Trauma Surgery & Acute Care Open

High-grade liver injury: outcomes with a trauma surgery–liver surgery collaborative approach

Rafael G Ramos-Jimenez,[1] Andrew-Paul Deeb,[1] Evelyn I Truong,[1] David Newhouse,[1] Sowmya Narayanan,[1] Louis Alarcon,[1] Graciela M Bauza,[1] Joshua B Brown,[2] Raquel Forsythe,[3] Christine Leeper,[1] Deepika Mohan,[1] Matthew D Neal,[4] Juan Carlos Puyana,[3] Matthew R Rosengart,[1] Vaishali Dixit Schuchert,[1] Jason L Sperry,[2] Gregory Watson,[1] Brian Zuckerbraun,[2] J Wallis Marsh,[5] Abhinav Humar,[1] David A Geller,[1] Timothy R Billiar,[6,7] Andrew B Peitzman,[1] Amit D Tevar[1]

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/tsaco-2024-001611).

[1]Surgery, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania, USA
[2]Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[3]University of Pittsburgh Medical Center Health System, Pittsburgh, Pennsylvania, USA
[4]Surgery, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania, USA
[5]West Virginia University Health Sciences, Morgantown, West Virginia, USA
[6]Department of Surgery, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania, USA
[7]Center for Inflammation and Regenerative Modeling, University of Pittsburgh McGowan Institute for Regenerative Medicine, Pittsburgh, Pennsylvania, USA

Correspondence to
Dr Andrew B Peitzman; peitzmanab@upmc.edu

Received 21 August 2024
Accepted 23 December 2024

To cite: Ramos-Jimenez RG, Deeb A-P, Truong EI, *et al*. *Trauma Surg Acute Care Open* 2025;**10**:e001611.

ABSTRACT

Background Operative mortality for high-grade liver injury (HGLI) remains 42% to 66%, with near-universal mortality after retrohepatic caval injury. The objective of this study was to evaluate mortality and complications of operative and nonoperative management (OM and NOM) of HGLI at our institution, characterized by a trauma surgery–liver surgery collaborative approach to trauma care.

Methods This was an observational cohort study of adult patients (age ≥16) with HGLI (The American Association for Surgery of Trauma (AAST) grades IV and V) admitted to an urban level I trauma center from January 2010 to November 2021. Data were obtained from the electronic medical record and state trauma registry. Patients were categorized by management strategy: immediate OM or planned NOM. The primary outcome was 30-day mortality.

Results Our institution treated 179 patients with HGLI (78% blunt, 22% penetrating); 122 grade IV (68%) and 57 grade V (32%) injuries. All abdominal gunshot wounds and 49% of blunt injuries underwent initial OM; 51% of blunt injuries were managed initially by NOM. Procedures at the initial operation included hepatorrhaphy±packing (66.4%), nonanatomic resection (5.6%), segmentectomy (9.3%), and hepatic lobectomy (7.5%). Thirty-day mortality in the OM group was substantially lower than prior reports (23.4%). Operative mortality attributable to the liver injury was 15.7%. 19.4% of patients failed NOM with one death (1.4%).

Conclusion We report an operative mortality of 23.4% for HGLI in a trauma care system characterized by a collaborative approach by trauma surgeons and liver surgeons.

Level of evidence III

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The operative mortality for high-grade liver injury remains 50%. Multiple factors have contributed to the loss of operative skillset essential for trauma surgeons in the treatment of these challenging injuries.

WHAT THIS STUDY ADDS

⇒ Our trauma surgeons and liver surgeons have collaborated for decades in the management of these high-grade liver injuries, with a 23.4% all-causes operative mortality.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Where available, trauma surgeons and liver surgeons should formally collaborate in the care of patients with high-grade liver injuries.

INTRODUCTION

The liver is the most injured solid abdominal organ in trauma patients. Severity is classified by The American Association for Surgery of Trauma (AAST) into low-grade and high-grade liver injury (HGLI), with high grade defined as grades IV and V.[1] More than 85% of blunt hepatic trauma is initially managed nonoperatively with a high success rate.[2–14] However, many of these series include predominantly grade I to III liver injuries. Despite advances in prehospital care, resuscitation, adjunct interventions, and refinement of damage control surgery, operative mortality (most often due to bleeding) for HGLI remains 50% (range, 42–68%) over three decades.[3 4 7 8 10 15–19] Juxtahepatic caval injuries are reported as lethal in 50% to 100%.[17 20–24] A recent multicenter study stated that "mortality is certain, both in the literature and in this study for retrohepatic injuries.".[20]

The initial decision to pursue operative management (OM) or nonoperative management (NOM) of HGLI presents a significant clinical challenge, particularly in light of historically poor outcomes with OM. NOM remains the standard of care for hemodynamically stable patients with success in 80% to 100% of appropriately selected patients.[2–14] However, failure of NOM is associated with increasing grade of liver injury, hypotension, hemoperitoneum, age, Injury Severity Score (ISS), and need for hepatic angioembolization.[3 4 10–13 25]

We previously published our experience (1986–2001) with OM demonstrating the efficacy of hepatic resection for HGLI.[26 27] Considering the national trend toward NOM in trauma surgery and the extant literature demonstrating high mortality for those managed operatively, we report our recent outcomes. Furthermore, the current literature lacks a granular evaluation of staged OM and its outcomes, including collaborative approaches with liver surgeons, for patients with HGLI. For several decades, we have employed a concerted approach to liver trauma that consists of collaboration between trauma surgeons and liver surgeons (hepatobiliary surgeon or transplant surgeon). The objective of this study was to evaluate mortality and complications of OM and NOM of HGLI at our institution, characterized by a trauma surgery–liver surgery collaborative approach to trauma care. Our operative approach is detailed in this paper.

PATIENTS AND METHODS

Study population

This is an observational cohort study of HGLI (AAST Grade IV and V) in adult trauma patients (age ≥16) presenting to our institution from January 2010 to November 2021. All patients were managed as trauma activations and were met by the trauma surgery team on arrival. Ten patients underwent emergency department thoracotomy. They were excluded from the analysis, as the two published series that reported ED thoracotomy for HGLI reported a mortality of 98.1% and others have excluded these patients from the analysis.[16 28]

Demographic data, mechanism of injury, ISS, admission vital signs, interventions, length of stay (LOS), intensive care unit (ICU) LOS, lactate levels, base deficit, morbidity, mortality, and cause of death were abstracted from the electronic medical record (Cerner, Kansas City, MO) and our trauma registry (Pennsylvania Trauma Systems Foundation). Patients were categorized into two groups by clinical management strategy. The OM group was defined as those who went directly from the emergency department to the operating room for laparotomy. CT imaging was obtained first in the trauma resuscitation area for selected patients with initial hemodynamic response to resuscitation. The NOM group was defined as those managed with admission to an intensive care or medical/surgical unit for planned observation. The operative indication, details of operations, and use of angioembolization or endoscopic retrograde cholangiopancreatography (ERCP) were recorded. Failure of NOM was defined as operative intervention (laparoscopy or laparotomy) for any indication for those patients initially managed nonoperatively.

Data from a 2008 study at our institution (including patients from 1986 to 2001) were reanalyzed evaluating only grade IV and V hepatic injuries.[26] Operative procedures were performed, and mortality was determined. Further comparison was not possible because of the unavailability of additional data.

Statistical analysis

The primary outcome measure was all-cause 30-day mortality. Secondary outcomes included the failure of NOM, 30-day liver-associated morbidity (defined as bile leak, biloma, or need for ERCP) and discharge disposition. Univariate analysis was used to compare management groups. Multivariable logistic regression was used to evaluate factors associated with mortality, including the lowest systolic blood pressure in the emergency department, ISS, and liver injury grade. A composite outcome of mortality and postoperative liver-related complications was analyzed to acknowledge the competing risk of death on liver-related morbidity.

Data analysis was conducted using Stata V.17MP (StataCorp, College Station, TX). The use of the electronic medical record and trauma registry minimized missing data. After triangulating these sources, only four patients (2.2%) were missing admission systolic blood pressure. No outcome data was missing. Given this low rate of missing data, a complete case analysis was performed. Continuous data are presented as median (IQR) and compared using Mann-Whitney U tests. χ^2 or Fisher's exact test was used for categorical variables as appropriate to the data. Results from logistic regression are reported as adjusted OR (aOR) and 95% CIs. A two-tailed p value <0.05 was considered statistically significant.

Table 1 Results by management strategy

	Operative management (OM) (n=107)	Nonoperative management (NOM) (n=72)	P values
Baseline characteristics			
Age (years)	28 (21–43)	30 (23–39)	0.62
Sex (male)	69 (64.0)	38 (53.0)	0.12
MOI (blunt)	68 (64.0)	72 (100.0)	<0.01
ISS	30 (25–38)	29 (25–35)	0.61
Lowest ED SBP, mm Hg (blunt)	81 (70–96)	117 (110–130)	<0.01
Lowest ED SBP, mm Hg (penetrating)	109 (87.5–130)	–	
Failed NOM	–	14 (19.4)	
Angiography±angioembolization	27 (25.2)	24 (33.3)	0.24
Outcomes			
LOS (days)	14 (7–23)	8.5 (5–14)	0.01
ICU LOS (days)	4 (2–10)	3 (1–6)	0.1
Discharge to home	48 (44.9)	54 (75.0)	<0.01
Mortality	25 (23.4)	1 (1.4)	
Liver-related mortality	17 (15.9)	–	

Continuous variables are presented as median (IQR).
Categorical variables are presented as n (%).
HR, heart rate; ICU, intensive care unit; ISS, Injury Severity Score; LOS, length of stay; MOI, mechanism of injury; SBP, systolic blood pressure.

RESULTS

Baseline characteristics

179 patients with HGLI were included; 140 (78%) by blunt trauma, median ISS of 29 (IQR 25–38). 122 (68%) grade IV and 57 (32%) grade V injuries were admitted. 15 patients experienced HGLI with associated juxtahepatic venous injuries; 4 were penetrating and 11 were blunt mechanisms. 107 (68 blunt, 39 penetrating) patients underwent OM, 72 were admitted for NOM (table 1) (figure 1). There were no significant differences in age or ISS between management groups (p>0.05). The transperitoneal injury was the indication for laparotomy in the 38 abdominal gunshot wounds. The single abdominal stab wound was hemodynamically unstable. Primary indications for initial laparotomy for blunt trauma were hypotension defined as systolic BP≤90 mm Hg despite resuscitation (60%) and transfer after damage control at an outside hospital (10%). Of the 16 of 68 operative blunt trauma patients who underwent abdominal CT in our trauma resuscitation area, further operative indications included associated nonhepatic abdominal injury including spleen, pancreas or intestine/mesentery (17%), hypotension after CT obtained in our emergency department (8%), or other (5%). Blunt patients undergoing laparotomy, compared with those managed nonoperatively, had significantly lower systolic blood pressure (81 mm Hg (IQR70–96 mm Hg) vs. 117 mm Hg (IQR110–130 mm Hg), p<0.01), were more likely to be grade V injuries, and had higher unadjusted mortality (see table 1) (online supplemental digital content file 1). Lactate levels were 4.25 mmol/L (2.9–7 mmol/L) for the operative blunt liver injuries and 3.8 mmol/L (2.8–5.7 mmol/L) for penetrating liver injuries (p=0.53). Base deficit was 10 (6–14) for the operative blunt liver

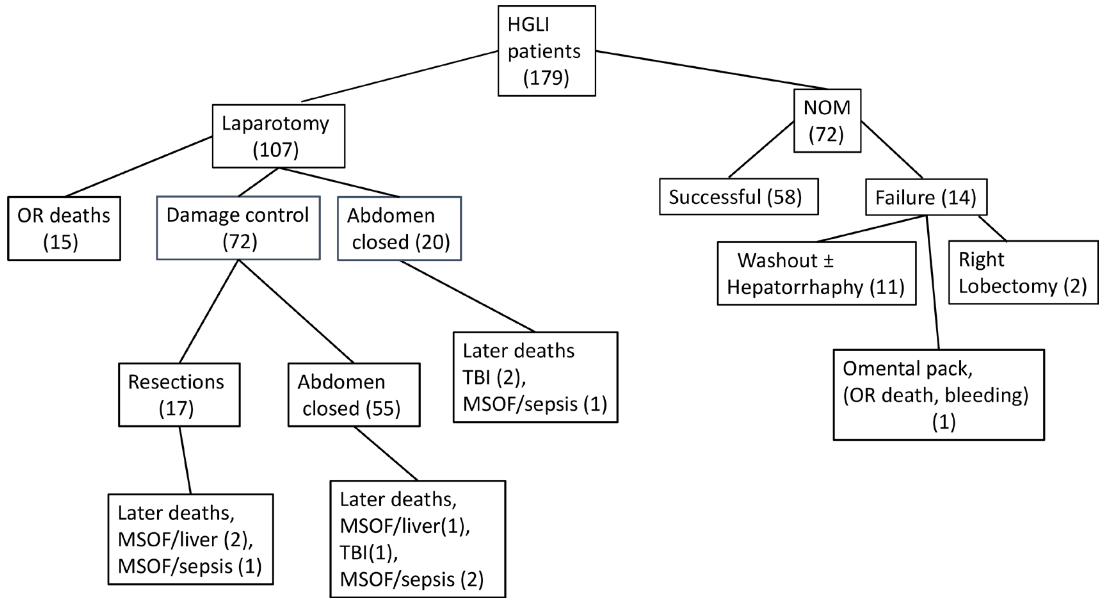

Figure 1 Flowchart of management of 179 patients admitted with high-grade liver injury. HGLI, high-grade liver injury; MSOF, multiple system organ failure; NOM, nonoperative management; OR, operating room; TBI, traumatic brain injury.

injuries and 6.5 (4–12) for penetrating liver injuries (p=0.014). These data were collected inconsistently in the NOM patients.

Operative management

All abdominal gunshot wounds and 49% of blunt injuries underwent immediate laparotomy (table 1). The median time from emergency department arrival to the operating room for the initial operation was 26 (IQR 19–32) minutes without a CT scan and 28 (IQR 20–40) minutes with a CT obtained first. Our operative approach is conceptually divided into two phases. The essential goal at the initial operation for HGLI is expedient hemorrhage control (figure 2). The return to the operating room (RTOR) after damage control is detailed in figure 3. After stabilization of the patient following damage control, an abdominal CT with IV contrast was obtained. Postoperative angioembolization was based on CT findings. RTOR occurred after 48 to 72 hours, with assessment of both the biliary system and the liver parenchyma with these findings dictating the need for resection. Assessment of the biliary system involved a cholecystectomy and intraoperative cholangiogram (IOC) via the cystic duct remnant with methylene blue or saline, followed by contrast. Assessment of the liver parenchyma was based on enhanced CT and operative findings. A significant volume of nonviable liver was generally treated with resection.

Procedures in the OM group at the initial operation included 72 (66.4%) hepatorrhaphy ± perihepatic gauze packing, 6 (5.6%) nonanatomic resections, 10 (9.3%) segmentectomies, and 8 (7.5%) hepatic lobectomies (table 2). Resections at the initial

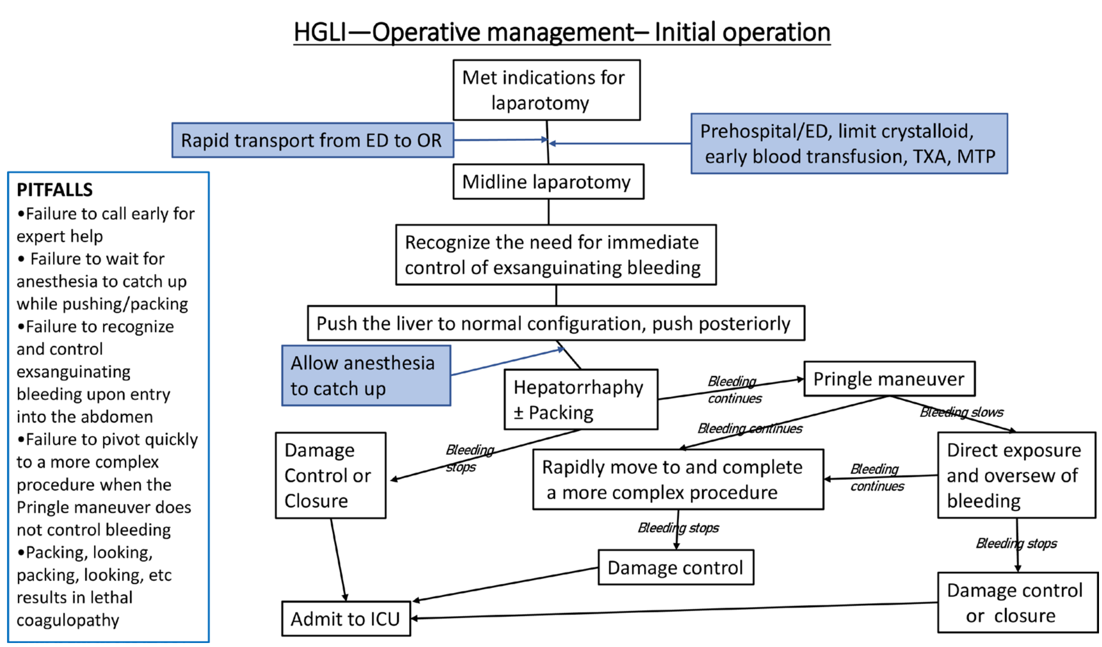

Figure 2 High-grade liver injury (HGLI)—initial operation flowchart. CVP, central venous pressure; ED, emergency department; ICU, intensive care unit; MTP, massive transfusion protocol; OR, operating room; TXA, tranexamic acid.

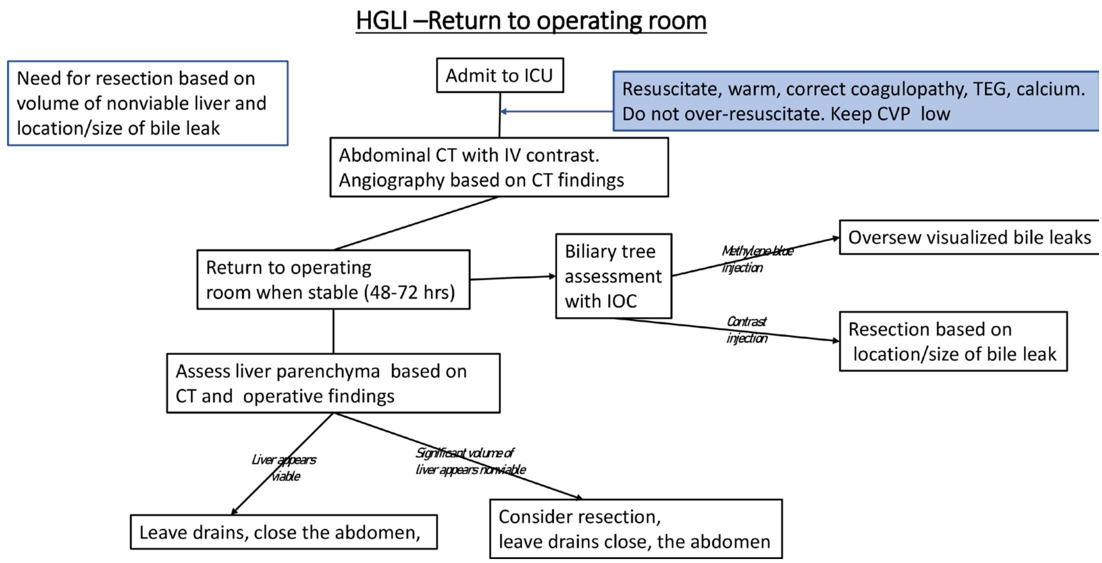

Figure 3 High-grade liver injury (HGLI)—return to operating room flowchart. CVP, central venous pressure; ICU, intensive care unit; IOC, intraoperative cholangiogram; TEG, thromboelastography.

operation, formal segmentectomy or lobectomy, are detailed in table 3 with 38.9% mortality. A liver surgeon was present at the initial operation for 40% of segmentectomies and 87.5% of lobectomies. At RTOR, 4.2% of patients underwent segmentectomy and 19.4% underwent anatomic lobectomy. The delayed anatomic resections in the OM group occurred at the second (11), third (4), fifth (1), or thirteenth (1) laparotomy, with a liver surgeon involved in 94.1% (table 4). Mortality was 17.6% for anatomic resection at RTOR (all were later deaths from MSOF). Forty-two percent of RTOR underwent IOC. Seventy percent were negative . The remaining 30% resulted in direct intervention, oversewing of a bile leak or anatomic resection. The 15 patients with juxtahepatic venous injuries underwent direct concomitant hepatic vein and/or inferior vena cava (IVC) repair (n=8) right lobectomy with repair (n=6)or nonanatomic resection with repair (n = 1) Two patients required veno-venous bypass; one with a contained suprahepatic IVC transection, the second with a retrohepatic IVC injury; both survived. Hepatic vascular isolation involving a sternotomy occurred once; he survived.

Twenty-five (23.4%) deaths occurred in the patients undergoing immediate operative intervention (tables 1, 2, and 3). The causes of mortality were bleeding (54.0%), multiple system organ failure (MSOF) due to non-hepatic sepsis (19.0%), MSOF due to liver injury (11.5%), TBI/anoxic brain injury (11.5%), and acute right heart failure from cardiac injury (4.0%). Deaths due to bleeding occurred early (92% in <6 hours). Time to death overall was <6 hours (58%), 6 to 24 hours (7%), and 1 to 30 days (35%). Operative mortality attributable to the liver injury was 15.7% (14 from hemorrhage, 3 from liver-related MSOF). Higher ED SBP (aOR 0.98; 95% CI 0.96to 0.99, p<0.01 per 1 mm Hg increase) was associated with lower odds of mortality, whereas grade V liver injury was associated with nearly fivefold higher odds of mortality (aOR 4.98; 95% CI 1.78 to 13.94, p<0.01).

Overall mortality was 56% for juxtahepatic venous injuries. During the first 5 years of the study, a second surgeon was called to assist with the operation. However, this second surgeon was a liver surgeon in only 14% of cases; the resultant mortality was 75%. In the last 7 years, as a liver surgeon assisted in 78% of

Table 2 Procedures: index operation in the OM group

Operative procedures in OM group	Number of patients (107)	Percent of OM group (%)	Mortality (%)
No hepatic intervention	1	0.90	100.00
Hepatorrhaphy and abdominal closure	20	18.70	30.00
Hepatorrhaphy and perihepatic packing	51	47.70	11.50
Hepatorrhaphy, perihepatic packing, repair portal vein, and common bile duct	1	0.90	0
Nonanatomic resection	5	4.70	40.00
Nonanatomic resection, pancreaticoduodenectomy	1	0.90	0
Repair retrohepatic IVC	3	2.80	33.30
Repair/oversew hepatic vein	3	2.80	33.30
Repair suprahepatic IVC/atrial injury	3	2.80	66.70
Superior vena cava/atrial injury, hepatic injury	1	0.90	100.00
High-grade injuries managed without anatomic resection	89	83.10	

IVC, inferior vena cava; OM, operative management .

Table 3 Anatomic resection at index operation in the OM group

Anatomic liver resection at index procedure in OM group	Number of patients	Percent of OM group (%)	Mortality (%)
Right hepatic lobectomy	6	5.50	66.70
Left hepatic lobectomy	2	1.90	0
Segments II/III resection	3	2.80	33.30
Segments II/III, portion of right lobe	2	1.90	50.00
Segment II/III, portion of IV	2	1.90	50.00
Segment II/III, IVB, V,	1	0.90	0
Segment II/III, distal pancreatectomy	2	1.90	0
High-grade injuries managed with anatomic resection at index operation	18/107	16.80	38.90

OM, operative management.

Table 4 Delayed anatomic resections (subsequent operation) in the OM group

Delayed anatomic liver resection	Number of patients	Mortality (%)
Anatomic right lobectomy	10	30
Anatomic right lobectomy, segment IV	1	0
Anatomic left lobectomy	2	0
Anatomic left, caudate lobectomy	1	0
Anatomic 5,6,7 segmentectomy	3	0
	17	17.6

OM, operative management.

cases; the mortality for retrohepatic venous injuries was 44%. Mortality based on operative approach was 42.8% for direct approach and repair and 66.7% for right lobectomy and repair.

Nonoperative management

Fifty-one percent of blunt injuries were admitted for NOM; 89% were admitted to the ICU.[2 6 11] NOM patients required angioembolization more frequently than the OM group (22.2% vs. 14.0%) (NS, p=0.15) (online supplemental digital content file 2). Of the patients undergoing angioembolization, 15.7% required subsequent liver resection for hepatic necrosis.[9 29 30]

Fourteen patients failed NOM (19.4%). The median ISS of NOM failures (32 (IQR 26–38)) was not significantly different from successful NOM (29 (IQR 24–35), p=0.44). Indications for operation in this failed NOM group were bile leak (36%), hypotension/bleeding (29%), concern for non-hepatic abdominal injury (14%), abdominal compartment syndrome (7%), increasing abdominal tenderness (7%), and large infected hepatic artery pseudoaneurysm (7%). Time to failure of NOM was <6 hours (three patients), 7 to 10 hours (five patients), 1 to 7 days (two patients), and >10 days (four patients) (see figure 1). Two of these patients required anatomic right lobectomy. One mortality occurred in the NOM group (1.4%). This patient ruptured an intrahepatic hematoma 3 hours after admission to the ICU; she died in the operating room (online supplemental digital content file 3).

Morbidity

From the total of 179 patients, 42 (23.5%) experienced biliary complications defined as bile leak, biloma, or need for ERCP; 19.4% of patients were admitted for NOM and 26.2% of patients treated with OM. Thirty-four patients developed bile leaks; 14 with bilomas and 30 patients were managed with ERCP±stent. Twenty-six ERCPs were performed postoperatively; 20 of 26 (77%) after hepatorrhaphy or nonanatomic resection, 4 after segmentectomy, and 2 after right lobectomy. When evaluating our composite outcome, grade V versus grade IV liver injury was associated with a higher odds of death or biliary complication (aOR 2.86; 95% CI 1.43 to 5.70, p<0.01), as was failed NOM (aOR 3.96; 95% CI 1.22 to 12.85, p=0.02).

Fifteen hepatic or perihepatic abscesses occurred in 14 patients (online supplemental digital content file 4). Postoperative hepatic abscesses occurred in 6 patients after hepatorrhaphy and packing, 1 after segmentectomy and no patient after lobectomy.

Reviewing the impact of the specific OM on composite biliary and hepatic infectious complications, these morbidities occurred in 41.6% of hepatorrhaphy±packing procedures, 53.8% of segmentectomies, and 12.5% of anatomic lobectomies (lobectomy vs. hepatorrhaphy, p=0.009; lobectomy vs. segmentectomy, p=0.007; hepatorrhaphy vs. segmentectomy, p=0.415).

This work differs from our prior analysis, as 52% of the earlier report were grade III liver injuries.[26] We reanalyzed the data from the 2008 report, including all operative cases (resection or nonresectional management) and included only the grade IV and V liver injuries, reviewing 104 operations for HGLI. Similar to the current series, 65% were grade IV and 35% were grade V. The blunt trauma cases treated operatively decreased from 67% to 49%. At the initial operation, 44% underwent resection in 2008 versus 22% in 2024, with a parallel increase in the use of hepatorrhaphy±packing. Nonanatomic resection decreased from 16.0% to 5.5%, and anatomic segmentectomy declined from 14.6% to 12.0%. Right or left lobectomy was performed in 10.0% in 2008 versus 20.3% in 2024. Comparing our earlier report to the current study, resections (anatomic and nonanatomic) were performed at the initial operation in 84% versus 55.8% (early vs. current) and the subsequent operation in 16% versus 44.2% (early vs. current). Overall mortality was 26.9% in 2008 versus 23.4% in this study. Intraoperative bleeding was the cause of death in 75% in 2008 versus 54% in 2024.

DISCUSSION

The current series of HGLIs reports an unadjusted operative mortality of 23.4%, with death due to liver injury in 15.7%. This is substantially lower than the 50% operative mortality in recent reports. As observed in this and other series, hepatorrhaphy±packing will tamponade the bleeding in the majority of patients, even with hepatic venous injury.[4–14] However, when these steps, followed by the Pringle maneuver or nonanatomic resection fail to control bleeding, an immediate change in strategy to a more complex operation must occur. Successful OM of these most challenging injuries often requires the additional expertise of a liver surgeon.

It is critical to understand that resection at the first operation was performed only after packing and the Pringle maneuver failed to staunch the bleeding, in an attempt to gain access to a bleeding juxtahepatic venous injury, or completing a resection that the injury had initiated. We and others[2] recommend avoidance of anatomic resection at the index operation. The anatomic resection is better tolerated in a stable patient, days after the injury and initial operation.

Planning for subsequent procedures (RTOR) included collaboration and active discussion between the trauma and the liver surgeons. The decision to proceed with resection at RTOR was based on (1) a substantial volume of nonviable liver noted on CT imaging or operative findings or (2) a demonstration of a proximal biliary duct injury on intraoperative cholangiography. The value of the IOC at RTOR has not been emphasized in the trauma literature. The operative goals at RTOR must include hemorrhage control, resection of nonviable liver, control of bile leaks, and drainage. In this circumstance, in a nonemergent, stable patient, anatomic liver resection is often the best option; it accomplishes all the goals of definitive OM of the liver injury, with significantly lower biliary/infectious morbidity in this series.[8 26 29 31–37]

A paradigm shift essentially abandoning formal hepatic resection followed studies from 1983 to 1990 documenting hepatic resection applied in 4% of patients with 55% mortality.[8 28 38] More recent case series from centers involving liver surgeons suggest better outcomes.[8 26 27 29 31–37] With our collaborative team of trauma surgeons and liver surgeons, hepatic resection is a major component of our OM. The total number of anatomic resections (lobectomy or segmentectomy) in this series was 37 patients: 18 at initial operation, 17 at re-exploration, and 2 for failure of NOM. Thus, 29% of patients requiring early operation or for surgical rescue of failed NOM (126 total) underwent anatomic liver resection.

The majority of blunt HGLIs can be safely managed nonoperatively in the hemodynamically stable patient.[2–14] The mortality for NOM in this series was 1.4%. However, many of these patients required an intervention (angioembolization, ERCP, interventional radiology drainage) for control of bleeding or treatment of a complication. This multidisciplinary approach remains important in the NOM of hepatic injury.[39] 19.4% of our patients admitted for NOM underwent an operation for a complication. Several authors have proposed that laparoscopic washout should be considered an extension of NOM rather than a failure of NOM.[2 5 40 41]

Our institutional model for the care of the HGLI is a collaborative approach of trauma surgeons with the liver surgeons. It is important to understand that our approach is beyond the sporadic involvement of the liver surgeon in the OM of these major liver injuries. It is an active partnership and collaboration between the liver surgeons and the trauma surgeons—a unified, standardized management strategy. In addition to the incorporation of their technical expertise in the OM of the HGLI, the collaboration includes joint decision-making on HGLI in the operating room, discussions in the ICU on both operative and NOM cases, joint development of patient management guidelines and algorithms, performance improvement with a shared review of protocol compliance, and outcomes and research projects. Additionally, participation by the trauma surgeon with the liver surgeon as the mentor and master surgeon in elective hepatic cases provides an invaluable opportunity for learning. A clear benefit of this collaboration has been the expansion of the skillset of our trauma surgeons following a common algorithmic guideline when dealing with HGLI in the operating room. The skills acquired were proportional to the time invested by the trauma surgeon with the liver surgeons.

We acknowledge that many institutions do not have hepatobiliary or liver transplant surgeons. However, we posit that in the majority of centers with liver surgeons on staff, the trauma surgeons and liver surgeons do not work collaboratively or optimally in the comprehensive management of these challenging injuries. A major goal of this study is to encourage a deliberate collaboration rather than a siloed approach where the expertise is available. In institutions without access to liver surgeons, the trauma surgeons must master the basic operative maneuvers for initial control of the bleeding liver: push, pack, the Pringle maneuver, local hemostatics, and energy devices. These basic maneuvers will provide tamponade with the majority of liver injuries. The patient can then be transferred to a center with hepatobiliary expertise for definitive management of the liver injury.

The study does have limitations. It is a retrospective study from a single institution. In addition, the structure of the trauma and transplant teams may not reflect that in other hospitals. The potential for confounding variables exists due to the retrospective nature of the study and other changes in resuscitation of the severely injured trauma patient over the time period of the study, which could result in differential outcomes. With concern for possible selection bias, we critically reviewed the records in detail, specifically addressing the indication for operation. Of the 16 patients who underwent CT prior to laparotomy at our institution, the indication for laparotomy was questionable in five cases. Excluding these cases would increase the operative mortality by only 1.5%. If these five cases had been managed nonoperatively, the proportion of blunt trauma victims managed operatively would have decreased from 49% to 45%.

CONCLUSION

This series reports an operative mortality of 23.4% for HGLI and timely surgical rescue of patients who fail NOM (1.4% mortality). We describe our institutional model for management of HGLI, which involves a collaborative approach of trauma surgeons with the liver surgeons. In addition, the current outcomes corroborate our 2008 report and demonstrate the maturity of our collaborative approach to HGLI.

Contributors RGR-J, A-PD, JBB, MN, MRR, ABP, and ADT (participated in research design, writing of the paper, performance of the research, and data analysis); EIT, DN, and SN (participated in writing of the paper, performance of the research, and data analysis); LA, GMB, RF, CL, DM, JCP, VDS, JLS, GW, BZ, JWM, AH, DAG, TRB (participated in research design, writing of the paper, and data analysis). ABP is the guarantor. Contribution to new reagents or analytic.

Funding This study was funded by NIH (5T32CA113263, R35GM119526)NIH Training Grant (T32GM008516).

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by the University of Pittsburgh IRB, Study #20070277 with waiver of consent.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request.

ORCID iDs

Joshua B Brown http://orcid.org/0000-0002-6936-035X
Christine Leeper http://orcid.org/0000-0001-9902-0340
Matthew D Neal http://orcid.org/0000-0001-8931-6236
Jason L Sperry http://orcid.org/0000-0003-3917-6479
Andrew B Peitzman http://orcid.org/0000-0001-7118-6576

REFERENCES

1 Kozar RA, Crandall M, Shanmuganathan K, Zarzaur BL, Coburn M, Cribari C, Kaups K, Schuster K, Tominaga GT, AAST Patient Assessment Committee. Organ injury scaling 2018 update: Spleen, liver, and kidney. *J Trauma Acute Care Surg* 2018;85:1119–22.
2 Coccolini F, Coimbra R, Ordonez C, Kluger Y, Vega F, Moore EE, Biffl W, Peitzman A, Horer T, Abu-Zidan FM, *et al*. Liver trauma: WSES 2020 guidelines. *World J Emerg Surg* 2020;15:24.
3 Polanco PM, Brown JB, Puyana JC, Billiar TR, Peitzman AB, Sperry JL. The swinging pendulum: a national perspective of nonoperative management in severe blunt liver injury. *J Trauma Acute Care Surg* 2013;75:590–5.
4 Leppäniemi AK, Mentula PJ, Streng MH, Koivikko MP, Handolin LE. Severe hepatic trauma: nonoperative management, definitive repair, or damage control surgery? *World J Surg* 2011;35:2643–9.
5 David Richardson J, Franklin GA, Lukan JK, Carrillo EH, Spain DA, Miller FB, Wilson MA, Polk HC, Flint LM. Evolution in the management of hepatic trauma: a 25-year perspective. *Ann Surg* 2000;232:324–30.
6 Ottolino P, Pust GD, Peck G, Razek T. Management of Liver Injuries: The Panamerican Trauma Society 2018 Consensus Guidelines. *Panam J Trauma Crit Care Emerg Surg* 2019;8:133–8.
7 Gaski IA, Skattum J, Brooks A, Koyama T, Eken T, Naess PA, Gaarder C. Decreased mortality, laparotomy, and embolization rates for liver injuries during a 13-year

period in a major Scandinavian trauma center. *Trauma Surg Acute Care Open* 2018;3:e000205.
8 Pachter HL. Prometheus bound: evolution in the management of hepatic trauma--from myth to reality. *J Trauma Acute Care Surg* 2012;72:321–9.
9 Keric N, Shatz DV, Schellenberg M, de Moya M, Moore LJ, Brown CVR, Hartwell JL, Inaba K, Ley EJ, Peck KA, *et al*. Adult blunt hepatic injury: A Western Trauma Association critical decisions algorithm. *J Trauma Acute Care Surg* 2024;96:123–8.
10 van der Wilden GM, Velmahos GC, Emhoff T, Brancato S, Adams C, Georgakis G, Jacobs L, Gross R, Agarwal S, Burke P, *et al*. Successful Nonoperative Management of the Most Severe Blunt Liver Injuries. *Arch Surg* 2012;147:423–8.
11 Boese CK, Hackl M, Müller LP, Ruchholtz S, Frink M, Lechler P. Nonoperative management of blunt hepatic trauma: A systematic review. *J Trauma Acute Care Surg* 2015;79:654–60.
12 Rouy M, Julien C, Hamouda I, Massalou D, Bege T, Leone M, Berdah S, Barbois S, Girard E, Arvieux C, *et al*. Predictive factors of non-operative management failure in 494 blunt liver injuries: a multicenter retrospective study. *Updates Surg* 2022;74:1901–13.
13 Hurtuk M, Reed RL II, Esposito TJ, Davis KA, Luchette FA. Trauma Surgeons Practice What They Preach: The NTDB Story on Solid Organ Injury Management. *J Trauma Inj Infect Crit Care* 2006;61:243–55.
14 Barbier L, Calmels M, Lagadec M, Gauss T, Abback P-S, Cauchy F, Ronot M, Soubrane O, Paugam-Burtz C. Can we refine the management of blunt liver trauma? *J Visc Surg* 2019;156:23–9.
15 Duane TM, Como JJ, Bochicchio GV, Scalea TM. Reevaluating the Management and Outcomes of Severe Blunt Liver Injury. *J Trauma Inj Infect Crit Care* 2004;57:494–500.
16 Asensio JA, Roldan G, Petrone P, Rojo E, Tillou A, Kuncir E, Demetriades D, Velmahos G, Murray J, Shoemaker WC, *et al*. Operative Management and Outcomes in 103 AAST-OIS Grades IV and V Complex Hepatic Injuries: Trauma Surgeons Still Need to Operate, but Angioembolization Helps. *J Trauma Inj Infect Crit Care* 2003;54:647–54.
17 Huerta S, Bui TD, Nguyen TH, Banimahd FN, Porral D, Dolich MO. Predictors of mortality and management of patients with traumatic inferior vena cava injuries. *Am Surg* 2006;72:290–6.
18 Braschi C, Keeley JA, Balan N, Perez LC, Neville A. Outcomes of Highest Grade (IV and V) Liver Injuries in Blunt and Penetrating Trauma. *Am Surg* 2022;88:2551–5.
19 Richardson DJ. Changes in the Management of Injuries to the Liver and Spleen. *J Am Coll Surg* 2005;200:648–69.
20 Stonko DP, Azar FK, Betzold RD, Morrison JJ, Fransman RB, Holcomb J, Bee T, Fabian TC, Skarupa DJ, Stein DM, *et al*. Contemporary Management and Outcomes of Injuries to the Inferior Vena Cava: A Prospective Multicenter Trial From PROspective Observational Vascular Injury Treatment. *Am Surg* 2021;89:714–9.
21 Buckman RF Jr, Miraliakbari R, Badellino MM. Juxtahepatic Venous Injuries: A Critical Review of Reported Management Strategies. *J Trauma Inj Infect Crit Care* 2000;48:978–84.
22 Bardes JM, Grabo D, Lam L, Tadlock MD, Strumwasser A, Inaba K. Treatment algorithm and management of retrohepatic vena cava injuries. *J Trauma Acute Care Surg* 2017;83:340–4.
23 Zargaran D, Zargaran A, Khan M. Systematic Review of the Management of Retro-Hepatic Inferior Vena Cava Injuries. *Open Access Emerg Med* 2020;12:163–71.
24 Castater CA, Carlin M, Parker VD, Sciarretta C, Koganti D, Nguyen J, Grant AA, Smith RN, Ramos CR, Sciarretta JD, *et al*. Intra-abdominal Inferior Vena Cava Injuries: Operative Strategies and Outcomes. *Am Surg* 2021;87:1316–26.
25 Dabbs DN, Stein DM, Scalea TM. Major Hepatic Necrosis: A Common Complication After Angioembolization for Treatment of High-Grade Liver Injuries. *J Trauma Acute Care Surg* 2009;66:621–9.
26 Polanco P, Leon S, Pineda J, Puyana JC, Ochoa JB, Alarcon L, Harbrecht BG, Geller D, Peitzman AB. Hepatic resection in the management of complex injury to the liver. *J Trauma* 2008;65:1264–9;
27 Peitzman AB, Marsh JW. Advanced operative techniques in the management of complex liver injury. *J Trauma Acute Care Surg* 2012;73:765–70.
28 Cogbill TH, Moore EE, Jurkovich GJ, *et al*. Severe hepatic trauma: a multi-center experience with 1,335 liver injuries. *J Trauma Acute Care Surg* 1988;28:1433–8.
29 Dabbs DN, Stein DM, Philosophe B, Scalea TM. Treatment of Major Hepatic Necrosis: Lobectomy Versus Serial Debridement. *J Trauma Acute Care Surg* 2010;69:562–7.
30 Segalini E, Morello A, Leati G, Di Saverio S, Aseni P. Primary angioembolization in liver trauma: major hepatic necrosis as a severe complication of a minimally invasive treatment-a narrative review. *Updates Surg* 2022;74:1511–9.
31 Strong RW, Lynch SV, Wall DR, Liu CL. Anatomic resection for severe liver trauma. *Surgery* 1998;123:251–7.
32 Tsugawa K, Koyanagi N, Hashizume M, Ayukawa K, Wada H, Tomikawa M, Ueyama T, Sugimachi K. Anatomic resection for severe blunt liver trauma in 100 patients: significant differences between young and elderly. *World J Surg* 2002;26:544–9.
33 Ball CG. Hepatobiliary and pancreatic hemorrhage: Technical tools and tricks. *Surg Open Sci* 2022;7:22–5.
34 Barrie J, Jamdar S, Iniguez MF, Bouamra O, Jenks T, Lecky F, O'Reilly DA. Improved outcomes for hepatic trauma in England and Wales over a decade of trauma and hepatobiliary surgery centralisation. *Eur J Trauma Emerg Surg* 2018;44:63–70.
35 Streith L, Silverberg J, Kirkpatrick AW, Hameed SM, Bathe OF, Ball CG. Optimal treatments for hepato-pancreato-biliary trauma in severely injured patients: a narrative scoping review. *Can J Surg* 2020;63:E431–4.
36 Barcu A, Mitricof B, Verdea C, Balanescu L, Tomescu D, Droc G, Lupescu I, Hrehoret D, Braşoveanu V, Popescu I, *et al*. Definitive Surgery for Liver Trauma in a Tertiary HPB Center (with video). *chr* 2021;116:678.
37 Badger SA, Barclay R, Campbell P, Mole DJ, Diamond T. Management of liver trauma. *World J Surg* 2009;33:2522–37.
38 Beal SL. Fatal hepatic hemorrhage: an unresolved problem in the management of complex liver injuries. *J Trauma Acute Care Surg* 1990;20:163–9.
39 Carrillo EH, Spain DA, Wohltmann CD, Schmieg RE, Boaz PW, Miller FB, Richardson JD. Interventional Techniques Are Useful Adjuncts in Nonoperative Management of Hepatic Injuries. *J Trauma Inj Infect Crit Care* 1999;46:619–24.
40 Chu M, How N, Laviolette A, Bilic M, Tang J, Khalid M, Bos C, Rice TJ, Engels PT. Delayed laparoscopic peritoneal washout in non-operative management of blunt abdominal trauma: a scoping review. *World J Emerg Surg* 2022;17:37.
41 Franklin GA, Richardson JD, Brown AL, Christmas AB, Miller FB, Harbrecht BG, Carrillo EH. Prevention of bile peritonitis by laparoscopic evacuation and lavage after nonoperative treatment of liver injuries. *Am Surg* 2007;73:611–6;