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Review

Importance of stent-graft design for aortic arch aneurysm repair

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Abstract: Aneurysm of the aorta is currently treated by open surgical repair or endovascular repair. However, when the aneurysm occurs in regions between the aortic arch and proximal descending aorta, it can be a complex pathology to treat due to its intricate geometry. When complex aortic aneurysms are treated with the conventional procedures, some of the patients present with significant post-operative complications and high mortality rate. Consequently, a clinically driven hybrid innovation known as the frozen elephant trunk procedure was introduced to treat complex aortic aneurysms. Although this procedure significantly reduces mortality rate and operating time, it is still associated with complications such as endoleaks, spinal cord ischemia, renal failure and stroke. Some of these complications are consequences of a mismatch in the biomechanical behaviour of the stent-graft device and the aorta. Research on complex aneurysm repair tended to focus more on the surgical procedure than the stent-graft design. Current stent-graft devices are suitable for straight vessels. However, when used to treat aortic aneurysm with complex geometry, these devices are ineffective in restoring the normal biological and biomechanical function of the aorta. A stent-graft device with mechanical properties that are comparable with the aorta and aortic arch could possibly lead to fewer post-operative complications, thus, better outcome for patients with complex aneurysm conditions. This review highlights the influence stent-graft design has on the biomechanical properties of the aorta which in turn can contribute to complications of complex aneurysm repair. Design attributes critical for minimising postoperative biomechanical mismatch are also discussed.

Keywords: aortic aneurysm; stent-graft; hemodynamics; compliance; spinal cord ischemia

Abbreviations:

OSR	Open surgical repair
EVAR	Endovascular aneurysm repair
PTFE	Polytetrafluoroethylene
TEVAR	Thoracic endovascular aneurysm repair
ET	Elephant trunk
FET	Frozen elephant trunk
SCI	Spinal cord ischemia
SCPP	Spinal cord perfusion pressure
FDS	Flow Diverter Stent
PET	Polyethylene terephthalate

1. Introduction

Cardiovascular disease is one of the leading causes of death in developed countries. One of the conditions that contribute to this mortality is aortic aneurysm. Aortic aneurysm is a condition whereby the aorta, a major blood vessel of the heart enlarges abnormally due to a weakened aortic wall [1]. Aortic aneurysm usually occurs in the abdominal aorta but can also extend into the thoracic region. When the aorta and thoracic aorta is beyond 55 and 65 mm in diameter, respectively and left untreated, life-threatening complications such as aortic rupture arise [1]. Aortic aneurysm is a primary cause of death for approximately 10,000 patients and a contributing cause of death for 17,000 patients annually in the United States [2]. Of these cases, more than 50% of the patients diagnosed with thoracic aortic aneurysms have complex or extensive aortic aneurysms [3]. Complex aneurysm is defined as aneurysm spanning from the aortic arch region to the descending thoracic aorta (Figure 1A).

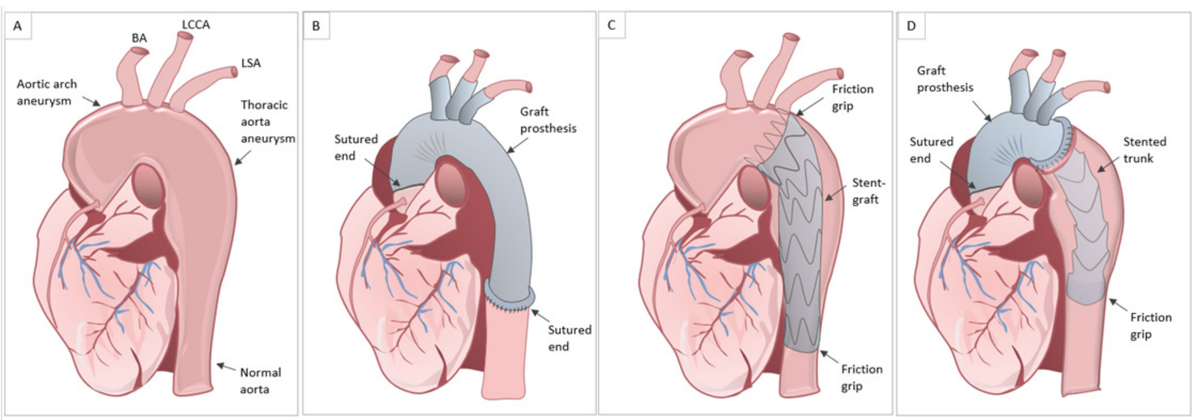

Figure 1. (A) Complex aortic aneurysm extending between aortic arch and thoracic aorta region, (B) Open surgical repair, (C) Endovascular repair, (D) Frozen elephant trunk hybrid repair. BA—Brachiocephalic artery, LCCA—Left common carotid artery, LSA—Left subclavian artery.

There are two main treatment options for aortic aneurysms: open surgical repair (OSR) and endovascular aneurysm repair (EVAR). OSR is considered the gold standard for treating aneurysms and the procedure is associated with very few long-term complications. However, being a highly invasive procedure, the OSR results in high perioperative mortality and is unsuitable for high-risk elderly patients [4,5]. This limitation led to the development of minimally invasive procedures such as EVAR which has improved the treatment of aneurysm in the last two decades.

While OSR and EVAR are suitable for aneurysms with straight aortic geometry (abdominal and thoracic aorta), treating complex aneurysms remains a clinical challenge as complicated anatomies involving acute aortic arch angulation and supra-aortic vessel re-construction (brachiocephalic artery, left common carotid artery, and left subclavian artery) need to be considered [6]. Even with recent technological advancements, both OSR and EVAR are still associated with significant post-operative complications and mortality [5,6]. These 2 procedures utilize a textile graft to treat the aneurysm and one of the factors that contributes to the post-operative complications is the structural design of the graft [7,8]. Parameters such as size specifications and ease of handling during the procedure are considered important while the influence of the stent-graft design on biomechanics and its impact on the hemodynamics of the aortic arch is often overlooked [9,10]. The purpose of this review is to highlight major biomechanical shortcomings of current stent-graft devices in relation to aortic arch geometry and its mechanics, and thus prompting the development of devices better suited for complex aneurysm repair.

2. Conventional Repair of Complex Aneurysms

Complex aneurysms are usually treated via OSR or EVAR. OSR is an invasive treatment that requires an incision in the abdomen or chest along the aorta followed by an insertion of soft tubular graft prosthesis to replace the aneurysmal site of the aorta (Figure 1B). These surgical grafts are usually made from Dacron® polyester or polytetrafluoroethylene (PTFE) and sutured to re-connect the healthy ends of the aorta. The less invasive EVAR is a procedure which involves a small incision in the groin area and a stent-graft is inserted through the femoral artery and up to the site of aneurysm in the aorta (Figure 1C). A stent-graft consists of a thin metal framework referred to as a stent that is attached to a Dacron® or PTFE graft. The stent-graft is inserted into the body in a collapsed form and re-opened at the site of the aneurysm in a spring-like fashion. The expansion force provides a passive friction grip to hold the stent-graft in place.

EVAR that is used to treat thoracic aortic aneurysm is referred to as thoracic EVAR (TEVAR) and this procedure has its own challenges due to the anatomy of the aortic arch. One of the limitations is the availability of appropriate landing zone to enable firm fixation of the stent-graft at its proximal and distal ends. Another major challenge is to deploy the stent-graft accurately in a large, mobile, curved aortic arch which is subject to high blood flow [11] and achieving conformability of the stent-graft with the curvature of the aortic arch [12]. Although TEVAR is less invasive, its long-term complication rates are higher than OSR [13,14]. The stent-graft related complications (migration, endoleaks, kinking, structural failure) occur because the stent-grafts which were designed for non-curved aneurysm treatment are also being used to treat complex aneurysms with little consideration to the morphological and hemodynamic characteristics of the aortic arch [15–18].

3. Hybrid Repair of Complex Aneurysms

In order to overcome the limitations of OSR and TEVAR, hybrid repair procedures, elephant trunk (ET; Figure 2) [19] and frozen elephant trunk (FET; Figure 3) [20,21] were introduced, respectively. These hybrid procedures had the major advantages of being easy to carry out and lower device related complications. This led to the procedures being used globally to treat complex aneurysms.

The ET procedure described by Borst in 1983 combined ascending aorta and aortic arch replacement, followed by placement of a free-floating graft into the descending thoracic aorta. This technique had the advantage of a graft already present in the descending thoracic aorta which could be utilised for thoracic aorta reconstruction at a later stage. The ET procedure offered the advantage of avoiding extensive dissection of the aorta in a single procedure. Additionally, clamping of the graft distal to the subclavian region rather than in the arch, as in the OSR, reduces hypothermic circulatory arrest time.

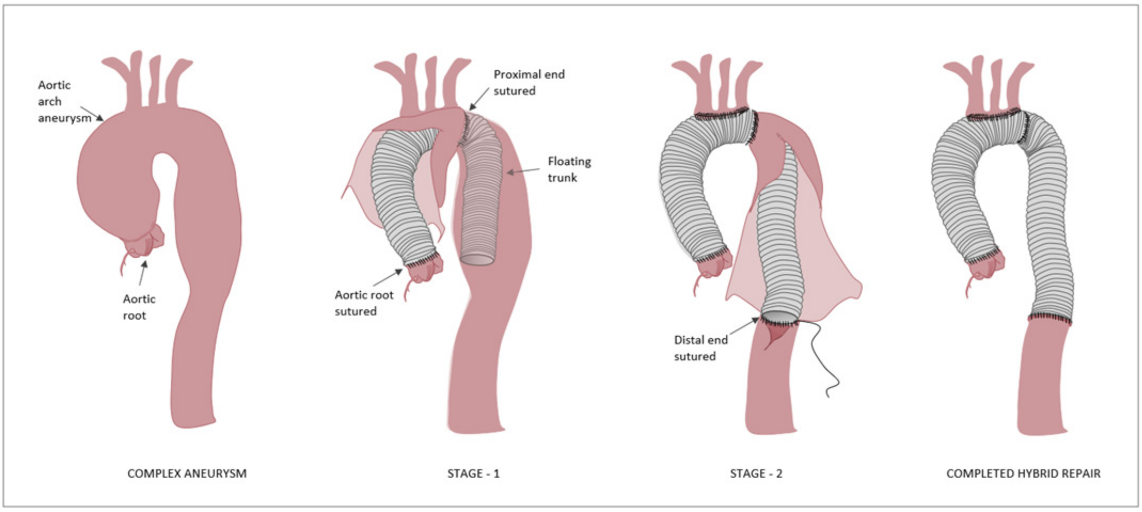

Figure 2. Two stage hybrid elephant trunk procedure with a long graft prosthesis as proposed by Borst (1983).

The FET procedure came into existence in the 1990s after the advent of the endovascular era, when surgeons started to combine ascending aorta and aortic arch repair with deployment of an endovascular stent-graft into the descending thoracic aorta. The benefit of a FET procedure was that it reduced the operative time significantly by turning the complex 2-stage ET procedure into a single surgery. The FET procedure combines OSR and EVAR treatment whereby a prosthetic graft is used to reconstruct the aortic arch region while a stented graft bypasses the thoracic aneurysm region in a single stage procedure (Figure 3) [22].

A typical hybrid device consists of a proximal non-stented woven Dacron® graft and a stented graft (trunk) at its distal end that bypasses the thoracic aortic aneurysm. The hybrid device is loaded in an introducer and inserted in an antegrade manner through the opened aortic arch (Figure 3A). The stented trunk is deployed deep inside the thoracic aorta supported by passive fixation at its distal end while the proximal end is sutured circumferentially in the distal aortic arch region (Figure 3B). The sutured anastomosis of the proximal end prevents the distal migration and type-1a endoleak complications associated with stent-grafts in TEVAR procedures [23]. The FET technique significantly reduced the mortality rate to 7%, compared to 8.9% (1st stage) and 7.7% (2nd stage) of the conventional hybrid procedure [6]. The FET procedure thus offers a better treatment option for complex aneurysms than OSR and EVAR by reducing the operative time and improving stent-graft stability.

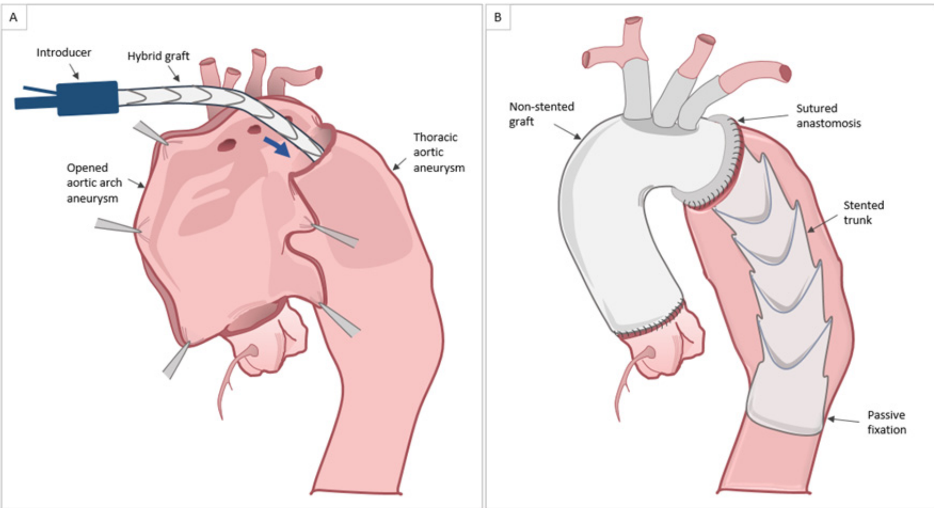

Figure 3. Single stage frozen elephant trunk hybrid repair procedure; (A) Stented trunk insertion in collapsed form in thoracic aorta, (B) Stented trunk deployed and aortic arch reconstructed with proximal graft.

4. Impact of Stent-graft Design in Complex Aneurysm Repair

Currently, there are several types of stent-grafts available in the market, all differing in design, thickness profile, metallic composition, graft construction and fixation method, making each device unique in its structure [24]. However, none of the device is free from post-operative complications [25]. While there has been intensive research in the last 30 years into improving hybrid procedures, there has been no significant improvement in the design of the hybrid device, which plays an important role in the post-operative success of the procedure [26].

4.1. Effect of stent-graft on hemodynamics of the aorta

The stent-graft design influences the outcome of an aneurysm repair especially when it is being considered as a replacement conduit for the aortic arch [27,28]. This is because the aortic arch region encounters dynamic forces that are completely different to the rest of the aorta due to its multiplanar geometry [12,29]. The aortic arch undergoes dynamic motion because it is attached to the beating heart [30]. The geometrical changes occur due to the three-dimensional spiralling of the aortic arch caused by strong contraction and relaxation movement of left ventricle (flexion) and high volume rotational blood flow patterns (torsion) [31].

An important function of the aorta is the *windkessel* function which maintains steady flow conditions throughout the arterial network [32]. The *windkessel* function prevents the arterial pressure from falling abruptly after the aortic valves close [33]. Aortic elasticity is a profoundly important determinant of *windkessel* function and hence the blood flow dynamics. The arterial compliance or elasticity of the ascending aorta and aortic arch is significantly higher than the rest of the aorta and is responsible for nearly 40% of the total arterial compliance [34,35]. On the contrary, biomechanical properties of stent-graft materials are significantly different to that of an aorta. A commercial woven Dacron® graft is 24 times stiffer than a healthy human aorta [36]. An unmatched radial compliance between a stent-graft device and aorta can trigger local hemodynamic disturbance after implantation [37–41]. The direct effect of this mismatch on aortic hemodynamics is observed as a deterioration in aortic *windkessel* function and increased cardiovascular load [42–46]. In the absence of systolic dilation, the stented aorta loses the ability to assist in diastolic flow (Figure 4). The stented region is unable to store extra blood volume during systole and hence the maximum portion of stroke volume flows through the aorta in a single systolic phase [47]. As a result, the diastolic phase experiences reduced blood flow, thus decreasing the diastolic blood pressure below the normal levels [47,48]. Lowered diastolic pressures, in turn, limit the blood flow to the coronary arteries [47,49,50,51].

Apart from altering the hemodynamics of the aorta, the poor radial compliance and longitudinal rigidity of the stent-graft also lead to migration from its fixation site. This is caused by the dilating aneurysm neck exceeding the maximum achievable diameter of the non-compliant stent-graft and thus disengaging it from the fixation site [52]. Similarly, lengthening of the aneurysm post-treatment can cause displacement of the stent-graft at the fixation site as its longitudinal rigidity does not allow it to extend to similar lengths [53,54].

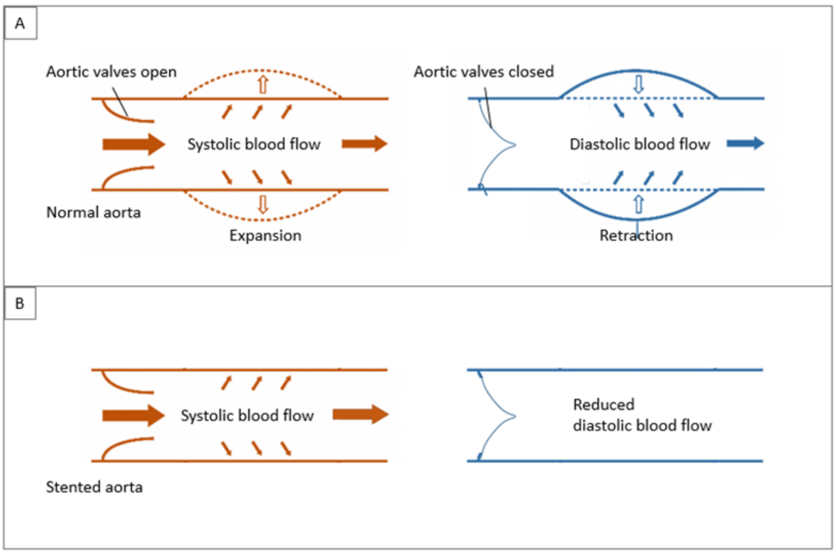

Figure 4. Role of aortic compliance in maintaining diastolic blood flow.

Another factor that contributes to poor stent-graft performance in tortuous anatomical location of the aortic arch is the high bending stiffness of the stent-graft [12,15,55,56,57]. Bending stiffness of the stent structure significantly hinders the ability of the device to conform to the aortic arch curvature. The stiffness also causes aortic wall injury due to pulsatile stress and configuration mismatch between stent-graft and aortic arch [56]. Commercial stent-grafts are designed to achieve high longitudinal rigidity as it provides columnar support to the structure and hence prevents migration [58,59]. However, this property is more beneficial when the device is used to treat straight abdominal aortas rather than the aortic arch and proximal thoracic aorta which have three-dimensional angulations. This is because blood traverses in curved regions of the aorta and creates centrifugal forces that are markedly higher than in straight regions [60]. A longitudinally rigid stent-graft that cannot be extended is incapable of absorbing pulsatile forces generated within the structure itself. Consequently, the collective lateral displacement forces from the curved section of stent-graft length are transmitted as migration (or drag) forces on distal fixation site leading to type-Ib endoleaks (Figure 5) [61–65]. The dreaded complication of stent-graft induced new entry (type-Ib endoleak) can also occur when a stiff stent-graft is implanted in the angulated regions of the aorta. The shear forces are high at the fixation point of the stent-graft which gets amplified with acute angulation of the aorta and oversizing of the stent-graft [66].

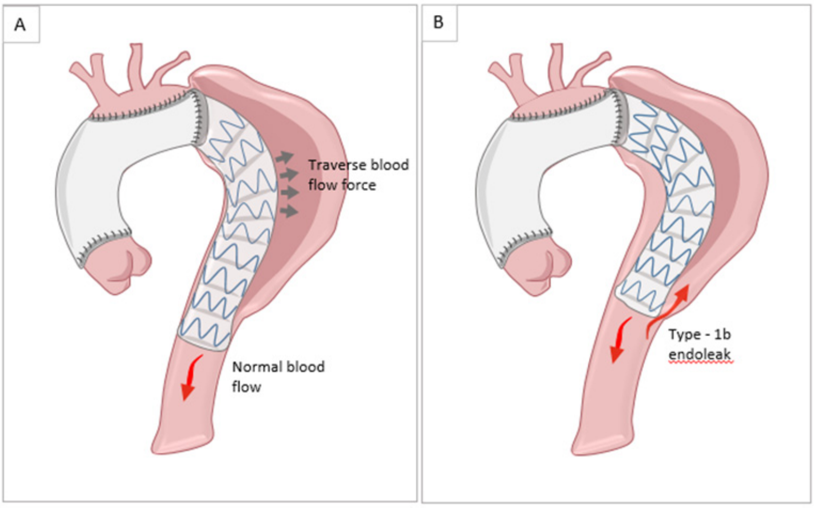

Figure 5. Distal end migration (Type-1b endoleak) of stented trunk in a hybrid device subjected to traversing blood flow forces in curved proximal descending aorta region.

5. Hybrid Stent-graft Designs

5.1. Customised devices

The first hybrid FET graft consisted of a stainless steel Z-shaped stent and woven polyester graft material [20]. This device was composed of a crimped graft prosthesis at the proximal end and an uncrimped graft with three Z-shape stent rings inserted and sutured to the graft circumference at the distal end (Figure 6). Following this, the Chavan-Haverich hybrid graft was created with similar design and composition which is currently manufactured in customised configurations by Curative Medical Devices GmbH, Germany [67]. Globally, most clinicians requiring customised hybrid grafts use the Chavan-Haverich graft tailored to the patients' needs. Clinical and follow-up studies showed promising results in terms of ease, effectiveness and safety of the procedure [68–74]. Another FET graft, Cronus® (MicroPort Medical Co. Ltd, China) was claimed to be superior to Chavan-Haverich graft owing to its technical simplicity [75]. The authors claimed that an extra length of normal graft on both ends allowed anastomosis to be performed conventionally and helped in avoiding endoleaks.

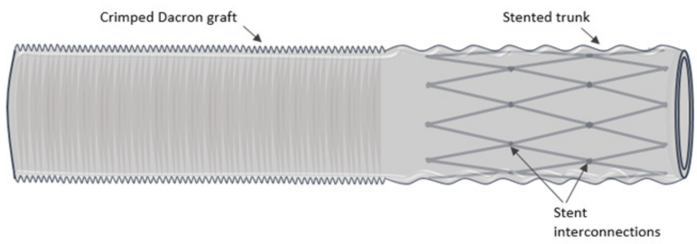

Figure 6. Typical design of first custom-built hybrid stent-graft device.

5.2. Off-the shelf devices

Currently available off-the-shelf devices have overcome a major shortcoming of early customised devices. The interconnections between adjacent stent rows (Figure 6) were eliminated in new devices which reduced the risk of stent rupture, commonly observed with early customised devices, due to repeated cyclic stresses. This also prevented occurrence of type-III endoleaks due to graft failure at interconnection points. The two commercially available FET hybrid devices are E-vita Open Plus graft (Jotec® GmbH, Germany) and Thoraflex hybrid graft (Vascutek®, Terumo, UK) [76,77]. The E-vita device consists of a crimped woven Dacron® graft 70 mm in length used for aortic arch reconstruction [78]. The graft further extends into a flexible nitinol z-shaped wire stented trunk with diameters and lengths ranging from 24–30 mm and 150–160 mm, respectively. The Thoraflex® hybrid graft consists of a four-branched arch graft (unlike the plain tubular graft of E-vita Open Plus device) with a stented trunk at the distal end [77]. The proximal part is a gel-coated woven polyester graft and the stented trunk is composed of oval shaped nitinol ring stents. The graft is available in different sizes (diameters of 28–40 mm and lengths of 100–150 mm). A major difference between E-vita Open Plus and Thoraflex hybrid graft is their stent ring configuration. The E-vita Open Plus has single wire stent rings, whereas the Thoraflex device consists of multiple wire rings which reduces the retraction force of the device and potentially improves longitudinal flexibility. However, to date, no data has been published on the comparison of mechanical properties between the 2 types of graft.

6. Complications Associated with Hybrid Devices

Clinical trials with new hybrid devices (E-vita and Thoraflex hybrid graft) have reported ease of deployment which significantly reduced the operative time compared to conventional OSR, TEVAR and ET procedures [79]. However, the FET procedure is not without complications (Table 1).

Endoleaks, a commonly reported problem, has an incidence rate of 1–15%, which requires a second stage aortic surgery or a TEVAR completion [70,80]. A recent 4-year study comprising 100 patients using Thoraflex® graft reported a high endoleak rate (43%), and corresponding high reintervention rate (60%) [81]. The distal endoleaks (or type-1b endoleaks) occur as a result of the stented trunk migrating towards the aortic arch in large aneurysms (Figure 5) [68,71,72]. Excessively short trunks (<5 cm) are inadequate for sealing the stent-graft, especially in severely tortuous aortas while an excessively long trunk (>15 cm) is prone to kinks and migration. Additionally, the diameter of the stent-graft is an important criterion in the long-term success of FET technique [82]. The use of stent-graft with diameter larger than that of the aneurysm neck can help to improve fixation at the distal end. However, clinically, this may not be feasible as stented trunks with excessively large diameters can lead to severe aortic wall damage or tearing [6,82].

Table 1. Limitations of current hybrid devices and future design concepts.

CURRENT STENT-GRAFTS				FUTURE STENT-GRAFTS	
DESIGN FEATURE	LIMITATION	ASSOCIATED COMPLICATION	REFERENCE	DESIGN FEATURE	ASSOCIATED IMPROVEMENT
Unibody structure	Low flexibility	Endoleaks	[68,70,71, 72,77,83]	Modular design	Improved structural flexibility
		Migration, Kinking	[84,85,86]	Multi-component assembly	
Non-compliant structural materials (Dacron fibre, metallic stents)	Low radial expandability	Reduced diastolic pressure	[47,49,50,51]	Compliant structural materials (elastic polymeric fibres, knitted graft structure)	Enhanced blood flow transmission
		Aortic wall injury	[56]		Reduced property mismatch with aortic tissue
	Disturbed spinal cord blood flow	Delayed spinal cord ischemia	[87–92]		Enhanced spinal cord blood flow
Diameter oversizing	Aneurysm neck stress	Aortic wall injury	[82,93]	Matched compliance with aortic wall	Reduced property mismatch with aortic tissue
Short trunk length	Inadequate sealing	Migration, Type 1b endoleaks	[68,71,72]	Biocompatible coatings and graft materials	Better tissue ingrowth and sealing
Long trunk length	Extensive aortic coverage	Spinal cord ischemia	[70,94–98]	Radially compliant trunk	Enhanced spinal blood flow via collateral supply vessels
				Flow diverter stents	

Another device related complication, commonly reported in treatment of kinked or tortuous aortas, is that the insertion of stented trunk becomes very difficult or impossible due to the stiffness of the trunk and the introducer sheath [86]. Sakurai et al. and Toyama et al. reported mid-zone migration of stent-graft and kinking [84,85]. Some studies suggested that use of longer trunk lengths (10–20 cm) can help in thrombosis of false lumen which can permanently prevent retrograde perfusion [99]. However, long trunk lengths have been shown to contribute towards spinal cord ischemia (SCI) and paraplegia in patients [70,94,97]. Therefore, there is a need for innovative fixation techniques which do not rely only on pressure contact between stent-graft and aortic tissue or mechanical hooks and more compliant/flexible structures which prevent transmission of migration (or drag) forces to the fixation sites.

SCI has recently been identified as a serious complication in hybrid repair with incidence rates ranging from 0 to 24% [100]. Incidence of SCI as high as 20% were reported in hybrid procedures using the E-vita graft [95,96,98]. The probable relationship of postoperative SCI and stent-graft design highlights the impact the design has on the hemodynamics of reduced aortic compliance after stent-graft implantation [38,46]. When a significant length of a compliant aorta is replaced with a non-compliant stent-graft, the pressure transmission ability of the aorta, within and at the distal end of the stented region is significantly reduced [43]. Consequently, *windkessel* function is lost over a long length of aorta (100–150 mm), leading to significant drop in diastolic pressure [87]. Since, a major portion of the spinal cord blood supply originates from non-compliant stented (left subclavian artery) and distal (intercostal arteries) regions during a hybrid repair, its effect on delayed SCI can be expected. Thus, the possible contribution of extensive coverage of supply arteries along with reduced pressure transmission ability of stented aorta towards SCI indicates that future design of stent-graft devices should take this aspect into consideration.

7. Improvements and Future Concepts for Hybrid Graft Design

The use flow diverter stents (FDS) is an emerging technique in treatment of complex aneurysms when endovascular and open surgical procedures are unsuitable. The FDSs are bare stents and designed to reduce the flow velocity vortex within the aneurysm and improve laminar flow in the main artery. When a FDS is placed inside an aneurysm, the blood flow into the sac becomes stagnant which promotes gradual thrombosis and neointimal modelling. At the same time, the blood flow into the branched vessels is maintained. The stent mesh density (or porosity) is an important factor deciding its healing performance and mechanical properties [101]. A mean porosity of 65% is considered optimal to modulate the flow in the sac [102]. The FDSs currently available are used for visceral and peripheral vascular applications which include the Pipeline Embolization Device (PED; ev3, Plymouth, Minn), the SILK Arterial Reconstruction Device (Balt Extrusion, Montmorency, France), and the Cardiatis Multilayer Stent (Cardiatis, Isnes, Belgium). The Cardiatis Multilayer Stent is a self-expanding stent consisting of multilayered braided structure of cobalt alloy wires. The stent is also available in sizes (20–45 mm) suitable of treating aortic aneurysms and has been reported to result in aneurysm thrombosis and aneurysm shrinkage while maintaining collateral branch patency [103–106]. Since branch vessel coverage is a critical issue during extensive coverage by hybrid stent-graft trunks, FDSs can be specifically beneficial in preventing SCI incidences by maintaining flow to the spinal cord supply vessels. However, the safety of FDSs in large aneurysms experiencing high blood flow rates is still not fully established and risk of aneurysm rupture requires close patient surveillance [107]. Also, the benefits of using FDSs are not immediate and can take months as complete aneurysm thrombosis is not instant and sac pressure can remain critically high during that time [102]. In such cases, with immediate risk of aneurysm rupture, use of covered hybrid stent-grafts is the only option. However, the dynamics of aortic arch and proximal descending aorta are so strong that simple stent-graft designs often fail due to their mismatched mechanical property. The use of even barbs/hooks are sometimes not sufficient to hold a stiff stent-graft in place [108,109], which directly suggests that longitudinal extensibility and flexibility of structure are important requirements especially in curved anatomic locations. However, the challenge is to maintain these features even under cyclic stretching force of high blood pressure inside them. This will require a detailed understanding of vascular wall structure and how aorta maintains its flexibility and extensibility without structural failure throughout its lifetime [110]. The *windkessel* or cushioning function of aorta has a practical importance as the heart behaves like a cyclic pump and flow fluctuations between phases (systolic and diastolic) can only be smoothed via this function which also relies on structural construction of the aortic wall.

Based on these understandings, some novel graft designs such as use of bilayered walls which improve graft compliance and match the non-linear extensibility property of the aorta have been trialled recently. Chen et al. fabricated a bilayered graft consisting of Poly(trimethylene terephthalate) filaments for the inner layer and Polyethylene terephthalate (PET) filaments for the outer layer [111]. Poly(trimethylene terephthalate) has a low tensile modulus and good elasticity, and when used as the inner layer of the graft, it increases the compliance of the inner wall. PET used as the outer layer provided a stronger and stiffer covering due to its higher tensile modulus. The two layers were stitched together loosely and such a design enabled only the inner layer of the graft to expand and contract during a low pulsatile pressure. As the pressure increased, the expanded inner layer would come into contact with the outer layer, thus expanding in unison. This resulted in a minimised pressure-induced compliance during high pressure situations, a characteristic that mimicked the native artery.

Other innovative solutions have utilized biomimetics to investigate biomechanical analogues of an aorta and created graft designs that mimic its multicomponent structure and hence exhibit matched biomechanical attributes, which have the potential to overcome current limitations (Table 1). Stent-graft comprising hard PET and soft spandex segments was created based on the hydroskeleton structure of caterpillars [112]. The biomimetic stent-graft demonstrated better radial compliance (0.0567 ± 0.006 ml/mmHg) than the commercial stent-graft device, Zenith™ FlexSG (0.0117 ± 0.004 ml/mmHg; Cook Medical Inc., USA) and was comparable to human aorta. Additionally, the soft segments were shown to absorb high extension and compression forces with minimal load transfer to the hard segments. This translated to the stent-graft improved flexibility and kink-free bending when pressure increased. These enhanced biomechanical properties also led to the multicomponent stent-graft to migrate less especially when placed in a curved configuration.

As shown in Table 1, some of the complications such as endoleaks arose due to the inflexibility of the stent-grafts which has been attributed to the rigid Z stent rings. The introduction of new oval ring stent designs in Anaconda® (Vascutek Ltd) and Aorfix® (Lombard medical Inc.) offer promising solutions to achieve better flexibility and kink resistance than Z-type stent rings [113,114]. Finite element analysis showed that the traditional Z-ringed stents were less flexible and as the curvature increased to 180°, the lumen of the stent graft decreased up to 80% as compared to 14.6% for the oval-ringed stents. Unlike the current Z-shape rings, the oval/circular shape of stent rings allows high curvature bending by preventing adjacent stent-stent interlocking which is the main cause of stent-graft collapse in curved aortic regions.

Although there are no current stent-grafts designed specifically for complex aortic arch aneurysm, there is increased awareness on designing stent-grafts that can be used for curved or complex geometric aneurysm instead of treating them similarly to the straight (abdominal) aneurysms. In addition, it is encouraging that more focus has been placed on addressing the current limitations by designing stent-grafts that are hemodynamically similar to native arteries.

8. Conclusion

Biomechanical shortcomings of current stent-grafts such as compliance mismatch and structural stiffness between stent-graft and aorta causes hemodynamic disturbances which can contribute to complications including graft migration, endoleaks, and spinal cord ischemia. A better understanding of factors that cause these complications has led to exploration of improved and innovative graft designs and modifications to produce mechanical properties that are comparable to the aorta. It is anticipated that the next generation of hybrid devices coupled with the current hybrid repair procedure will provide a treatment with fewer complications for patients with complex aneursym.

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Conflict of Interest

All authors declare no conflict of interest in this paper.

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