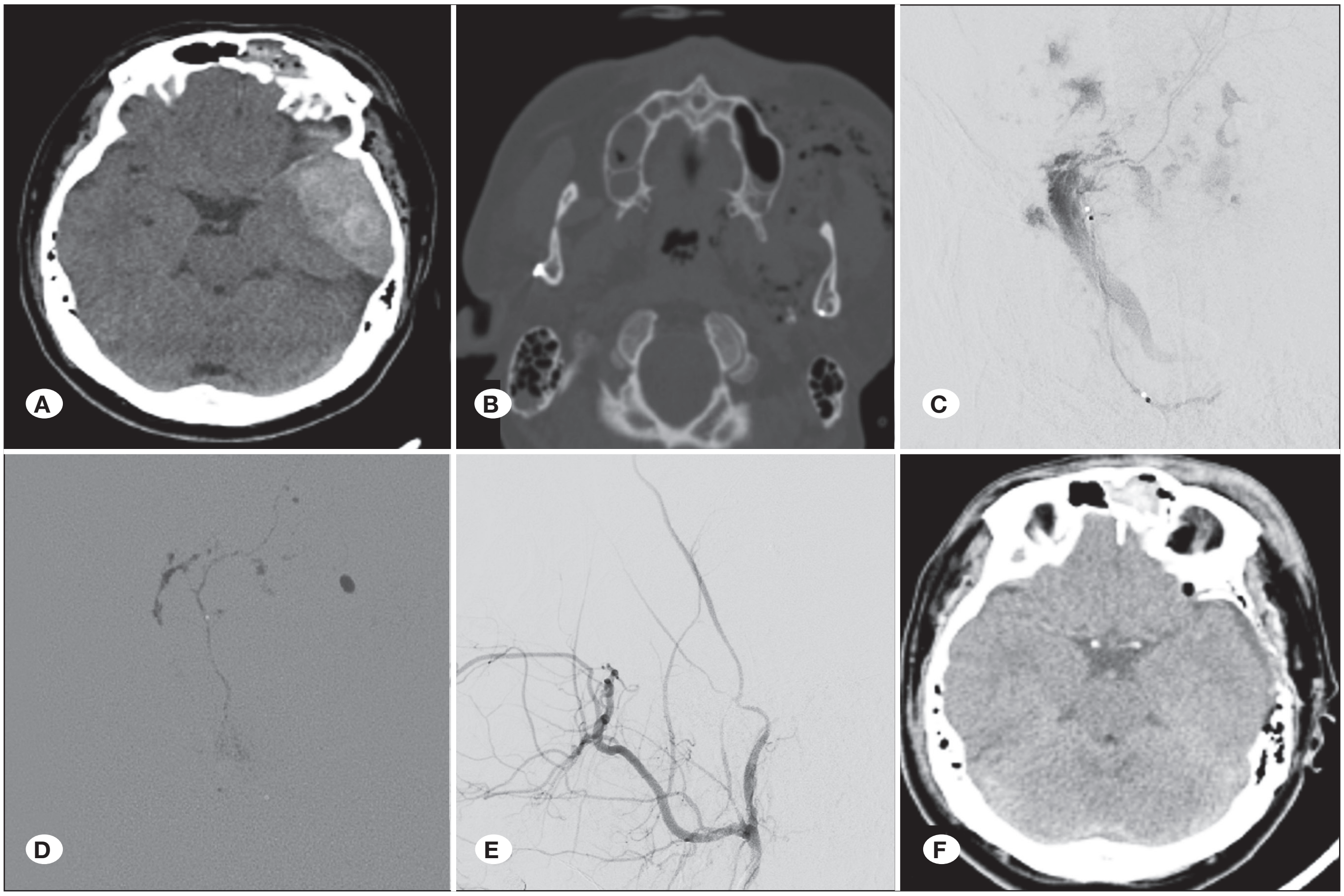

Figure 3: Illustrative case 3. **A)** Brain CT after a motorcycle accident showing an epidural hematoma and skull fracture. **B)** Facial bone CT demonstrating a large hematoma around the left maxillary and mandibular areas caused by active bleeding. **C)** n-BCA embolization of actively bleeding branches of the left external carotid artery performed in the HOR. **D, E)** Additional embolization of the left middle meningeal artery using n-BCA glue for further bleeding control. **F)** Postoperative CT scans showing complete evacuation of the primary hematoma and successful control of active bleeding. **CT:** Computed tomography; n-BCA, N-butyl cyanoacrylate glue; **HOR:** Hybrid operating room.

mately 14.5 ± 7 min, ensuring a highly efficient workflow while minimizing the risk of secondary brain injury.

Postoperative hemorrhagic progression remains a major concern in the management of sTBI, with conventional treatment protocols reporting progression rates of 15–25% (1,4,9,29). Traditional surgical workflows often fail to detect delayed intraoperative hematoma expansion, necessitating reoperation in up to 18.5% of cases because of unrecognized residual or new hemorrhages (13,40). In our study, Xper-CT was utilized intraoperatively in 100% of patients, providing immediate post-evacuation assessment and facilitating early detection of any persistent or new hemorrhagic foci. This real-time imaging modality enables prompt surgical correction and prevents delayed hematoma expansion, which may only have been detected postoperatively. Previous studies have demonstrated that the implementation of intraoperative CT may provide a nearly 60% chance of changing the surgical plan from hematoma removal to surgical decompression (5). Our findings further substantiate this trend, as none of the patients (0%) in our cohort required reoperation for postoperative hemorrhage, reinforcing the critical role of intraoperative imaging in optimizing surgical outcomes and minimizing the need for secondary interventions (4,29).

Beyond hemorrhage control, ICP elevation remains a significant secondary complication of sTBI, occurring in 23.2% of patients treated with conventional management (25,34). Delayed recognition of cerebral edema, progressive mass effect, or midline shift frequently necessitate secondary decompressive craniectomy, which has been associated with poor neurological outcomes (37). In our study, intraoperative evaluation using Xper-CT allowed immediate surgical decision-making. Postoperative Xper-CT confirmed that patients exhibiting severe ICP elevation underwent extended decompressive craniectomy and EVD without delay, demonstrating effective ICP reduction and adequate decompression. No patient required postoperative secondary decompressive craniectomy, indicating that integrating intraoperative imaging and aggressive surgical intervention within the HOR effectively mitigated the need for additional procedures. These findings align with those of previous studies emphasizing the role of real-time intraoperative ICP monitoring and hemorrhage control in reducing the need for secondary decompression and improving overall neurological outcomes (13,34,40).

The integration of the Xper-CT guidance system within the HOR significantly enhanced procedural precision in sTBI, particularly in cases that required hematoma aspiration and EVD placement (10). Given that conventional EVD placement is associated with a 21–30% misplacement rate owing to anatomical distortion following sTBI, optimizing accuracy is critical for improving patient outcomes (4,10,38). In our study, not a single misplacement occurred when Xper-CT-guided EVD placement was used, demonstrating the system's real-time trajectory visualization and immediate intraoperative feedback capability. This approach minimizes procedural errors by ensuring precise catheter placement and reducing reliance on anatomical approximations, which is particularly crucial in cases of significant cerebral edema or midline shifts (37-40). Furthermore, the incorporation of real-time X-ray flow navigation facilitated the dynamic assessment of needle trajectories and catheter depth, ensuring safer and minimally invasive interventions (25,34). Importantly, Xper-CT navigation significantly reduced the risk of inadvertent cortical injury, reinforcing its role in reducing neurotrauma surgical workflows and improving procedural safety (5,29).

Another notable benefit of the HOR is the integration of endovascular techniques, such as embolization, into the neurosurgical workflow, providing an effective approach for managing complex TBIs, particularly in cases involving extensive base of skull fractures with active hemorrhage (14,31). By enabling concurrent endovascular embolization and surgical hematoma evacuation, the HOR ensures rapid hemostasis, significantly reducing intraoperative blood loss and enhancing hemodynamic stability (17,30). Techniques such as polyvinyl alcohol particle or N-butyl cyanoacrylate glue embolization of the meningeal branches beneath the foramen spinosum or sphenopalatine branches provide precise, targeted occlusion at the hemorrhage source, effectively halting active bleeding. Additionally, in cases of traumatic pseudoaneurysms causing persistent bleeding from major arteries, such as the vertebral artery and the posterior inferior cerebellar artery, endovascular coiling offers a minimally invasive approach that not only ensures rapid hemorrhage control but also preserves the integrity of the surrounding vasculature (20). This direct endovascular approach mitigates the risk of hemorrhagic shock and minimizes the need for secondary surgical intervention, thereby ensuring effective hemorrhage control in complex neurotrauma.

Beyond hemostasis, the HOR setup facilitates the real-time identification and management of major vessel injuries, including dissection of the carotid or vertebral artery and dural sinus tears (15,16). These neurovascular complications, often difficult to address using conventional open surgical techniques alone, can be effectively managed within the hybrid environment through a synergistic approach that integrates endovascular and microsurgical interventions (6,31). The immediate availability of endovascular modalities within the HOR facilitates rapid and efficient interventions for complex neurovascular injuries, minimizing morbidity, optimizing surgical outcomes, and enhancing long-term prognoses in patients with sTBI (17,31).

Despite the promising results of the present study, a few limitations must be acknowledged. First, this was a single-center retrospective analysis, which limits the generalizability of our findings to broader populations. Although our results suggest that the HOR approach improves workflow efficiency and clinical outcomes, larger multicenter prospective studies are necessary to validate these findings across diverse institutional settings. Second, although intraoperative Xper-CT demonstrated significant advantages in real-time decision making, its resolution remains inferior to that of standard multidetector CT scanners. Consequently, small-volume hemorrhages or subtle ischemic changes may be underrecognized, potentially influencing postoperative management strategies. Third, this study focused on patients with sTBI, and the findings may not be directly applicable to mild-to-moderate TBI cases, which may require different treatment approaches. Additionally, our cohort included a relatively small sample size, which may have limited the statistical power of our outcome assessments, particularly in evaluating long-term neurological recovery. Fourth, although the HOR facilitates the integration of neurosurgical and neurointerventional techniques, it requires significant institutional investment and multidisciplinary coordination which may not be feasible in resource-limited settings. The availability of clinical staff trained in neurointerventions, dedicated hybrid surgical teams, and the financial burden of maintaining an advanced HOR infrastructure must be carefully considered when adopting this model in clinical practice.

CONCLUSION

The integration of the HOR in the management of sTBI represents a significant advancement in neurotrauma care, offering a unified platform that combines real-time imaging, neurointervention, and surgical treatment. By optimizing procedural workflows and minimizing treatment delays, the HOR approach enhances surgical precision and facilitates immediate intraoperative decision making, which may improve patient outcomes. As neurosurgical technology continues to evolve, a hybrid approach is likely to become an essential component of neurotrauma management, particularly in complex cases requiring rapid multidisciplinary intervention. However, further large-scale multicenter studies are required to validate the long-term efficacy of this approach, optimize patient selection criteria, and refine standardized protocols for broader implementation in emergency neurosurgical care.

Declarations

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Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

Disclosure: The authors declare no competing interests.

AUTHORSHIP CONTRIBUTION

Study conception and design: HSA, HJJ, SHP

Data collection: HSA, HJJ

Analysis and interpretation of results: HSA, BMC

Draft manuscript preparation: HSA, HJJ, SHP

Critical revision of the article: HSA, HJJ

All authors (HSA, BMC, HJJ, SHP) reviewed the results and approved the final version of the manuscript.

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