Failure modes of thoracic endografts: Prevention and management

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Failure modes of thoracic endografts can be broadly categorized as those that typically occur early in the perioperative period and those that occur during late follow-up. In the former category, failures principally involve delivery, deployment, and conformation to the local anatomy. In the postoperative period, failures can manifest as endograft collapse, component separations, and metallic fractures and fabric tears. Some of these events are preventable with careful case selection, planning, and procedural technique, but others require active management with advanced endovascular or surgical adjuncts. No endograft system is immune from these problems. Endograft failure is an equal-opportunity hazard, which underscores the absolute need for diligent, long-term follow-up. (J Vasc Surg 2009;49:792-9.)

Careful patient selection and case planning is critical to the early and late success of thoracic endovascular aortic aneurysm repair (TEVAR). It can be said that 90% of the battle is won or lost before stepping into the operating room. Although repair of an uncomplicated mid-descending thoracic aneurysm is fairly straightforward, most thoracic pathologies lie close to the arch vessels proximally or mesenteric vessels distally, or both. Meticulous attention to detail and proficiency in advanced endovascular skills are required to safely complete these procedures and avoid the myriad of potential pitfalls that can lead to lethal complications.

Experience with abdominal endografts is useful, but TEVAR is sufficiently different due to the extreme tortuosity of the thoracic aorta that is not easily corrected with stiff wires, the greater hemodynamic forces in the arch, the remote location of the pathology relative to the remote entry site, and the significantly increased risk of iatrogenic dissection and aortic injury that is not readily surgically accessible.1

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EARLY FAILURES

Inability to advance delivery catheter. Thoracic aneurysmal disease frequently involves tandem segments of severe aortic tortuosity that are not readily corrected with stiff guidewires. The ability to push the guidewire is lost with each successive turn of the bend. Most delivery catheters have a stiffness transition between the relatively stiff proximal end, where the endograft is loaded, and the distal shaft. This forms a flexion point where the delivery catheter can bend at the vertex of an angulation. In certain severe cases, because the vector forces are not coaxial to the delivery catheter, continued pushing of the catheter can paradoxically retract the proximal end of the device. Aortic tortuosity can be partially overcome with use of superstiff “buddy wires” or even “buddy dilators,” where a stiff dilator of an introducer sheath is inserted from the contralateral femoral artery (Fig 1).

The only method of reliably overcoming severe aortic tortuosity is to use a transbrachiofemoral wire (Fig 2). The transbrachiofemoral wire represents the ultimate form of a stiff rail because it provides two points of fixation. In this technique, a 6F 65-cm guide sheath is inserted through the right brachial artery, a long guidewire is directed into the descending thoracic aorta, snared, and brought out through the femoral sheath. Both ends are secured. The delivery catheter is advanced over this guidewire while both ends are held taught.

For proximal lesions, the nose cone of the delivery catheter sometimes will need to be advanced into the innominate artery while backing up the 6F guide sheath. This guide sheath is important to prevent inadvertent aortic injury or dissection with the guidewire (“cheese-cutter”
effect) pressing against the innominate artery origin and
can also be used to obtain control angiograms before or
during deployment of the endograft.

**Unintended device movement.** Unintentional move-
ment of the endograft can occur during or after deploy-
ment and result in inadvertent coverage of vital branch
vessels or geographic miss of a part or the entire landing
zone. Two mechanisms of endograft deployment are used
by all of the commercially manufactured thoracic devices.
The most common mechanism is the pin-pull method of
unsheathing the self-expanding endograft, similar to de-
ployment of a peripheral stent. Some delivery systems use a
torque-transfer mechanism to reduce the actual pull force
needed to unsheathe the device, especially in tortuous
anatomies (Fig 3). When the proper dynamic pin-pull
tension is not applied, the device can migrate forward,
especially during the initial few centimeters of deployment,
or retract backwards in tortuous anatomies, where the
stored potential energy of the stent graft can be released
suddenly.

**Fig 1.** Severe aortic tandem tortuosity is partially corrected using
a “buddy” dilator inserted over a superstiff Lunderquist guidewire
(Cook Medical, Bloomington, Ind) from a contralateral femoral
access.

**Fig 2.** In the transbrachiofemoral wire technique, a guidewire is introduced from the right brachial artery over a long
guide catheter or sheath and snared from a femoral approach. The thoracic endograft is advanced over the guidewire,
applying firm tension at both ends. The long guide sheath can be used to inject contrast for control angiography during
the deployment.

**Fig 3.** The Valiant thoracic endograft (Medtronic, Santa Rosa,
Calif) has a deployment handle that rotates in a counterclockwise
manner to unsheathe the endograft. This significantly helps to
overcome the high frictional forces required to deploy this en-
dograft using standard pin-pull mechanism.
These difficulties are amplified in small access vessels when the resistive forces of the constraining sheath against the endograft internally and the friction of a tightly fitting arterial wall externally must both be overcome. This problem may be partially obviated by use of a conduit. When the forces involved are understood, inadvertent movement of the endograft can be avoided by firmly “pinning” or even applying slight backward tension on the delivery catheter at the beginning of deployment, and once the proximal segment is firmly seated, the force is reversed and slight forward pressure is applied while the deployment is completed. This allows the distal segment to provide the necessary slack to the endograft as it conforms to the outer curve and reduce the risk of retraction of the proximal attachment site.

The TAG endograft (W. L. Gore and Assoc, Flagstaff, Ariz) is a device with a unique, single-step deployment mechanism. The stability of the deployment depends on fixation of the device against the outer wall of the thoracic aorta. Owing to its unusual deployment from its middle portion and outward, the first point of contact (and fixation) may be in the middle of the aneurysm sac. In tortuous anatomies, especially near the apex of a tight curve (eg, distal arch) and most of the endograft is essentially floating in lumen of the aorta, the nose cone of a second device can inadvertently push the middle segment of the first device against the outer aortic wall while trying to make the curve and pull out the endograft from its proximal or distal attachment, or both. To avoid this problem in severely angulated anatomy a transbrachiofemoral wire may be used, which can effectively guide the delivery system along the convexity of a bend away from the outer wall, and reduce the risk of distraction of the endograft ends.

Device misdeployment. As previously mentioned, most of the commercial devices use a pin-pull method of deployment whereby the self-expanding endograft is slowly unsheathed in a proximal to distal manner. Fortunately, deployment failures are rare, but when they do occur, they are in the setting of severe aortic tortuosity and near the distal arch. One type of misdeployment has been variably termed spring flip, misaligned deployment, or bare-spring eversion. Although the exact incidence of this failure mode is uncertain, it has been associated with the Talent thoracic and Valiant (Medtronic Cardiovascular, Santa Rosa, Calif) endografts that have a proximal bare-spring (Free-Flo) configuration. Review of intraoperative images showed eccentric flaring of the bare stent component of the proximal main device due to apposition of the leading end of the delivery system against the outer curve (Fig 4). This failure minimized by using the shortest device (10 cm) in critical areas. On the other hand, using this technique necessitates use of at least a second device when a single device could have been used based on length of the lesion alone.

Another mechanism of device migration can occur from actual movement of an endograft that has been just deployed either during passage of a second endograft through it or during removal of the delivery system. Fortunately, this is a rare occurrence, but under the wrong set of circumstances, one edge of the endograft can interact with another edge of the delivery system in such a way that the endograft can actually be pushed upwards, dragged distally, or even cause the device to be completely invaginated within itself.

Occasionally, when the first device is deployed within a large sac that is located near the apex of a tight curve (eg, distal arch) and most of the endograft is essentially floating in lumen of the aorta, the nose cone of a second device can inadvertently push the middle segment of the first device against the outer aortic wall while trying to make the curve and pull out the endograft from its proximal or distal attachment, or both. To avoid this problem in severely angulated anatomy a transbrachiofemoral wire may be used, which can effectively guide the delivery system along the convexity of a bend away from the outer wall, and reduce the risk of distraction of the endograft ends.
mode has been associated with aortic anatomies that involve significant tortuosity, especially in the distal arch, small radius curvature, and larger diameters. To date, no adverse clinical sequelae from these events have been reported.

Once a bare-spring eversion occurs, there is no easy remediable solution, and the best management is prevention. Some technical tips that have been suggested include avoidance of deployment in adverse anatomies, deployment proximal to the intended landing zone and pulling backwards, and rapid deployment of the first one or two covered stents to tubularize the device to force the bare crowns near the inner curve against the aortic wall. None of these technical solutions is optimal, and the only reliable method of prevention is incorporation of a tip-capture mechanism in the delivery system (Fig 5).

Although the TAG device does not involve an unsheathing process, instances have occurred where the device failed to deploy fully. Unlike conventional pin-pull mechanisms, which in cases of failure simply require removal of the undeployed delivery system, when the TAG device fails to deploy either fully or partially, significant adjunctive techniques may be required to salvage the problem.

In all the reported cases of partial TAG deployment, the proximal end of the endograft had failed to deploy. These were associated with longitudinal compression of the undeployed endograft against the distal olive tip, which uncoupled the proximal constraining mechanism from the rest of the endograft. In these situations, the open distal end of the endograft was catheterized similar to the catheterization of the contralateral gate of an abdominal bifurcated endograft, an 0.014-in guidewire insinuated between the undeployed endograft and the central shaft, and the space serially dilated starting with a 3-mm coronary balloon up to a 10- or 12-mm balloon inflated to 8 to 10 atmospheres, forcibly breaking the constraining expanded polytetrafluoroethylene suture (Fig 6).

Device infolding. Most self-expanding aortic endografts are oversized 10% to 20% above the true inner or outer wall diameter to obtain an adequate friction fit for seal and fixation at the landing zones. The larger-diameter devices typically fall in the lower end and smaller devices are oversized towards the higher end of this range. Oversizing beyond this range may result in infolding of the endograft (Fig 7). Infolding near the proximal or distal landing zone may lead to a type I endoleak, stent fatigue, luminal flow disturbances, and thrombotic complications.

In anatomies that have discrepant diameters between the proximal and distal landing zones, the endograft is typically selected according to the larger of the two aortic diameters, which means that at the smaller end, the endograft will be oversized significantly beyond the upper range of recommended device oversizing. One extreme example of this scenario occurs during off-label treatment of type B/III aortic dissections. The endograft is typically sized to the undissected segment of the aortic arch, but the rest of the device is deployed in a narrowed true lumen. Even if this lumen expands, it does not expand to the size of the reference arch diameter.

Prevention of this failure mode includes following the manufacturer’s sizing guidelines, use of tapered devices, and stepwise upsizing of the endografts either proximal to distal or vice versa (shingling). The ideal solution, however, is a tapered or reverse-tapered endograft configuration with a broader range of diameter gradients (current devices only allow for a 4-mm taper) and improved stent designs that allow for a wider tolerance for oversizing and circumferential radial expansion.

Arch conformation. Nearly every device has a minimum radius of curvature to which it can conform, and below which malapposition of the endograft to the inner curve can occur (Fig 8). The inner curve acts as a fulcrum over which the proximal edge of the endograft hangs over the ascending aorta. This can lead to a type I endoleak and
even complete endograft collapse. Prevention and management include identification of the proper landing zone beyond the simple considerations of its length and diameter. In the case of a proximal descending lesion, if there is adequate length of nonaneurysmal aorta, the endograft should be deployed sufficiently proximal to the apex of the arch, even if the left subclavian artery must be covered, or entirely distal (down slope) to it so that the device lands in a parallel segment of the aorta (Fig 9).

Alternatively, device-specific improvements in terms of stent fabric construction and delivery system design are clearly needed to remedy this failure mode moving forward. Although manufacturers have used a proximal bare stent to help align the first covered (sealing) stent along the inner curve, there have been rare cases of aortic perforations and retrograde type A dissections that were associated with the use of bare stents to repair type B aortic dissections.3

LATE FAILURES

Endograft collapse. Proximal endograft collapse (compression) has been most commonly reported with the TAG device.4,5 Indeed, as of the manufacturer’s 2008 Annual Clinical Update, at least 95 cases had been confirmed. This failure mode has been associated with deployment of the endograft near the distal arch with a small radius of curvature and excessive oversizing. As described, the endograft fails to conform to the inner curve of the arch, which acts like a fulcrum over which the endograft hangs like a ledge. The high aortic blood flow can push up against this ledge and result in a complete collapse of the endograft and a type I endoleak (Fig 10). This can be managed with placement of a bare metal balloon-expandable stent (eg, P4010, P5010) or another endograft within the collapsed segment. The long-term safety of this approach has not been established, and occurrence of this complication should be considered an indication for surgical conversion.

As a technical matter, deployment of a large-diameter balloon-expandable stent near the arch is not trivial. The stent can slip off the balloon, be asymmetrically crushed by the balloon during expansion, and migrate from the target location due to the pulsatile forces present near the proximal aorta. Significant reduction of blood pressure is frequently required for accurate deployment.

Component separation. Component separation is a well-recognized late failure of all modular aortic endograft systems. Close surveillance and inspection of component
Fig 9. The top two panels illustrate selection of an ideal landing zone either (top left) proximal or (top right) distal to the apex of the arch. The bottom panels illustrate deployment near the apex resulting in malapposition of the endograft along the inner curve.

Fig 10. Complete collapse of the TAG endograft (W. L. Gore and Assoc, Flagstaff, Ariz) at the proximal attachment site.
overlap with either multiview chest radiographs or maximum intensity projection reconstructions of computed tomography data sets are critical to the overall long-term treatment algorithm after TEVAR. This obviously requires recognition of the terminal markers of the endograft components, and those devices that have easily visible markers facilitate this task. Junctions that lie near a curve and within the main aneurysmal segment of the thoracic aorta have the greatest risk of separation. Endograft movement is dependent on the pulsatility of the blood flow and the intraluminal and extraluminal (intrasaccular) pressure gradient. Under a specific set of hemodynamic and anatomic conditions, the components that initially coursed along the inner wall will continue to bow out towards the outer curve until the device hits the opposite wall of the aorta or separates completely (Fig 11).

Prevention is always easier and safer than treatment. Introduction of some redundancy in the endograft path during the original deployment, generous overlap (>5 cm) between devices, and prophylactic correction of impending

Fig 11. Component separation. **Left,** At the predischarge computed tomography scan, a three-stent overlap was noted between the proximal and distal components. **Middle,** At 12-months, the separation has started to occur, leaving only a two-stent overlap. **Right,** This patient underwent elective revision with a bridging endograft after his 24-month follow-up showed further separation with less than one-stent overlap but without an endoleak.

Fig 12. Longitudinal bar fracture in the first-generation TAG device (W. L. Gore and Assoc, Flagstaff, Ariz). This feature has been eliminated from the subsequent modification of the endograft.
separation are important to the prevention of this complication. The treatment is fairly straightforward, with insertion of a bridging endograft between the two endografts.

**Wireform fractures and fabric tears.** Stent fractures and fabric tears can occur at any point during the postoperative follow-up period. Mechanically, wireform fractures are mainly due to metal fatigue from repetitive torsional and bending motions and high loads. They have been more commonly associated with straight elements of the endograft construction, such as longitudinal connecting bars intended to impart column strength. Fabric tears have occurred from surface erosion by repetitive motion of calcific lesions along the luminal contact surface or the sharp edge of a fractured stent or the connecting bar. Despite the frequency of its occurrence in some of the earlier endograft designs, the incidence of serious adverse events associated with this failure mode has been relatively infrequent (Fig 12).

Wireform fractures are typically clinically silent and seen as an incidental finding on follow-up x-ray imaging. Fabric tears are more serious and may present with acute aneurysm-related symptoms and, by definition, a new type III endoleak. Diagnosis of a fabric tear, however, is really one of exclusion. The source of an endoleak occurring in the vicinity of an endograft junction or visible intercostal vessel can be difficult to establish. Fortunately, as long as a type II endoleak can be ruled out, treatment is the same with placement of another endograft.

**CONCLUSIONS**

There are multiple failure modes that can affect the short-term and long-term safety and performance of a thoracic endograft. Some of these failure modes require prevention by careful case selection and meticulous attention to detail, and others require active management using adjunctive endovascular and other techniques. Although all devices are at risk, some failures are more specific to one device over another and can only be remedied with improvements in design and construction. What may not have been fully appreciated in the past, but which is now well recognized today, is that the delivery system is as important as the endograft in determining the early and late outcomes of the therapy. No matter how effective the endograft, if it cannot be delivered in a safe, consistent, and reliable manner, the repair will be ineffective. Therefore, research and development in this therapy must be encouraged in both fronts.

**REFERENCES**


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