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

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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*

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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].

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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

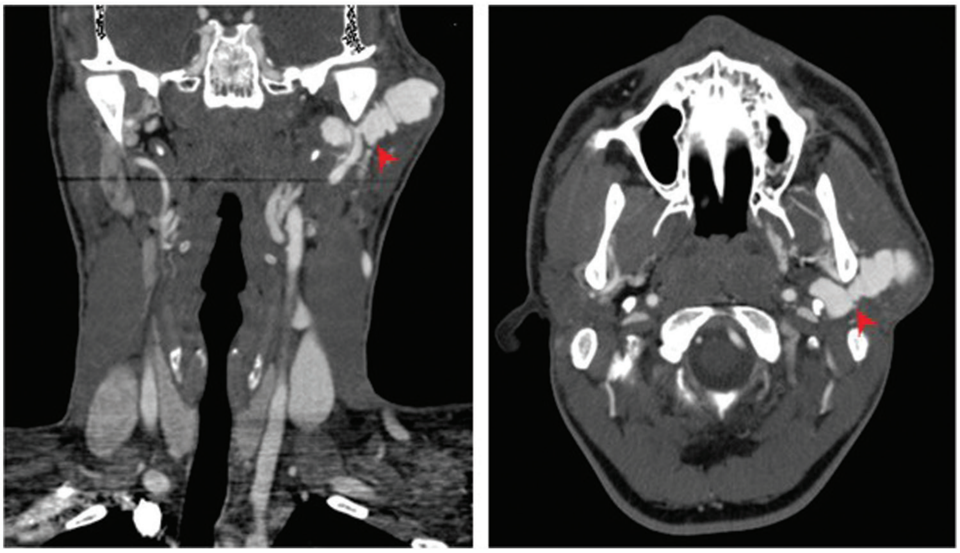

Figure 1 Radiographic evidence of zone III external carotid artery injury. Coronal (left) and axial (right) views of left-sided zone III external carotid artery pseudoaneurysm and perivascular hematoma with active extravasation of blood (red arrows) on CTA .

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].

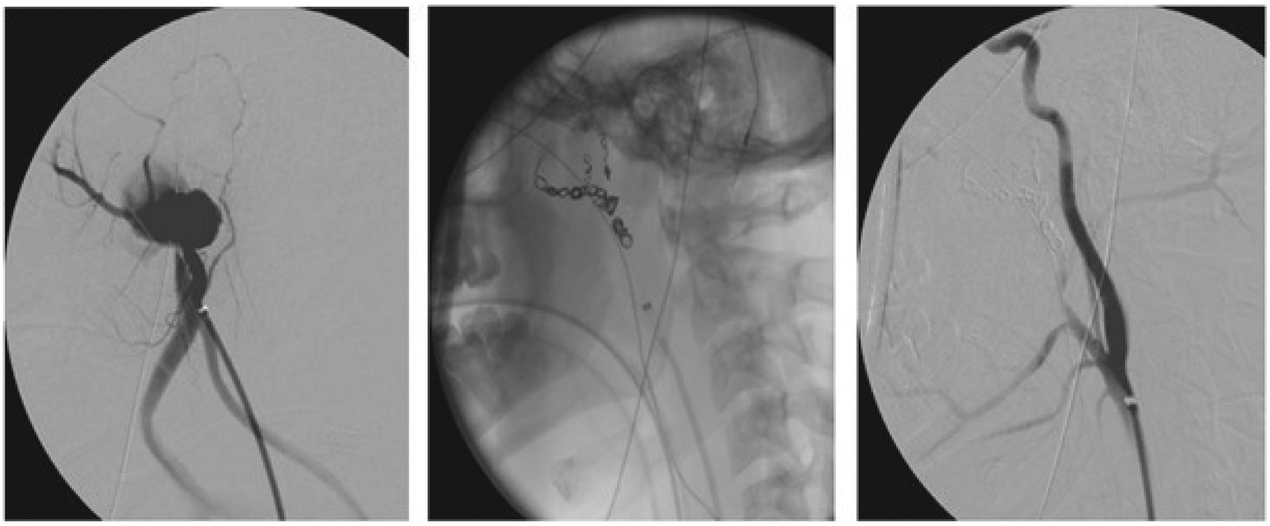

Figure 2 Coil embolization of a zone III carotid injury. Cerebral angiography reveals traumatic pseudoaneurysm of the ECA in zone III (left). Coils are deployed to the distal ECA and its branches at the level of, and just proximal to, the pseudoaneurysm (middle). Completion angiography reveals successful 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 in-patient, 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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