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REVIEW

The Role of Stent-Grafts in the Management of Aortic Trauma

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Abstract Stent graft has resulted in major advances in the treatment of trauma patients with blunt traumatic aortic injury (TAI) and has become the preferred method of treatment at many trauma centers. In this review, we provide an overview of the place of stent grafts for the management of this disease. As a whole, TEVAR repair of TAIs offers a survival advantage and reduction in major morbidity, including paraplegia, compared with open surgery. However, endovascular procedures in trauma require a sophisticated multidisciplinary and experienced team approach. More research and development of TAI-specific endograft devices is needed and large, multicenter studies will help to clarify the role of TEVAR compared with open repair of TAI.

Keywords Acute aortic syndrome · Endovascular treatment · Aorta · Trauma · Graft/endograft · CT/CTA

Introduction

Blunt traumatic aortic injuries (TAI) is the second most common cause of death in trauma patients, accounting for approximately 8,000 deaths per year in the United States [1, 2]. The diagnosis and management of TAI have undergone some major changes during the past few years. The replacement of chest X-rays and angiography by CT angiography, the introduction of beta blockers and delayed operation in selected cases, the liberal use of bypass techniques, the nonoperative management of selected cases, and endovascular interventions have contributed to an earlier diagnosis and reduction of mortality and serious complications. In this review, we provide an overview of the place of thoracic endovascular repair (TEVAR) for the management of this disease.

Mechanism of Injury

TAI most often occurs after sudden deceleration, usually in automobile crashes. In a prospective study of hospital admissions involving blunt aortic injury, the crash impact was most often head-on (72%), followed by side impact (24%) and rear impact (4%) [1]. TAI occurs in <1% of motor vehicle crashes but is responsible for 16% of the deaths and is second only to head injury as the leading cause of death [3, 4]. The autopsy study by Parmley et al. [5] showed that up to 80% of patients die before their arrival at a hospital.

Despite the increased use of restraint systems, the overall incidence of blunt aortic injury that is associated with fatal vehicular crashes has remained the same during the past 12 years [6]. The factors that appear to have a strong correlation with thoracic aortic injury are a sudden change in velocity, impact on the patient's side of the car, and the intrusion of the vehicular wall into the passenger compartment [7]. Restraint devices, such as front airbags and seat belts, provide little protection in side-impact crashes. In one study of severe car crashes in which the majority of patients with thoracic aortic injury did not survive, 85% of patients with thoracic aortic injury had been involved in a crash in which the primary impact was

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against the side of the vehicle [7]. Another recent autopsy study demonstrated that 42% of fatalities involving blunt aortic injury were due to side-impact crashes [6].

Pathophysiological Features

The postulated mechanism of this injury includes (1) shear forces caused by relative mobility of a portion of the vessel adjacent to a fixed portion (the descending aorta is fixed to the chest wall, whereas the heart and great vessels are relatively mobile), (2) compression of the vessel between bony structures ("osseous pinch"), and (3) the so-called "water-hammer" effect with a profound intraluminal hypertension during the severe traumatic event [8]. In fact, most injuries probably involve a combination of these forces. TAI usually involves the proximal descending aorta, usually near the isthmus (54–65%) but can involve other segments, i.e., the ascending or transverse aortic arch (10–14%) and mid or distal descending thoracic aorta (12%) or multiple sites (13–18%) [9].

From the literature, different terms, including tear, laceration, disruption, transection, rupture, and pseudoaneurysm, are used to describe certain forms of traumatic aortic injuries, which can lead to misinterpretation of findings or diagnoses. In blunt aortic injuries, the arterial wall is damaged from inside to outside, from the intima toward the adventitia [10]. Commonly, CT scan demonstrates aortic dissection or pseudoaneurysm. Periaortic hematoma, hemomediastinum, pleural effusion, and bones fractures often are associated, but with improvements in imaging technology, evermore-subtle lesions are being identified. The term "minimal aortic injury" often is used to describe a lesion of the aorta associated with blunt injury that is believed to carry a relatively low risk of rupture (Fig. 1). This lesion can be present in approximately 10% of patients whose blunt aortic injury is identified by CT. It has been reported that up to 50% of minimal aortic injuries that are identified by CT are missed on angiography [11]. The natural history of these minimal aortic injuries is unclear as well, and the management of these lesions (which were classically not seen by the "old gold standard" the angiography) is still subject of discussion. In one study, in which minimal aortic injury was defined as an intimal flap <1 cm with no or minimal periaortic hematoma, 50% had developed pseudoaneurysms by 8 weeks after injury [11].

Perioperative Assessment

The diagnosis and management of TAI have undergone several major changes during the past decades. The rapid advancement of computed tomography availability, with its less invasive nature and its sensitivity and specificity, has resulted in its almost-complete replacement of aortography for the diagnosis of TAI. CT imaging should be performed with 1- to 2-mm intervals to optimize the detection and evaluation of intimal defects of the aorta. It is critical that three-dimensional and centerline double-oblique reconstructions be performed to identify not only the location of the injury but also accurately measure the aortic diameter, the distance from branched vessels, and the pelvic arteries for the vascular access.

Although some observers have suggested that screening CT is overused, others note a 28% rate of missed diagnoses and recommend that CT be performed in all patients with a history of a motor-vehicle crash at a speed of 10 miles per hour (mph) or faster for unrestrained drivers and of 30 mph or faster for restrained drivers [12]. The ability of CT to diagnose accurately blunt aortic injury as well other serious injuries has led to its liberal use in most institutions.

Management

The optimal timing for definitive repair of TAI is not known. Traditionally, early repair was preferred in all patients; however, patients often have multisystem injuries,

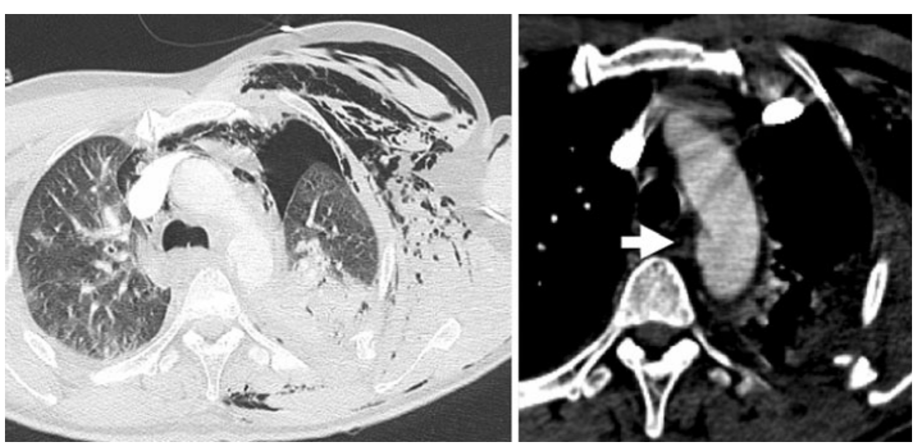

Fig. 1 Minimal aortic injury. Transverse contrast-enhanced multi-detector CT scan shows limited intimal flap (*arrow* on the right panel) at the level of the arch with no peri-aortic hematoma (note on the left panel, a pneumothorax with mediastinal and subcutaneous emphysema on the left side)

including head injury, exsanguinating abdominal or pelvic injury, and coexisting lung injury, which complicates aortic repair [1]. Injuries to other organs may make it difficult to decide which injury to treat first [13]. In patients with multiple trauma, we must weigh the chances of rupture against the lethality of the remaining injuries.

Generally, patients with TAI are categorized as “unstable” (in whom survival is extremely low) and “stable.” Clearly, for unstable patients, immediate intervention is indicated, because delay to evaluation and transfer to the operating room are risk factors for mortality. For stable patients, the timing of surgical repair changed during the early 1990s, with the concept of deliberate delay of TAI surgery for patients under blood pressure control. Fabian et al. [14] performed a prospective study using beta-blockers with or without vasodilators to maintain a systolic blood pressure of approximately 100 mmHg and a pulse rate of <100 beats per minute, in selected patients with coexisting head injury, pulmonary injury, or cardiac insufficiency. In this study, no patient had an aortic rupture while awaiting repair. On the other hand, the literature demonstrated that, in selected cases with major associated injuries, delaying surgical repair while maintaining the patients under antihypertensive therapy regimen with B-blockers can reduce in-hospital free rupture in these critical patients, resulting in a further decrease of in-hospital mortality. For these reasons, there has been a consensus to shift from early to delayed surgical repair. Nevertheless, even if adequate blood pressure control minimizes the risk of free rupture, this risk remains as high as 4% [13, 15].

The question is whether the introduction of the endovascular approach should encourage a change in the timing of treatment of the aorta. Jonker et al. believe that delayed repair may allow complete resuscitation, and additional CT imaging can provide more reliable data regarding the actual aortic measurements for endograft sizing in these patients. However, this strategy is only possible in selected TAI patients, and delaying TEVAR could be fatal in some hemodynamically unstable patients [16].

We believe that as the risk of rupture is as high as 4%, even if adequate blood pressure control, early endovascular treatment can be recommended, not only for patients at high risk of free rupture but also for the clinically stable. This should be done as soon as the primary survey is complete and the patient is stabilized, generally within 4–6 h after the trauma. This way, TEVAR can be performed during the daytime when all of the team is present to ensure the best support. Delay should be considered only when the patient has respiratory problems or is hemodynamically unstable from causes other than the aortic lesion, and systolic blood pressure should then be kept below 140 mmHg [13].

For patients with “minimal aortic injury,” from a practical point of view, in our practice we consider that a small intimal flap in the absence of periaortic hematoma or pseudoaneurysm can be safely followed by serial CT. Inversely, if a minimal aortic injury is associated with significant thrombus, periaortic hematoma, lumen encroachment, or pseudoaneurysm, TEVAR is proposed, particularly if the anatomy is favorable.

Open Surgery

Despite developments in trauma management, operative techniques, and perioperative care, considerable mortality and morbidity associated with these injuries prevail [17]. Briefly, open surgery (OS) by direct suture or interposition of a prosthetic graft is associated with an operative mortality rate from 9–15% and is approximately 10% in stabilized patients [18–20]. Operation also may lead to major morbidity, such as paraplegia and stroke; the incidence of paraplegia varies from 2.3% with active distal aortic perfusion to 19.2% with a “clamp and sew” technique [21, 22]. Respiratory complications are the most common postoperative morbidity. Demetriades et al. demonstrated that procedure-related paraplegia after open surgery for TAI has significantly decreased from 8.7 to 2.9% during the past decade. This improved outcome could be the result of better resuscitation and a more controlled environment during delayed repair of TAI [23]. Furthermore, shorter aortic cross-clamp time and adjuncts for distal aortic perfusion during open TAI repair might have contributed to the observed decrease in the incidence of paraplegia [1, 21].

Endovascular Repair

The advancement of endovascular techniques and devices is revolutionizing our approach to TAI. In many centers, TEVAR has become the procedure of choice for TAI, even in young patients. In the United States, TEVAR rapidly became the preferred technique for TAI by 2006, exceeding the use of open repair for TAI in 2007 [24]. The theoretical advantages of this technique are numerous: there is no need to open the chest cavity; blood loss is minimal; and the risk of paraplegia is minimized. TEVAR allows quick exclusion of the aortic lesion and is less invasive than open surgery, which is particularly desirable in patients with TAI and multiple associated injuries [24].

Moreover, TEVAR may be favored in unstable polytraumatized patients to avoid thoracotomy and subsequent pulmonary collapse [25], to disregard the longer and more difficult dissections with direct approach over the actively bleeding fields [26, 27], to avoid extracorporeal circulation with total heparinization, potentially increasing hemorrhagic complications, and to decrease the visceral and spinal ischemic risks associated with total aortic clamping [28]. Thus, blood loss is minimized and systemic heparinization and perioperative lung ventilation less often are necessary [24].

Device Selection

Currently there are several commercially approved devices for thoracic aortic aneurysmal disease, ranging from 22 to 46 mm, enabling the treatment of aortic sizes from 18 to 42 mm in diameter [29]. Although each of these devices has different proximal and distal configurations, none has a disease-specific indication for treating aortic transections. As such, they are prone to certain device-specific complications.

Trauma patients tend to be younger and have smaller-diameter aortas (the average diameter of the thoracic aorta, proximal and distal to the ruptured site, in patients with trauma is 19 mm) [30]. Before 2010, when the aortic diameter was <23 mm, endovascular specialist had to choose between using TEVAR with an oversizing of more than 20% and using an infrarenal aortic cuff or an iliac extension of an abdominal aortic stent graft, to exclude the lesion [31]. Cuffs eliminated oversizing, which in certain instances lead to device collapse, but the use of devices meant for repair of infrarenal aortic aneurysms may be limited by short delivery systems that do not reach the thoracic aorta in taller patients from a femoral approach, requiring an iliac artery or aortic cutdown. Another disadvantage of cuffs is the short length, usually shorter than the lesion to treat, so multiple cuffs are needed, leading to type III endoleaks. Nevertheless, these devices could be useful for very young patients, as demonstrated by Gunabushanam et al. [32] who successfully treated an 11-year-old boy for TAI who was contraindicated for surgery by using an iliac extension of an abdominal stent graft.

In addition, in young patients, the aortic arch is usually acutely angulated. The variable anatomy of the thoracic aorta may be a significant problem, which might result in endoleaks. Borsa et al. [33] reported that in many patients with traumatic thoracic aortic rupture, the angle between the left subclavian artery (LSA) and the aorta distal to the ruptured site can be up to 90°. This may result in poor alignment of the device with the inner surface of the aortic arch. Angulations and excessive oversizing of the stent graft to address this problem may result in collapse of the device with devastating consequences [34, 35]. For Canaud et al. [36] this complication was related to excessive stent-graft oversizing, the radius of curvature of the aorta, as well as the choice of the device (i.e., stent-graft collapse was observed only with 2 types of stent graft without proximal bare stent). A more sophisticated design of curved prostheses, which addresses the specific anatomic needs of each individual patient, is an exciting possibility that may reduce complications [37].

Procedural Details

The endovascular procedure is done in an interventional or surgical suite. Although the procedure can be undertaken with local or regional anesthesia, most patients receive general anesthesia with tracheal intubation and mechanical ventilation, unless contraindicated, allowing for better breathing control during subtracted angiography of the chest. The patient is positioned in the supine position, and the operative field is prepared and draped for thoracotomy should the endovascular device not be deployed or a major complication occurred. Cardiopulmonary bypass equipment is readily available if such a complication occurs.

After a femoral arteriotomy, an intravenous bolus of 5,000 IU of heparin is administered. However, the level of heparinization during the TEVAR implantation varied among the case series, with several authors, including us, reporting successful TEVAR repair without the use of any systemic heparin in case of contraindication (associated closed head injury or other high risks for bleeding).

In some cases, side-limb graft attached to the lower aorta or the common iliac artery to allow stent-graft insertion can be used in difficult configurations. Conduits should be avoided, however, in patients with pelvic fractures or hematomas [29]. Additional brachial or preferably contralateral femoral arterial accesses may be exploited to allow: (1) easy completion of control angiograms during procedures; (2) straightforward marking off of the LSA ostium just before stent-graft deployment. Alternatively, completely percutaneous approach has been described, which may be appealing in cases of pelvic trauma [38].

An initial aortogram with a 5-F pigtail catheter introduced through the contralateral access helps to determine the best incidence. Correct image orientation and angle is critical for precise device deployment. Angiographic delineation of the anatomy is achieved with a perpendicular view to the aortic arch (usually 35–50 degrees left anterior oblique views). If LSA coverage is planned, vertebral angiography must be conducted before device insertion, especially if intracranial imaging was not obtained before TEVAR with CT. Typically, 260-cm long, 0.035-inch stiff wires are used during the procedure (Lunderquist [Cook Inc., Bloomington, IN] or Back up-Meier [Boston Scientific, Natick, MA]) and retroflexed off the aortic valve. Once this has been established, the device can be brought up near the intended implantation site. Once appropriate angles and orientation is determined, the device is deployed under fluoroscopic guidance (Fig. 2).

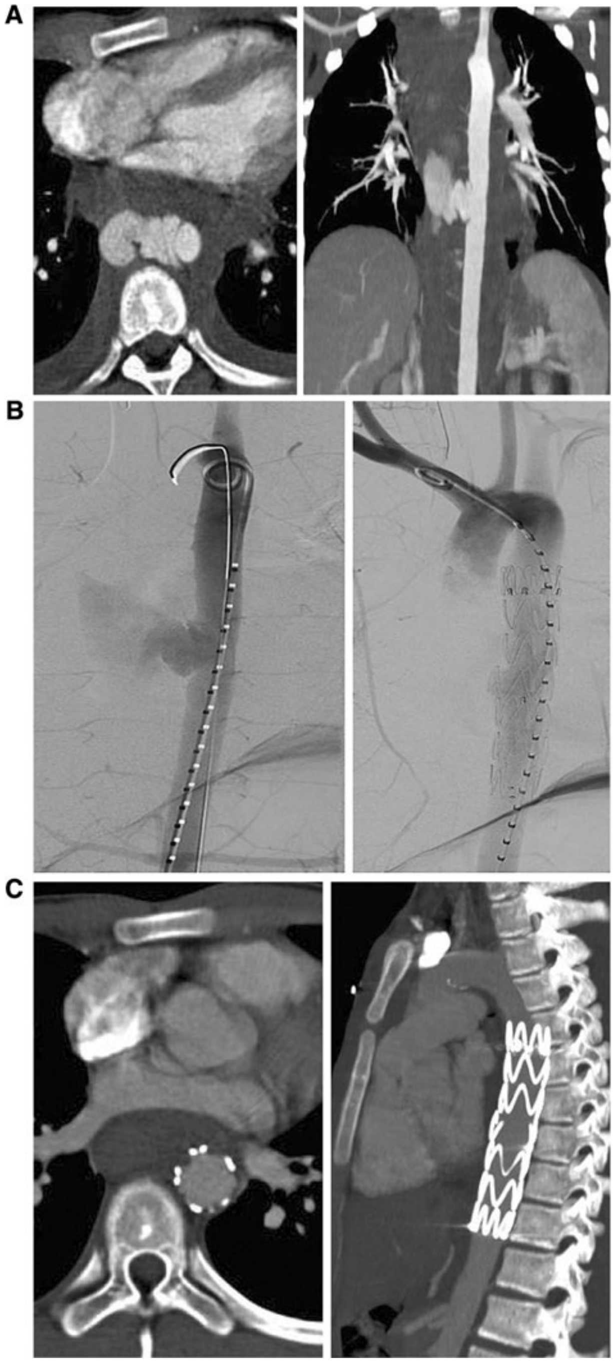

Fig. 2 Aortic injury with associated pseudoaneurysm. **A-1** Transverse contrast-enhanced multi-detector CT scan reveals an aortic injury (pseudoaneurysm), distant from the left subclavian artery with associated mediastinal hemorrhage adjacent to the medial wall of descending thoracic aorta, highlighted in the three-dimensional reconstruction (**A-2**). **B-1** Initial pre-deployement angiogram revealing active bleeding with contrast extravasation from the site of injury. **B-2** Control angiogram after stent-graft deployment showing adequate sealing of the bleeding site. Endograft Repair was successful and the patient survived the injury. **C-1** Axial view of the postoperative scan shows a patent endograft with complete resolution of the pseudoaneurysm, with a three-dimensional reconstruction. **C-2** Also we can note complete resolution of the mediastinal hemorrhage and pleural collection

The delivery system is positioned at the predetermined level in front of the aortic tear. A mean arterial pressure <70 mmHg is maintained during implantation with inflow occlusion balloons or pharmacologic means. Variable stent grafts are available on the market with one-step release (GORE) or with two-step release mechanism with proximal fixation (Medtronic, Cook, Bolton). Choice of the device depends on the complexity of the anatomy and the level of accuracy required for deployment. Thereafter, no compliant balloon is used to expand fully the stent into the nonaneurysmal wall of the aorta. Finally, the introducer delivery system is removed, and the arteriotomy is repaired after arteriographic controls. In some cases, the stent graft is deployed over the LSA ostium to prolong the landing zone to ensure complete exclusion the pseudoaneurysm and adequate sealing.

Anticoagulation is maintained for 48 h in the absence of contraindications and then followed by aspirin 250 mg per day. A large-spectrum prophylactic antibiotic (cefuroxime, 1500 mg administered intravenously *die*) is systematically administered during the procedure and maintained for 24 h after the procedure.

Results

Comparative Studies, Meta-Analysis, and Literature Review

There have been several case reports, retrospective series, and registry data describing treatment of patients with TAI using TEVAR. Most are single-center studies with a limited number of patients. Few studies compare retrospectively, in each center, conventional open surgery (OS) with TEVAR. In this review, we identified 22 studies (Table 1). Five meta-analyses are available, but no randomized study has been published so far [39–43].

Similar results were observed in all these meta-analyses. Tang et al. [41] published recently a meta-analysis of 33 articles reporting 699 procedures in which 370 patients were treated with TEVAR and 329 patients were managed with open surgery. No statistical differences were found between patient groups for mean age (41.3 vs. 38.8 years; $P < 0.1$), injury severity score (39.8 vs. 36; $P < 0.1$), or technical success rates of the procedure (96.5 vs. 98.5%; $P = 0.58$). In contrast, mortality was significantly lower in the TEVAR group (7.6 vs. 15.2%; $P = 0.0076$) as were rates of paraplegia (0 vs. 5.6%; $P < 0.0001$) and stroke (0.85 vs. 5.3%; $P = 0.0028$). The most common procedure-related complications for each technique were iliac artery injury during TEVAR and recurrent laryngeal nerve injury after open surgery.

The only large evaluation that did not support the superiority of TEVAR for TAI was the study by Arthurs et al. [44]

Table 1 Studies comparing open and endovascular repair of blunt thoracic aortic injury

				Modality		Mortality		Paraplegia	
		Start	End	OR	Tevar	OR (%)	TEVAR (%)	OR (%)	TEVAR (%)
Doss [46]	2003	1999	2002	12	4	17	0	0	14
Kasirajan [45]	2003	1999	2002	10	5	50	20	0	0
Amabile [47]	2004	1998	2004	11	9	9	0	0	0
Ott [48]	2004	1991	2002	12	6	17	0	0	14
Pacini [68]	2005	1980	2003	51	15	8	0	8	0
Rousseau [49]	2005	1981	2003	35	29	0	17	9	0
Andrassy [52]	2006	1998	2004	16	15	18	13	13	0
Broux [69]	2006	1995	2005	17	13	24	15	6	0
Cook [70]	2006	2000	2005	23	19	25	21	4	0
Lebl [51]	2006	1997	2003	10	7	20	14	0	0
Reed [71]	2006	2000	2005	11	13	9	23	0	0
Akowuah [27]	2007	2000	2006	8	7	13	0	13	0
Kokotsakis [53]	2007	2002	2006	10	22	10	5	10	0
Midgley [72]	2007	1994	2006	16	12	0	31	6	0
Riesenman [73]	2007	1993	2006	48	14	14	40	0	0
Stampfl [74]	2007	1993	2004	5	5	0	0	0	0
Buz [75]	2008	1987	2007	35	39	20	8	0	0
Chung [76]	2008	1995	2006	42	29	10	0	8	0
Moainie [77]	2008	2005	2008	26	26	15	15	0	0
Yamane [78]	2008	1999	2007	12	14	0	0	0	0
Azizzadeh [65]	2009	2005	2008	15	27	0	0	0	0
Geisbusch [79]	2009	1990	2007	14	14	36	14	0	0
Jonker [24]	2010	2000	2007	261	67	17	6	2	0
Total				700	411	13	11	3	1

which found a 30-day mortality of 19 and 18% after open repair and TEVAR, respectively. However, in their nationwide analysis of patients with blunt TAI, they evaluated the results between 2000 and 2005 of open and the initial experience of endovascular repairs with custom-made devices or off-label use of aortic cuffs. This may explain the increased mortality after TEVAR in their analysis compared with our results and those in the literature.

Takagi et al. identified 17 retrospective nonrandomized comparative studies of TEVAR versus OS for TAI. In 11 of the 17 studies, the TEVAR and OS groups had similar preoperative variables, including the injury severity score. Fifteen of the 17 individual studies demonstrated a statistically nonsignificant benefit of TEVAR compared with OS for mortality, whereas only one study demonstrated a statistically nonsignificant mortality reduction with OS compared with TEVAR. Pooled analysis of all 17 studies (representing 565 patients) demonstrated a statistically significant 57% reduction in mortality with TEVAR relative to OS (8.1% in the TEVAR group vs. 20.8% in the OS group; odds ratio 0.43; 95% confidence interval (CI) 0.25–0.76; $P < 0.01$). There was neither study heterogeneity of results ($P = 0.96$) nor evidence of significant publication bias ($P = 0.32$) [39].

In the more recent meta-analysis of retrospective studies comparing TEVAR vs. OS in each center, Akowuah et al. [43] identified 10 articles with 262 patients: 153 who underwent OS and 109 who underwent TEVAR were identified. Operative mortality and postoperative paraplegia rates were significantly less for TEVAR compared with OS (7 vs. 19%; $P = 0.01$) and (1 vs. 6%; $P = 0.01$), respectively. Major morbidity was more common in OS patients: two patients had acute respiratory distress syndrome (ARDS), three patients had acute renal failure, and nine patients had major neurologic complications, including damage to the left recurrent laryngeal and the phrenic nerve. Major morbidity for TEVAR was as follows: three cases (3.5%) of conversion to open surgery due to technical failures or acute hemodynamic instability, two cases of stent collapse resulting in severe aortic outflow obstruction, one fatal case of iliac artery rupture reported, and one case of left main bronchus compression caused by the stent, treated by a bronchial stent. Other major complications included one case of ARDS and one case of a pulmonary embolism [27, 45–53]. Long-term data were poorly reported, included in only five of the ten studies. In these studies, duration of follow-up was a median of 36 months. A primary endoleak was the most common complication, observed in six (5.5%) cases of TEVAR. Five of these patients required additional endovascular stenting or balloon dilation of the original stent. In 11% of patients, the origin of the LSA was covered by the stent. Complications attributed to this were rare, although two patients required LSA to carotid artery grafts. There were two cases of late coarctation of the aorta, one within the stent itself.

Limitations of these Data

We identified five meta-analyses that compared OS with TEVAR in patients with TAI; all concluded in favor of endovascular repair. However, there are in theory obvious limitations with selection and confounding bias in all the studies in favor of TEVAR.

Most published series comparing open and endovascular repair have given little information regarding the anatomic degree and severity of these injuries. This reinforces the need for a degree of injury classification system [54]. These studies are limited by the small number of patients, heterogeneity with respect to the type of TEVAR used, timing of the intervention, and patient characteristics. Of note, none are randomized and, therefore, are highly susceptible for major selection bias. The selection of TEVAR vs. OS was completely at the discretion of the attending clinicians, which allows for selection bias.

Traditionally, it is well known that the introduction of any new intervention invites the publication of highly selected success stories, leading to publication bias. It is self-evident that these large series represent the results of groups with a longstanding interest and expertise in endovascular thoracic aortic treatment, but whether these results can be reproduced and translated to general utility is unknown. Because the results from the experienced centers are similar to those of cumulative published experience, the data set is probably a "best estimate" of the current outcome of endovascular treatment of traumatic aortic rupture.

As a whole, because meta-analysis studies do not generate any new data, inevitably, all of these reports are pooled analysis of the same low-powered, retrospective studies outlined above. The reader must be cautioned against meta-analysis of small studies with similar bias, because combining them will only amplify the deviation away from reality.

Controversies

The Achilles heel of endovascular repair of TAI is considered the paucity of long-term results [24]. This treatment population is young with an expected life expectancy of at least 30–40 years of age. Material failures, such as stent fractures and fabric fatigue, may become more significant during these ensuing decades of follow-up. Nevertheless, at least 15 years of follow-up are available for different type of stent grafts with a very limited number of graft complications. Long-term assessment of open repair also is lacking in the literature. Pseudoaneurysm or graft-related complications might be found if open repair is held to the same scrutiny as endovascular repair. Moreover, if future reports of long-term results do not favor endovascular repair, endovascular repair can still be considered a better short- to midterm solution. If needed, open repair or revision can be accomplished when the patient can better tolerate a major surgery. Finally, until endovascular repair for TAI is "on-label," it seems reasonable to offer patients a repair with a mortality of one-third that of open repair and a lower paralysis rate.

Device Selection in Shocked Patients

Another problem is the choice of the diameter of the stent graft in hemodynamically unstable patients. A considerable percentage of patients with TAI are admitted in hypovolemic shock. In a retrospective study, Jonker et al. compared the aortic diameters at different levels in the initial CT performed while the patient is hemodynamically unstable versus the control CT performed when the shock has been corrected. They found an overall mean increase in aortic diameter varying from 3.3% ($P = 0.012$) at the level of the ascending aorta to 11.2% ($P < 0.001$) at the level of the distal aorta [16]. A staggering 30% increase in aortic diameter after correction of shock also has been reported by van Prehn et al. [55]. Both reports draw our attention to this vital factor, which may lead to underestimation of the true size of the descending aorta after resuscitation, namely the influence of hemodynamic instability on the aortic diameter. The variation in aortic diameter with possible miscalculation of the adequate suitable graft size is another issue that supports delayed management for some authors [16].

Impact of Design Evolution on Sizing

The choice of the type of stent graft also is a point of debate. Early-generation thoracic TEVARs were designed as straight tubes for larger diameter vessels as seen with degenerative aortic disease. Few reports of stent-graft collapse has been published, and mostly before 2008 [34, 35, 56, 57]. The authors attributed this to poor quality of previous-generation endograft devices that were somewhat rigid and lacked good conformability, flexibility, and vessel wall approximation, especially around areas of acute angulations. Current TEVAR design includes smaller diameter grafts with modifications to accommodate the tight aortic arches of the typically younger TAI patients. Graft design is improving and newer generation devices have more optimized sizes for smaller vessels and conform better to the tighter curves of the aortic arch. Nevertheless, for emergency TEVAR, physicians can only use those endografts that are available as stock [16].

Device Sizing in Younger Patient

As smaller devices are now commercially available, many authors prefer choosing small stent grafts in direct correlation to the size of the aorta in question, disregarding the immature nature of the aorta in young patients, whose aortas will continue to grow wider during progressing years. The study by Wolak et al. [58] demonstrated a mean increase of at least 10 mm between 40 and 65 years. For these reasons, smaller devices appropriately sized at the time of implantation may lead to a coarctation syndrome or lose fixation over time. What remains unknown is whether the placement of an endograft changes this dilatory tendency; in fact, some animal research suggests that the inflammatory response to an endograft inhibits this dilatation [59]. On the other hand, in our experience of more than 50 patients with TAI treated by TEVAR, exceeding the

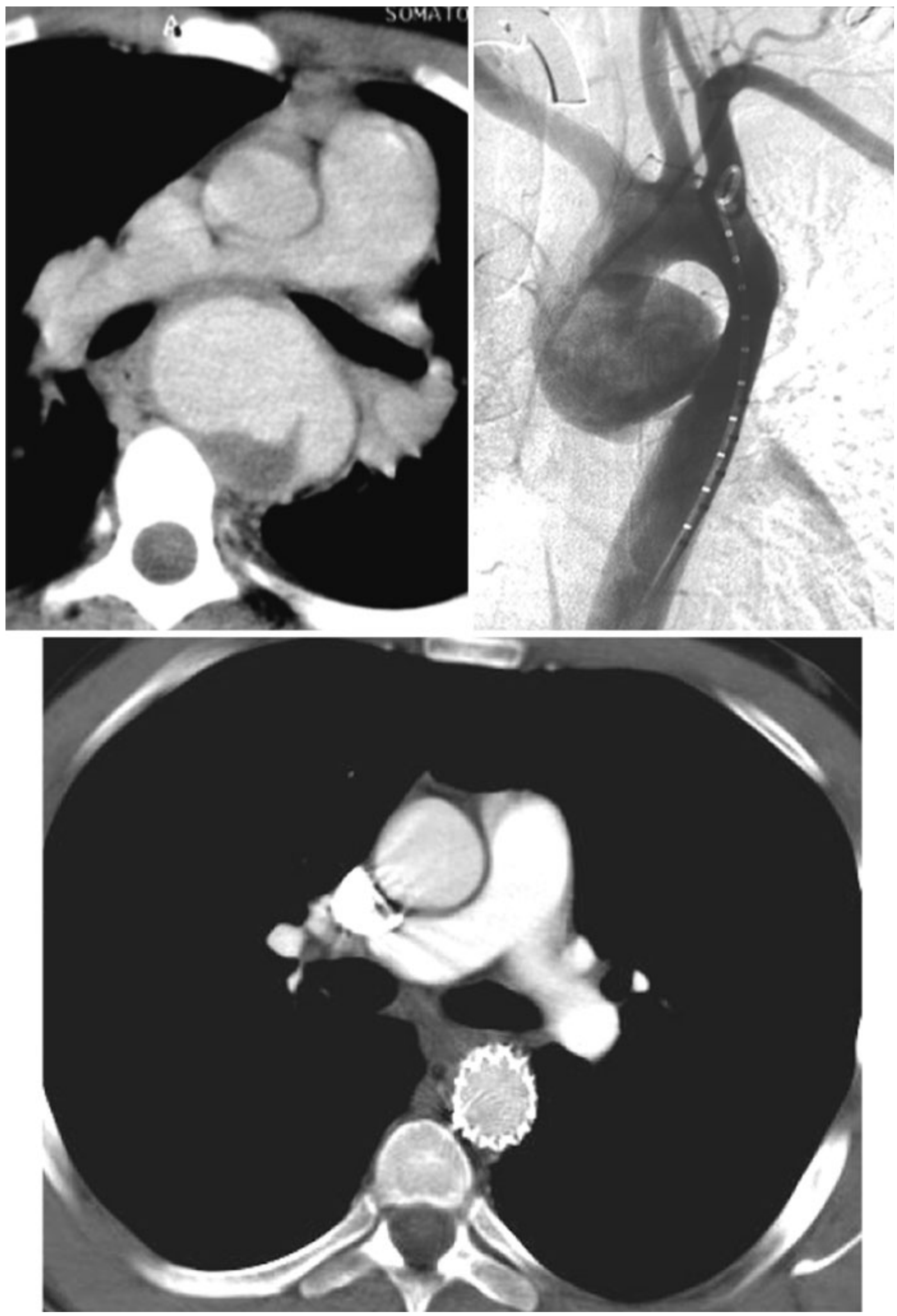

Fig. 3 **A-1** Pre-operative CTA and **A-2** angiogram before endograft implantation, showing traumatic transection and false aneurysm of the distal aortic arch. **B** At 10 years, control CTA shows the exclusion of the lesion with a complete resolution of the aneurysm sack

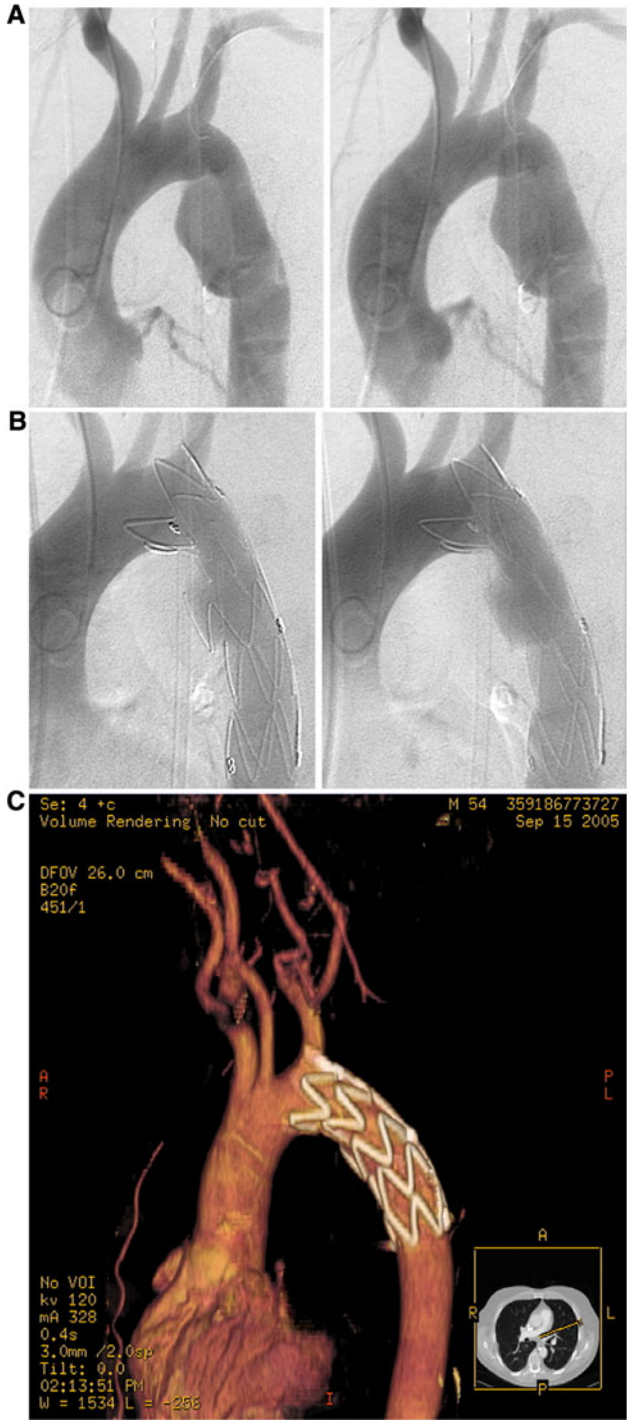

Fig. 4 **A** Angiography in young male patient following high-velocity motor vehicle collision. The conventional angiogram in left anterior oblique projection shows traumatic disruption of the aorta with a pseudoaneurysm formation. **B** Angiogram following stent-graft deployment shows exclusion of transection from the aortic lumen. We can note a complete expansion of the stent graft opposite the pseudoaneurysm, with relative constrictions at both ends inside the normal aorta. **C** Five years follow up multi-detector CT scan with 3D-volume rendering reconstruction, shows complete exclusion of the lesion of proximal descending thoracic aorta with adequate remodeling of the aorta

classical 10% oversizing to 15–20% in younger age groups has passed without complications, and with the long-term controls positive aortic remodeling was observed in all cases (Figs. 3, 4).

LSA Exclusion in Short Neck Lesions

Traditionally, the proximal landing zone or “neck” length must be at least 15 mm to obtain adequate proximal seal; however, the presence of supra-aortic branches may limit the length of a landing zone [60]. We have seen above that for anatomic reasons of high angulations of the distal end of the arch in young patients, the LSA may be covered during the deployment up to 50% of the time. To decrease neurologic complications, LSA revascularization can be achieved by subclavian-carotid transposition or bypass. The surgical approach for both procedures is similar, but carotid-subclavian bypass requires ligation of the LSA proximal to the vertebral artery to prevent type II endoleak. Transposition necessitates more extensive dissection and mobilization of the LSA. The procedure can be performed in conjunction with stent grafting; however, many authors favored delayed transposition only in symptomatic patients [60].

Dunning et al. [61] identified 20 studies with more than 10 cases of LSA coverage without previous revascularization. From 498 covered LSA, complications included 13 strokes (2.6%), 8 cases of paraplegia or paraparesis (1.6%), and 6 endoleaks due to subclavian backflow (1.2%). Of note, there were 51 cases of ischemia or other symptoms attributable to poor blood flow (10%), which resulted in 20 postprocedural revascularizations (4%). The conclusion of this paper is that coverage of the LSA artery has a low, but not insignificant, incidence of side-effects.

The society of vascular surgery published their recommendations for patients where a proximal seal necessitates coverage of the LSA. They suggest routine preoperative revascularization in elective situations (Grade 2, level C evidence), although they strongly recommend routine preoperative LSA revascularization in selected patients who have an anatomy that compromises perfusion to critical organs (Grade 1, level C evidence). Finally, for patients who need urgent TEVAR for life-threatening acute aortic syndromes, they suggest that revascularizations should be individualized and addressed expectantly on the basis of anatomy, urgency, and availability of surgical expertise (Grade 2, level C evidence) [62, 63]. Nevertheless, whereas SCA revascularization may reduce paraplegia risks for patients with aneurysmal disease, the risk of paraplegia with TEVAR repair of TAI is almost nonexistent with only one reported case.

Thus, we can recommend that the supra-aortic arteries must be fully assessed by angiography or CT scanning when the LSA exclusion is negotiated. In the absence of vertebral artery anomalies, intentional exclusion can be performed safely, with delayed revascularization performed only in symptomatic patients. Conversely, an absent right vertebral artery, diseased carotid arteries or an incomplete Circle of Willis must be considered as a contraindication to LSA coverage without prior transposition or bypass grafting of the LSA. Alternatively, in our experience, when such contraindication of intentional LSA exclusion is present, a chimney technique is performed. In such a case, concomitant endovascular revascularization of the LSA could be safely performed via stenting of the LSA using a noncovered stent just after deployment of the TEVAR stent graft, thus avoiding the associated risks with the revascularization procedure (Fig. 5). The same technique was performed routinely by Faber et al. [29] without any reported complications and without increasing the incidence of type Ia endoleak in their experience.

A

B

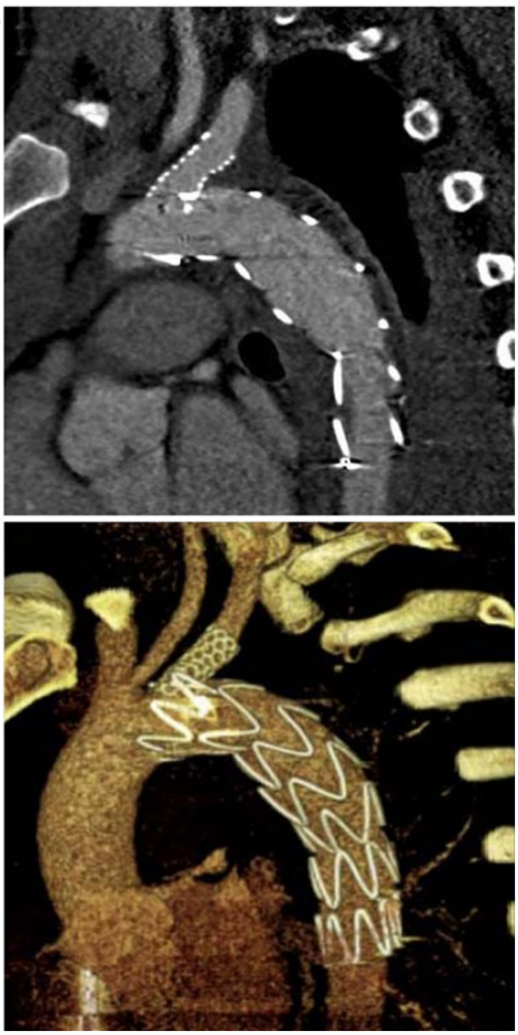

Fig. 5 Contained aortic rupture at the level of the isthmus with almost no proximal neck. **A** As the pre implantation angiogram demonstrated the absence of basilar trunk, the restoration of the LSA flow was achieved using a "chimney technique" by placing a bare stent at the origin of the LSA after stent-graft deployment. **B** Double oblique 3D MPR and SSD projection of the aortic arch with volume rendering demonstrated correct deployment of the endograft distal to the patent left carotid artery. Normal flow of the left subclavian artery is maintained through the bare stent

Another concern is the expertise of the centers with endografting, particularly in emergency for young patients. Historically, the management of TAI involved open surgical repair, with or without the protective adjunct of distal aortic perfusion. At a minimum, the surgery requires left thoracotomy, single lung ventilation, and aortic cross clamping with complex cardiorespiratory support. For the polytrauma patient, typical of those seen with this injury, the magnitude of open aortic reconstruction can be prohibitive. We can consider that the experience with endovascular aortic grafting is more widespread and is applicable to thoracic aortic injury. It is certain that emergency endovascular repair of TAI requires endovascular expertise, but the sophisticated anesthetic and hemodynamic manipulations characteristic of open thoracic aortic surgery are not required. For these reasons, a worthy opponent pointed out that treatment of TAI is not common in most trauma centers and advocates TEVAR as a less-demanding procedure for the occasional surgeon. However, a multivariate analysis showed that centers with high volume of endovascular procedures had significantly fewer systemic complications (adjusted $P = 0.001$), fewer local complications (adjusted $P = 0.033$), and shorter hospital lengths of stay (adjusted $P = 0.005$) than low-volume centers [64]. For these reasons, we believe that the argument of a less-demanding procedure is flawed. TAI does not occur in isolation but usually afflicts patients with severe multisystem injuries. Treatment for such patients should only be performed in level 1 trauma hospitals that are well-equipped to provide comprehensive care for every aspect of the injured patient's needs, including open and endovascular capabilities for the injured aorta. To suggest that widespread endovascular capability of hospitals will enable less experienced surgeons (and hospitals) to treat TAI is dangerous because this can lead to inappropriate triage of the severely injured and further dilute the limited experience for all major trauma centers. For these reasons, it seems reasonable to suggest sending the patient with TAI in references center to avoid lost time and experience.

Follow-up Intervals and Modalities

Follow-up intervals and duration of follow-up, and the appropriate diagnostic modality, are still a subject of discussion. Whenever an endovascular technique is used to treat aortic pathologies, long-term surveillance is recommended to monitor graft-related problems. The compliance of the trauma population regarding follow-up imaging after TEVAR is another major concern. In their recent series, Azizzadeh et al.

[65] showed that only 56% of the TEVAR patients were fully compliant with their surveillance imaging protocol. The reason for poor follow-up may be due to the young age of this population and their mobile, transient nature. Because this procedure is in its infancy and long-term results are unknown, these patients ideally should be monitored closely for possible late TEVAR complications, including stenosis, collapse, thrombosis, migration, recurrent endoleak, and pseudoaneurysm formation. Without follow-up, early detection of the above-mentioned problems will be impossible, and it is conceivable that late catastrophic aortic complications could befall these lost patients. Because conventional surgery is not free of secondary major problems, the same argument could be used for surgery for this indication.

On the other hand, considering the proposed imaging follow-up protocols, the radiation exposure burden becomes a viable concern in view of the cumulative radiation dose and the younger age of TAI population. Although there is no currently published follow-up protocol, routine follow-up is performed by using CT angiography at 1, 6, and 12 months, and then yearly. Nevertheless, it seems reasonable, if a repair remains stable on CT angiography during a 2-year period, evaluating device configuration on plain radiography may suffice. Fortunately, the majority of modern materials used in TEVAR stent grafts are MRI-compatible. Thus, follow-up protocols could avoid radiation exposure.

Cost of TEVAR vs. Surgery

Studies of TEVAR treatment for aortic aneurysms reveal higher cost for endograft patients in terms of operating room spending, follow-up imaging, and repeat interventions [66]. One can expect the same or higher cost with TEVAR for patients with TAI because higher reintervention rates are beginning to be established, and these patients will have longer life expectancy. Surprisingly, the study by Tong et al. [67] concluded that TEVAR for patients with TAI offers a survival advantage as well as a reduction in major morbidity and results in a cost reduction at 1 year, compared with open surgery.

Conclusions

TEVAR repair of TAIs offers a survival advantage and a reduction in major morbidity, including paraplegia, compared with open surgery. Endovascular procedures in trauma, especially in the presence of complex associated injuries, require a sophisticated multidisciplinary team approach and experience with the technique. More research and development of TAI-specific endograft devices is needed and large multicenter studies will help to clarify the role of TEVAR compared with open repair of TAI. Although prospective, randomized studies are mandatory to demonstrate the definite advantage of TEVAR, such studies are considered very difficult to conduct at the current time.

Conflict of interest Herve Rousseau is a Consultant for Medtronic – Gore – Bolton. None of the other authors has any potential conflict of interest.

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