Editorial

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EVTM After COVID

Rishi Kundi, Jonathan Morrison and Thomas Scalea

R. Adams Cowley Shock Trauma Center, Baltimore, MD, USA

The start of the 2021 EVTM Symposium last month came more than two years after the Pan-American meeting in Denver. For many of us, it was the first time we had traveled internationally since that meeting. For all of us, it was a long-awaited reunion of colleagues.

During that interval, medicine seemed to evolve to be COVID and nothing but COVID. Even the contents of medical journals hinted that the novel coronavirus was the only game in town, regardless of the specialty or topics typically covered. Yet other medical problems continued. In Baltimore, every day of the past two years we cared for victims of motor vehicle collisions, shootings, stabbings, and the usual improbable accidents. Trauma volumes fell for the first six weeks of the pandemic and then rebounded with enthusiasm – particularly trauma from interpersonal violence.

Sadly, Baltimore will likely set yet another per capita record for homicides in 2021. Given the sophistication of the Maryland Trauma System, one can only postulate how much worse it could be without this system. The strain of the pandemic has made rapid resuscitation and treatment even more difficult, but the trauma community everywhere showed up, working around the clock and around the limitations of the pandemic, and did the best they could.

The pandemic and its response provide a clear lesson for the EVTM constituency. When presented with a universal threat from unknown pathology, medicine scrambled to investigate, respond, and devise the best possible treatment. The omnipresent turf wars went away. There were no society statements proclaiming that COVID pneumonia was properly the province of the intensivist. Pulmonologists did not angrily declaim that hematologists had no business managing COVID coagulopathy.

Instead, there was a mad rush to collaborate. Information was prized and those who found it celebrated, regardless of their field. In academic institutions, community medical centers, and *ad hoc* field hospitals, nephrologists were given crash courses in ventilator management and family practice doctors refreshed their central line techniques. For the last two years, medicine has not been about domain and territory; it has been about having someone at the bedside when someone is needed at the bedside. It has been about having a set of skills when those skills were needed.

Our motto – "no ego, just good science and collaboration" – could easily have been that of our COVID response. As the world starts to resume its routines, the discussions and debates about trauma and resuscitation care have picked up again. Commentaries, responsa, and letters to the editors debate who is best equipped to care for these patients. Compared to those before the pandemic, these claims are no longer laced with righteous indignation. Instead of stubborn flag-planting, the pieces end with an assertion that cooperation is needed, that the way forward is together. Perhaps the pandemic has reminded all of medicine that we must stand, and work, together.

At Shock Trauma, we have been pleased to be at the forefront of the use of endovascular care for trauma. We pride ourselves in harnessing collaborative expertise from diverse practitioners from many disciplines when caring for the sickest and most complex patients in the United States. We were honored to present a session in Sweden and hope it was useful to the audience. In this spirit, we are pleased to announce that the 2022 EVTM Symposium will be held in Baltimore, Maryland. The R. Adams Cowley Shock Trauma Center looks forward to hosting all of you and to further discussions about the future of endovascular trauma care and resuscitation.

Corresponding author:
Rishi Kundi, Assistant Professor of Surgery, University of Maryland School of Medicine, Programs in Trauma, Vascular/Endovascular Trauma, and Critical Care, R. Adams Cowley Shock Trauma Center, University of Maryland Medical Center, Baltimore, MD, USA.

Email: RKundi@som.umaryland.edu

Editorial

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REBOA for Inter-Hospital Transfer: Are We Walking in the Dark?

Maya Paran[1], Mickey Dudkiewicz[2] and Boris Kessel[1]

[1]Division of General Surgery, The Hillel Yaffe Medical Center, Hadera, affiliated with The Rappaport School of Medicine, Technion, Haifa, Israel
[2]Hospital Administration, Hillel Yaffe Medical Center, Hadera, Israel

Worldwide, interest in resuscitative endovascular balloon occlusion of the aorta (REBOA) for different indications is consistently growing. Initially implemented for trauma and vascular surgery, the current literature includes multiple publications reflecting successful broadening indications for the use of REBOA, including non-traumatic bleeding, obstetrics catastrophes, prehospital care, and many others. Over recent years, experience with REBOA has been growing with a better understanding of various physiological processes occurring during REBOA use. Continuous efforts are being made to increase and diversify REBOA indications. Recently, we are witnessing an attempt to insert REBOA for inter-hospital transfer.

Transfer of patients to a higher level-of-care hospital is, without a doubt, an important aspect of trauma care, aimed to provide optimal care for all trauma patients. The key fundamentals of this sophisticated process involve the decision to transfer, strict protocols of communication between hospitals, choosing the optimal transportation mode and the appropriate team, and ensuring adequate documentation of events occurring before and during the transfer. The central and probably the most important element is the decision regarding pretransfer patient's stabilization procedures. The question of whether unstable patients may be transported safely remains open and has been readdressed in multiple debates.

May REBOA make trauma patients' transfer safer? There are multiple reports of successful "out-of-hospital" REBOA use, including military/other austere environment settings as well as civil prehospital REBOA [1–4]. Lastly, several reports of REBOA performed for inter-hospital transfer have been published, including in the pages of *JEVTM*. For example, Beldowicz et al., in the first REBOA use for inter-hospital transfer, described a balloon inflation time of nearly two hours when previously unprepared paramedics were instructed to inject an additional 4 mL of saline into the balloon whenever the patient became hypotensive during the transport [5]. The possible consequences of REBOA use during transportation have been well described in a review study by Goforth et al. [6]. However, even when reporting on a safe air evacuation, the authors concluded that, due to the risk of potentially life-threatening balloon migration, REBOA is contraindicated during flight [6]. Nevertheless, it remains unclear which data supports this conclusion.

In our certainly debatable opinion, these publications raise several concerns that should be evaluated and addressed before any conclusions can be made. First, we assume that significant differences exist between prehospital or military settings, where REBOA serves as a last resort to get the patient alive to reasonable medical care and inter-hospital transfer. We are completely aware of the variety of different national trauma systems, times of transportation, and distances between countries. The reported American College of Surgeons (ACS) definitions of trauma care levels also vary significantly between countries. For example, in Israel, the single difference between a Level I and II trauma center is a lack of cardiothoracic and neurosurgical services in a Level II center. Therefore, REBOA use for inter-hospital transfer, in the vast majority of cases, is not relevant in most situations where a patient is being transferred from a Level II to a Level I center. The reality is very different in larger countries, with longer transportation times and greater differences in the abilities of various trauma centers.

Adaptation of REBOA use for inter-hospital transfer requires addressing some fundamental questions. When the patient is stable before the transfer, is there any role for insertion of a REBOA balloon without inflation? Is it to reassure the referring team only? Or is it rather a new tool that may mark a new transfer era and allow for a safer transfer? Do we really know how many initially

Corresponding author:
Maya Paran, MD, Hillel Yaffe Medical Center, Ha-Shalom St., Hadera, 3846201, Israel.
Email: paran.maya@gmail.com

stable/resuscitation-responding patients have deteriorated during their transportation?

In this editorial, we call for action and for the conduction of a multicenter study, which may shed some light on this issue. When the patient is unstable before the transfer, is there any role for the REBOA balloon inside? After all, we know that the maximal safe inflation time for REBOA is approximately 60 minutes. How should we act in cases when the expected transportation time is much longer? Is the use of partial/intermittent REBOA during the transport safe? Especially when performed by an inexperienced team? Perhaps better definitions of specific scenarios in which a patient should be evacuated directly to a Level I trauma center could prevent the need for inter-hospital transfer.

In summary, we believe that there are more questions than answers regarding this matter. In order to shed some light on this topic, we would like to emphasize the need for an open discussion in this journal.

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Original Article

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Flying with a Safety Net: Use of REBOA to Enable Safe Transfer to a Level 1 Trauma Center

Robert Weir, Jeffery Lee, Shelly Almroth and Jodie Taylor

St. Anthony Summit Medical Center, Frisco, CO, USA

Background: Using Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) during air and ground transport requires coordination among the responding clinical team, transport team, and receiving surgical team. Here we describe the development of a REBOA transport program in a civilian medical system that demonstrates the value of REBOA as part of the toolkit for safe casualty transport.
Methods: The regional REBOA program was developed at St. Anthony Summit Medical Center (SASMC) in a multistep planning and training process to ensure coordination among the facilities and transport resources during trauma patient care. Retrospective record review was performed on all patients ($n = 5$) that received REBOA for transport from the Level 3 Trauma Center to the Level 1 Trauma Center, since the inception of the program in March 2019. Data were gathered from hospital electronic medical records.
Results: SASMC has transported five trauma patients under the REBOA program; all successfully arrived at the Level 1 Trauma Center to receive definitive care. The integrated arterial blood pressure monitoring capability in the REBOA catheter provided robust physiologic data to enable data-driven interventions during transport.
Conclusions: The REBOA program described here is a model of how REBOA can be used to enable safe transport between levels of care when, without REBOA, such transport might not be possible. The model is applicable during care of civilian trauma patients and combat casualties, where injured patients are initially treated in a prehospital or Role 1/2 environment but require transport to a Level 1 Trauma Center or Role 3+ for definitive care.

Keywords: *REBOA; Non-compressible Hemorrhage; Patient Transport*

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INTRODUCTION

In the past 40 years, trauma systems in the United States have moved to a regionalized approach to health services including trauma care to provide optimal care through the rational distribution of medical services. Although difficult to isolate as a stand-alone factor, research has shown regional networks of trauma systems to be effective in reducing trauma related mortality [1]. Transfer of select patients from hospitals with fewer resources and capabilities to those with higher capabilities has numerous advantages; however, inherent in this approach is a period where the patient moves into a care environment with lower resources and capabilities, such as either a ground or air ambulance. In order to mitigate this risk, several approaches are routine, including preparing the patient for transfer, reducing exposure to the lower capability time using high-speed platforms such as helicopters, and the strategic addition of capabilities to transport platforms.

St. Anthony Summit County Regional Medical Center is a state-verified Level 3 Facility located in Frisco, Colorado, USA. As part of our ongoing process improvement efforts, we conducted an analysis of the capabilities at our facility, the affiliated Level 1 facility, and our transport platforms in an effort to identify opportunities for improved safety of trauma patients during transport. Transport times are managed through the use of a high-speed helicopter platform (Figure 1) that has both a higher speed and bypasses traffic delays, which can be significant due to a lack of redundant ground transportation corridors between the Level 3 in Summit County and the affiliate Level 1 in the Denver Metro Area (Figure 2). Transportation times in this system are generally around 1 hour; however, when weather conditions deteriorate, these times can be greatly extended as ground transportation

Corresponding author:
Jodie Taylor, 340 Peak One Drive, Frisco, CO 80443, USA.
Email: jodietaylor.md@gmail.com

Figure 1 Flight for Life Colorado provides helicopter transport for critically ill patients from St. Anthony Summit Medical Center (Level 3 Trauma Center) to St. Anthony Hospital (Level 1 Trauma Center).

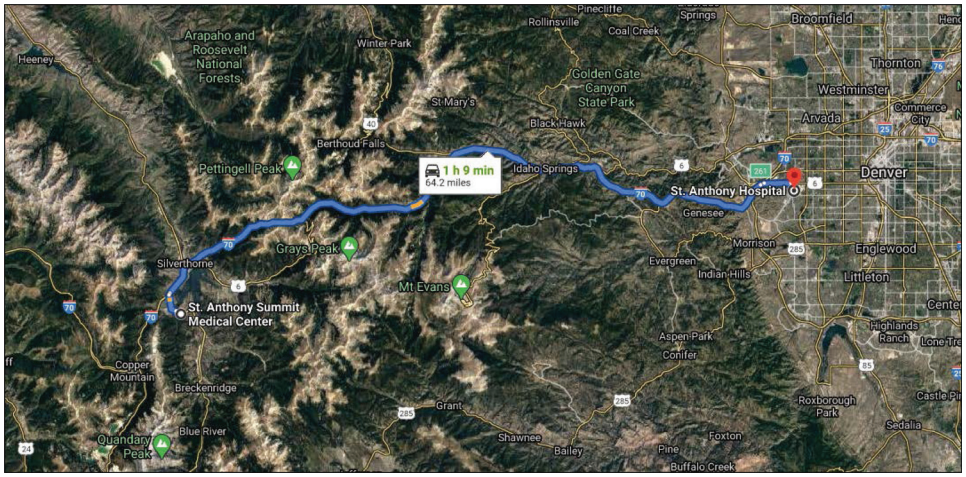

Figure 2 Ground route between St. Anthony Summit Medical Center (Level 3 Trauma Center) and St. Anthony Hospital (Level 1 Trauma Center). The typical ground transport time is around 1 hour with ideal weather and traffic. Helicopter flight time is significantly shorter. Poor weather can ground helicopters and increase drive time. Note the lack of redundant drive routes between hospital centers. Map image generated on Google Maps on 4 September 2020.

speed is greatly reduced by the same weather conditions which ground helicopters. There are numerous capability differences between our Level 3 and the Level 1 hospital; for trauma patients, the key factors that necessitate transfer are the need for definitive endovascular hemorrhage control, intensive care capabilities, and neurosurgical intervention. Access to these capabilities requires a facility transfer. We sought to leverage emerging technology to enable providers in transport platforms increased capability to intervene should patients decompensate during transport to the Level 1 center. As has been discussed by numerous authors, resuscitative endovascular balloon occlusion of the aorta (REBOA) has the potential to serve this function for bleeding trauma

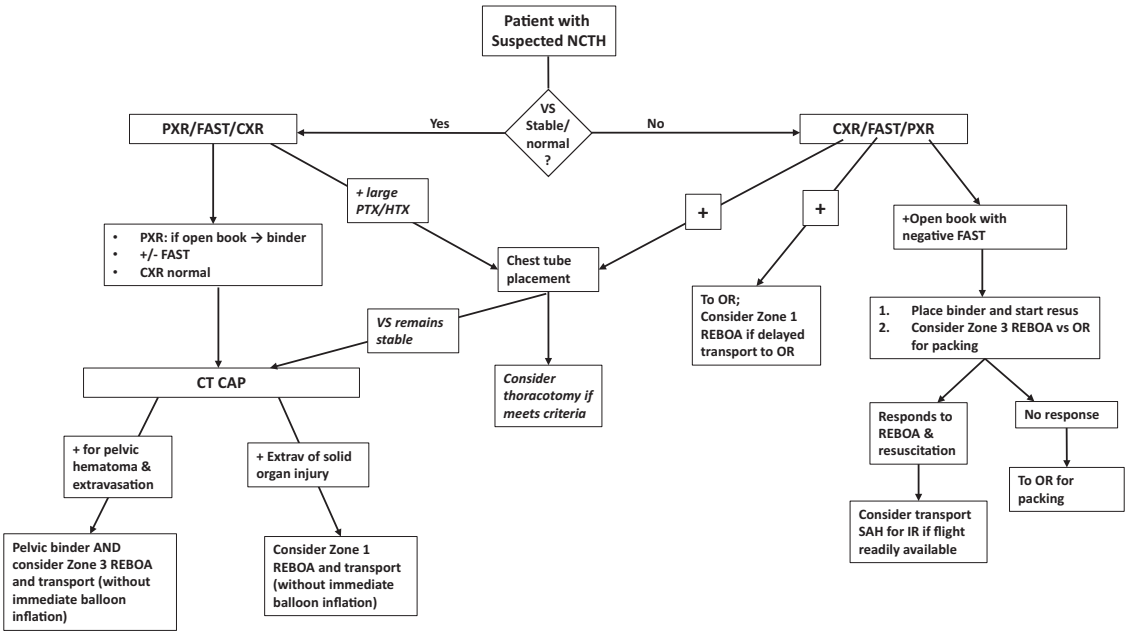

Figure 3 Course of care and transport decision protocol for the St. Anthony Summit Medical Center Regional REBOA Transport Program for patients with suspected non-compressible torso hemorrhage (NCTH). PXR, pelvic x-ray; FAST, focused assessment with sonography in trauma; CXR, chest x-ray; +, positive; VS, vital signs; PTX, pneumothorax; HTX, hemothorax; OR, operating room; CT CAP, computed tomography chest abdomen pelvis; REBOA, resuscitative endovascular occlusion of the aorta; SAH, St. Anthony's Hospital (Lakewood, CO, USA); IR, interventional radiology.

patients [2–4]. Use of endovascular balloon occlusion is rapidly evolving. Significant advances in devices have enabled its use in emergency care environments. Along with these device advances, clinical care approaches which leverage the full spectrum of REBOA-associated technology include: (a) timely invasive arterial monitoring, (b) established femoral artery access, (c) diagnostic imaging and surgical planning, (d) endovascular hemorrhage control, and (e) balloon occlusion to respond to decompensation [5]. This approach, termed "Step-Up REBOA", seeks to utilize the benefits of arterial access and endovascular interventions while avoiding the major limitation of prolonged use of aortic occlusion, distal ischemic injury. Here we report the development of a regional REBOA program developed to enable safe transfer of trauma patients from a Level 3 to a Level 1 Trauma Center and review the series of cases where we have implemented this protocol.

METHODS

Development of the Regional REBOA Program

New medical procedures are commonly first implemented in specialized centers and REBOA followed that pattern with initial clinical implementation at St. Anthony Hospital, an American College of Surgeons verified Level 1 Trauma Center, in early 2017. As REBOA rapidly moved into more diverse medical facilities, we embarked on a deliberate pathway to bring REBOA to the regional trauma system including the St. Anthony Summit Medical Center, a state-verified Level 3 Trauma Center, and the Flight for Life air ambulance, which transports patients from a regional base at St. Anthony Summit Medical Center to St. Anthony Hospital. In early 2018, after a year of experience with REBOA at the Level 1 Trauma Center, we initiated planning through a cross disciplinary approach involving personnel at both hospitals and the flight nurses responsible for patient care during transport. Trauma Surgery, Emergency Medicine, Vascular Surgery, Interventional Radiology, and the transportation medical director participated in the development of clinical practice guidelines and communication protocols. Prior to initiating the regional REBOA program, we conducted simulation-based training and validation in collaboration with the device manufacturer (Prytime Medical Devices, Inc., Boerne, TX, USA).

Our flight nurse crew was trained first, followed by the Emergency and Trauma Physicians. Simulation trainers for arterial access and REBOA manikins were used to confirm device performance and usability during flight, and the program was initiated in March 2019. We employed a multidisciplinary REBOA transport protocol at the Level 3 Trauma Center (Figure 3), protocols for the medical transport team, and integration with the existing REBOA protocol at the Level 1 Trauma Center.

Although our hospital has an air transport/critical care crew based at our center, the crew services a significant

Table 1 Clinical data for each of 5 patients treated under the St. Anthony Summit Medical Center regional REBOA transport program.

	Patient 1	*Patient 2*	*Patient 3*	*Patient 4*	*Patient 5*
Gender, age	M, 19	M, 51	M, 59	M, 68	M, 21
MOI	Snowboard fall	Mountain biking	Motor vehicle accident	Fall from height (8 feet)	Snowboard fall
PPE	Helmet	Helmet	Seatbelt, rear pass	None	Helmet
Scene/clinic BP/other	136/85, FAST negative.	117/73, P62		146/90; P80	Walk-in – no prehospital BP available
Scene GCS	15	15	15	15	15
Pre-L3 time	3 h	30 min	45 min	57 min	8 h
L3 Initial SBP, FAST	116/75, FAST Pos.	90/60; FAST positive	98/74; pulse 106; FAST negative	119/81; P84; FAST negative	128/59; P63
Imaging	CT: pan scan	CXR, PXR, no CT	CXR, PXR, pan-scan	CT: pan-scan	CT: pan-scan
L3 Blood	Yes	Yes	Yes	Whole blood	None
Means of CFA access	Ultrasound guided	Ultrasound guided	Ultrasound guided	Ultrasound guided	Ultrasound guided
TXA given?	No	Yes	Yes	Yes	No
L3 diagnosis	Grade 5 spleen, grade 2 kidney (left)	Mesenteric hematoma with active extravasation	Retroperitoneal bleed[1], sternal fracture, rib fractures; abdominal wall dehiscence	Right superior and inferior pelvic rami fracture; sacral fracture; extraperitoneal extravasation	Grade 4 spleen[2]
L3 surgery avoided/ deferred	Avoided	Deferred to L1	Deferred to L1	Avoided	Avoided
Zone of REBOA insertion	Zone 1	Zone 1	Zone 1	Zone 3	Zone 1
Transport time	32 min/helicopter	24 min/helicopter	32 min/helicopter	70 min/ambulance	65 min/ambulance
Transport blood	None	Plasma	2 units PRBCs	Plasma and PRBCs	None
L1 blood	None		MTP	No	None
L1 diagnosis	Grade 5 spleen, grade 2 kidney (left)	Mesenteric hematoma with active extravasation	SB transection/ avulsion mesentery	R sup & inf rami fracture; sacral fracture; extraperitoneal hematoma	Grade 4 spleen injury;
Hemorrhage diagnosis	No active extravasation on CT	Small bowel mesenteric hemorrhage	Retroperitoneal hematoma, mesenteric bleeding	Extraperitoneal hematoma	No extravasation on CT
Definitive surgical procedure	Splenic artery embolization	Ex lap, bowel resection x 2	Ex lap; bowel resection; left in discontinuity; non-expanding retroperitoneal hematoma	Angiography	Angiography
Nadir BP				55	120
REBOA complication	None	None	None	None	None
Surgical complication	N/A	None	MI-death	N/A	N/A
Total AO time	None	None	None	None	None
Disposition	Discharge to home day 4	Discharge to home day 5	Death	Discharge to rehab day 4	Discharge to home day 4

[1]Source of bleeding: non-surgical retroperitoneal muscular contusion. [2]Hospital system protocol and Colorado state law dictates that all Grade 4 solid organ injuries are transferred to a L1 Trauma Center for definitive care; in the case that Interventional Radiology is required, this resource is only available at the L1 Trauma Centers. M, male; MOI, mechanism of injury; PPE, personal protective equipment; BP, blood pressure; FAST, focused assessment with sonography in trauma; GCS, Glasgow Coma Score; L3, Level 3 Trauma Center; CXR, chest x-ray; PXR, pelvic x-ray; CT, computed tomography; CFA, common femoral access; TXA, tranexamic acid; L1, Level 1 Trauma Center; REBOA, resuscitative endovascular balloon occlusion of the aorta; PRBCs, packed red blood cells; MTP, massive transfusion protocol, SB, small bowel, Ex lap, exploratory laparotomy; MI, myocardial infarction; AO, aortic occlusion.

portion of the central mountain region of Colorado and can be called away for other patient transporting needs. Patients did not enter the protocol if trained Flight for Life personnel were unavailable for transport, if blood pressure was sustained at <90 mmHg, or if the patient required ongoing blood resuscitation to maintain systolic blood pressure (SBP) >90 mmHg. In addition, hemodynamically normal and stable patients who could receive immediate helicopter load were not included in the REBOA protocol to ensure the fastest transport times.

While this protocol provides guidance for clinical decision-making, ultimately, the course of treatment and decision to place a REBOA catheter are at the discretion of the treating physician. The physician also has discretion to transfer patients as needed, although Colorado state law and regional transfer agreements dictate that certain injuries require transport to a Level 1 Trauma Center (e.g. Grade 4+ solid organ injury, spinal column injury with neurological deficit, epidural brain hemorrhage, etc.). During flight, the nurse flight crew manages the REBOA catheter by closely monitoring patient vital signs. Aortic occlusion is initiated when a patient's SBP drops below 90 mmHg. At the time of writing this manuscript, five transport cases have been performed under this program.

Retrospective Record Review

As part of this program, we established a process improvement initiative to review cases where REBOA is used during transport. Hospital electronic patient records (n = 5) from this process improvement initiative were analyzed for this case series.

Ethical Approval and Informed Consent

Authorization for the publication of this work was provided by the Catholic Health Initiatives Institute for Research and Innovation Institutional Review Board (CHIRB). Informed consent was not required for the publication of this article.

RESULTS

In the first 12 months after establishing our regional REBOA transport program, the intervention was performed in five patients (Table 1). All patients were male and the mechanism of injury was representative of the patients seen in this medical center, with alpine recreational mishaps and a motor vehicle collision resulting in blunt trauma with helmet and seat belt use appropriate to the activities. Time elapsed prior to admission to the Level 3 Trauma Center was widely variable. Concurrent with the establishment of the REBOA program, the Flight For Life critical care transport system also initiated blood product resuscitation capability with both fresh whole blood and component therapy. As a result the patients in this series received a combination of interventions for hypotension at the Level 3 Trauma Center including blood products (4/5), tranexamic acid (2/5), 7 Fr common femoral artery (CFA) access, and prophylactic placement of a REBOA Balloon Catheter (ER-REBOA™, Prytime Medical Devices, Boerne, TX, USA). Blood products were also administered during transport in three of five patients. Initial care of these patients at the Level 3 Trauma Center was accomplished by a team consisting of surgeons and emergency medicine physicians who collaborated to initiate diagnostic and therapeutic procedures. All of the CFA access procedures were accomplished under ultrasound guidance, with the Emergency Medicine physicians responsible for performing this procedure.

All patients responded to resuscitative treatments at the Level 3 Trauma Center and during transportation resulting in no instances of inflation of the occlusion balloon. Imaging files from patients were available in the shared Emergency Medical Records system and available for physicians at both Level 3 and Level 1 Trauma Centers contemporaneously so that no repeat imaging was required once patients reached the Level 1 Trauma Centers. Upon arrival at the Level 1 Trauma Center, these patients underwent definitive treatment, which commonly was endovascular, to include additional diagnostic radiography and embolization. In total, two of the five patients did not have extravasation of contrast at the Level 1 center indicating that hemorrhage had stopped, and additional bleeding control was unwarranted. There were no complications associated with the use of REBOA or CFA access.

DISCUSSION

All of the patients in this case series had near normal scene Glasgow Coma Scale (GCS) scores and this, along with protective equipment use (primary injury prevention), contributed to the positive outcomes seen and the short course of hospitalization with 4 of 5 patients discharged within 5 days and most discharged home. Concurrently, with the development and implementation of the REBOA program, this regional trauma system also implemented a whole blood resuscitation program at the Level 3 Trauma Centre and in the helicopter platforms. This resulted in variable blood product use with balanced component therapy used in three patients, and whole blood used in one. These programs are complementary and best implemented in combination to leverage the strengths of each [6]. While none of the patients in this study progressed to the point where aortic occlusion was necessary, providing transport between the Level 3 and Level 1 Trauma Centers with an uninflated REBOA in place gives the transport team a tool to rapidly respond if a patient were to become hemodynamically unstable. We have experienced this situation twice in years past, before our REBOA Transport Program was

in place; transport with REBOA provides additional safety to the patients and a higher level of confidence in the decision to transport the patients to the Level 1 Trauma Center with success. Furthermore, several benefits of this treatment were realized in addition to the added safety of having an intervention to treat emergent decompensation. These benefits included improved situational awareness from accurate, real-time arterial line pressure monitoring, and subsequent use of arterial access for endovascular interventions, and avoidance of morbid invasive procedures such as laparotomy and splenectomy [5]. As the practice of partial REBOA is more widely adopted, additional benefits can be realized. Partial REBOA gives the clinical team the ability to balance distal ischemia with proximal perfusion, thus extending the potential window for hemorrhage control [7]. The partial REBOA technique could be especially beneficial in transport cases that encounter extreme weather, traffic conditions, or long distances that increase the time needed to move a trauma patient from a Level 3 to Level 1 Trauma Center. Transport of the five patients resulted in three cases receiving definitive care through Interventional Radiology, a capability not available at the Level 3 Trauma Center. Of note, any hemodynamically unstable patients with a positive FAST are taken directly to the operating room without computed tomography (CT) scanning and do not enter the REBOA protocol. Patients are only transferred if they are hemodynamically stable and are determined by the sending physician to be best served by urgent interventional radiology or a more robust surgical intensive care unit.

CFA access is widely recognized as the most important step in enabling endovascular aortic occlusion and was a focus of our planning and training efforts [5,8]. While some trauma surgeons may not routinely perform ultrasound-guided vascular access, these procedures are common in the practice of Emergency Medicine physicians. To ensure access success, this REBOA program includes Emergency Medicine physicians who are responsible for gaining access, achieving a high success rate while also freeing the trauma surgeon to perform other tasks. Time from beginning to gain CFA access to having the REBOA catheter in place took less than 10 minutes in all cases, and typically occurs within 5–7 minutes. Since the placement of REBOA is ongoing simultaneously with additional patient preparation or treatment, there is low risk of the REBOA placement causing a delay in the departure of a patient for transfer. We found this to be the best practice and recommend against excluding Emergency Medicine physicians from REBOA procedures as this is counterproductive [9]. Early access gained by a provider proficient in ultrasound-guided access avoids the pitfalls of a difficult access caused by hypotension, low-flow, and vasospasm.

Non-compressible hemorrhage in the abdomen and pelvis remains a clinical challenge, one often best met at well-resourced Level 1 Trauma Centers. To facilitate safe transfer of patients to these capabilities, we instituted a transport REBOA program, and reviewed the indications, implementation and outcomes for patients treated using this protocol. We found this capability useful and safe as evidenced by patients arriving at the Level 1 Trauma Center, having been cared for in route according to the established plan. Initial care at the Level 3 center was significantly enhanced through our multidisciplinary approach. As noted by many, access has been shown to be the critical, often rate limiting, factor in the successful use of REBOA [10]. By using an interdisciplinary approach, this essential procedure is performed by those with experience, which in our center are the Emergency Medicine physicians who routinely practice vascular access under ultrasound guidance. We consider this inclusive approach to be a best practice rather than a surgeon-only approach to REBOA procedures, especially in settings like ours in which surgical personnel are limited or have not yet arrived at the hospital. While the ability to use REBOA if needed has value in bringing patients to the needed capability, this procedure is fundamentally linked to blood product resuscitation, and in our program these interventions have proved synergistic. While animal model studies often examine REBOA in the absence of blood product use, this does not reflect clinical care where transfusion and hemorrhage control are practiced together to achieve a common goal. Inclusion of state-of-the-art blood product transfusion practices is an essential part of the successful implementation of transport REBOA as it avoids the known limitations of each approach, thereby maximizing the impact of each.

In our Transport REBOA program, the occlusion of the aorta is the final step in a set of capabilities which we have found useful in the treatment of trauma patients. Initial vascular access enables us to transduce an accurate, real-time arterial pressure which is of use as resuscitation proceeds and additional diagnostic procedures such as CT imaging are conducted. The availability of an appropriate CFA access point ensures that diagnostic procedures can be conducted with the knowledge that a rescue procedure is rapidly available should the patient decompensate. Likewise, this access point has proven valuable at the Level 1 center where endovascular procedures to achieve definitive care are enabled. All of the patients in this case series had endovascular evaluation as part of their definitive care.

CONCLUSION

This regional approach to trauma care along with the use of helicopters to transport trauma patients are examples of trauma innovations where the transfusion of technologies between civilian and military trauma care have benefitted both [11]. The development and implementation of REBOA technology optimized for emergency and critical care environments is

another example. The military, in collaboration with universities and industry, developed catheters designed for this environment, and their use has been refined as this technology and approach has been adopted in civilian centers [12]. We anticipate that, in addition to civilian regional trauma systems, military trauma systems may benefit from the successful development of protocols and training for use of REBOA during medical evacuation.

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Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

RW, JL, SA, and JT report no proprietary or commercial interest in any product mentioned or concept discussed in this article.

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Author Contributions

RW, JL, SA, and JT contributed to the development of the Regional REBOA Transport Program. JT performed patient record review and drafted the manuscript. RW, JL, and SA critically edited the manuscript. All authors have read and approved the manuscript.

Data Availability

Hospital electronic patient records were analyzed for this case series. These data are not available for distribution.

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Original Article

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Morphometric Analysis of the Aorto-Esophageal Relationship in Swine for Trans-Esophageal Aortic Blood Flow Occlusion

Samuel G Savidge[1], Hossam Abdou[2], Joseph Edwards[2], Neerav Patel[2], Michael J Richmond[2], Rebecca Treffalls[2], Joseph Rabin[2] and Jonathan J Morrison[2]

[1]University of Maryland School of Medicine, Baltimore, Maryland, USA
[2]R Adams Cowley Shock Trauma Center, University of Maryland Medical System, Baltimore, Maryland, USA

Background: Trans-esophageal aortic blood flow occlusion (TEABO) is an emerging technology undergoing laboratory research that offers a strategy for temporary hemorrhage control. The purpose of this study was to evaluate the anatomical relationship between the esophagus and descending thoracic aorta in two breeds of swine to support a porcine model for future TEABO investigations.
Methods: Thoracoabdominal computed tomography scans were compared in Hanford miniature swine and Yorkshire swine. Measurements were taken at the five vertebral levels proximal to the gastroesophageal junction. Data collected included the distance between the center of the esophagus and the center of the descending aorta, the angle between the vertebral column, descending aorta, and esophagus, and the length the thoracic esophagus travels anteriorly to the descending aorta.
Results: Ten Hanford swine and ten Yorkshire swine were compared. In Hanford swine, the distal thoracic esophagus travels anteriorly to the descending aorta for a mean distance of 11.5 ± 2.3 cm. In Yorkshire swine, the thoracic esophagus travels to the right of the descending aorta. The mean angle between the vertebral body, descending aorta, and esophagus was 79.6 to 97.8 degrees higher in Hanfords compared with Yorkshires ($P < 0.0001$ at all five vertebral levels compared). The mean distance between the esophagus and descending aorta was 0.2 cm to 0.6 cm higher in Hanfords compared with Yorkshires with a significant difference found at only two vertebral levels ($P = 0.01$ and $P = 0.02$).
Conclusions: Hanford miniature swine possess an aorto-esophageal relationship comparable to humans and should be the preferred animal model for TEABO studies.

Keywords: *Hemorrhage; Esophagus; Aorta; Swine; Anatomy; Transesophageal*

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INTRODUCTION

Hemorrhage is the leading cause of potentially preventable death in trauma patients, accounting for 30–40% of deaths following traumatic injury [1–5]. Non-compressible torso hemorrhage (NCTH) is particularly fatal and is associated with up to 85% mortality in the military setting and 50% mortality in civilian patients [6,7]. For patients with NCTH, rapid intervention is imperative to control bleeding and prevent exsanguination and death.

The upper gastrointestinal tract serves as a window to several important cardiovascular structures. Trans-esophageal echocardiography takes advantage of this relationship to assess the heart and aorta. In addition, a new technique – gastroesophageal (GE) resuscitative occlusion of the aorta – has been shown to achieve full, temporary aortic occlusion through deployment of a device within the proximal stomach [8]. Trans-esophageal aortic blood flow occlusion (TEABO) is another emerging technology undergoing laboratory research, which offers a strategy for temporary hemorrhage control in the pre-hospital setting prior to definitive surgical control. TEABO operates via deployment of a compressive actuation mechanism within the distal esophagus to

Corresponding author:
Jonathan J Morrison, R Adams Cowley Shock Trauma Center, 22 S. Greene Street, Baltimore, Maryland 21201, USA.
Email: jonathan.morrison@som.umaryland.edu

compress the adjacent segment of the descending aorta. This compression allows for temporary occlusion of the thoracic aorta until definitive hemostasis can be achieved in the operating room. The TEABO delivery system is designed to be deployed in the distal thoracic esophagus where the esophagus crosses anterior to the descending aorta. At this level, the actuator mechanism can compress the aorta posteriorly against the vertebral column and occlude the vessel. Due to TEABO's strict dependence on the anatomical relationship between the esophagus and descending aorta, this intimate association is an essential criterion when selecting an animal model to study such a trans-esophageal strategy.

Domestic swine (*Sus scrofa domestica*) are used extensively in research settings. They have similarities in gross anatomy, size, and vasculature [9–11]. Functionally, their cardiovascular, digestive, dermal, and urinary processes are analogous to humans [12]. Moreover, their physiologic response to hemorrhage and hemorrhagic shock is more comparable to humans than any other non-primate [13–15]. There is significant evidence that swine would be a suitable physiological model to further evaluate TEABO techniques. However, no study thus far has explored the anatomical relationship between the porcine esophagus and descending aorta. This information must be obtained prior to selecting a porcine model for TEABO research.

The aim of this study is to characterize the anatomical relationship between the esophagus and descending aorta in two breeds of domestic swine. By defining this relationship, we hope to establish the porcine anatomy as functionally suitable for future TEABO studies. In addition, the included cross-sectional images will illustrate the anatomical window for deployment of a trans-esophageal aortic occlusion device.

METHODS

Morphometric analysis of the relationship between the porcine esophagus and descending thoracic aorta was conducted by evaluating computed tomography (CT) scans in two breeds of domestic swine. Yorkshire swine (a common domestic farm breed) and Hanford miniature swine (a common miniature breed) were compared. The CT images used in this study were previously collected by a translational research laboratory. All data were acquired from Institutional Animal Care and Use Committee (IACUC) approved protocols (IACUC protocols 1119008, 0221009, and 0920007). As this study analyzed retrospective data, IACUC approval was not required.

The laboratory's picture archiving and communication system was searched for swine with thoracoabdominal CT scans, and images were obtained. All scans in the laboratory were acquired with a 16-slice portable machine (OmniTom, Samsung Neurologica Corporation, Danvers, MA, USA) using a helical acquisition. Pigs were placed in the supine position when thoracoabdominal scans were taken. All swine included in this study were euvolemic and under general anesthesia at the time of imaging. The swine were maintained under general anesthesia with 1.5–3% isoflurane in 40% oxygen. Animals were mechanically ventilated using a volume-controlled mode of 12–15 ml/kg with a respiratory rate of 10–15 breaths/min. The breed, weight, and sex were obtained for all swine included in this study. Images acquired from the archive were analyzed using Horos v3.3.6 (Brooklyn, NY, USA), an open-source medical image viewer. Several data points were collected using tools within Horos. The length between the center of the esophagus and the center of the descending aorta was measured at the five vertebral levels proximal to the GE junction. In addition, the angle between the vertebral body, the center of the aorta, and the center of the esophagus was measured at the same vertebral levels. Angles were measured such that 180 degrees indicated a straight line between the vertebral body, the aorta, and the esophagus. A value less than 180 degrees indicated the esophagus was to the right of the aorta, and a value greater than 180 degrees designated the esophagus was to the left of the aorta. Length and angle measurements were taken in the axial plane. Finally, a curved planar reformation was generated for the course of the esophagus that was anterior to the descending aorta. The length of the three-dimensional Bezier path produced was measured to quantify the length of the esophagus anterior to the aorta.

Numerical data were collected and stored in a Microsoft Excel (Redmond, WA, USA) file and analyzed using GraphPad Prism v9.1.2 (GraphPad Software Inc, La Jolla, CA, USA). All data are presented as mean with standard deviations. Unpaired *t*-tests were used to compare measurements between Hanford and Yorkshire swine at each vertebral level. Vertebral levels were normalized to the level of the GE junction prior to comparison. Linear regression analysis of the relationship between weight and the mean morphometric measures studied was performed to evaluate the impact of weight on the data. An unpaired *t*-test was also used to compare the weights of the Hanford and Yorkshire swine populations. A P value of less than 0.05 was considered significant.

Ethical Approval and Informed Consent

Ethical approval was not required. Informed consent was not required.

RESULTS

A total of twenty swine were included in this investigation. Thoracoabdominal CT scans were found for ten Yorkshire swine and ten Hanford miniature swine. The Yorkshire swine population consisted of seven males weighing between 54 kg and 76 kg and

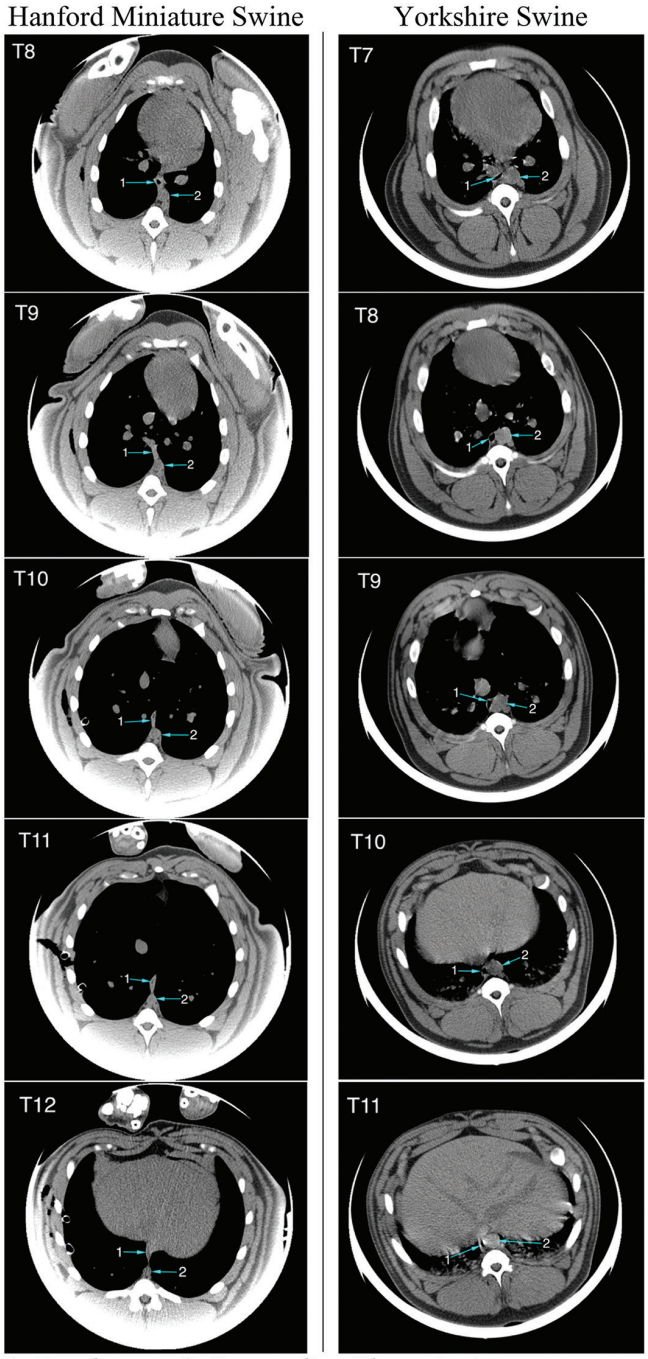

Figure 1 Representative CT images of Hanford miniature swine and Yorkshire swine at the five vertebral levels proximal to the gastroesophageal junction.

three females weighing between 36 kg and 38 kg. The Yorkshire population had a mean weight of 55.2 ± 15.0 kg. The Hanford miniature swine population consisted of ten males weighing between 63 kg and 71 kg with a mean weight of 67.2 ± 2.7 kg. The mean weight of the Hanford swine population was 12.0 kg larger than the mean weight of the Yorkshire population ($P = 0.023$).

The five vertebral levels proximal to the GE junction spanned from T8–T12 in Hanford miniature swine and from T7–T11 in Yorkshire swine. Since data were normalized to the level of the GE junction, measurements taken at T8 in Hanford swine were compared with T7 in Yorkshire swine, T9 in Hanfords with T8 in Yorkshires, and so on. Figure 1 depicts comparative cross-sectional images in both breeds of swine at the five vertebral levels proximal to the GE junction.

As seen in Figure 1, the gross relationship between the esophagus and descending aorta differs in Hanford miniature swine and Yorkshire swine. In Hanford swine, the esophagus travels anteriorly and slightly to the right of the descending thoracic aorta. As the thoracic esophagus descends, it moves from slightly right of the aorta to directly anterior and remains anterior to the aorta through the esophageal hiatus. The esophagus travels anteriorly to the descending aorta for a mean distance of 11.5 ± 2.3 cm. The walls of the thoracic esophagus and the descending aorta in Hanford miniature swine are either in direct contact or only slightly separated at all five vertebral levels proximal to the GE junction.

In Yorkshire swine, the thoracic esophagus descends immediately to the right of the aorta. The esophagus remains to the right of the aorta through the esophageal hiatus, and only the GE junction itself passes anterior to the aorta. There was one outlier in the Yorkshire swine population where the thoracic esophagus travels anterior to the aorta, but in all other swine, the esophagus remains to the right of the descending aorta. The walls of the thoracic esophagus and descending aorta in Yorkshire swine are in direct contact with one another at all five vertebral levels proximal to the GE junction.

Measurements of the distance between the center of the esophagus and the center of the descending aorta in both breeds of swine are depicted in Figure 2 and summarized in Table 1. The mean distance between the esophagus and aorta is 0.2 to 0.6 cm higher in Hanford miniature swine compared with Yorkshire swine. No significant difference was found at three out of five vertebral levels.

Measurements of the angle between the vertebral column, descending aorta, and esophagus in both breeds of swine are depicted in Figure 3 and summarized in Table 2. The mean angle was 79.6 to 97.8 degrees higher in Hanford miniature swine compared with Yorkshire swine and was significantly different at all vertebral levels. This difference correlates with the fact that the esophagus travels much more anteriorly to the aorta in Hanford swine.

Linear regression analysis revealed no statistically significant relationship between weight and any of the mean morphometric measures evaluated in the Hanford miniature swine population. In Yorkshire swine, there was no significant relationship between weight and the mean angle between the vertebral column, aorta, and esophagus. However, a statistically significant positive relationship was found between weight and the mean distance between the esophagus and aorta. For every 1 kg increase in

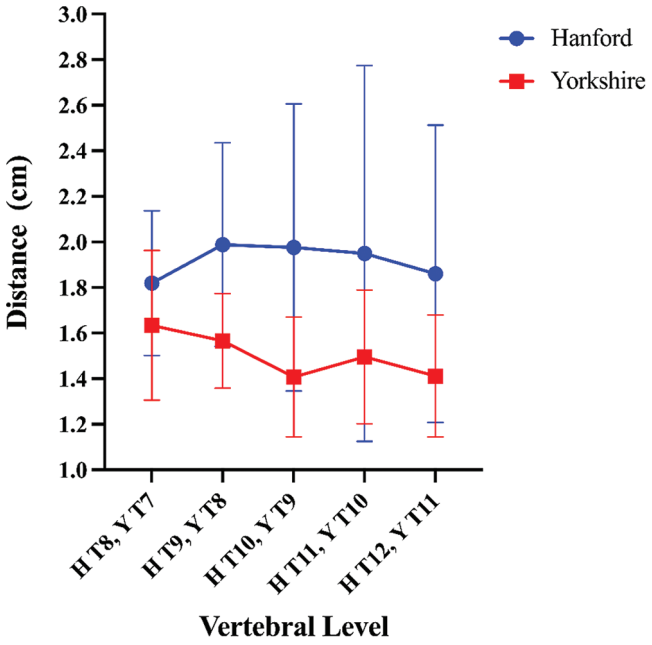

Figure 2 Mean distance between the center of the esophagus and the center of the descending aorta in Hanford miniature swine and Yorkshire swine at the five vertebral levels proximal to the gastroesophageal junction. All values are expressed as mean with standard deviation in centimeters. H: Hanford; Y: Yorkshire.

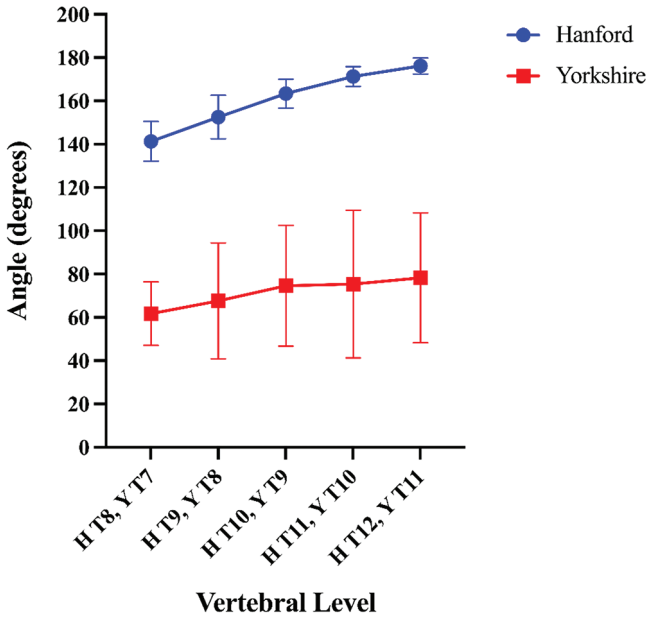

Figure 3 Mean angle between the vertebral body, descending aorta, and esophagus in Hanford miniature swine and Yorkshire swine at the five vertebral levels proximal to the gastroesophageal junction. All values are expressed as mean with standard deviation in degrees. H: Hanford; Y: Yorkshire.

Table 1 Mean measurements of the distance between the center of the esophagus and the center of the descending aorta.

Vertebral Level	*Hanford Miniature Swine*	*Yorkshire Swine*	*P value*
H T8, Y T7	1.8 ± 0.3	1.6 ± 0.3	0.2163
H T9, Y T8	2.0 ± 0.5	1.6 ± 0.2	0.0144
H T10, Y T9	2.0 ± 0.6	1.4 ± 0.3	0.0168
H T11, Y T10	2.0 ± 0.8	1.5 ± 0.3	0.1187
H T12, Y T11	1.9 ± 0.7	1.4 ± 0.3	0.0597

All values are given as mean ± standard deviation in centimeters. H: Hanford; Y: Yorkshire.

weight, the mean distance increased by 0.003 cm in Yorkshire swine ($F(1,8) = 24$, $P = 0.0012$, $R^2 = 0.75$).

DISCUSSION

In summary, the gross anatomical relationship of the thoracic esophagus and descending aorta differs in Hanford miniature swine and Yorkshire swine. The distal thoracic esophagus travels anterior to the aorta in Hanford swine, whereas it travels to the right of the aorta in Yorkshire swine. In addition, the center of the esophagus is further from the center of the aorta in Hanford swine compared with Yorkshire swine. These two differences must be considered for selection of an ideal animal model for investigation of anatomically relevant trans-esophageal technologies such as a TEABO device.

Successful trans-esophageal occlusion of the aorta requires the esophagus to be both anterior to the aorta and close enough to the vessel, so an actuator can compress the aorta posteriorly against the vertebral column. The current TEABO device under investigation has a compression mechanism with a diameter expandable to more than 3 cm. The distance between the esophagus and aorta in both Hanford miniature swine and in Yorkshire swine is less than this diameter at all vertebral levels analyzed and thus close enough for the actuator to compress the aorta; however, the thoracic esophagus is only anterior to the descending aorta in Hanford miniature swine. This relationship is not only imperative for a TEABO device to function, but also it parallels the human anatomy. In humans, the thoracic esophagus lies anterior to the descending aorta from T8 to the esophageal hiatus [16]. Therefore, Hanford miniature swine possess an anatomical relationship similar to humans. Conversely, in Yorkshire swine, the thoracic esophagus lies to the right of the aorta. In this case, the deployment of a compressive actuator

Table 2 Mean measurements of the angle between the vertebral body, descending aorta, and esophagus.

Vertebral Level	*Hanford Miniature Swine*	*Yorkshire Swine*	*P value*
H T8, Y T7	141.3 ± 9.2	61.7 ± 14.7	<0.0001
H T9, Y T8	152.5 ± 10.1	67.6 ± 26.8	<0.0001
H T10, Y T9	163.4 ± 6.7	74.6 ± 27.9	<0.0001
H T11, Y T10	171.2 ± 4.5	75.4 ± 34.1	<0.0001
H T12, Y T11	176.1 ± 3.7	78.3 ± 30.0	<0.0001

All values are given as mean ± standard deviation in degrees. H: Hanford; Y: Yorkshire.

would likely displace the descending aorta leftward into lung tissue, which is expected to be too compliant to provide sufficient counterforce to compress the aorta.

The results of this study clearly identify Hanford miniature swine as an appropriate animal model for further investigation of TEABO technologies. Swine are used extensively in biomedical research and have already been established as physiologically comparable organisms [9–15]. This study provides additional evidence that the anatomical relationship between the thoracic esophagus and descending aorta in Hanford miniature swine is both comparable to humans and suitable for evaluating anatomically sensitive trans-esophageal strategies such as TEABO. We have found that the thoracic esophagus is anterior to the aorta for a mean distance of 11.5 ± 2.3 cm in Hanford miniature swine. In addition, the center of the esophagus is an average of 1.8–2.0 cm away from the center of the aorta at the five vertebral levels proximal to the GE junction. These values denote an ample anatomical window that the TEABO mechanism can be effectively deployed within. However, one can assume that the closer to 180 degrees the angle between the vertebral column, aorta, and esophagus is, the more successful the TEABO deployment will be. At T11 and T12 in Hanford miniature swine, the mean angle is 171.2 ± 4.5 degrees and 176.1 ± 3.7 degrees, respectively. Thus, the window from T11–T12 is likely the most ideal target to deploy the TEABO device in future investigations.

It should be noted that the region of potential trans-esophageal aortic occlusion in both Hanford miniature swine and in Yorkshire swine is proximal to the celiac trunk. Across all swine analyzed, the celiac trunk arises distally to the level of the GE junction. Thus, TEABO would produce Zone 1 aortic occlusion in swine at any point within the distal esophagus. In humans, TEABO is also expected to produce Zone 1 aortic occlusion, since once again the level of the GE junction is proximal to the celiac trunk [16].

One limitation of this study is that the Hanford miniature swine analyzed were all males with a weight range of 63–71 kg. In addition, the Hanford swine had a mean weight of 12.0 kg larger than the Yorkshire swine ($P = 0.023$). It is possible that female Hanfords or Hanfords with a significantly lower weight could have a different anatomical relationship between the esophagus and aorta; however, this is unlikely. There was no gross difference observed between the male and female Yorkshire swine included in this investigation. Furthermore, for Hanford miniature swine with much lower weights, the aorta and esophagus would likely be closer without any significant difference in angle, as was observed in the Yorkshire swine population.

The fact that Hanford miniature swine had a higher average weight than Yorkshire swine may partly explain why the mean distance between the aorta and esophagus was higher in Hanfords than in Yorkshires. However, linear regression analysis in Yorkshire swine still predicts that the mean distance between the aorta and esophagus would be 0.4 cm higher in Hanfords compared with Yorkshires at an equivalent mean weight of 67 kg. Nevertheless, this increased distance should not significantly impact the efficacy of TEABO as Hanford miniature swine are still within the expected functional range of the device.

Another limitation of this study is that the swine analyzed were normovolemic at the time of imaging. However, TEABO will be utilized in the setting of hemorrhage. Current research shows that the descending thoracic aorta diameter decreases by an average of 32% after a blood loss of 40% in swine [17]. This decrease in diameter is not expected to significantly impact the aorto-esophageal relationship. Moreover, measurements in this study were taken between the center of the esophagus and the center of the aorta, and a reduction in vessel diameter alone would not impact any of our measured values.

There are several potential complications that could result from a technology such as TEABO. When deploying a trans-esophageal compression device, there is clearly the possibility of esophageal mucosal injury and perforation. This outcome will need to be thoroughly investigated in future TEABO studies. The porcine esophagus is pathologically and physiologically similar to humans and should serve as an appropriate model for identifying mucosal injury. Notably, the porcine and human esophagus have similar size and thickness of the esophageal layers, and both swine and humans possess esophageal submucosal glands, not found in many other animal models, that likely play a role in esophageal repair postinjury [18,19]. In addition, one can expect that the aortic occlusion produced by TEABO will result

in similar complications seen with Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA), including ischemia distal to the site of aortic occlusion, multiple organ dysfunction, and ischemia-reperfusion injury [20–22]. All these risks will need to be further explored in future TEABO investigations.

In conclusion, TEABO is an exciting new technology that offers a strategy for temporary hemorrhage control. TEABO has the potential to allow for rapid intervention to stop bleeding and can be deployed with limited medical training. While much research is still required, this study proposes that Hanford miniature swine will be an ideal animal model to further investigate TEABO.

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

J.R. has intellectual property associated with the TEABO technology discussed in this study that is assigned to the University of Maryland. All other authors declare no conflict of interest.

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Author Contributions

S.G.S., J.J.M., and J.R. designed the study. S.G.S., H.A., J.E., N.P., M.J.R., and R.T. completed data collection. S.G.S. completed data analysis. S.G.S. wrote the manuscript. J.J.M., H.A., J.E., and J.R. provided critical revisions.

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Narrative Review Article

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Endovascular Instead of Open Surgical Repair of Axillosubclavian Artery Injuries: An Evolving Paradigm Shift

Shreya Jalali[1], Derek J Roberts[2], Megan L Brenner[3], Joseph J DuBose[4], Laura J Moore[5] and Adam H Power[1]

[1]Division of Vascular Surgery, Department of Surgery, Western University, London Health Sciences Centre, Victoria Hospital, London, Ontario, Canada
[2]Division of Vascular and Endovascular Surgery, Department of Surgery, University of Ottawa, The Ottawa Hospital, Civic Campus, Ottawa, Ontario, Canada
[3]Department of Surgery, University of California Riverside, Riverside, California, USA
[4]R Adams Cowley Shock Trauma Center, University of Maryland School of Medicine, Maryland, USA
[5]Department of Surgery, The University of Texas Health Science Center, Houston, Texas, USA

Axillosubclavian injuries (ASI) comprise a small proportion of vascular injuries, yet their morbidity and mortality is high. This is often attributable to non-compressible bleeding in the apical thorax, hemodynamic instability, and the anatomically challenging location of these vessels making them difficult to access and control quickly. While the traditional management of ASI was with open surgical repair, recent years have seen an evolution towards less invasive endovascular repair (EVR). In patients with these injuries, EVR may be a safer alternative that achieves similar immediate results with significantly lower complication and mortality rates than the highly morbid open surgical option. In this article, we review and compare the two approaches, providing an overview of patient selection, anatomic considerations, techniques, postoperative management, and outcomes. With the advent of endovascular trauma management and more trauma team members capable of endovascular management of vascular trauma, a paradigm shift towards EVR for ASI is taking place.

Keywords: *Axillosubclavian; Vascular Trauma; Endovascular; EVTM*

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INTRODUCTION

Blunt or penetrating trauma to the axillosubclavian arterial segment comprises 5% of all vascular injuries [1,2]. These most often occur because of stab or gunshot wounds [3–5] and less commonly after motor vehicle collisions or falls from heights [6]. Concurrent injuries to the brachial plexus, pharynx or esophagus, and trachea, bronchi, and lung are common [1,7–10]. Blunt axillosubclavian injuries (ASI) are frequently associated with clavicle fractures, fractures of the first three ribs, and shoulder dislocations [6]. Patients can present with hemorrhage, diminished or absent upper limb pulses, arterial bruits, hematomas, or neurologic deficits [11].

Despite being relatively uncommon, the morbidity and mortality of ASI is high [6,11–13]. Mortality estimates in contemporary series remain as high as 20.5% [7] to 39% [4]. This is often secondary to non-compressible bleeding in the apical thorax, hemodynamic instability, and the frequently deep junctional location of these vessels, which makes them difficult to access and control quickly.

In this article, we review and compare endovascular and open surgical repair (OSR) of ASI. Specifically, we discuss patient selection, technical considerations, postoperative management, and outcomes of endovascular and open management of ASI.

Corresponding author:
Adam H Power, Division of Vascular Surgery, Department of Surgery, Western University, London Health Sciences Centre, Victoria Hospital, London, Ontario, Canada. Room E2121. 800 Commissioners Rd East, London, Ontario, Canada, N6A 5W9.
Email: Adam.Power@lhsc.on.ca

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OPEN SURGICAL REPAIR

The traditional approach to these injuries has been OSR. This often involved generous para-clavicular incisions [14,15], sternotomy, or thoracotomy for exposure and proximal and distal control [1,2,16]. This is because of the anatomical constraints of obtaining surgical exposure in the apical thorax, a relatively small confined space densely packed with neurovascular structures such as the brachial plexus. If they have not already been injured, these structures are prone to inadvertent injury as the surgical dissection often occurs in a bleeding field with tissues that may have been distorted by hematoma.

In order to obtain control of a proximal left subclavian artery injury, a high anterolateral thoracotomy is often required. Proximal right subclavian or innominate artery injuries often require sternotomy for proximal control and exposure. These injuries can be primarily repaired or replaced with autogenous or prosthetic graft material depending on the extent of injury and contamination. Distal injuries are usually exposed more directly with control near the injury site and have been treated with direct repair, anatomic bypass, or extra-anatomic bypass, including axillary-brachial or carotid-brachial bypass [17].

Anatomical considerations that support OSR may include very long segment injuries, insufficient proximal or distal normal vessel fixation points for stents, and extensive total arterial transection [11]. In cases of severe uncontrolled bleeding, concurrent venous injury or transection, upper extremity compartment syndrome resulting in neurovascular compression, or concurrent injuries requiring OSR or debridement, OSR would usually be the first choice.

OSR of ASI is associated with a high risk of mortality ranging from 5% to 30% [18–20]. The mortality rates of OSR for penetrating injuries of the subclavian artery have been particularly high [4,7,21,22]. In one large retrospective study, the mortality of penetrating ASI was 34.2% overall and 14.8% for those that made it to the operating room [7]. It follows that this increased mortality could in large part be attributed to the hemodynamic instability that patients with penetrating ASI often present with.

OSR also has been reported to be associated with long operative durations, lengths of hospital stay, and a higher risk of postoperative complications [3,6,13]. A 10-year analysis of the National Trauma Databank identified 3,628 patients with ASI, of with only 9% undergoing endovascular repair (EVR) versus OSR [3]. Complication rates were notably different when compared; for instance, surgical site infections occurred in 7% of OSR cases versus 4% of EVR, pneumonia in 8% of OSR versus 5% of EVR, and ICU admission in 31% of OSR versus 21% of EVR cases. Further, the overall mortality rate was significantly greater for OSR at 14.2% versus 8.8% for EVR ($P = 0.01$). It should of course be noted that despite concluding that EVR was independently associated with lower odds of complications after controlling for confounding variables such as admission vitals and ISS, there is inextricable bias in that patients selected for EVR are generally already those likely to have more favorable outcomes.

EVOLUTION OF EVR

The inception of stents in the 1960s occurred when the first "endoluminal splint" was reported to be placed post-angioplasty to prevent recoil and dissection [23]. In 1991, Parodi et al. began to use the first stent-grafts covered with fabric for abdominal aortic aneurysm treatment [24]. Through the 1990s, stents for cardiovascular procedures gained significant traction with improvement of technologies and by the 2000s, EVRs had become mainstream.

Stent grafts have since been adopted in many trauma centers for use in arterial injuries as well, including of the brachiocephalic vessels, aorta, and lower extremity arteries [25,26]. They can be used as a first-line treatment for both blunt and penetrating injuries, and the remote approach avoids the morbid dissection described above while producing safe and effective immediate results thus far [6,11,17,27]. EVR is now increasingly being used as a viable management option even for critically ill, hemorrhaging patients with traumatic vascular injuries [28,29], consistent with the paradigm shift towards endovascular trauma management (EVTM) for hemodynamically unstable patients with vascular injuries [30]. It is important to note, however, that risk of perioperative rupture remains ever-present and during EVR one should always be prepared to convert to open surgical bypass or reconstruction if required. Branco and DuBose in 2016 found that, among 92 ASIs, 88 (95.6%) had successful endovascular stent placement but 4 (4.3%) required open conversion [31].

EVR of arterial injuries mitigates the significant risks associated with open repair, which is conceivably a major reason for its uptake in contemporary management of ASI. EVR of traumatic arterial injuries has been documented in aortic and iliac vessels as well as axillary and subclavian injuries. For ASI, the rates of EVR have been increasing significantly in recent years. In one review, from 2003 to 2013 the rate of EVR increased from 5.3% to 22.2% with the incidence of these injuries remaining unchanged [12]. EVR has been performed in penetrating, iatrogenic, and blunt injuries. Blunt injuries often present with multiorgan issues which require OSR to address, whereas EVR is best utilized for focal lesions that can be safely traversed with a guidewire [13].

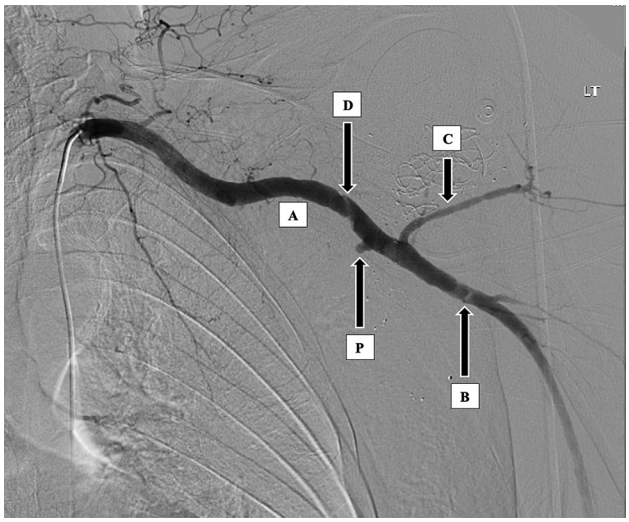

Figure 1 EVR of ASI due to a gunshot wound – before. An oblique lucency is visible through the mid axillary artery (A) at the lateral scapular margin, presumably representing a dissection flap (D). There is a 5 mm saccular outpouching 1 cm proximal to the circumflex humeral artery (C), likely a small axillary artery pseudoaneurysm (P). Curvilinear lucencies within the proximal left brachial artery (B) likely represent an intimal flap as well.

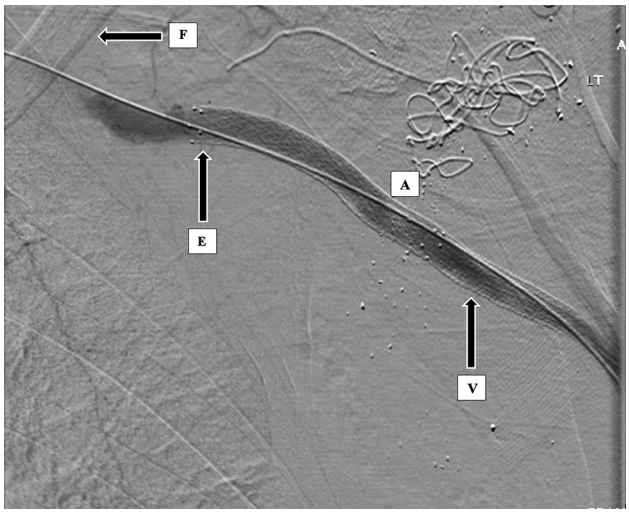

Figure 2 EVR of ASI due to a gunshot wound – after. The lateral margin of the first rib (F) is seen medially. Thereafter, the axillary artery (A) has two self-expanding Viabahn covered stents (V) placed within it, successfully covering the injured segments with no further arterial extravasation visible. An Epic self-expanding bare metal stent (E) has also been placed to exclude further medial extension of axillary artery injury.

Figures 1 and 2 demonstrate an example of EVR used for emergent repair in the case of penetrating ASI with focal lesions. While EVR historically failed when the injured vessel was completely transected or had an associated hematoma, technical advances are making this increasingly surmountable [13]. Combined approaches that establish through-and-through access, such as antegrade femoral access with a retrograde brachial cutdown, can help overcome these aforementioned challenges.

THE EVOLVING PARADIGM SHIFT IN THE MANAGEMENT OF ASI

The management of arterial trauma, particularly of junctional arterial trauma such as ASI, is a rapidly evolving landscape. A retrospective review of 153 ASIs noted that from 2003 to 2013 rates of EVR increased from 5.3% to 22.2% despite the absolute numbers of ASIs per year remaining constant [1,4–5]. Meanwhile, the incidence of OSR decreased from 47% to 32% in a different study from 2002 to 2014 [3]. Danetz et al. also noted in a 2005 retrospective review of 46 ASIs that up to 50% of them could have been managed with EVR, but the actual proportion of EVR was much lower. 25% of those patients were hemodynamically unstable, which could explain that proportion receiving OSR. The indications for EVR are not uniform, and surgeon-preference/ability is a major factor [10,11]. OSR is more likely to be selected by a surgeon who is not confident in EVR techniques or more comfortable with OSR. However, with the advent of ever-improving endovascular devices and techniques, a paradigm shift towards EVR is gradually taking place.

PATIENT SELECTION

The selection of candidates for EVR instead of OSR has evolved in recent years. Anatomic considerations are first and foremost given the unique position and physical confinement of axillary and subclavian arteries. For injuries in an anatomically inaccessible segment of the vessel adjacent in the chest or posterior to the clavicle, EVR is often the best first-line option. When the injured segment is adjacent or posterior to the clavicle, OSR is particularly challenging due to the requirement for sternotomy or high anterolateral thoracotomy to obtain adequate exposure for proximal and distal control. However, EVR carries risks of stent fatigue and fracture given the stress of repetitive subclavian artery compression between the first rib and clavicle, and of the axillary artery at the junction of the thorax and upper arm [17,32].

When EVR is the chosen method of repair, fabric covered stents may be at risk of covering some branches of the subclavian artery causing ischemia. Despite this concern, collateral or first-order branch vessels have been safely sacrificed [11,21] in prior reports, including the internal mammary artery (although this may be required in future coronary artery bypass grafting) and ostensibly non-dominant vertebral arteries. Whenever a vertebral artery ostium is at risk of being covered during EVR, the supra-aortic trunk must be carefully assessed for the presence of excellent cerebral primary collateral circulation. EVR may also be suboptimal for long segment

Table 1 Comparative morbidity and relevant operative details for OSR versus EVR of ASI from select contemporary studies.

	In OSR Cases	*In EVR Cases*	*P-value*
Morbidity			
Surgical site infection [3]	7.1%	4.2%	0.03
Pneumonia [3]	8.3%	5.1%	0.03
Iatrogenic brachial plexus injury [42]	14.3%	0%	n/a
ICU admission [3]	31%	21%	0.01
Overall mortality [3]	14.2%	8.8%	0.01
Operative Details			
Estimated blood loss, mean	220 ml	70 ml	0.01 [10]
	1225 ml	50 ml	0.03 [15]
Operative time, mean	193 min	132 min	0.04 [10]
	230 min	149 min	0.03 [15]
Length of stay, median [3]	8 days	4 days	0.01

injuries, as longer stent length may increase thrombotic risk and inadvertent coverage of small branches that could become collaterals later – this would essentially "burn bridges" and risk more severe ischemia from stent thrombosis than a failed surgical bypass [17].

Hemodynamic Stability and Balloon Occlusion

Patients that are hemodynamically unstable or receiving cardiopulmonary resuscitation are less likely to be deemed candidates for EVR [17]. They are also more likely to have multi-system injuries necessitating prompt open surgery rather than isolated endovascular intervention. Moreover, patients with large hematomas at risk of compressing the brachial plexus and leading to persistent neurologic deficits may also require OSR rather than EVR to evacuate it [13]. Whereas hemodynamic instability was previously cited as a contraindication to EVR, now, in the era of EVTM and hybrid ORs, it is an evolving indication [33–35]. With innovations such as resuscitative endovascular balloon occlusion of the aorta (REBOA) and proximal balloon occlusion of the subclavian artery, it is becoming more realistic to take unstable patients for hybrid or EVR [12,28] even with active extravasation and expanding hematoma [36]. External balloon catheter tamponade can also be helpful, for example, with a large (e.g. 20 cc) Foley balloon inserted through the bleeding injury tract and then inflated to the point of hemostasis. This measure for damage control is particularly invaluable for junctional injuries such as ASI [37] as it can transform an emergent situation into a controlled one. If able to cover the injury, a non-compliant angioplasty balloon could provide both proximal and distal control, thereby facilitating a hybrid solution. It warrants emphasis that endovascular techniques do not exclude OSR and can in fact be valuable adjuncts to it.

Despite the theoretical increase in bleeding proximal to the site of aortic occlusion, some authors support the use of EVR with REBOA [3,31,33,34], following basic resuscitation (blood product resuscitation, tube thoracostomy), and have published reports of positive outcomes thereafter [38]. Branco and DuBose reviewed 7 studies on REBOA and 10 on EVR of ASI, concluding that REBOA was a safe and effective alternative to open thoracotomy in critically ill trauma patients [31]. One head-to-head comparison from a large American trauma registry also posited there was no significant difference between REBOA and emergency thoracotomy [38]. If REBOA is utilized pre-procedure, further clinical deterioration can be rapidly temporized, and as this is now more commonplace in major trauma centers, it may contribute to the shift towards EVR of traumatic vascular injuries such as ASI as well. It has been postulated that the only absolute contraindication to EVR would be failure to cross the injured area with a wire [3], although it is also important to recognize that acute care providers who can use REBOA may not also be trained for more complex EVR of ASI.

TECHNIQUES

The techniques of EVR for ASI involve some consistent elements. It usually takes place in a hybrid operating room or a room with full endovascular suite capabilities. An anesthesiologist is present and general anesthesia is utilized. Antibiotic prophylaxis is administered, but most patients are not heparinized leading up to the procedure nor during it. Patients are prepped and draped for both endovascular and possible open repair.

Most cases start with percutaneous access via the common femoral artery, which can be ultrasound-guided if required. Percutaneous brachial access with a low profile 4-French introducer sheath is also an option, although it tends to be reserved as accessory access when dual access is required. If immediate proximal control of hemorrhage is required, selection of the injured vessel for the aortic arch is performed and balloon occlusion is

performed. Commonly used balloons to do so include larger profile compliant aortic molding balloons, appropriate diameter semi-compliant or non-compliant angioplasty balloons, or lower profile REBOA specific occlusion devices.

A soft guidewire and diagnostic catheter is typically used to access the injured vessel and selective angiography is done to define the target lesion. This can also be used for device sizing (based on the normal parent vessel diameter) if not already planned using prior preoperative computed tomography angiography. Then, a long sheath (8–10 French) is typically inserted reaching just proximal to the site of injury if from the femoral access, and 4–5 French from the secondary (e.g. brachial access) if present. When the brachial artery is the primary approach for actual stent deployment, a brachial artery cutdown is often required to accommodate larger device and sheath sizes (>6 French). Radial access is also becoming an option, with advances in lower profile endovascular systems. The retrograde transbrachial approach can be particularly helpful when a total occlusion exists or antegrade guidewire crossing of the injured segment is unsafe. Snaring of the wire to allow for through-and-through "body-floss" technique is often a helpful adjunct as well. Advancing the stent via brachial artery access alone if possible can potentially be safer, as it avoids the neurologic complications of negotiating aortic arch vessels, which can be anatomically variant or thrombus laden, with a large sheath and covered stent [13]. For the subclavian artery, the stent size is usually 6–8 mm (including oversizing the device by 10–20% or about 1 mm to ensure adequate seal) × 40 mm length [12,34]. Generally, either side of the stent-graft incorporates 1–2 cm of normal artery [13,27,34]. A completion angiogram is done, which confirms distal runoff through to the forearm.

If a hematoma continues to expand or hypotension persists after successful arterial stenting, concurrent venous injury (especially in the setting of penetrating trauma) is a crucial consideration. This can also be investigated either with a venogram or open surgical exploration.

Periprocedural complications to be aware of include local access site related events such as artery thrombosis, pseudoaneurysm or intimal flap development, nerve injury, compartment syndrome from hematoma (brachial access), phlebitis, and lymphangitis [31,39]. Arterial closure devices can be used if indicated. Remote complications such as embolic events, cerebral infarction, and one immediate peri-procedural mortality have also been reported [31,39].

DEVICES

The use of both balloon-expandable and self-expanding stents, generally oversized 10–15%, covered with Dacron or PTFE have been used for ASI. Those that feature commonly in reported cases and series include the Viabahn (Gore and Associates, Flagstaff, AZ, USA), iCAST (Atrium Interventional, Hudson, New Hampshire, USA), Covered Wall-Stent (Boston Scientific, Watertown, MA, USA), PTFE-covered Palmaz stent (Cordis Corporation, Miami Lakes, FL, USA), and Fluency stent (Bard, Murray Hill, NJ, USA). The choice of balloon-expandable versus self-expanding stent corresponds to the specific site of injury along the vessel. A key anatomic difference across the subclavian and axillary arteries is the extent of repetitive movements at the junction of the clavicle and first rib as well as the thorax and upper arm. This often precludes placement of a balloon-expanding stent at the thoracic outlet, distal subclavian or axillary arteries, as repeated movements increase their risk of stent fracture and thrombosis. For a proximal subclavian injury, on the other hand, balloon-expanding stents allow more deployment precision if landing close to other key vessels such as the vertebral artery ostium. Figure 2 illustrates an example of the use of both a Viabahn self-expanding covered stent and an Epic self-expanding bare metal stent. To date, no study has compared the patency of ASI stents by types or locations. Stent selection currently appears to be based on provider preference and appraisal of these key anatomic considerations.

Post-operative surveillance is generally accompanied by imaging of the entire axillosubclavian segment and its adjacent inflow and outflow arteries at regular intervals, initially at 1 month, 6 months, and then annually. This is typically accomplished by Duplex ultrasonography of the entire axillosubclavian segment. Patients receive varied durations of antiplatelet therapy thereafter, ranging from 1 month to lifelong [6,17,39]. Follow up is limited in most cases with a wide range, from none post-discharge to 6 years [35,39].

OUTCOMES

Contemporary studies of the outcomes of OSR versus EVR of ASI suggest significantly lower in-hospital mortality in general. A head-to-head comparison across two high-volume American trauma centers of EVR and OSR that propensity-matched patients also showed that EVR reduced in-hospital mortality and rates of surgical site infections [12]. EVR causes less disruption of adjacent tissues, and reduces operative time and need for blood products [15,40,41]. Patients have lower rates of post-operative complications such as pneumonia, fewer ICU admissions, and shorter hospital length of stay, and overall EVR has been independently associated with improved survival [3]. Multiple series comparing the outcomes of EVR versus OSR for ASI have concluded that EVR involves reduced operative times and blood loss [10,15] as well as lower rates of brachial plexus injury [42]. Table 1 summarizes these key results. One series of 27 ASIs demonstrated a 95% success rate with EVR, with the few failed attempts being due to stent deployment failure or inability to fully cover the lesion [10]. Therein, the 12 "endofeasible" lesions that successfully underwent EVR had similar 1-year arterial patency as OSR.

An early retrospective review of 46 ASIs found only 21 that acutely received preoperative diagnostic arteriography, and among those only 3 had endovascular intervention. Two had EVR to treat injured first order subclavian artery branches, and one had an axillary artery transection for which proximal control was obtained with a 5-mm balloon in the distal subclavian artery prior to OSR [11]. Of note, 6 patients with subclavian vascular injury underwent emergency department thoracotomy and none of them survived. A more recent retrospective review of EVR versus OSR outcomes for civilian arterial traumatic injuries from 2002 to 2014 showed the rate of EVR increasing from 3.1% to 8.9%, which is a clear upward trajectory [3]. However, the same study still noted continued cautious selection because EVR patients were older, with higher systolic BP and lower heart rate on admission, and their time to repair was faster, all reflective of lower injury severity scores (ISS) [3]. Despite propensity score matching, confounders in patient selection of EVR over OSR inevitably make EVR outcomes appear more favorable as patients selected for EVR tend to have lower ISS and those who have OSR tend to start with more extensive traumatic injuries.

Primary patency of covered stents has been called the Achilles' heel of EVR [17], and the outcome data does remain limited to case reports and case series or retrospective reviews. These are rare injuries, and the population they occur in is especially challenging to follow up, leaving long-term outcomes after EVR a matter of ongoing concern. Primary patency of covered stents for ASI ranges from 69% to 88% [28,43]. A large retrospective review on EVR of ASI found 84.4% stent patency for the duration of patient follow-up [39]. However, stent-related complications have been noted. In one retrospective study the rate was 2/15 for a type 1A endoleak and a stent thrombosis [12], which has also been reported in multiple large retrospective reviews [6,17]. Another small series of six ASIs resulted in 2/6 patients with persistent endoleaks requiring balloon angioplasty to improve stent apposition [34]. Although stent thrombosis is encountered at times, it does not always necessitate reintervention if asymptomatic [6]. Close follow-up, which may prevent this, has proven difficult to achieve in this patient population. Moreover, the burden of intensive long-term post-operative surveillance is not insignificant [32] and can be hard to maintain, particularly in younger patients. While it is too early for truly long-term outcomes of stent-grafting for ASI to be established, its utility even as a temporizing measure or bridge to later definitive repair [6,17] is still important and may improve the outcomes of OSR done later in a non-emergent manner.

CONCLUSION

In patients with ASI, a junctional traumatic vascular injury in which OSR is highly morbid, EVR can be a safer alternative that achieves similar immediate results. With continually better tools and a paradigm shift towards more extensive endovascular training and hybrid operating suites, EVR is likely to grow with more well-trained practitioners comfortable with EVR of traumatic vascular injuries. As we enter an era of EVTM, vascular surgeons and interventional radiologists in many systems are increasingly likely to work collaboratively with trauma teams. The resulting paradigm shift towards EVR may notably improve morbidity and mortality for the young patients that suffer from these injuries even in extremis. Trauma registries may be an important alternative to randomized control trials for future research.

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Author Contributions

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Tips and Techniques

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Hybrid Management of Acute Portal Vein Thrombosis Complicated by Mesenteric Ischemia

Sayuri P Jinadasa[1], Mira Ghneim[1], Brittany O Aicher[2], Rishi Kundi[1], John Karwowski[3], Jose J Diaz[1] and Joseph J DuBose[1]

[1]R Adams Cowley Shock Trauma Center, University of Maryland Medical System, Baltimore, MD, USA
[2]Division of General Surgery, University of Maryland Medical System, Baltimore, MD, USA
[3]Division of Vascular Surgery, University of Maryland Medical System, Baltimore, MD, USA

Acute portal vein thrombosis complicated by mesenteric ischemia requires emergent treatment to address the compromised bowel as well as the portal vein thrombus. We report a novel hybrid approach to managing this disease process. The procedure we discuss entails exploratory laparotomy and small bowel resection by the acute care emergency surgery team. Following this, the vascular surgery team performs a portal venogram through a branch mesenteric vein accessed through the laparotomy incision and then places a thrombolysis catheter. This technique and approach allows us to provide initial management efficiently and effectively under one operation.

Keywords: *Mesenteric Ischemia; Endovascular Surgery; Emergency General Surgery; Portal Vein Thrombosis*

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The prevalence of portal vein thrombosis is estimated to be approximately 1% in the general population, with cirrhosis and hepatic carcinoma being the highest risk factors [1]. Portal vein thrombosis is often an incidental finding [2]; however, complete acute portal venous thrombosis can lead to abdominal pain and ascites. Intestinal ischemia and necrosis are the most serious complications [3,4]. The prevalence of this complication is not known; however, cases are described in the literature [4–6].

The goal of treatment is recanalization of the portal vein and prevention of thrombus extension. In cases with no clinical consequences, systemic anticoagulation is the treatment of choice [2]. Percutaneous endovascular catheter-directed and indirect thrombolysis, thrombectomy, and agitation thrombolysis [3] via transjugular or transhepatic access [7–9] are techniques developed for treatment of acute symptomatic portal vein thrombosis.

Our vascular surgery and acute care emergency surgery services developed a feasible and repeatable intraoperative hybrid technique to manage acute complicated portal vein thrombosis (Figure 1). Preoperatively, the patient is anticoagulated with systemic heparin. Upon abdominal exploration, the nonviable intestine is identified and resected in standard fashion (Figure 2). Within the cut edge of the mesentery along the line of the small bowel resection, a small distal branch vein is identified and cannulated with a micro-puncture needle, and subsequently a 5-French sheath is placed and a mesenteric venogram is performed (Figures 3 and 4). In the case being presented, the venogram demonstrated occlusive thrombus within the portal vein. A thrombolysis catheter is placed into the region of heaviest thrombus burden. Any areas of intra-abdominal bleeding are addressed with electrocautery and packed to avoid further bleeding when tissue plasminogen activator (tPA) administration is initiated post-operatively. At the end of the operation, an ABThera dressing (3M/KCI, St. Paul, MN, USA) is placed to allow for open abdominal packing while incorporating the thrombolytic catheter in a secured fashion (Figure 5).

Corresponding author:
Sayuri P Jinadasa, R Adams Cowley Shock Trauma Center University of Maryland Medical System, 22 South Greene Street, Room T4N24, Baltimore, MD 21201, USA.
Email: Sayuri.jinadasa@som.umaryland.edu

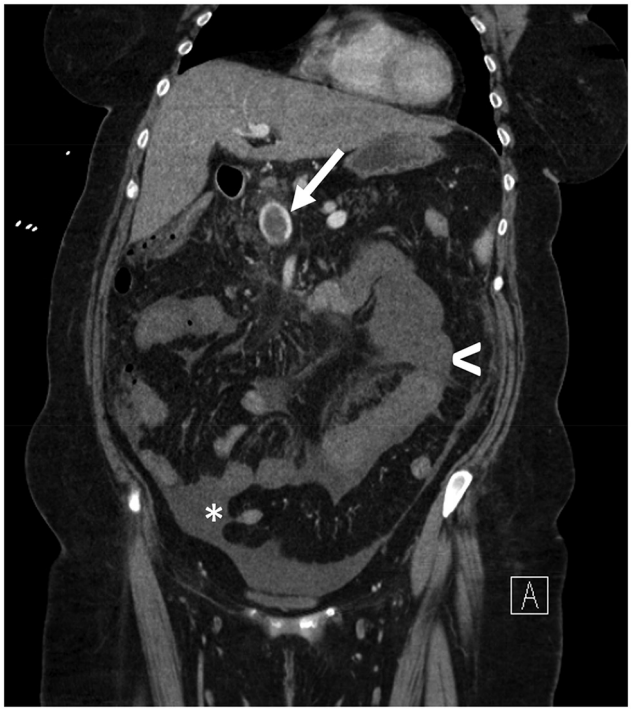

Figure 1 Computed tomography scan showing portal vein thrombus indicated by the arrow. Thickened small bowel with adjacent mesenteric edema is indicated by the arrowhead. The asterisk indicates free fluid.

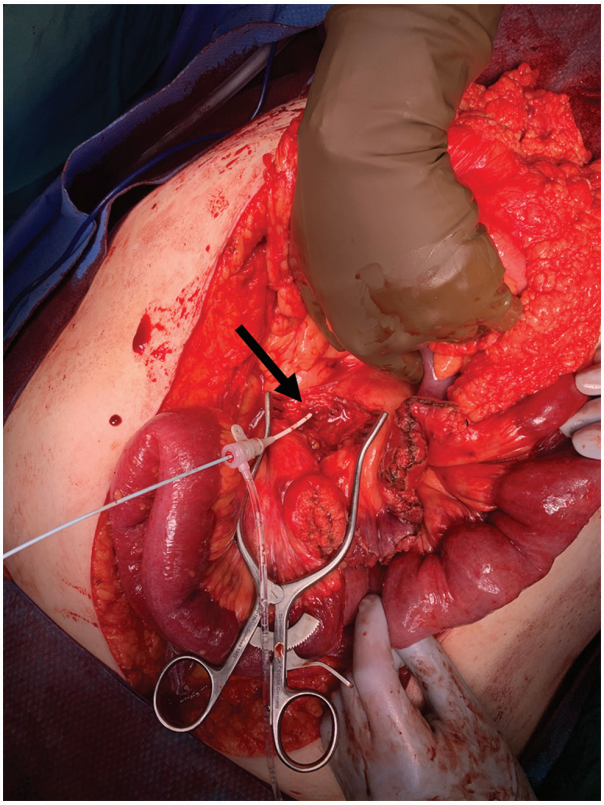

Figure 3 Venous system access with a 5-French sheath.

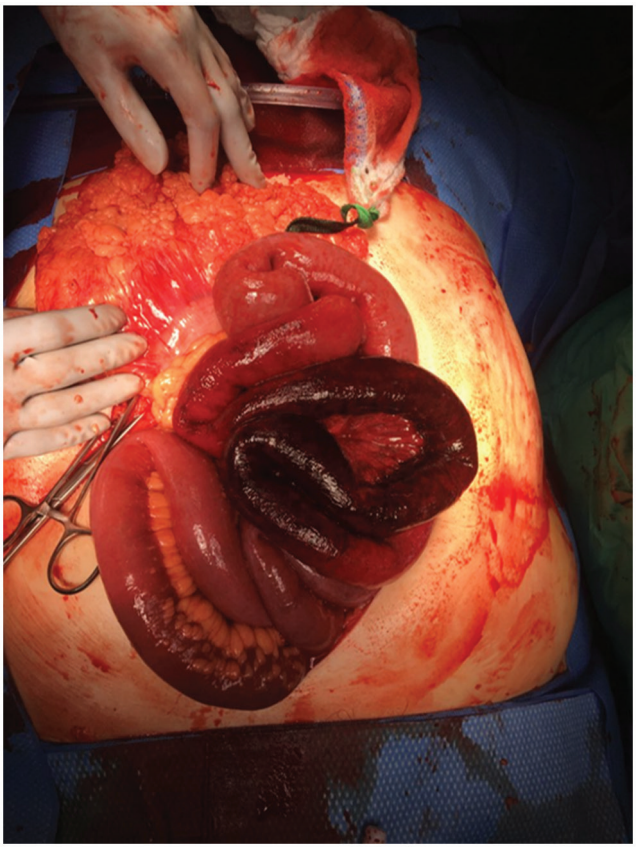

Figure 2 Nonviable jejunum identified during exploratory laparotomy.

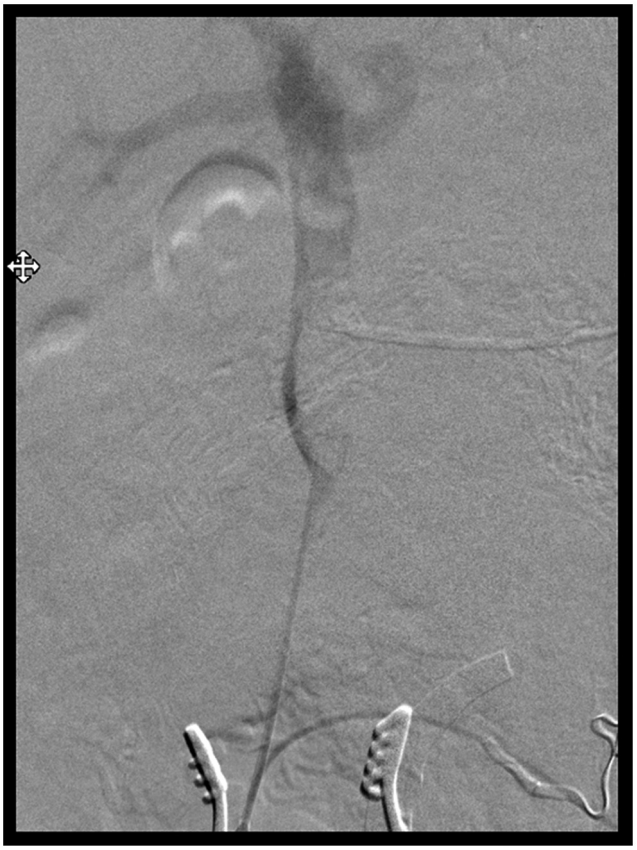

Figure 4 Pre-thrombolysis mesenteric venogram showing significant clot burden in the portal vein.

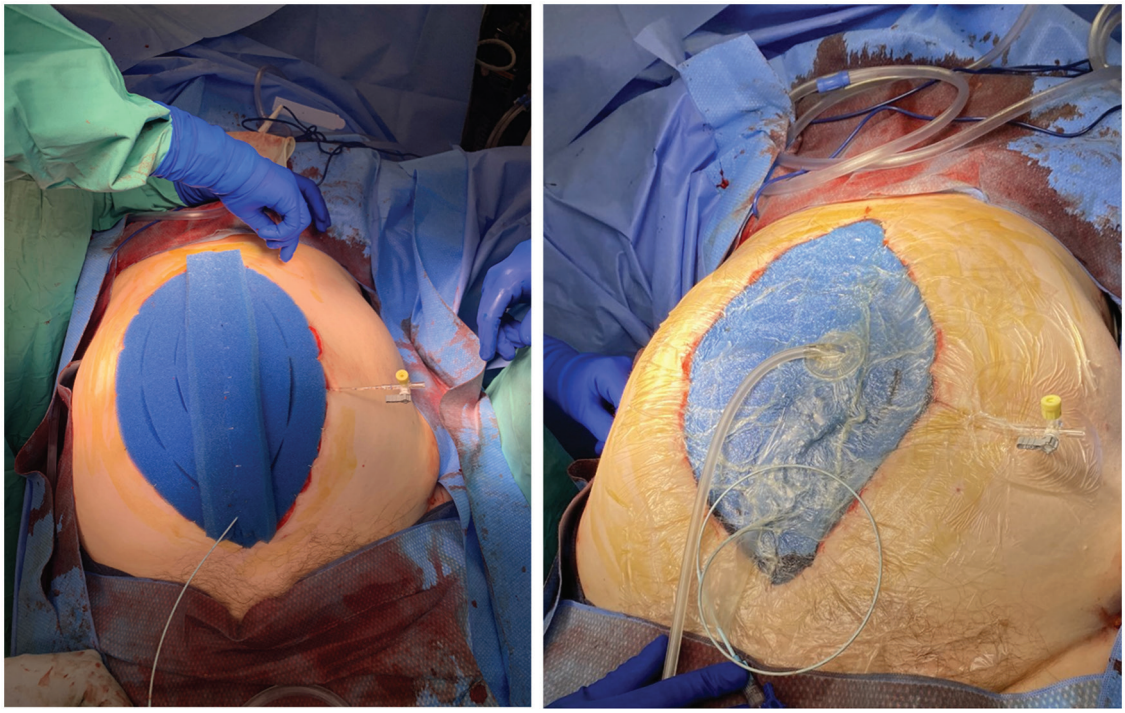

Figure 5 Placement of ABThera device in the OR with the sheath and thrombolysis catheter in place.

Postoperatively, the patient is monitored in the intensive care unit. tPA is administered initially via the catheter at a dose of 0.5 mg/kg/hr and then titrated to maintain the fibrinogen level (checked every 6 hours) between 200 and 299 mg/dL. Heparin is infused systemically to achieve a partial thromboplastin time level between 60 and 80 seconds as well as directly into the sheath at a non-titrated subtherapeutic dose of 500 units/hr.

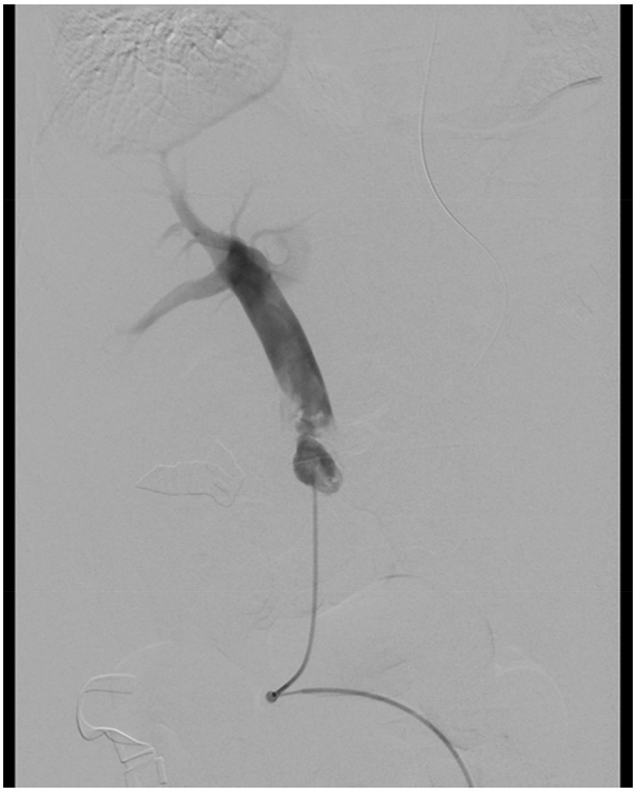

Figure 6 Post-thrombolysis mesenteric venogram showing reduction of clot burden.

Approximately 24 hours later, the patient is taken back to the operating room for re-evaluation of the intestine and repeat venogram (Figure 6). In the case of the presented patient, the repeat venogram showed a dramatic decrease of the portal vein clot burden and good outflow. The sheath is removed and the entry vein is suture ligated. Continuity of the intestine is re-established in standard fashion and the abdomen is closed if appropriate.

As described, this is a straightforward hybrid approach to manage portal vein thrombosis complicated by mesenteric ischemia that allows for efficient care of the patient, avoids the need for transhepatic cannulation for obtaining a venogram and placing a thrombolysis catheter, and obviates the need to obtain percutaneous venous access.

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Author Contributions

JJ DuBose, JK, and RK participated in the development of the technique. SPJ participated in the literature review. SPJ, JJ DuBose, BOA, and MG participated in the drafting of the article. SPJ, JJ Diaz, BOA, MG, RK, JJ Dubose and JK participated in the critical revision of the article. SPJ, JJ Diaz, MG and JJ Dubose participated in the approval of the version being submitted. All authors have contributed to the writing and editing of this manuscript.

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Images of interest

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TEVAR and Delayed Left Subclavian Artery Chimney for Thoracic Aortic Transection

Mohamad Nogedat, Hashem Hayeq and Offer Galili

Department of Vascular & Endovascular Surgery, The Lady Davis Carmel Medical Center, Haifa, Israel

Keywords: *Emergent TEVAR; Vascular Surgery Trauma; Vascular Surgery*

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The following photos describe the endovascular treatment of an unstable patient with a traumatic rupture of the thoracic aorta following blunt chest trauma.

A 57-year-old male presented to the Emergency Department with blunt trauma due to a high fall. On presentation the patient was unstable (systolic blood pressure 70, heart rate 120). The procedure was performed in two sessions. The first session was the emergency deployment of a Zenith Alpha (Cook Medical) thoracic endo-graft in the descending thoracic aorta with intentional covering of the left subclavian artery. The patient was stabilized in ICU. Then, in the second session, due to left upper limb ischemia, a parallel "chimney" Be-Graft (Bentley) covered balloon expandable stent was deployed in the left subclavian artery (retrograde approach) after 24 hours from the index procedure. The patient was mobilized with complete recovery after 48 hours. Computed tomography angiography (CTA) revealed complete resolution of the thoracic rupture with the patent left subclavian "chimney" stent.

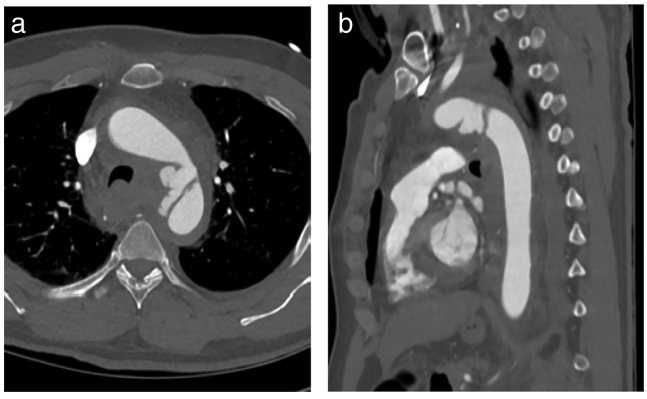

Figure 1 Preoperative chest CTA showing partial transection of the aorta (Grade III), 1.5 cm distal to the left subclavian artery. (**a**) Axial view. (**b**) Sagittal view.

Corresponding author:
Offer Galili, Head of Vascular & EndoVascular Surgery Department, The Lady Davis Carmel Medical Center, Haifa, Israel.
Email: offerga@clalit.org.il

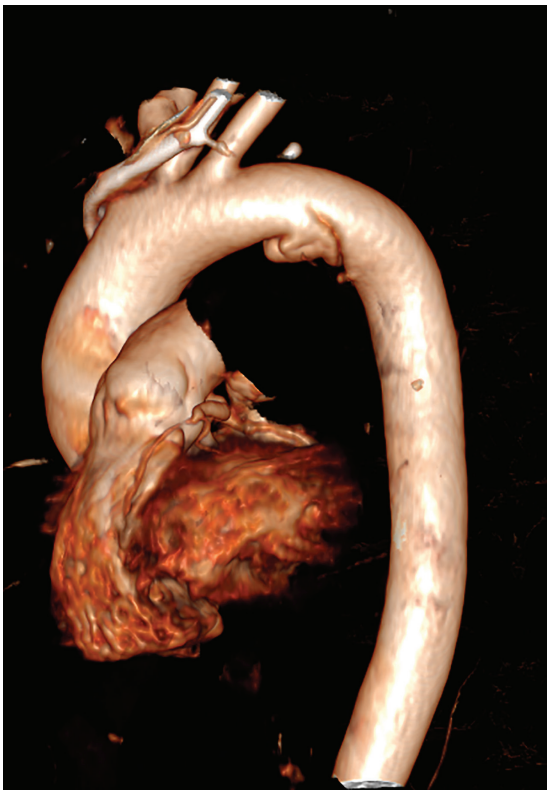

Figure 2 Three-dimensional CTA reconstruction of the descending aorta showing Grade III blunt aortic injury.

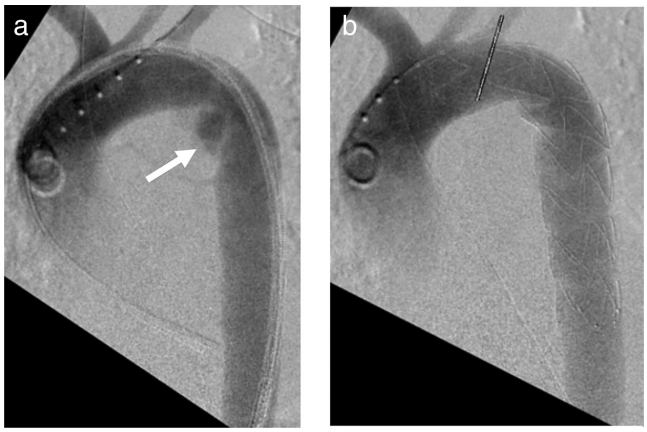

Figure 3 Intraperative angiography. (**a**) Ruptured descending thoracic aorta (white arrow). (**b**) Deployed stent graft covering the left subclavian artery without any extravasation.

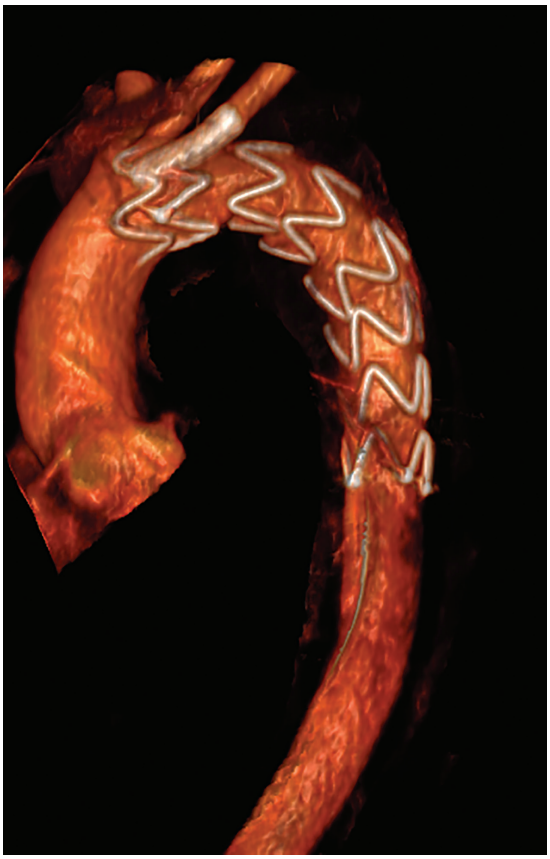

Figure 4 Three-dimensional CTA reconstruction of the aorta with parallel aortic stent graft and "chimney" graft in the left subclavian artery (72 hours after the index procedure).

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.
(3) The images were published with permission from the patient.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Author Contributions

All authors contributed substantially to the study and writing of the manuscript.

Case Report

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Hemoperitoneum Due to Penetrating Intercostal Artery Injury: A Case Report of a Rare and Still Understudied Entity

Maya Paran[1], Sivan Barkai[1], Gerardo Camarillo[1], Boris Kessel[1] and Alexander Korin[2]

[1]*Surgical Division, Hillel Yaffe Medical Center, Hadera, Israel, affiliated with Rappaport Medical School, Technion, Haifa, Israel*
[2]*Trauma Unit, Hillel Yaffe Medical Center, Hadera, Israel, affiliated with Rappaport Medical School, Technion, Haifa, Israel*

Intercostal artery injury may be life-threatening and usually presents as hemothorax. We report a unique case of penetrating injury, causing hemoperitoneum due to intercostal artery injury, without thoracic involvement. During urgent laparotomy, no intra-abdominal organ injury was found. Hemostasis was successfully achieved via suturing through an additional lateral 10 cm incision through the left thorax.

Keywords: *Intercostal Artery; Penetrating Injury; Intraabdominal Injury*

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INTRODUCTION

Intercostal artery injuries have been reported to be caused by blunt and/or penetrating injuries [1] as well as iatrogenic injuries [2]. Traumatic injuries to the intercostal artery most commonly cause large hemothorax. We report a unique case of a penetrating injury, causing massive intra-abdominal bleeding from an intercostal artery, without any diaphragmatic injury or hemothorax.

CASE PRESENTATION

A 54-year-old male presented to a regional Level II trauma center after sustaining multiple stab wounds to his left chest at the posterior axillary line level, as well as the left back and both buttocks. On admission, the patient was noted to have active bleeding from his wounds, controlled by pressure dressings. Initial chest X-ray performed at the trauma bay was interpreted as normal. The patient remained hemodynamically stable and was referred to the radiology department for computed tomography (CT) scan of the chest and abdomen. Chest CT did not reveal any pathological findings, with no pneumohemothorax. Abdominal CT revealed a significant hemoperitoneum (Figure 1), with active extravasation from the left intercostal artery in the posterior aspect of the tenth intercostal space (Figure 2). The patient progressively developed hemodynamic instability and underwent emergency laparotomy. On surgery, approximately 2 liters of blood were evacuated from the abdominal cavity. Exploration of the abdomen did not reveal any parenchymal or hollow viscus injury. Active bleeding was detected in the posterior abdominal wall, which was treated with simple suturing followed by packing. However, this was not sufficient for control of bleeding. Therefore, it was decided to attempt control through an additional lateral incision. A 10 cm incision was performed through the stab wound on the lateral aspect of the left thorax, similar in location to a posterior lateral thoracotomy incision. Via this approach, hemostasis was achieved by sutures pulled through the chest wall from the inside out, around the ribs adjacent to the bleeding intercostal artery. During surgery, the patient received 4 units of packed red blood cells and 2 units of fresh frozen plasma. The patient was stabilized, underwent primary abdominal closure, and transferred

Corresponding author:
Maya Paran MD, Hillel Yaffe Medical Center, Ha-Shalom St. Hadera, Israel.
Email: paran.maya@gmail.com

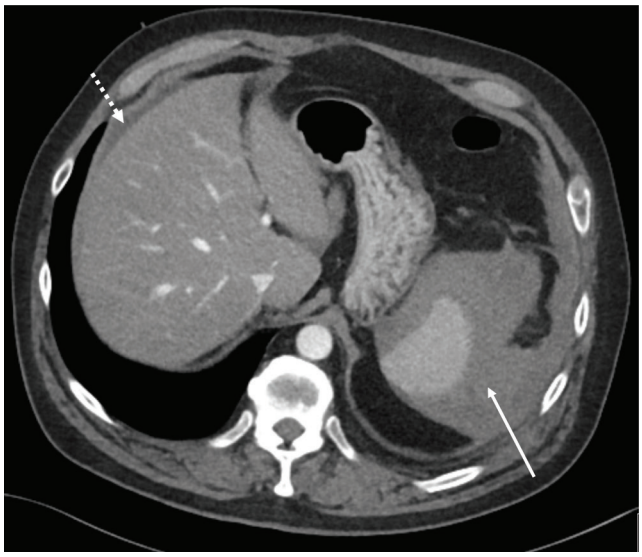

Figure 1 Abdominal CT showing significant hemoperitoneum. The white arrow shows hemoperitoneum around the spleen. The white shattered arrow shows blood in the right subdiaphragmatic space.

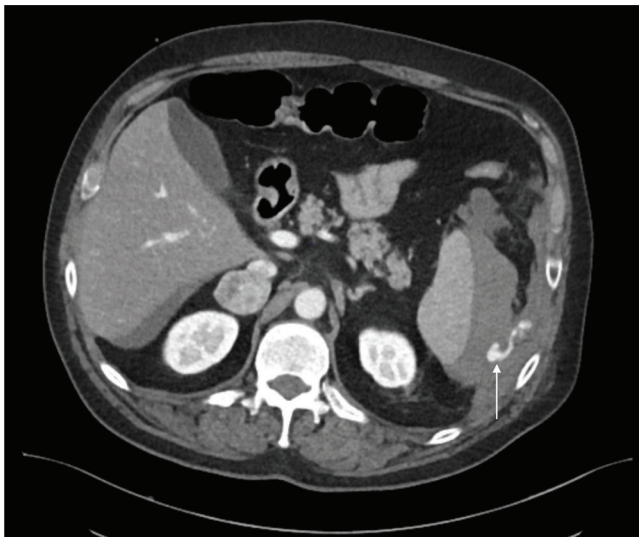

Figure 2 Abdominal CT showing active bleeding from the left intercostal artery. The white arrow shows active extravasation from the left intercostal artery in the posterior aspect of the tenth intercostal space.

to the intensive care unit. The patient was weaned from mechanical ventilation the following morning. The postoperative course was without complications, hemoglobin levels remained stable, and the patient was uneventfully discharged on postoperative day 7.

Ethical Approval and Informed Consent

Ethical approval was not required, informed consent was not required and all data was annonymized.

DISCUSSION

Intercostal artery injuries are occasional but potentially fatal injuries. The real incidence of such injuries either resulting from blunt or penetrating mechanisms remains unclear. Most studies on this topic include case series or single case reports alone. For example, during an eight-year period Tamburini et al. [3] described only 18 patients with traumatic intercostal artery injury. In this work, the mortality rate was 23% and the incidence of penetrating injury was not reported. In a different study, which collected data regarding both iatrogenic and blunt trauma patients with intercostal artery injury, Chemelli et al. [4] reported an overall mortality of 30% among 24 patients.

Hemorrhage control in such cases may be achieved surgically or by angioembolization [5]. The latter is only relevant in scenarios of hemodynamically stable patients. When approaching these arterial vessels intraoperatively, hemostasis can be achieved by suture ligation. However, in some cases surgical hemostasis can be very difficult. The literature clearly points out the challenge of controlling posterior intercostal bleeding, mostly due to the limited space/exposure where the ribs have the least mobility and the intercostal space is smallest [6]. The accepted practice is performing a posterior lateral thoracotomy. However, previously described cases reported that the clinical manifestation of intercostal artery injury is mostly massive hemothorax. To the best of our knowledge, only a single case of hemoperitoneum necessitating laparotomy due to an intercostal artery injury, resulting from blunt chest trauma and rib fractures, has been reported [7]. This is the first description of an isolated massive hemoperitoneum caused by bleeding from an intercostal artery due to a penetrating injury. In our opinion, despite the findings on the CT scan, in the presence of a significant amount of blood in the abdominal cavity, the explorative laparotomy and meticulous revision of the abdominal cavity were mandatory in order to exclude intra-abdominal organ injury. In retrospect, a midline incision substantially restricted the exposure of the posterior intercostal space. As a result, additional posterior lateral thoracotomy was required to provide an adequate approach for hemostasis achievement. This created a unique problem, associated with placing a patient with an open and packed abdomen in a lateral decubitus position.

We believe that this case raises the possibility that some patients with a penetrating flank/back injury and massive hemoperitoneum may have an intercostal artery injury, even without hemothorax or diaphragmatic injury. A posterior wound may possibly raise a suspicion of an intercostal artery injury. This awareness is even more important in unstable patients who are operated upon immediately, without additional imaging.

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

We confirm that there are no known conflicts of interest associated with this publication.

Funding

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Residents Corner

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Endovascular and Hybrid Open and Endovascular Management of Blunt and Penetrating Zone III Carotid Artery Injuries

Shira A Strauss[1], Adam Power[2], Sudhir K Nagpal[1,3], Michael K Tso[4], Megan L Brenner[5], Joseph J DuBose[6] and Derek J Roberts[1,3,7]

[1]Division of Vascular and Endovascular Surgery, Department of Surgery, University of Ottawa, Ottawa, Ontario, Canada
[2]Division of Vascular Surgery, Department of Surgery, Schulich School of Medicine and Dentistry, Western University, London, Ontario, Canada
[3]The Ottawa Hospital Research Institute, The Ottawa Hospital, Ottawa, Ontario, Canada
[4]Division of Neurosurgery, Department of Surgery, Kelowna General Hospital, Kelowna, British Columbia, Canada
[5]Department of Surgery, University of California Riverside, Riverside, California, USA
[6]Divisions of Surgical Critical Care and Vascular Surgery, Department of Surgery, University of Maryland, Baltimore, Maryland, USA
[7]The O'Brien Institute for Public Health, University of Calgary, Calgary, Alberta, Canada

Injuries to zone III of the carotid artery, located between the angle of the mandible and the skull base, are uncommon, associated with a high risk of adverse neurologic events and mortality, and challenging to treat. These lesions are difficult to access and treat surgically due to their anatomic location. Therefore, endovascular and hybrid open and endovascular techniques have emerged as a minimally invasive, and in many cases, safer and more effective alternative to open surgery. Endovascular techniques for use in this anatomical region include balloon catheter tamponade, embolization, balloon angioplasty, and endovascular stenting. Selection of the most appropriate treatment strategy is dependent on the: (1) concomitant injuries of the patient, (2) location (external versus internal carotid artery) and nature (intimal tear, dissection, pseudoaneurysm, transection, occlusion, or arteriovenous fistula) of the injury, and (3) whether the operating surgeon believes it is necessary to revascularize or sacrifice the injured carotid artery. The purpose of this article is to review the present endovascular and hybrid open and endovascular therapies available for zone III penetrating and blunt carotid trauma. We begin by describing the clinical presentation and diagnosis of these injuries and then discuss management of an undifferentiated zone III vascular injury. This is followed by a discussion of the management of zone III external and then internal carotid artery injuries. We conclude by describing postoperative management, follow up, and future directions.

Keywords: *Zone III Carotid Artery Injuries; Endovascular Repair; Hybrid Open and Endovascular Repair; Endovascular Resuscitation and Trauma Management*

Received: 12 June 2021; Accepted: 1 December 2021

BACKGROUND

Traumatic injuries to the carotid artery in zone III of the neck, located between the angle of the mandible and skull base [1,2] are uncommon and associated with a high risk of morbidity and mortality. Zone III injuries account for only 4–19% of penetrating neck trauma [3–6]. Further, while most (97%) blunt carotid artery injuries (BCI) are located in zone III, they are seen in less than 0.25% of blunt trauma victims [7]. Penetrating injuries to zone III of the carotid artery have an associated mortality rate of approximately 9% [8] while blunt injuries have a mortality rate as high as 28%, likely secondary to the concomitant injuries suffered by the patient [7]. These injuries are also linked with a risk of permanent severe neurologic sequelae (including hemispheric stroke) in up to 58% of survivors [7].

Corresponding author:
Derek J Roberts, Division of Vascular and Endovascular Surgery, Department of Surgery, University of Ottawa, The Ottawa Hospital, Civic Campus, Room A280, 1053 Carling Avenue, Ottawa, Ontario, Canada K1Y 4E9.
Email: Derek.Roberts01@gmail.com

Vascular structures in zone III of the neck are difficult to access using standard open surgical techniques. Adequate exposure may necessitate wire-mediated anterior subluxation of the mandible or mandibular osteotomy, which are complex maneuvers that are unfamiliar to many trauma, vascular, and neurological surgeons [9]. These techniques are time-consuming and associated with a high risk of cranial or peripheral nerve injury. Further, if open surgical exploration is attempted, extensive hemorrhage can rapidly impede visualization . Although proximal control of the injured internal carotid in zone III is typically readily obtained, open distal control of retrograde bleeding from the distal internal carotid artery (ICA) is rarely possible [10].

Endovascular and hybrid open and endovascular techniques may offer safer and more effective alternatives to open attempts at managing zone III carotid injuries. Intervention is indicated for penetrating zone III carotid injury in patients with hard signs of vascular or aerodigestive injury (e.g., expanding hematoma, active bleeding, hemodynamic instability, airway compromise, or hematemesis) [11,12]. It is indicated for BCI in patients with expanding pseudoaneurysms and neurologic events (secondary to arterial dissection or thrombus formation/embolization) despite maximal medical management (e.g., intravenous heparin or antiplatelets), and vessel transection [13,14]. Various endovascular and hybrid therapies exist, including stenting, embolization, balloon angioplasty, and any of the above techniques combined with balloon catheter tamponade or open exploration (for hematoma decompression or addressing adjacent injuries).

The purpose of this article is to review the current endovascular and hybrid therapies available for zone III penetrating and blunt carotid trauma.

CLINICAL PRESENTATION AND DIAGNOSIS OF ZONE III CAROTID ARTERY INJURIES

Patients with zone III carotid artery injuries vary in clinical presentation. In a cohort study of 24 patients with angiographic evidence of penetrating zone III vascular injury, five (21%) presented with hypotension and nine (38%) with respiratory distress necessitating a definitive airway due to tracheal compression, aspiration of blood from the nose or mouth, apnea, or coma [8]. Active external hemorrhage from the mouth, cheek, nose, and/or ear was seen in eight patients (33%), and stable or expanding hematomas were found in the nasal or oropharynx of 11 patients (46%) and necks of 11 patients (46%). Among 16 patients with penetrating zone III ICA injuries, 5 (31%) had no neurologic sequelae while 11 (69%) demonstrated central neurologic or cranial nerve deficits, including coma, hemiparesis, aphasia, and injury to cranial nerves III, IV, VI, VII, VIII, IX, X (with vocal cord paralysis), and XII [8].

Blunt carotid injuries, most often localized to zone III [7], likewise present with a range of symptoms. A multicenter review of 60 BCIs in 49 patients revealed that 12 patients (25%) presented with hypotension and 18 (37%) presented with a Glasgow Coma Scale (GCS) score <7 [15]. Although 24 patients (49%) presented with an initially normal or essentially normal neurologic exam, delayed presentations (>12 hours after initial assessment) of significant neurologic deficits were common (29% of patients), often manifesting as contralateral motor deficits. Concomitant injuries were frequent, including craniocerebral trauma, facial and spinal fractures, and innominate and vertebral artery trauma [15]. Carotid-cavernous sinus fistulae (CCF) represent another type of zone III carotid injury, which may be seen with either blunt or penetrating trauma [16]. CCF are rare (0.2% of head traumas overall) and classically present with Dandy's triad—exophthalmos, bruit, and conjunctival chemosis—although hemiparesis may be seen as well.

Considering the variety of clinical presentations associated with zone III carotid injuries, radiographic imaging is an essential component of diagnosis. Early diagnosis of blunt cerebrovascular injury may lead to lower stroke rates [17]. All patients with suspected traumatic zone III vascular injury should undergo computed tomography angiography (CTA) for further evaluation [11,12]. Specific indications include mid-face fracture, mandible fracture, basal skull fracture involving the carotid canal, cervical spine fracture, severe traumatic brain injury with Glasgow Coma Scale <6, and near-hanging mechanism [17]. CTA may reveal direct signs of vascular injury, such as vessel transection, partial or complete occlusion, active bleeding, pseudoaneurysm, intimal injury, dissection, arteriovenous fistula, or luminal caliber changes (Fig. 1). In addition, it may reveal indirect signs of vascular injury, such as perivascular hematoma, fat stranding, gas, or foreign bodies and bone fragments [18]. It is worth noting that, while most guidelines favour CTA [12,19], cerebral angiography was previously considered the gold standard for diagnosis of zone I and III injury [12,20], has demonstrated greater accuracy for the diagnosis of blunt injuries in some studies [21], and may be appropriate for select patients who require simultaneous diagnosis and endovascular intervention . Once the extent and location of the zone III vascular injury are identified—as well as any other concomitant injuries (e.g., zone II injury, aerodigestive injury, or intracranial lesions)—a decision can be made about appropriate treatment for the injured vessel.

UNDIFFERENTIATED ZONE III VASCULAR INJURY

In patients with active external bleeding and suspected zone III vascular injury, hybrid techniques are particularly useful. Different combination therapies exist: an open surgical technique may be employed to obtain hemostasis until an endovascular technique can establish

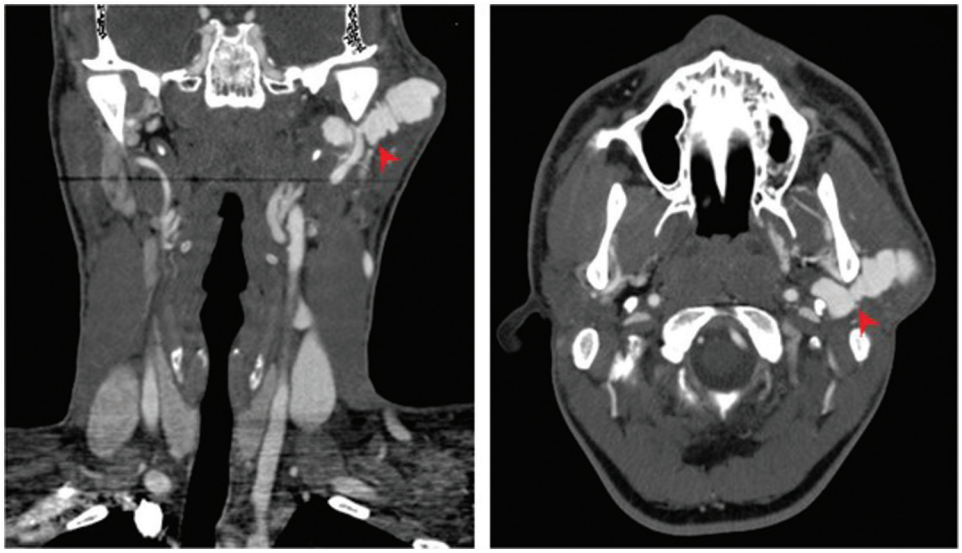

Figure 1 Radiographic evidence of zone III external carotid artery injury. Coronal (left) and axial (right) views of left-sided zone III external carotid artery pseudoaneurysm and perivascular hematoma with active extravasation of blood (red arrows) on CTA .

definitive control. Alternatively, an initial endovascular technique may be used to obtain hemostasis in zone III, as discussed later in this section, so that additional neck injuries may be safely explored in an open fashion. If taking the former approach, balloon catheter tamponade may be used for the open portion of the hybrid technique. Balloon catheter tamponade is a type of vascular damage control surgery that is used to obtain hemostasis in anatomical areas that are challenging to access [22]. Balloon catheter tamponade can be performed by internally occluding the damaged vessel using a Fogarty balloon catheter, or externally compressing the damaged vessel using either a large Fogarty balloon or Foley catheter. It is a particularly useful tool for vascular injuries that are technically challenging to access and/or repair, such as zone III of the neck [22,23]. Once hemostasis has been obtained using these open techniques, an endovascular approach can be employed to definitively treat the lesion.

To perform internal balloon catheter tamponade (i.e., from within the ICA) to control a zone III injury, the ipsilateral common carotid is dissected out proximal to the injury (usually in zone II where exposure is most accessible), and a small, transverse arteriotomy is made. An appropriately sized Fogarty balloon catheter (#3 or #4) is advanced through the arteriotomy into the distal ICA and slowly inflated until hemostasis is obtained [24]. If the carotid is completely transected or the balloon cannot be inflated precisely at the level of the defect to occlude it, then the balloon may be inflated distal to the injury while proximal control is obtained under direct visualization. This method may be preferred in patients with concomitant zone II carotid injury that requires exploration and/or in patients who are sufficiently stable to withstand a surgical cut-down. Ideally, this approach should take place in a hybrid suite, where diagnostic/therapeutic imaging may follow once hemostasis is obtained. If excessive hemorrhage precludes this approach, a larger (#3 to #8) Fogarty or 5-mL Foley balloon catheter may alternatively be "blindly" passed directly through the cervical wound towards the presumed source of hemorrhage. The balloon is then slowly inflated—irrespective of whether it is within the artery or externally compressing it—until the bleeding is controlled [24]. Once the patient has stabilized, further diagnostic imaging can be performed to help guide next steps.

In some patients, definitive control via an endovascular or open surgical approach may not be feasible following initial balloon catheter tamponade. For example, in patients with distal carotid transections, deflation of the Fogarty balloon—even for a brief period to allow passage of an endovascular wire—may result in significant retrograde bleeding from the distal end, leading to poor visualization and worsening hemodynamic instability. In these patients, prolonged balloon inflation may be required until the vessel thromboses. Fortunately, the inflated balloon can be left in position with close neurologic monitoring for up to 48 hours. If the balloon is to remain inflated for a prolonged period, it should be filled with radiopaque contrast so that positioning can be readily confirmed as needed, and sutured to the arteriotomy and/or skin insertion site. In patients with altered consciousness, postoperative electroencephalography and continuous intracranial pressure monitoring are indicated as well [24]. If the patient deteriorates, the next steps in management will be dictated by the underlying cause. For example, if the patient acutely deteriorates after a period of relative stability, the balloon may require repositioning;

alternatively, if the patient steadily declines while the balloon is in place, a last-ditch effort to definitively repair the lesion—despite the associated risks—may be warranted if it aligns with the patient's goals of care.

In patients with zone III carotid injury *and* extensive neck lacerations that necessitate exploration (e.g., those that extend into adjacent neck zones and/or non-vascular structures such as the airway), or significant hematoma that requires decompression, the latter hybrid approach—in which endovascular therapy precedes open surgery—may be appropriate. A case series published in 2011 documented success with this hybrid approach in two patients with penetrating carotid injuries [25]. Both demonstrated extensive neck wounds and required massive transfusions on arrival. CTA revealed contrast extravasation from each patient's carotid artery, and therefore emergent angiography via a femoral approach was performed and confirmed zone I and zone III carotid lacerations, respectively. Both patients' carotid lesions were treated with covered stent grafts, and their neck injuries were then surgically explored under general anaesthetic to evacuate the hematoma and rule out other injuries or sources of bleeding. Each patient underwent repeat angiography the following day, which confirmed accurate stent positioning and lack of contrast extravasation. Both patients were maintained on antiplatelet therapy for 12 months following their traumatic injuries, and neither developed complications during the follow-up period. This small case series demonstrates the potential for hybrid therapies to address complex injuries that traverse both accessible and inaccessible locations in a safe and expeditious manner.

EXTERNAL CAROTID ARTERY INJURY

Most of the literature relating to traumatic external carotid artery (ECA) injury is not specific to zone III. However, based on the general vascular neck trauma literature, ECA injuries are frequently associated with additional vascular injuries and often present with external bleeding [26,27]. Fortunately, the ECA and its branches can usually be sacrificed with impunity, and coil embolization is the most common technique employed (Fig. 2) [27,28]. In addition to metallic coils, there are a number of embolization agents available, including Gelfoam, N-butyl cyanoacrylate (NBCA), and endovascular balloons.

Choice of agent depends on availability, vessel size, need for permanent versus temporary occlusion, and thrombogenicity of the patient (as coagulopathy associated with trauma and resuscitation may impede thrombus formation) [29]. In general, Gelfoam can be used for temporary embolization while coils should be reserved for permanent occlusion. The two agents may also be combined to form a denser plug and facilitate thrombosis of the target vessel. NBCA is a liquid embolic agent, which can be deployed quickly and accurately. It induces thrombus formation on contact with ionic fluids such as water or blood, and does not depend on the patient's thrombogenicity [30]. While it is currently only approved by the US Food and Drug Administration for embolization of cerebral arteriovenous malformations, it has various off-label uses, such as arterial pseudoaneurysms and endoleaks, and is the preferred agent for trauma patients at some centers [29,30].

In a 2011 review of endovascular treatment of penetrating neck trauma, embolization using various agents was performed on 14 of 15 ECA injuries [27]. Embolization successfully occluded the target vessel in all cases. One of these cases, which involved balloon occlusion of an ECA pseudoaneurysm, was complicated by embolization to the middle cerebral artery. This was treated with intra-arterial thrombolysis, which unfortunately led to post-procedural fatal epistaxis. The authors concluded that ECA embolization was an effective treatment; however, they stressed the importance of assessing for anastomotic channels between the ECA and ICA to prevent complications [27].

CAROTID CAVERNOUS FISTULAE

Carotid cavernous fistulae (CCF) are another type of skull base vascular trauma that are amenable to embolization by an experienced neurointerventionalist in hemodynamically stable patients. CCF are best accessed transarterially, as outlined in a 2016 review on the management of vascular skull base trauma [31]. A microcatheter can be directed from the carotid artery into the cavernous sinus if the arterial defect is easily visualized. If it cannot be visualized despite magnification and high frame rates, a microwire should be advanced so that the direction of blood flow can guide the wire through the communication. Once the cavernous sinus is accessed, the microcatheter is advanced as far as possible and coils are deployed. Coil embolization may be further supported by liquid embolic agents such as Onyx (Medtronic). Inflation of an endovascular balloon in the cavernous portion of the carotid artery can help distinguish the carotid from the cavernous sinus and prevent arterial coil placement. As the coils slow the flow through the fistula, the balloon can also be inflated for several minutes to completely seal the fistula off [31].

If the transarterial approach fails to facilitate access into the CCF, it may be substituted for a transvenous approach via the inferior petrosal sinus (ipsilateral or contralateral), via the superior ophthalmic vein directly, or from the common facial vein [32,33]. It is important to consider all potential access points for CCF embolization, as flexibility in one's approach can improve technical success rates—defined as occlusion of the retrograde drainage channels to the ophthalmic and superficial middle cerebral veins, occlusion of the target cavernous sinus, and obliteration of the CCF—from 72% to 100% [32].

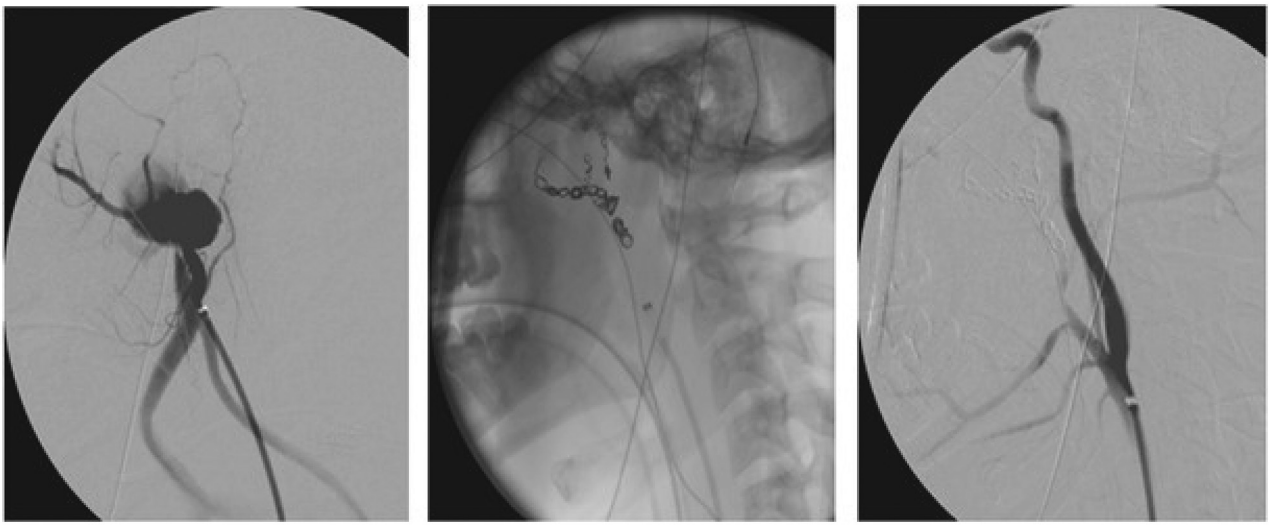

Figure 2 Coil embolization of a zone III carotid injury. Cerebral angiography reveals traumatic pseudoaneurysm of the ECA in zone III (left). Coils are deployed to the distal ECA and its branches at the level of, and just proximal to, the pseudoaneurysm (middle). Completion angiography reveals successful exclusion of the pseudoaneurysm via coil embolization of the distal ECA and its branches, with preserved patency of the ipsilateral ICA (right).

In addition to coils, balloon embolization has been described for the treatment of CCF. With this method, a guiding catheter is directed into the ICA via a femoral approach, and a balloon-mounted microcatheter is advanced into the fistula [34]. Contrast is injected through the guiding catheter to reassess the fistula and, once the balloon is in place, it is inflated within the cavernous sinus and permanently detached to obliterate the fistula. In a series of 58 patients with traumatic CCF, all CCFs were successfully treated with detachable balloons, and all patients demonstrated gradual resolution of symptoms associated with the CCF following the procedure [34]. During the three-year follow-up period, seven patients developed CCF recurrence. Despite studies reporting success with the use of detachable balloons for the treatment of CCF [34,35], detachable balloons are of limited variety and availability, were entirely pulled from the United States market in 2003, and are not currently used in many non-American centers [31,36].

INTERNAL CAROTID ARTERY INJURY

Revascularization, as opposed to vessel sacrifice, should be attempted for zone III traumatic ICA injuries whenever feasible. Stenting can be used to treat both flow-limiting lesions, such as dissections or occlusions, as well as actively extravasating defects, such as pseudoaneurysms, partial transections, or AV fistulas. Similar to the literature on ECA trauma, most of the studies on stenting for ICA trauma include, but are not limited to, zone III injury.

In a review of 113 patients with traumatic (blunt and penetrating) ICA injury, endovascular stent placement successfully excluded the injury while maintaining vessel patency in 76% of patients [37]. The follow-up data extending to two years from successful stent placement were promising as well: 94% of patients remained alive without new neurological symptoms related to stent placement, and 80% demonstrated stent patency on follow-up imaging. Neurologic sequelae developed in four patients (3.5%) after stent placement, and there was one death (0.9%).

While use of balloon-expandable stents for carotid trauma has been documented [27], self-expanding stents are preferred for cervical vascular injury due to their superior flexibility and ability to withstand compression (as opposed to balloon-expandable stents, which offer more accurate positioning) [29]. Both uncovered and covered stents play a role in ICA trauma. Uncovered stents are usually sufficient for flow-limiting lesions, as they can effectively tack down dissection flaps and recanalize stenoses and occlusions. They can also be used to treat pseudoaneurysms and fistulas, alone or in combination with coil embolization.

When partnered with coil embolization, an uncovered stent is first deployed across the defect in the artery, and a catheter is threaded through the stent struts into the pseudoaneurysm or fistula [38,39]. Coils are then released to induce thrombosis, while the stent protects the injured vessel from migrating coils or thrombus. Even without coil embolization, however, uncovered stents may be effective in treating pseudoaneurysms, as demonstrated in a 2011 study on the endovascular treatment of carotid trauma [27]. In this study, 36 patients with traumatic extracranial carotid injuries underwent endovascular treatment using a variety of techniques. Among them, nine had carotid pseudoaneurysms that were treated with uncovered stents. Uncovered stents successfully induced stagnant flow immediately following

deployment in all cases, as well as angiographic occlusion at six months in 78% of cases.

Despite the aforementioned findings, several studies and guidelines on carotid trauma recommend covered stents as the primary treatment modality for zone III carotid injuries requiring revascularization [11,28]. In patients with extensive wall damage in particular, such as long arterial lacerations and/or large, adjacent pseudoaneurysms, covered stents may provide a more definitive and robust solution compared to other endovascular options [27,40,41]. Covered stents also offer a theoretical advantage with respect to embolization risk [42]. In a 2006 review of 20 patients with traumatic extracranial zone III ICA pseudoaneurysms, covered stenting was associated with a 15% overall ICA occlusion rate during the follow-up period (to a maximum of two years) and no serious complications [40]. Antithrombotic therapy was contraindicated in one of the three patients who developed occlusions. Based on these data, both covered and uncovered stents are durable options, although randomized data comparing the two therapies for carotid trauma are lacking.

It is important to note that stenting outcomes vary between studies, and stenting may not be the ideal treatment for all types of zone III ICA trauma. Specifically, in a cohort study specific to blunt carotid injuries published in 2005, 46 patients with ICA pseudoaneurysms were treated with either a self-expanding uncovered stent or no stent with or without antithrombotic therapy [43]. All patients without contraindications were initiated on a six-month course of antithrombotic therapy—either in the form of anticoagulation (initially intravenous heparin sulfate and then transitioned to oral warfarin), or dual antiplatelet therapy with aspirin and clopidogrel—immediately following diagnosis of a grade III BCI (i.e., pseudoaneurysm) by cerebral angiography. Patients who had persistent pseudoaneurysms on follow-up angiography at seven to ten days were eligible for stent placement. A third angiogram performed at three to six months following discharge from hospital revealed significantly higher rates of ICA occlusions in patients who received carotid stents compared to those who did not (45% versus 5%). Patients with carotid stents also had more complications, with three strokes and one subclavian artery dissection in the stenting group compared to one stroke in the non-stenting group. Unfortunately, this study did not stratify outcomes according to antithrombotic regimen. While the evolving antithrombotic protocol at the host institution may have impacted the high occlusion rates within the stenting group in this study, the authors nevertheless concluded that antithrombotic therapy alone is preferred to stenting in patients with blunt carotid injury, and that stenting should be reserved for select cases. Considering the low complication and occlusion rates cited in subsequent literature reviews on stenting for carotid trauma [37,40]—which included both blunt and penetrating carotid injuries—further studies are needed to determine whether blunt carotid injuries are at inherently higher risk of adverse events with carotid stenting.

Flow Diverting Technologies

One final device relevant to the endovascular management of ICA pathology is flow diverters. Originally designed to treat large or wide-necked intracranial ICA aneurysms [44], flow diverters are highly porous stents that, when deployed across an aneurysm neck, slow the blood flow through the aneurysm while maintaining flow through the main artery. The resulting stasis at the injured portion of the artery leads the aneurysm neck to thrombose, and the mesh of the stent helps impart strength to the weakened portion of the vessel wall. As described in a recent review [45], flow diverters alter the flow at the level of the vessel injury while providing support to the vessel wall through three stages: (1) the hemodynamic stage, which takes effect the moment the flow diverter is deployed and is characterized by reduced blood flow velocity and shear stress within the aneurysm; (2) the thrombus formation stage, which immediately follows stage one and results in thrombosis and ultimately occlusion of the aneurysm; and (3) the endothelialization stage, which takes place over months to years and sees the artery remodel using the flow diverter as a scaffold. Flow diverters now have an expanding list of carotid indications, including CCFs. They also offer improved deployment flexibility across tortuous segments and allow pseudoaneurysms to thrombose without the need for coils. Dual antiplatelet therapy is used alongside flow diversion to reduce the risk of thromboembolic complications.

The aforementioned systematic review by Dandapat et al. [45] documented success with the use of flow diverters for the treatment of intracranial ICA aneurysms, with early (six-month or one-year) complete aneurysm occlusion rates ranging from 66% to 94% [46,47]. Flow diverters have also been used to treat CCFs [48–50] but with mixed results. One case series, which enrolled three patients with traumatic and two with spontaneous CCF, demonstrated complete and durable fistula obliteration, symptom resolution, and no complications in 100% of patients [49], while another, which enrolled four patients with traumatic, two with spontaneous, and seven with iatrogenic CCF, found that 57% of patients required reintervention [50]. Data on the use of flow diverters in the extracranial ICA are limited; however, there was one literature review published in 2017 that highlighted their role in the treatment of dissections and pseudoaneurysms in the extracranial cervical ICA [51]. The review included 12 patients from four studies, of which three studies enrolled non-trauma participants [51–53] and one enrolled a combination of trauma and non-trauma participants [54]. The study reported a 100% technical success rate (defined as correct stent positioning without migration,

dissection, kinking, or embolization), no complications, and no neurological events during the follow-up period [51]. While flow diverters represent a promising novel technique, there are no studies to date (with the exception of case reports) that focus exclusively on their role in the management of blunt and penetrating zone III carotid trauma. Further research delineating the risks and benefits must precede their widespread dissemination in this population.

Post-Procedural Antithrombotic Therapy

Antithrombotic therapy is an important adjunct to stenting in the treatment of zone III ICA injuries, regardless of stent type. Unfortunately, there is no consensus on the optimal antithrombotic regimen in this setting. In the aforementioned review on covered stenting, dual antiplatelet therapy (DAPT) was most commonly prescribed (45% of patients) following stent placement; however, studies varied with respect to duration of therapy (from two weeks to indefinitely) and continuation of post-procedure heparin infusion while in hospital [40]. Other prescribed regimens included single antiplatelet therapy with or without post-procedure heparin infusion and warfarin. In the absence of studies comparing antithrombotic therapies in patients undergoing stenting for traumatic ICA injuries, guidelines pertaining to *atherosclerotic* carotid disease may provide some insight: in patients undergoing carotid stenting, DAPT should be continued for at least one month once bleeding has been controlled, followed by aspirin therapy indefinitely [55]. Antiplatelet treatment with or without heparin bolus may be initiated during the stenting procedure. When adapting these guidelines to patients with ICA trauma, the need for adjuvant heparin as an inpatient, oral anticoagulation as an out-patient, or extended DAPT can be determined on a case-by-case basis, bearing in mind the patient's other injuries, type of vascular injury, and whether a covered stent was used or not.

Post-Procedural Radiographic Surveillance

Similar to post-procedure antithrombotic regimens, there is no uniform protocol for follow-up imaging after ICA stenting for traumatic injuries. The purpose of post-procedural surveillance is to monitor for clinical and anatomical sequelae, including new neurologic deficits, stent occlusions/stenoses, and arteriovenous fistulae. Based on a 2008 review of 113 patients who underwent stenting for traumatic ICA injuries, post-procedural surveillance protocols varied between studies: 62% used angiography, 21% color doppler, 5% clinical assessment, 4% CTA, <1% magnetic resonance angiography, <1% angiography and duplex, and surveillance practices were unknown for the remaining 5% [37]. Likewise, duration of follow-up surveillance ranged from two weeks to two years. As previously mentioned, stent patency was high (80%) during the follow-up period. Unfortunately, among the 13% of patients who developed adverse anatomical sequelae, the study neither comments on the timing of said observations, nor does it report whether they were associated with adverse clinical events. Yearly duplex ultrasound surveillance following carotid intervention is the practice at our institution; however, long-term data specific to zone III traumatic ICA injury that documents surveillance protocols and complications following stenting is needed to inform clinical practice guidelines.

CONCLUSIONS AND FUTURE DIRECTIONS

While the endovascular and hybrid approaches to carotid trauma have advanced significantly over the past few decades, uncertainty surrounding the management of zone III carotid injury persists for several reasons. Evidence specific to this zone is limited due to the rarity of zone III carotid injury and the recent emergence of endovascular therapy for neck trauma. The minimal zone III-specific data, especially as it relates to penetrating trauma, is usually in the form of case reports [25,42,56–58]. As a result, evidence is extrapolated from larger case series, cohort studies, and reviews on endovascular therapy across all carotid zones [27,37,40,43,59]. These heterogenous studies vary not only with respect to anatomic location, but also indication for endovascular therapy (i.e., penetrating versus blunt trauma), type of injury (e.g., pseudoaneurysm, fistula, dissection, occlusion, etc.), choice of endovascular therapy (embolization versus stenting versus hybrid), technique (e.g., covered versus non-covered stent, balloon-expandable versus self-expandable, coil embolization versus detachable balloons, etc.), and antithrombotic regimen (choice and duration). Consequently, outcomes may vary drastically between studies and lead to contradictory conclusions. This is most pronounced when comparing studies on stenting for carotid trauma, where one study concluded that stenting was not an ideal option for blunt carotid trauma owing to its high occlusion and complication rates [43], while another, which included a majority (77%) of blunt carotid trauma cases, found stenting to be a safe and durable option [37]. Finally, since endovascular and hybrid therapies are still in their relative infancy, long-term follow-up data is notably absent from the literature. As the prevalence of—and experience with—endovascular therapies increase, larger case volumes and procedural uniformity will hopefully lead to more precise comparisons between treatment options, anatomic locations, techniques, antithrombotic regimens, and surveillance protocols. Increasing experience will also help shape the team dynamics required to treat these complex injuries. A multidisciplinary approach, which combines the expertise of the trauma surgeons, vascular surgeons, interventional neuroradiologists, neurosurgeons, and/or otolaryngologists,

will prove invaluable when introducing these techniques into the zone III carotid trauma treatment algorithm. In the interim, endovascular and hybrid techniques offer a safe and promising option for zone III carotid injuries, which are otherwise inaccessible and exceptionally challenging to treat.

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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