REVIEW

The long-term follow-up of large-diameter Dacron® vascular grafts in surgical practice: a review

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ABSTRACT

Synthetic grafts have been widely used in cardiac and vascular surgery since the mid-1970s. Considering the relative lack of randomized clinical trials or systematic analyses in the field of prosthetic large vessel diameter replacement, we reviewed the literature on the long-term performance and surgical management of complications of Dacron® grafts in both thoracic and abdominal aorta reconstruction and in the pediatric population. MedLine, Embase and Cochrane Library databases were searched for meta-analyses, reviews, clinical trials, and case reports pertinent to the study object. Aortic replacement with Dacron® prostheses is widely performed with acceptable outcome and a relatively low rate of graft-related and postimplantation complications, such as rupture, infection and fistulization. However, progressive dilation and mechanical failure of the grafts represent the most worrisome complication in all the districts analyzed. The emerging concept of the mismatch in the biomechanical properties between the prosthetic material and native aorta is thought to be at the root of these complications leading to even more daunting consequences when the ascending aorta is involved. Indeed introduction of a non-compliant prosthesis in place of the native ascending aorta can exert detrimental effects not only at the level of the anastomosis, leading to pseudoaneurysm, but also can influence the optimal performance of the aortic root complex with consequent valve dysfunction and ventricular hypertrophy. Albeit confirming their overall successful performance, this review launches a warning on the current liberal use of non-compliant grafts in aortic position, remarking the need for alternative vascular conduits mimicking the native artery compliance.

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Expanded polyethylene terephthalate (Dacron®) or polytetrafluoroethylene (ePTFE) synthetic grafts, have been available since the mid-1970s and represent the most widely used vascular substitutes worldwide in cardiovascular surgery.

Continuous development of manufacturing technique and material performance since 70's have brought to the market a large variety of grafts and have allowed for treatment of a wide range of vascular pathologic conditions related to atherosclerosis in both large vessel and peripheral districts.

Considering the artificial nature of these grafts and the complex interplay underlying the tissue-prosthesis and blood-prosthesis interactions, a number of concerns arise from their use in clinical settings, mainly including thrombosis or stenosis, dilatation, rupture, and infections. However, the most eloquent clinical consequences of these complications have been reported in the treatment of peripheral artery disease, somehow concealing large vessel pathology and large-diameter grafts from the interest of clinical and basic science researchers over time. Conversely, albeit numerous reports on

single center experience with the use of artificial grafts in large artery disease can be found in the literature, only few standardized or randomized trials on the use of prosthetic material are present, thus obstructing a systematic review of the data or an adequate comparison of the outcomes with other approaches. Additionally, selection criteria and variable techniques adopted by the single operators conspired against the possibility to analyze data through a systematic approach; at present, the only clarified point regards the use of Dacron over ePTFE for aorta reconstruction.¹ Differently from Dacron, a thermoplastic polyester manufactured in woven or knitted fibers to fabricate a vascular tube, ePTFE is a fluorocarbon polymer produced by extrusion in a form of solid nodes organized in a non textile porous vascular prosthesis. Chemical and structural composition confers to ePTFE different mechanical properties and a peculiar blood-material interface rendering the graft more suitable for smaller vessels (7-9 mm).^{1, 2}

A probable reason for the general lack of randomized data in this field has to be found in the overall satisfactory performance of large caliber grafts which generally showed an optimal long-term patency, with the biomaterial-related thrombogenicity being amply counterbalanced by the massive blood flow and thus rarely achieving the dignity of a clinical complication.

Five-year patency of aorto-iliac substitutes reaches 90%³ with anecdotal report of graft clotting, incidence of graft infections ranges between 0.5% and 6% in abdominal vascular surgery and aortoenteric fistulas (another rare complication) show an incidence of 0.5% to 2.5%.⁴

Conversely, after 50 years of implantation of Dacron grafts for reconstructive purposes, what is emerging as a worrisome concern regards the long-term outcome of these artificial grafts, mainly including dilation or aneurysm, para-anastomotic pseudoaneurysm, mechanical failure, and size mismatch due to their inability to grow. The last issue is even more daunting in the field of pediatric cardiac surgery, because of the gradual growth of the anatomic structures, that will cause patients to often outgrow their vascular grafts and require additional surgery.²

Experimental studies claimed the mismatch between the effective mechanical properties of the grafts and those of the vascular structures as candidate pathogenic mechanism underlying the failure of this prosthesis. Inadequate compliance of the graft and failure to simulate the elastic and mechanical properties of the native

arteries, determines a wide spectrum of hemorheologic anomalies leading to dilation and alteration of wall components.⁵ Compliance mismatch has been shown to induce flow disturbances and turbulence and exert a pulsatile mechanical stress on the host artery at the level of the anastomosis. This might mechanically lead to line suture disruption and aneurysm formation,⁶ but, more importantly, might result in vascular damage triggering a reactive vessel remodeling which includes smooth muscle cell proliferation and extracellular matrix deposition.⁷ Additionally, an accompanying paracrine response deriving from the endothelial cells, damaged by the augmented shear stress, perpetrates the damage. This response is mainly constituted by nitric oxide synthetase activation, and expression of endothelin-1, platelet-derived growth factor,⁸ transforming growth factor and adhesion molecules.⁹ The cascade of biophysical and molecular events triggered by this state of “tissue incompatibility” eventually leads on endothelial dysfunction, intimal hyperplasia,⁹ thrombosis¹⁰ and to several functional consequences on the cardiovascular system.¹¹

This review will focus on the long-term performance and complications of Dacron grafts for large vessel reconstruction in the abdominal and thoracic districts with particular attention to their clinical influence and to the consequences on the surgical management. Considering the focus on large arteries and the above-mentioned differences among ePTFE and Dacron, this review will not discuss the data regarding the ePTFE grafts.

For this review, two authors independently searched the Cochrane Controlled Trials Registered, MEDLINE, EMBASE databases and reference lists of original articles. Given the exiguity of randomized control trials, search has been extended to non-randomized studies, cohort studies, perspective studies, and case reports. Previous meta-analyses and other reviews were analyzed and their reference lists considered. There were no language restrictions. No unpublished or congress communications data were included. Terms inserted in the search engines included “aorta” OR “Dacron” OR “prosthesis” OR “graft” OR “large diameter” AND “long-term” AND “complications”.

Abdominal aorta

Although the emerging technology of endovascular stenting is nowadays rapidly gaining space in the treat-

ment of abdominal aortic disease, Dacron grafts are widely employed in the repair abdominal aneurysm and in aorto-iliac bypass surgery. Despite the high material safety offered by vascular grafts, complications including para-anastomotic pseudoaneurysms (0.2% to 15% incidence), graft clotting, and graft infections (0.5% to 6%) have been described (12). Additionally, a more rare complication is represented by the formation of aorto-enteric fistulas, with a reported incidence of 0.5% to 2.5% (4). Among late complications, progressive dilation up to graft rupture due to material fatigue has been reported (13).

Infection of an abdominal aortic graft is considered a life-threatening event that, albeit not frequent, is carrying high rate of mortality (10%-30%) and lower limb amputation (25%), depending on the anatomic location of the infected graft, the graft material itself, and the virulence of the bacteria (14). About 53% of infections occur within the first 30 days and 70% occur in the first 60 days (15), with different pathogens being responsible of early or late infections. Early infections (< 4 months) are mainly due to *Staphylococcus aureus* (32%), while *S. epidermidis* causes the majority of late infections (4 months post op) together with methicillin-resistant *S. aureus* (MRSA). In particular, *S. aureus* is able to deeply affect the long-term outcome of prosthetic aortic grafts and is reported to particularly cause infections in residents of long term care facilities (23%-49%), being extremely invasive and accompanied by septicemia (14). Even if this complication is not frequent, its surgical management is delicate and involves eradication of aortic infection by removing the infected prosthetic graft, debridement of infected and/or necrotic periprosthetic tissue, and revascularization of the distal aorta and its branches. Extra-anatomic bypass grafting procedures (such as unilateral or bilateral axillo-femoral bypass grafting) have been described (16), but the caliber of the graft is often insufficient to supply abdominal organs, spinal cord, and lower extremities, and to relieve hypertension in the proximal arterial system. An alternative is the so-called "ventral aorta" *i.e.* a bypass between the ascending aorta and the abdominal aorta, but this technique is affected by several postoperative complications (17). In this regard, Kieffer *et al.* (18) reported their cohort of infected infrarenal aortic prosthetic grafts successfully treated with *in situ* arterial allograft. Kitamura *et al.* (19) reported a series of 17

patients treated favorably with cryopreserved allografts. Noteworthy, in consideration of the profound effect that these complications might have on the long-term outcome of abdominal aorta replacements, a pilot study of a triple antimicrobial-bonded Dacron graft designed for the prevention of aortic graft infection has been recently performed in pigs with encouraging results (20).

Another late-term, potentially devastating complication regards the development of aorto-enteric fistulas. This event might occur even at 10 years after the initial aortic surgery and is thought to be due to progressive aortic prosthesis erosion into the duodenum, with an incidence of 0.5-2.5% of aortic prosthetic graft repairs.²¹ The chronic foreign body reaction surrounding the synthetic graft — especially at the level of the anastomoses — is claimed to induce the formation of strong adhesions with the bowels. Mechanically-induced irritation of the intestinal tissue might further lead to a direct communication between the aorta and the bowel.²² Surgical management of this condition usually includes extra-anatomic bypass grafting, aortic ligation and graft removal. This approach carries a 25-90% operative mortality rate, an amputation rate of 5-25% and an aortic stump rupture rate of 10-50%.⁴ Alternatively, *in situ* aortic reconstruction has been suggested as a less morbid alternative to ligation and bypass grafting also for graft infection, with a reported perioperative mortality rate of 27-30%.²³

An increasing piece of evidence is confirming interventional radiology solutions (*e.g.* endovascular stenting) as resolving — with case series of successful total repair —^{4, 24} or as an adequate temporary treatment of acute bleeding before definitive therapy.²⁵

Para-anastomotic aneurysms constitute another life-threatening complication of open abdominal aorta replacement. The reported incidence after aortic reconstruction ranges from 0.2 to 15% and in a report of 100 patients undergoing postoperative routine ultrasound it was denoted with 10%.²⁶ Noteworthy, while the more frequently occurring condition in the treatment of aneurysmal disease regards the development of true aneurysms at the sites of anastomoses, para-anastomotic aneurysms subsequent to aortic surgery for occlusive disease are believed to be more often pseudoaneurysms.²⁷ Emerging strategies to manage their long-term evolution, clearly represented by further expansion and rupture, are increasingly considering percutaneous en-

dovascular stenting procedures, especially in light of a mortality rate associated with attempted surgical repair of ruptured para-anastomotic aneurysms ranging from 67 to 100%.⁴

Nonetheless, dilation is considered as the most common destiny of Dacron graft. Over the last 30 years, this argument has been widely debated among vascular surgeons, as it remains still unexplained whether the continuous enlargement process is at the root of the aforementioned graft-related complications. Propensity of knitted Dacron grafts to dilation and the loss of tissutal strength and bursting resistance is well documented with reports demonstrating different degrees of grafts dilatation, up to twice the original graft diameter.² We have reviewed the majority of the studies on dimensional follow-up of polyester grafts, and we overall found a dilation ranging between 18% and 58% in a time period spanning between 12 days and 73 months.^{13, 28-30} A recent study from Stollwerck *et al.*¹² comparing long-term results of ePTFE, knitted and woven Dacron grafts, demonstrated a dilation at 5 years of 33% by computed tomography. However, in 1990 Nunn *et al.*³¹ reported a maximum dilation of 67% in a large series. Early studies from Berger *et al.*³² performed on specimens from 493 explants, showed alterations in the microstructure of Dacron grafts. Thinning, flattening, distortion of filaments, transverse or oblique cracking, “greenstick” fractures, or complete breakage of fibers have been described. It is difficult to clarify if graft dilation *in vivo* grows to an asymptotic maximum or continues to gradually increase. In the former case, graft rupture would be improbable, whereas in the latter, a critical expansion, followed by graft rupture, would be possible after a long implantation time. The dilation profile and the expansion rate is scarcely predictable and an additional difficulty in understanding this phenomenon arises from the imaging technique used to detect graft dilation in the studies here reviewed, as ultrasound imaging tends to be less sensitive than CT, as shown by Nunn *et al.*³¹ *In vitro* and engineering studies demonstrated a non-linear behavior with the dilation curve progressively raising over time and then decelerating as time from implantation increases. Recent reports attributed the initial phase of dilation seen after implantation to Dacron crimps flattening and yarn reorganization, while the late expansion would be associated to fiber deformation and elongation secondary to material fatigue and biodegradation of the

material itself.¹³ In the latter phase the graft would show a dramatic decrease in its elastic modulus and compliance justifying the aforementioned dilation profile.^{12, 33} However, the large number of observational studies — often not randomized — has not brought additional evidences to elucidate the clinical impact of long-term aortic grafts dilation. A recent report from Schroeder *et al.*³⁴ could not demonstrate a direct association between graft dilation and general surgical complications; neither was it possible to correlate graft dilation to aneurysmal or occlusive pathology. Still, a more pronounced dilation was found in hypertensive patients, suggesting the need of both blood pressure control and CT scan monitoring in the follow-up.³¹

In any case, if the dilation process is counterbalanced by phenomena of intimal hyperplasia so that the overall hemodynamics and flow is not affected, the dilation and the compliance decrease could exert a detrimental load on the perianastomotic region leading to suture overstress and eventually pseudoneurysm.³⁴ The latter might represent a worrisome concern in the long-term performance of these grafts.

However, the overall performance of Dacron grafts for abdominal aorta still remains undoubtedly satisfactory and the data here reviewed confirm their status of standard treatment for abdominal aortic aneurysm and aortic occlusive disease.

Ascending aorta

Early complications after ascending aorta replacement might include aortic rupture, visceral ischemia, and cardiac tamponade, while leakage within, or at the proximal or distal edge of the graft associated with pseudoaneurysm development and prosthesis dilation could occur at a later stage. Additionally, prosthetic graft infection represents an important post-implantation complication occurring during the acute and sub-acute phases.³⁵

Because of continuous and high-pressure blood flow through the graft and the relatively rapid formation of pseudointima over the anastomotic site, the risk for focal bacterial infection or vegetation is moderately low, and long-term infection of a prosthetic graft in the ascending aorta over a period of more than 5 years after the operation is rare.³⁶⁻³⁸ In any case, extending these considerations to other aorta segments, it remains un-

clear why ascending aorta or aortic arch undoubtedly scores the less frequent rate of infection. Possible explanations might include either the high mortality or its catastrophic sequelae, so that an only small amount of report is brought up in the literature, or the smaller number of aortic root replacements generally performed. However, the anatomical topography implying contaminations from the lung (during descending aortic surgery) or from the bowel (during abdominal aortic replacement) might play a pathogenic role.

Miyazaki *et al.*³⁹ reported a case of graft infection at 10 years after surgery with distal septic embolization that required extensive replacement of the graft. Authors have suggested that the pathogenic mechanism at the root of this occurrence might be found in the adhesion of microorganisms to small stitch holes in the prosthetic material during transient bacteremia. However, the natural consequence of a postoperative ascending aorta graft infection leads to devastating mediastinitis with high mortality rate, demanding an immediate intervention.⁴⁰ Surgical management of ascending aorta graft infection faces with different obstacles and requires a careful evaluation of the treatment strategy. First, in contrast to prosthetic valve infection, the replacement of aortic root using conventional artificial grafts is associated with an exorbitantly high mortality due to either the procedure itself or subsequent re-infection.⁴¹ Secondly, the aforementioned extra-anatomical re-routing options are not applicable at the site of the aortic root and within the arch. Therefore, the available surgical strategies in this situation consist in the removal of all infected artificial substances and the replacement of the aorta using cryopreserved homografts.^{41, 42} Indeed, replacement of the graft with another artificial graft, though soaked in antibiotics, has not proved to be successful.⁴¹ The use of silver-coated grafts has been suggested, but they have shown limited performance in case of frank infections.⁴³ The use of autologous material, such as the deep femoral vein, for *in situ* reconstruction, has not been tested in ascending aorta infections and is probably not suitable in this context.⁴⁴ However, self-made autologous pericardial tube grafts have been suggested as an alternative to homografts.⁴⁵ Additionally, combination of aortic stent implantation and cryopreserved graft has been reported.^{46, 47} The second principle in the treatment strategy regards the prevention of infection recurrence. To this extent, covering the new

graft with viable tissue (*e. g.* omentum) has been proposed, but again it scarcely applies to ascending aorta graft infections for the additional trauma induced by laparotomy, and the risk of introducing infection into the abdomen. Conversely, drainage of the infected site and stringent antibiotic treatment, together with the use of neomycin-loaded fibrin glue to seal the suture lines and to cover the homografts remain suggested procedures.⁴⁸ However, no conclusive data on the significance of graft impregnation with antibiotics can be extrapolated from the literature.^{46, 48} Homografts are more resistant to re-infection,^{49, 50} but one of the major drawbacks regards the possibility of valve deterioration requiring reoperation. Since this phenomenon does not occur in patients after heart transplantation, an immunogenic mechanism against the graft has been thought to be at the root of this complication.⁵¹ Nevertheless, considering a potential infectious substrate, immunosuppressant agents cannot be clearly considered an option in this context, but reoperation is associated to good results in expert hands.⁴⁶

Pseudoaneurysm occurs infrequently and derives from total or partial dehiscence of the prosthesis from the aortic wall. Site of interface between synthetic materials (*i.e.* Prolene™ suture and Dacron) and native aorta is further weakened by the inflammatory reaction elicited by the presence of foreign body, and create a region where the damage could potentially originate. Clinical manifestations include life-threatening complications such as rupture, fistula formation, and thrombosis, compression of organs in the vicinity or simple increase in aortic dimensions.⁵² Surgical approach foresees either a simple direct suture for repair purposes or replacement with homograft but both the techniques are affected by high morbidity and mortality. In reported series, mortality ranged between 12.5% and 41%;⁵³ however, Mohammadi *et al.*⁵⁴ have identified false aneurysm rupture during re-sternotomy as one of the main causes of fatality and have analyzed possible surgical strategies for operative risk reduction, underpinning the significance of elective cannulation of the carotid arteries to guarantee cerebral perfusion and safely perform reentry in the chest and mediastinal dissection. In the case of fistulization homograft use is the preferred option but when unavailable Yamanaka *et al.* suggested the use of rifampicin-bonded gelatin-sealed Dacron graft.⁵⁵

Conversely, graft thrombosis is a rare complication

and is usually prevented by either preclotting or pretreatment with gelatin,⁵⁶ collagen⁵⁷ or albumin⁵⁸ in the fabrication process.

The long-term evolution of grafts for ascending aorta is mainly characterized by dilation. Mattens *et al.* reported a 31.4% increase in graft diameter over 2 years follow-up,⁵⁹ while a more recent study reported a staged dilation with an initial 26% diameter increase in comparison to the package size, just after implantation, then, a further increase of 10.5% compared to the diameter at discharge, and an increase of 3.23% per year over a 5 years follow-up period.⁶⁰ The results are in agreement with previous data published by Mattens *et al.* reporting a similar per-year rate of increase. In any case, while the reported initial enlargement soon after implantation is thought to be caused by the loss of graft crimpage, the progressive continuous dilation can be attributed to yarn slippage or yarn deterioration.⁶¹ Undoubtedly, material degradation itself, together with the changes achieved in the yarn architecture at a later stage following dilation, is bringing the system to the upper right side of the pressure-volume curve, in close vicinity to the asymptotic point. Literature is divided on the actual significance of aorta ascendens graft dilation in terms of eventual rupture or pseudoaneurysm, and while some Authors claim late graft ruptures even after 19 years,^{62, 63} others underestimate the potential clinical relevance of prosthesis dilation.⁶⁰ What is on the other side emerging as a daunting issue in this particular district of the aortic tree is represented by the compliance mismatch between the graft and the native tissue. Different from the abdominal district, the loss of compliance in the ascendens aorta region can exert detrimental effects not only at the level of the anastomosis, leading to pseudoaneurysm, but, more importantly, can influence the optimal performance of the aortic root complex.¹¹ The latter is responsible for long-term aortic valve dysfunction, as shown in large clinical series with a cumulative percentage of more than 40% patients showing a mild-to-moderate aortic valve insufficiency after full root prosthetic replacement.⁶⁴ Introduction of a non-compliant prosthesis in place of the native ascending aorta modifies the elastic properties of the arterial system and blunt the well-known “hydraulic damper” function of the native aorta (*i.e.* Windkessel effect).⁶⁵ Loss of compliance and subsequent increased arterial impedance transmit retrogradely an augmented hemodynamic load on the aortic

valve, determining its malfunction, accelerating degenerative changes in the aortic cusps^{11, 66} and further inducing progressive annular dilation, thus precipitating valve incompetence.⁶⁷ Evidently, loss of compliance does not determine a significant surgical urgency and David *et al.* in a large series reported a freedom from reoperation on the aortic valve for aortic insufficiency at 1, 5, 10, and 15 years of 99.7%±2.0%, 99.7%±2.0%, 97.8%±5.3%, and 97.8%±5.3%, respectively.⁶⁸ Similar results were reported by Shrestha *et al.* with a freedom from reoperation at 1, 5 and 10 years of 96%, 91% and 87%, respectively.⁶⁹ However, longer follow ups, especially in young patients with higher life expectancy, might reveal higher prevalence of aortic disturbance or reoperation rates. Additionally, increased stiffness and rigidity of the neo-aortic root have been shown to reflect in increased workload for the left ventricle given the unfavorable hemodynamic properties imparted by the graft in ascending aorta position⁷⁰ and the increased energy demand and oxygen consumption.⁷¹ The long-term consequence of this situation is the left ventricle adaptation with eventual remodeling and hypertrophy.⁷² Clinical studies have shown left ventricular hypertrophy after extra-anatomic bypass of the aorta⁷³ or replacement of the aorta itself with unaltered cardiac output and mean aortic pressure.^{74, 75}

Therefore the recent literature is warning about aortic substitution with unelastic prosthetic materials as potentially resulting in changes in arterial wall,⁶⁵ aortic leaflets,^{67, 76} and ventricular loads.^{11, 71, 73, 74} These consequences might translate in the medium term in functional complications and, in a small percentage of the population, in the need for re-operation.^{11, 65} Longer-term follow-up studies will unveil the actual clinical significance of these findings and aortic replacement with Dacron graft still remains the standard surgical therapy for aneurysmal ascending aorta disease. However, the need of vascular substitutes mimicking the histoarchitectural and mechanical properties of the normal aorta is increasingly perceived in cardiovascular surgery⁷⁷ and the novel field of tissue engineered biological vascular graft is providing interesting new avenues in this context with potential clinical translations in the near future.⁷⁸

Aortic arch and descending aorta

For aortic arch and descending aorta districts, literature on surgical complications after prosthetic replace-

ment is mainly restricted to cohort studies and case reports. Graft rupture, infection, pseudoaneurysm and fistulization have been reported but the incidence of these complications is extremely low. Graft infection represents a life-threatening condition as usually leading to anastomotic line disruption with overwhelming bleeding or to fistulization into esophagus or surrounding bronchial structures.⁷⁹ Incidence has been reported to range between 1 and 2% with an etiology mainly including *Staphylococcus aureus* and *Escherichia coli* for early infections and *Staphylococcus epidermiditis* for late infections.⁸⁰ Different approaches have been suggested in the surgical management of this complication. Extra-anatomical bypass with oversewing of aortic stomp has been the traditionally used strategy but carries potential for insufficient distal perfusion, infection of the new graft or massive bleeding from the aortic stomp.⁸¹ To obviate the shortcoming related to distal inadequate perfusion and limb-salvage operations, *in situ* prosthetic replacement has been suggested with good results⁸² even if the risk of graft reinfection is still worrisome. Cryopreserved allograft, thought to be more resistant to infections than synthetic grafts, have been described with positive results.⁸³ However, mortality associated to redo surgery with graft replacement is extremely high and alternative graft-sparing approaches consisting in surgical wide disinfection and coverage of the arch prosthetic graft with an omentum vascularized flap are available.⁸⁴ Coselli *et al.* firstly described a series of patients receiving an omentum flap after extensive debridement of infected and necrotic tissues with effective results.⁴⁰ Tassios *et al.* performed a detailed review of the published series using this approach and focused on the Osaka treatment protocol as a more effective modification of this strategy.⁸⁴ The Osaka protocol consists in a two-stage procedure including a graft antiseptic irrigation with povidone iodine solution and a subsequent omentum flap wrapping, providing a conservative non-resectional approach circumventing the risks associated to graft replacement.⁸⁴ An alternative strategy described by Okamoto *et al.* consists in the *in situ* replacement of the aortic graft with a superficial femoropopliteal vein panel surgically manufactured as an aortic substitute.⁷⁹

Pseudoaneurysm at the level of anastomotic site is an infrequent complication after thoracic aorta surgery but requires immediate treatment considering the

high morbidity and mortality associated to this circumstance.⁸⁵ Redo interventions are technically challenging and usually foreseen graft replacement with an overall mortality ranging between 3 and 6%. Carrel *et al.* in a large series of 876 patients suggested the use of homograft for complications related to infection of the prosthetic graft especially in ascending position and, in light of the experience achieved with reoperation, concluded that a definitive surgical repair for aortic arch pathology should be attempted at the first stage.⁸⁵ Endovascular repair of pseudoaneurysm after prosthetic repair might also be effectively applied and carries significant lower mortality and avoiding the risks and complications associated to open surgery.⁸⁶ In this regard, Ito *et al.* reported significant positive midterm results and described the possibility of conversion to traditional open surgical intervention in case of not successful delivery of the prosthesis.⁸⁷ However, this approach remains controversial in the cases in which pseudoaneurysm is associated to infection as the risk of perpetuating the contamination introducing a prosthetic material within an infected field is high. However Kan *et al.* reported a series of 48 pseudoaneurysm related to mycotic infection describing an incidence of persistent infection of 22.9% with a 30-day and 2-years survival rates of 89.6% and 82.2%, respectively.⁸⁸

Fistulization after aortic arch surgery is also a rare event which is often associated to graft infection. Yamashita *et al.* reported a case of aorto-pulmonary fistula caused by an infected pseudoaneurysm after a total arch replacement and stenting of the thoracic aorta.⁸⁹ Aortobronchial fistulas have been described by Wheatley *et al.* who successfully adopted endovascular stenting as best option for surgical treatment.⁹⁰ However, fistulization into esophagus is a more frequent and described complication reaching 2% incidence in thoracic aorta surgery⁹¹ with elevated morbidity and mortality.⁹² Primary repair of esophagus with interposition of omentum or ruptured aneurysmal wall, followed by aortic *in situ* graft replacement or extraanatomical bypass appear to be the preferred approaches.⁹³ The latter is of interest in concomitant infective conditions, but staged procedures with rifampicin-bonded gelatin-sealed Dacron grafts have also been recently suggested.⁵⁵

However, the increasing use of endovascular stents for two staged procedure is progressively unveiling a wide range of complications related to pseudoaneu-

rysm, endoleaks, infections and fistulization of the graft percutaneously placed, actually constituting a new entity in aortic pathology.⁹⁴ Failure of the endograft in inducing thrombosis of the false lumen in aortic dissections might lead to progressive increase in aneurysm diameter leading to extension to the abdominal aorta⁹⁴ or to fistulization in the surrounding structures.⁹⁵ These conditions often require highly invasive procedures or thoracoabdominal repairs.⁹⁶ However, Langer *et al.* extensively reviewed the literature and individuated Type I endoleaks,^{97, 98} retrograde type A dissection,^{99, 100} ruptures,¹⁰¹ stent migration,¹⁰² stent collapse¹⁰³ and infections¹⁰⁴ as the main causes of conversion to open repair.⁹⁴ Even if the best treatment option for endoleaks concerns a redo endovascular procedure, the majority of the cases requires open repair or additional procedures whose clinical success is highly dependent on the experience of the surgical team, on the adequacy of the cerebral and distal aortic perfusion strategy and on the presence of a constant neurological monitoring.¹⁰⁵ Clearly these procedures are recommended to be performed only in specialized centers.¹⁰⁵

Table I⁴⁻¹²² summarizes the most common complications of Dacron grafts in ascending and abdominal settings and their proposed surgical management. Table II reports a detailed summary of the clinical experience (clinical studies, clinical trial, case reports) on the long-

term Dacron graft complications for abdominal, ascending, arch and descending aorta.¹⁸⁻¹³⁷

Pediatric cardiac surgery

In pediatric cardiac surgery, Dacron-related drawbacks are even more troublesome, because of the growth of the native structures to which grafts are anastomosed. Aortic coarctation is one of the more frequent pediatric pathologies requiring a prosthetic replacement. Despite the number of techniques employed, surgical repair is afflicted by long-term complications¹⁰⁶ and mainly results in aneurysmal degeneration up to failure and rupture. Aneurysm formation is time-dependent, with a reported incidence changing according to the technique used. The highest incidence of aneurysm seems to be associated with Dacron patch angioplasty, reaching 38% with a 7% risk of rupture-related death.^{107, 108} Conversely, subclavian flap angioplasty and tube graft repair hold a 17% and 6% incidence of aneurysmatic degeneration, respectively;¹⁰⁹ interestingly, the end-to-end anastomosis technique, not involving the use of graft interposition, carries only 3% risk of dilation (110). Despite an univocal explanation has not been given yet, there is a general consensus about a “hemodynamic theory” involving flow turbulence and compliance mismatch between the native aortic wall and the patch employed

TABLE I.—Clinical management of Dacron® graft-related major complications.

Complications	Abdominal aorta	Ascendens aorta	Aortic arch and descendens aorta
Infections	Extra-anatomical bypass ¹⁶ Ventral aorta ascendens→abdominal ¹⁷ Cryopreserved allograft ¹⁹ Antimicrobial-bonded graft ²⁰	Cryopreserved homograft ⁴¹ 2-staged endovascular + cryopreserved homograft ¹²² Silver-coated graft ⁴⁸ <i>In situ</i> reconstruction ⁴⁴ Pericardial tube ⁴⁵	Extra-anatomical bypass ⁸¹ In situ prosthetic replacement ⁸² Cryopreserved homograft ⁸³ Debridement and omentum vascularized flap ^{40, 41} Conservative two-staged omentum flap wrapping Osaka protocol ⁸⁴ Aortic substitute made by superficial femoropopliteal vein panel ⁷⁹
Fistulization	Extra-anatomical bypass ⁴ <i>In situ</i> aortic reconstruction ²³ Endovascular repair ²⁵	Cryopreserved homograft Rifampicin-bonded gelatin-sealed graft ⁵⁵	<i>In situ</i> replacement or extra anatomical bypass ⁹³ Endovascular stenting ⁹⁰ Rifampicin-bonded gelatin-sealed graft ⁵⁵ Combined arch replacement and endovascular stenting aorto-pulmonary fistula ⁸⁹
Para-anastomotic pseudoaneurysm	Surgical repair Endovascular stenting ⁴	Cryopreserved homograft Direct suture ⁵³	Homograft ⁸⁵ Endovascular stenting ^{86, 87}

TABLE II.—Summary of clinical experience clinical studies, clinical trial, case reports on the long-term Dacron graft complications for abdominal, ascending, arch and descending aorta. Follow up column indicates the overall study duration for each reported complication and relative incidence. For case reports the follow up column indicates the time-to-event after Dacron graft implantation.

	Complication	Incidence	Follow-up	Study
Abdominal Aorta	Infection	0.77%	25 yrs	O'Hara ¹²³
		2.5%	7 yrs	Goldstone ¹²⁴
		2.6%	4 yrs	Lorentzen ¹²⁵
		2.0%	8 yrs	Bisdas ⁵⁰
	Fistulization	0.8%	11 yrs	Peck ¹²⁶
		1.1%	12 yrs	Plate ¹²⁷
		0.7%	12 yrs	Bergqvist ¹²⁸
	Para anastomotic Aneurysm	13.8%	8 yrs	den Hoed PT ¹²⁹
		3%	15 yrs	Szilagyi ¹³⁰
		15%	15 yrs	Edwards ¹³¹
Ascending Aorta	Late rupture	1 case	19 yrs	Wilson ⁶²
		1 case	17 yrs	Shingu ¹³²
	Infection	1.9%	6 yrs	Hargrove ³⁷
		1 case	10 yrs	Mizayaki ³⁹
	Pseudoaneurysm	4 cases	6 yrs	Soyer ³⁸
		3.1%	24 yrs	Mohammadi ⁵⁴
		2.09%	10 yrs	Bachet ¹³³
	Aortic valve dysfunction cumulative mild to severe and requiring operation	31 cases	25 yrs	Sullivan ⁵³
		40%	7,5 yrs	Leontyev ⁶⁴
		46.2%	8 yrs	Shrestha ⁶⁹
Arch and descending thoracic	Infection	11%	15 yrs	David ¹³⁴
		5.5%	13 yrs	Zehr ⁶⁷
		0.9%	30 yrs	Svensson ⁹²
		1%	11 yrs	Khaladi ¹³⁵
		0.8%	7 yrs	Czerny ⁴⁵
		0.6%	8 yrs	Kieffer ¹⁸
	Fistulization	1 case aorto-pulmonary	5 yrs	Yamashita ⁸⁹
		4 cases aorto-bronchial	3 yrs	Thompson ¹³⁶
	Late rupture	2% aorto-esophageous	29 yrs	Lawrie ⁹¹
		1 case	23 yrs	Kawamura ¹³⁷

for angioplasty.^{111, 112} The redistribution of the forces on the native wall subsequent to the prosthetic replacement would lead to progressive dilation with the typical aneurysm formation at the opposite site of the patch.¹¹³ To this extent, congenital weakness of the aorta or acquired atherosclerotic changes might play an additional role, and it has been shown that concomitant hypoplastic transverse arch¹¹⁴ or older age of the patients undergoing initial repair would predispose to similar aneurysms formation at the repair site.¹¹⁰

In a recent study from Troost *et al.*,¹¹⁵ describing the long-term behavior of polyester grafts in adult patients with repaired coarctation of the aorta at pediatric age, tube grafts were found to be dilated up to 50% of their original size. This study had a follow-up period of nearly 14 years and showed, analogously to

others,¹⁰⁸⁻¹¹⁰ that the most prominent changes in graft diameter occurred within the first year following surgery,¹¹⁵ with a greater degree of dilation in knitted than in woven graft types.⁵⁹ The mechanisms underlying graft dilation are less clear and remain still hypothetical. Progressive stretching of the fiber loops by pressurization of the graft seems to be at the root of this phenomenon,^{28, 59, 116} although a number of studies report that dilation already starts perioperatively, immediately after declamping the aorta.^{117, 118} However, beside dilation, long-term complications of prosthetic aorta replacement in pediatric population regard the development of false aneurysm of the suture line. Troost *et al.*¹¹⁵ reported an 8% incidence in the long-term follow-up of their series and interestingly noted as direct surgical repair of aortic coarctation without graft interposition

was not associated with pseudoaneurysm, claiming that a surgical suture problem or continuous traction on the suture lines on inextensible materials would be potentially responsible for this issue. As previously showed by Berger *et al.*, chronic fatigue and hydrostatic forces result in Dacron fiber deterioration with frayed ends, creeping or total breaks,³² but the rate of degradation and the timing for graft failure is difficult to be predicted considering the multitude of variables involved in an *in vivo* system after implantation. However, these studies have a mean follow up of 38 months and more recent studies on pediatric population are pointing out that graft dilation begins to appear more frequently when the follow-up period of grafts interposition exceeds 20 years.¹¹⁵ Whether the general belief of stability of the Dacron grafts is arising from a bias in choosing follow-up times and the “pediatric experience” is now teaching about the actual behavior of prosthetic materials in the high flow vascular system, warning about potential failures, is hard to demonstrate and mandates for a greater number of observations. However, the clinical impact of aneurysms and pseudoaneurysms needs to be taken into consideration as it might lead to life-threatening situations such as rupture or fistulization to surrounding structures.

Conclusions

Aortic replacement with Dacron® prostheses is nowadays widely performed with acceptable outcome and a relatively low rate of graft-related and post-implantation complications, such as rupture or infection. In the management of abdominal aortic grafts, infections and fistulization need to be taken into account as the most worrisome complications. Several surgical strategies are available to resolve these infrequent but life-threatening events, mainly including extra-anatomical bypass and endovascular stenting. Despite late ruptures are relatively uncommon, the issues of progressive dilation and compliance incompatibility of the grafts with their potential detrimental reflex at the anastomotic side,³⁴ might pose relevant questions regarding the more appropriate clinical management and monitoring of the patients bearing an abdominal aorta prosthesis. In this regard a still unanswered question concerns the need of periodical routine CT controls in these patients as suggested by the work of Nunn *et al.*³¹ and by reports of

late dilation and rupture of abdominal aortic graft.¹² For this purpose, *ad hoc* studies and cost-benefit analysis are eventually required. For ascendens aorta, the topographical anatomy of the graft poses additional problems in the management of the complications arising from its long-term implantation. Infections, dilatation, pseudoaneurysm cannot be easily solved with classical re-routing interventions in this context and the use of cryopreserved homografts is suggested and widely accepted in the literature. In the arch and descendens districts Dacron graft-related complications pose also daunting issues. However, the increasing diffusion of endovascular procedures in this region is now unveiling a new pathological entity constituted by the complications associated to the implant of the endografts, which often require complicated open surgical repairs. On the other side, the “pediatric experience” is unveiling the real long-term behavior of prosthetic material in aortic position. Even if aggravated by the additional complication related to inability to grow and to match the dimensional demand of a growing structure, the rate of late graft aneurysm, failure or rupture is high and still remain a daunting problem in the surgical management.

At the end of this review of the long-term surgical experience with Dacron® grafts, authors feel to draw the attention on the emerging concept of the mismatch in the biomechanical properties between the prosthetic material and native aorta. From the recent literature it appears that that prolonging this state of “tissue incompatibility” might be at the root of daunting issues in the long-term follow up and it might deserve a more careful consideration when performing the surgical work-up of these patients. On the other side, the new emerging field of vascular tissue engineering is increasingly proposing vascular substitutes designed and manufactured to mimic the histoarchitecture and the elastomechanical properties of the normal arteries. Several bioresorbable polymers as polyglycolic acid, polylactic acid, and polycaprolactone have been demonstrated to be effective in manufacturing functional vascular engineered conduits matching the mechanic properties¹¹⁹ and compliance of native vessels.¹²⁰ A pilot human clinical trial has been performed successfully in the pediatric population using a tissue engineered vascular construct¹²¹ and the encouraging results obtained might in the future fuel further research in this novel and exciting field.

References

- Kannan RY, Salacinski HJ, Butler PE, Hamilton G, Seifalian AM. Current status of prosthetic bypass grafts: a review. *J Biomed Mater Res B Appl Biomater* 2005;74:570-81.
- Chlupac J, Filova E, Bacakova L. Blood vessel replacement: 50 years of development and tissue engineering paradigms in vascular surgery. *Physiol Res* 2009;58 Suppl 2:S119-39.
- Brewster DC. Current controversies in the management of aortoiliac occlusive disease. *J Vasc Surg* 1997;25:365-79.
- El Sakka K, Halawa M, Kotze C, Francis I, Doyle T, Yusuf W. Complications of open abdominal aortic surgery: the endovascular solution. *Interact Cardiovasc Thorac Surg*. 2008;7:121-4.
- Haruguchi H, Teraoka S. Intimal hyperplasia and hemodynamic factors in arterial bypass and arteriovenous grafts: a review. *J Artif Organs* 2003;6:227-35.
- Paasche PE, Kinley CE, Dolan FG, Gozna ER, Marble AE. Consideration of suture line stresses in the selection of synthetic grafts for implantation. *J Biomech* 1973;6:253-9.
- Sottiurai VS. Biogenesis and etiology of distal anastomotic intimal hyperplasia. *Int Angiol*. 1990;9:59-69.
- Palumbo R, Gaetano C, Antonini A, Pompilio G, Bracco E, Ronnstrand L, *et al*. Different effects of high and low shear stress on platelet-derived growth factor isoform release by endothelial cells: consequences for smooth muscle cell migration. *Arterioscler Thromb Vasc Biol* 2002;22:405-11.
- Abbott WM, Megerman J, Hasson JE, L'Italien G, Warnock DF. Effect of compliance mismatch on vascular graft patency. *J Vasc Surg* 1987;5:376-82.
- Moreno MJ, Ajji A, Mohebbi-Kalhor D, Rukhlova M, Hadjizadeh A, Bureau MN. Development of a compliant and cytocompatible micro-fibrous polyethylene terephthalate vascular scaffold. *J Biomed Mater Res B Appl Biomater* 2011;97:201-14.
- Spadaccio C, Rainer A, Barbato R, Chello M, Meyns B. The fate of large-diameter Dacron(R) vascular grafts in surgical practice: Are we really satisfied? *Int J Cardiol* 2013;168:5028-9.
- Stollwerck PL, Kozlowski B, Sandmann W, Grabitz K, Pfeiffer T. Long-term dilatation of polyester and expanded polytetrafluoroethylene tube grafts after open repair of infrarenal abdominal aortic aneurysms. *J Vasc Surg* 2011;53:1506-13.
- Riepe G, Loos J, Imig H, Schröder A, Schneider E, Petermann J, *et al*. Long-term in vivo alterations of polyester vascular grafts in humans. *Eur J Vasc Endovasc Surg* 1997;13:540-8.
- Bandyk DF. Vascular surgical site infection: risk factors and preventive measures. *Semin Vasc Surg* 2008;21:119-23.
- Calligaro KD, Veith FJ, Schwartz ML, Dougherty MJ, DeLaurentis DA. Differences in early versus late extracavitary arterial graft infections. *J Vasc Surg* 1995;22:680-5; discussion 5-8.
- Hageman JH, Nein AG, Davis JT. Primary aorto-esophageal fistula caused by an atherosclerotic thoracoabdominal aortic aneurysm: a case report and review of the literature. *Cardiovasc Surg* 1995;3:495-9.
- Barnard SP, Dark JH, Jones NA. Prosthetic graft infection in the descending thoracic aorta treated by extra-anatomic rerouting. *Cardiovasc Surg* 1995;3:703-5.
- Kieffer E, Sabatier J, Plissonnier D, Knosalla C. Prosthetic graft infection after descending thoracic/ thoracoabdominal aortic aneurysmectomy: management with *in situ* arterial allografts. *J Vasc Surg* 2001;33:671-8.
- Kitamura T, Morota T, Motomura N, Ono M, Shibata K, Ueno K, *et al*. Management of infected grafts and aneurysms of the aorta. *Ann Vasc Surg* 2005;19:335-42.
- Aboshady I, Raad I, Shah AS, Vela D, Dvorak T, Safi HJ, *et al*. A pilot study of a triple antimicrobial-bonded Dacron graft for the prevention of aortic graft infection. *J Vasc Surg* 2012;56:794-801.
- Busuttill SJ, Goldstone J. Diagnosis and management of aortoenteric fistulas. *Semin Vasc Surg* 2001;14:302-11.
- Norgren L, Jernby B, Engellau L. Aortoenteric fistula caused by a ruptured stent-graft: a case report. *J Endovasc Surg* 1998;5:269-72.
- Gordon LL, Hagino RT, Jackson MR, Modrall JG, Valentine RJ, Clagett GP. Complex aortofemoral prosthetic infections: the role of autogenous superficial femoropopliteal vein reconstruction. *Arch Surg* 1999;134:615-20; discussion 20-1.
- Burks JA, Jr., Faries PL, Gravereaux EC, Hollier LH, Marin ML. Endovascular repair of bleeding aortoenteric fistulas: a 5-year experience. *J Vasc Surg* 2001;34:1055-9.
- Biancari F, Romsis P, Perala J, Koivukangas V, Cresti R, Juvonen T. Staged endovascular stent-grafting and surgical treatment of a secondary aortoduodenal fistula. *Eur J Vasc Endovasc Surg* 2006;31:42-3.
- Magnan PE, Albertini JN, Bartoli JM, Ede B, Valerio N, Moulin G, *et al*. Endovascular treatment of anastomotic false aneurysms of the abdominal aorta. *Ann Vasc Surg* 2003;17:365-74.
- Morrissey NJ, Yano OJ, Soundararajan K, Eisen L, McArthur C, Teodorescu V, *et al*. Endovascular repair of para-anastomotic aneurysms of the aorta and iliac arteries: preferred treatment for a complex problem. *J Vasc Surg* 2001;34:503-12.
- Blumenberg RM, Gelfand ML, Barton EA, Bowers CA, Gittleman DA. Clinical significance of aortic graft dilation. *J Vasc Surg* 1991;14:175-80.
- Nunn DB, Carter MM, Donohue MT, Pourdeyhimi B. Dilative characteristics of Microvel and Vascuflow-II aortic bifurcation grafts. *J Biomed Mater Res* 1996;30:41-6.
- Utoh J, Goto H, Hirata T, Hara M, Kitamura N. Dilatation of sealed Dacron vascular prostheses: a comparison of Gelseal and Hemashield. *J Cardiovasc Surg (Torino)* 1998;39:179-80.
- Nunn DB, Carter MM, Donohue MT, Hudgins PC. Postoperative dilation of knitted Dacron aortic bifurcation graft. *J Vasc Surg* 1990;12:291-7.
- Berger K, Sauvage LR. Late fiber deterioration in Dacron arterial grafts. *Ann Surg* 1981;193:477-91.
- Mary C, Marois Y, King MW, Hong T, Laroche G, Douville Y, *et al*. *In vitro* and *in vivo* studies of a polyester arterial prosthesis with a warp-knitted sharkskin structure. *J Biomed Mater Res* 1997;35:459-72.
- Schroeder TV, Eldrup N, Just S, Hansen M, Nyhuus B, Sillesen H. Dilatation of aortic grafts over time: what to expect and when to be concerned. *Semin Vasc Surg* 2009;22:119-24.
- Fann JJ, Smith JA, Miller DC, Mitchell RS, Moore KA, Grunke-meier G, *et al*. Surgical management of aortic dissection during a 30-year period. *Circulation* 1995;92(9 Suppl):113-21.
- Hagan PG, Nienaber CA, Isselbacher EM, Bruckman D, Karavite DJ, Russman PL, *et al*. The International Registry of Acute Aortic Dissection (IRAD): new insights into an old disease. *JAMA* 2000;283:897-903.
- Hargrove WC, 3rd, Edmunds LH, Jr. Management of infected thoracic aortic prosthetic grafts. *Ann Thorac Surg* 1984;37:72-7.
- Soyer R, Bessou JP, Bouchart F, Redonnet M, Mouton-Schleifer D, Arrignon J. Surgical treatment of infected composite graft after replacement of ascending aorta. *Ann Thorac Surg* 1994;58:425-8.
- Miyazaki S, Fukushima K, Sawaki D, Otani Y, Sekita G, Takeuchi H, *et al*. A case of graft infection 10 years after ascending aorta replacement. *Ann Vasc Surg* 2004;18:755-7.
- Coselli JS, Crawford ES, Williams TW, Jr., Bradshaw MW, Wiemer DR, Harris RL, *et al*. Treatment of postoperative infection of ascending aorta and transverse aortic arch, including use of viable omentum and muscle flaps. *Ann Thorac Surg* 1990;50:868-81.
- Coselli JS, Koksoy C, LeMaire SA. Management of thoracic aortic graft infections. *Ann Thorac Surg* 1999;67:1990-3; discussion 7-8.
- Vogt PR, Turina MI. Management of infected aortic grafts: development of less invasive surgery using cryopreserved homografts. *Ann Thorac Surg* 1999;67:1986-9; discussion 97-8.
- Bisdas T, Wilhelm M, Haverich A, Teebken OE. Cryopreserved arterial homografts vs silver-coated Dacron grafts for abdominal aortic infections with intraoperative evidence of microorganisms. *J Vasc Surg* 2011;53:1274-81 e4.
- Aavik A, Lieberg J, Kals J, Pulges A, Kals M, Lepner U. Ten years

- experience of treating aorto-femoral bypass graft infection with venous allografts. *Eur J Vasc Endovasc Surg* 2008;36:432-7.
45. Czerny M, von Allmen R, Opfermann P, Sodeck G, Dick F, Stellmes A, *et al.* Self-made pericardial tube graft: a new surgical concept for treatment of graft infections after thoracic and abdominal aortic procedures. *Ann Thorac Surg* 2011;92:1657-62.
 46. Khaladj N, Pichlmaier U, Stachmann A, Peterss S, Reichelt A, Hagl C, *et al.* Cryopreserved human allografts (homografts) for the management of graft infections in the ascending aortic position extending to the arch. *Eur J Cardiothorac Surg* 2013;43:1170-5.
 47. Kato M, Imanaka K, Kyo S, Ohuchi H, Asano H, Takamoto S. Successful treatment of ascending aortic graft infection after operation for acute aortic dissection with peripheral malperfusion. *Ann Thorac Surg* 2004;77:2194-5.
 48. Bisdas T, Beckmann E, Marsch G, Burgwitz K, Wilhelmi M, Kuehn C, *et al.* Prevention of vascular graft infections with antibiotic graft impregnation prior to implantation: *in vitro* comparison between daptomycin, rifampin and nebacetin. *Eur J Vasc Endovasc Surg* 2012;43:448-56.
 49. Litzler PY, Thomas P, Danielou E, Lucq J, Jacques B, Frebourg N, *et al.* Bacterial resistance of refrigerated and cryopreserved aortic allografts in an experimental virulent infection model. *J Vasc Surg* 1999;29:1090-6.
 50. Bisdas T, Bredt M, Pichlmaier M, Aper T, Wilhelmi M, Bisdas S, *et al.* Eight-year experience with cryopreserved arterial homografts for the *in situ* reconstruction of abdominal aortic infections. *J Vasc Surg* 2010;52:323-30.
 51. Wilhelmi MH, Bara C, Kofidis T, Wilhelmi M, Pichlmaier M, Haverich A. Long-term cardiac allograft valves after heart transplant are functionally and structurally preserved, in contrast to homografts and bioprostheses. *J Heart Valve Dis* 2006;15:777-82.
 52. Mulder EJ, van Bockel JH, Maas J, van den Akker PJ, Hermans J. Morbidity and mortality of reconstructive surgery of noninfected false aneurysms detected long after aortic prosthetic reconstruction. *Arch Surg* 1998;133:45-9.
 53. Sullivan KL, Steiner RM, Smullens SN, Griska L, Meister SG. Pseudoaneurysm of the ascending aorta following cardiac surgery. *Chest* 1988;93:138-43.
 54. Mohammadi S, Bonnet N, Leprince P, Kolsi M, Rama A, Pavie A, *et al.* Reoperation for false aneurysm of the ascending aorta after its prosthetic replacement: surgical strategy. *Ann Thorac Surg* 2005;79:147-52; discussion 52.
 55. Yamanaka K, Nonaka M, Iwakura A, Asao Y. Repair of aorto-esophageal fistula after total aortic arch grafting. *Interact Cardiovasc Thorac Surg* 2011;12:655-6.
 56. Jonas RA, Ziemer G, Schoen FJ, Britton L, Castaneda AR. A new sealant for knitted Dacron prostheses: minimally cross-linked gelatin. *J Vasc Surg* 1988;7:414-9.
 57. Scott SM, Gaddy LR, Sahmel R, Hoffman H. A collagen coated vascular prosthesis. *J Cardiovasc Surg (Torino)* 1987;28:498-504.
 58. Cziperle DJ, Joyce KA, Tattersall CW, Henderson SC, Cabusao EB, Garfield JD, *et al.* Albumin impregnated vascular grafts: albumin resorption and tissue reactions. *J Cardiovasc Surg (Torino)* 1992;33:407-14.
 59. Mattens E, Engels P, Hamerlijnck R, Kelder J, Schepens M, de Valois J, *et al.* Gelseal versus Gelweave dacron prosthetic grafts in the descending thoracic aorta: a two-year computed tomography scan follow-up study. *Cardiovasc Surg* 1999;7:432-5.
 60. Takami Y, Tajima K, Kato W, Fujii K, Hibino M, Munakata H, *et al.* Long-term size follow-up of knitted Dacron grafts (Gelseal) used in the ascending aorta. *Interact Cardiovasc Thorac Surg* 2012;14:529-31.
 61. Clagett GP, Salander JM, Eddleman WL, Cabellon S, Jr., Youkey JR, Olson DW, *et al.* Dilation of knitted Dacron aortic prostheses and anastomotic false aneurysms: etiologic considerations. *Surgery* 1983;93:9-16.
 62. Wilson SE, Krug R, Mueller G, Wilson L. Late disruption of Dacron aortic grafts. *Ann Vasc Surg* 1997;11:383-6.
 63. Han I, Shigematsu H, Nunokawa M, Matsuzaki H, Iwata K, Nakamura S, *et al.* Nonanastomotic aneurysm formation in a Dacron arterial graft: report of a case. *Surg Today* 1994;24:1007-10.
 64. Leontyev S, Trommer C, Subramanian S, Lehmann S, Dmitrieva Y, Misfeld M, *et al.* The outcome after aortic valve-sparing (David) operation in 179 patients: a single-centre experience. *Eur J Cardiothorac Surg* 2012;42:261-6; discussion 6-7.
 65. Bauernschmitt R, Schulz S, Schwarzhaupt A, Kiencke U, Vahl CF, Lange R, *et al.* Simulation of arterial hemodynamics after partial prosthetic replacement of the aorta. *Ann Thorac Surg* 1999;67:676-82.
 66. Fokin AA, Robicsek F, Cook JW, Thubrikar MJ, Schaper J. Morphological changes of the aortic valve leaflets in non-compliant aortic roots: in-vivo experiments. *J Heart Valve Dis* 2004;13:444-51.
 67. Zehr KJ, Orszulak TA, Mullany CJ, Matloobi A, Daly RC, Dearani JA, *et al.* Surgery for aneurysms of the aortic root: a 30-year experience. *Circulation* 2004;110:1364-71.
 68. David T, Armstrong S, Manliot C, McCrindle BW, Feindel CM. Long-term results of aortic root repair using the reimplantation technique. *J Thorac Cardiovasc Surg* 2013;145:S22-5.
 69. Shrestha M, Baraki H, Maeding I, Fitzner S, Sarikouch S, Khaladj N, *et al.* Long-term results after aortic valve-sparing operation (David I). *Eur J Cardiothorac Surg* 2012;41:56-61; discussion -2.
 70. Ioannou CV, Stergiopoulos N, Katsamouris AN, Startchik I, Kalangos A, Licker MJ, *et al.* Hemodynamics induced after acute reduction of proximal thoracic aorta compliance. *Eur J Vasc Endovasc Surg* 2003;26:195-204.
 71. Morita S, Asou T, Kuboyama I, Harasawa Y, Sunagawa K, Yasui H. Inelastic vascular prosthesis for proximal aorta increases pulsatile arterial load and causes left ventricular hypertrophy in dogs. *J Thorac Cardiovasc Surg* 2002;124:768-74.
 72. Ioannou CV, Morel DR, Katsamouris AN, Katranitsa S, Startchik I, Kalangos A, *et al.* Left ventricular hypertrophy induced by reduced aortic compliance. *J Vasc Res* 2009;46:417-25.
 73. Morita S, Kuboyama I, Asou T, Tokunaga K, Nose Y, Nakamura M, *et al.* The effect of extraanatomic bypass on aortic input impedance studied in open chest dogs. Should the vascular prosthesis be compliant to unload the left ventricle? *J Thorac Cardiovasc Surg* 1991;102:774-83.
 74. Maeta H, Hori M. Effects of a lack of aortic "Windkessel" properties on the left ventricle. *Jpn Circ J* 1985;49:232-7.
 75. Kim SY, Hinkamp TJ, Jacobs WR, Lichtenberg RC, Posniak H, Pifarre R. Effect of an inelastic aortic synthetic vascular graft on exercise hemodynamics. *Ann Thorac Surg* 1995;59:981-9.
 76. Monti L, Mauri G, Balzarini L, Tarelli G, Brambilla G, Vitali E, *et al.* Compliance of the Valsalva graft's pseudosinuses at midterm follow-up with cardiovascular magnetic resonance. *Ann Thorac Surg* 2011;91:92-6.
 77. Tremblay D, Zigras T, Cartier R, Leduc L, Butany J, Mongrain R, *et al.* A comparison of mechanical properties of materials used in aortic arch reconstruction. *Ann Thorac Surg* 2009;88:1484-91.
 78. Udelsman BV, Maxfield MW, Breuer CK. Tissue engineering of blood vessels in cardiovascular disease: moving towards clinical translation. *Heart* 2013;99:454-60.
 79. Okamoto H, Tamenishi A, Matsumura Y, Niimi T. Composite vein graft reconstruction for infected descending aortic prosthesis. *Ann Thorac Surg* 2012;93:2061-3.
 80. Earnshaw JJ. Conservative surgery for aortic graft infection. *Cardiovasc Surg* 1996;4:570-2.
 81. Yeager RA, Taylor LM, Jr., Moneta GL, Edwards JM, Nicoloff AD, McConnell DB, *et al.* Improved results with conventional management of infrarenal aortic infection. *J Vasc Surg* 1999;30:76-83.
 82. Young RM, Cherry KJ, Jr., Davis PM, Gloviczki P, Bower TC, Panneton JM, *et al.* The results of *in situ* prosthetic replacement for infected aortic grafts. *Am J Surg* 1999;178:136-40.
 83. Vogt PR, Brunner-LaRocca HP, Lachat M, Ruef C, Turina MI. Technical details with the use of cryopreserved arterial allografts for aortic infection: influence on early and midterm mortality. *J Vasc Surg* 2002;35:80-6.
 84. Tossios P, Karatzopoulos A, Tsagakis K, Sapolidis K, Grosomanidis

- V, Kalogera A, *et al.* Treatment of infected thoracic aortic prosthetic grafts with the *in situ* preservation strategy: a review of its history, surgical technique, and results. *Heart Lung Circ* 2014;23:24-31.
85. Carrel T, Pasic M, Jenni R, Tkebuchava T, Turina MI. Reoperations after operation on the thoracic aorta: etiology, surgical techniques, and prevention. *Ann Thorac Surg* 1993;56:259-68; discussion 69.
 86. Preventza O, Wheatley GH, 3rd, Williams J, Ramaiah VG, Rodriguez-Lopez JA, Diethrich EB. Novel endovascular repair of the small thoracic aorta: customizing off-the-shelf endoluminal grafts. *J Card Surg* 2007;22:434-5.
 87. Ito T, Kurimoto Y, Kawaharada N, Koyanagi T, Hashiguchi H, Yamashita A, *et al.* Endovascular stent-grafting of anastomotic pseudoaneurysms following thoracic aortic surgery. *Gen Thorac Cardiovasc Surg* 2009;57:528-33.
 88. Kan CD, Lee HL, Yang YJ. Outcome after endovascular stent graft treatment for mycotic aortic aneurysm: a systematic review. *J Vasc Surg* 2007;46:906-12.
 89. Yamashita S, Dohi T, Shimizu Y, Momomura S. Aortopulmonary fistula caused by an infected thoracic aortic false aneurysm rupturing after endovascular stent placement. *Drug Discov Ther* 2012;6:278-82.
 90. Wheatley GH, 3rd, Nunez A, Preventza O, Ramaiah VG, Rodriguez-Lopez JA, Williams J, *et al.* Have we gone too far? Endovascular stent-graft repair of aortobronchial fistulas. *J Thorac Cardiovasc Surg* 2007;133:1277-85.
 91. Lawrie GM, Earle N, De Bakey ME. Evolution of surgical techniques for aneurysms of the descending thoracic aorta: twenty-nine years experience with 659 patients. *J Card Surg* 1994;9:648-61.
 92. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Experience with 1509 patients undergoing thoracoabdominal aortic operations. *J Vasc Surg* 1993;17:357-68; discussion 68-70.
 93. Wickstrom PH, Streitz JM, Jr., Erickson RV, Hoffman BD. Repair of aortoesophageal fistula after aortic grafting. *Ann Thorac Surg* 1997;64:253-5.
 94. Langer S, Mommertz G, Koeppl TA, Schurink GW, Autschbach R, Jacobs MJ. Surgical correction of failed thoracic endovascular aortic repair. *J Vasc Surg* 2008;47:1195-202.
 95. Chiesa R, Melissano G, Marone EM, Marrocco-Trischitta MM, Kahlberg A. Aorto-oesophageal and aortobronchial fistulae following thoracic endovascular aortic repair: a national survey. *Eur J Vasc Endovasc Surg* 2010;39:273-9.
 96. Obitsu Y, Koizumi N, Iida Y, Iwahashi T, Saiki N, Watanabe Y, *et al.* Long-term results of second-stage thoracic endovascular aortic repair following total aortic arch replacement. *Gen Thorac Cardiovasc Surg* 2010;58:501-5.
 97. Adams JD, Tracci MC, Sabri S, Cherry KJ, Angle JF, Matsumoto AH, *et al.* Real-world experience with type I endoleaks after endovascular repair of the thoracic aorta. *Am Surg* 2010;76:599-605.
 98. Parmer SS, Carpenter JP, Stavropoulos SW, Fairman RM, Pochettino A, Woo EY, *et al.* Endoleaks after endovascular repair of thoracic aortic aneurysms. *J Vasc Surg* 2006;44:447-52.
 99. Neuhauser B, Greiner A, Jaschke W, Chemelli A, Fraedrich G. Serious complications following endovascular thoracic aortic stent-graft repair for type B dissection. *Eur J Cardiothorac Surg* 2008;33:58-63.
 100. Neuhauser B, Czermak BV, Fish J, Perkmann R, Jaschke W, Chemelli A, *et al.* Type A dissection following endovascular thoracic aortic stent-graft repair. *J Endovasc Ther* 2005;12:74-81.
 101. Zipfel B, Hammerschmidt R, Krabatsch T, Buz S, Weng Y, Hetzer R. Stent-grafting of the thoracic aorta by the cardiothoracic surgeon. *Ann Thorac Surg* 2007;83:441-8; discussion 8-9.
 102. Flores J, Shiiya N, Kuniyama T, Yoshimoto K, Matsuzaki K, Yasuda K. Reoperations after failure of stent grafting for type B aortic dissection: report of two cases. *Surg Today* 2005;35:581-5.
 103. Hinchliffe RJ, Krasznai A, Schultzekeol L, Blankensteijn JD, Falkenberg M, Lonn L, *et al.* Observations on the failure of stent-grafts in the aortic arch. *Eur J Vasc Endovasc Surg* 2007;34:451-6.
 104. Canaud L, Ozdemir BA, Bee WW, Bahia S, Holt P, Thompson M. Thoracic endovascular aortic repair in management of aortoesophageal fistulas. *J Vasc Surg* 2014;59:248-54.
 105. Canaud L, Alric P, Gandet T, Ozdemir BA, Albat B, Marty-Ane C. Open surgical secondary procedures after thoracic endovascular aortic repair. *Eur J Vasc Endovasc Surg* 2013;46:667-74.
 106. Hoimyr H, Christensen TD, Emmertsen K, Johnsen SP, Riis A, Hansen OK, *et al.* Surgical repair of coarctation of the aorta: up to 40 years of follow-up. *Eur J Cardiothorac Surg* 2006;30:910-6.
 107. Cohen M, Fuster V, Steele PM, Driscoll D, McGoon DC. Coarctation of the aorta. Long-term follow-up and prediction of outcome after surgical correction. *Circulation* 1989;80:840-5.
 108. Parks WJ, Ngo TD, Plauth WH, Jr., Bank ER, Sheppard SK, Pettigrew RI, *et al.* Incidence of aneurysm formation after Dacron patch aortoplasty repair for coarctation of the aorta: long-term results and assessment utilizing magnetic resonance angiography with three-dimensional surface rendering. *J Am Coll Cardiol* 1995;26:266-71.
 109. Aebert H, Laas J, Bednarski P, Koch U, Prokop M, Borst HG. High incidence of aneurysm formation following patch plasty repair of coarctation. *Eur J Cardiothorac Surg* 1993;7:200-4; discussion 5.
 110. von Kodolitsch Y, Aydin MA, Koschik DH, Loose R, Schalwat I, Karck M, *et al.* Predictors of aneurysmal formation after surgical correction of aortic coarctation. *J Am Coll Cardiol* 2002;39:617-24.
 111. Kinley CE, Marble AE. Compliance: a continuing problem with vascular grafts. *J Cardiovasc Surg (Torino)* 1980;21:163-70.
 112. Heikkinen L, Sariola H, Salo J, Ala-Kulju K. Morphological and histopathological aspects of aneurysms after patch aortoplasty for coarctation. *Ann Thorac Surg* 1990;50:946-8.
 113. DeSanto A, Bills RG, King H, Waller B, Brown JW. Pathogenesis of aneurysm formation opposite prosthetic patches used for coarctation repair. An experimental study. *J Thorac Cardiovasc Surg* 1987;94:720-3.
 114. Bogaert J, Gewillig M, Rademakers F, Bosmans H, Verschakelen J, Daenen W, *et al.* Transverse arch hypoplasia predisposes to aneurysm formation at the repair site after patch angioplasty for coarctation of the aorta. *J Am Coll Cardiol* 1995;26:521-7.
 115. Troost E, Gewillig M, Daenen W, Meyns B, Bogaert J, Van Deyk K, *et al.* Behaviour of polyester grafts in adult patients with repaired coarctation of the aorta. *Eur Heart J* 2009;30:1136-41.
 116. Shah DM, Darling RC, 3rd, Kreienberg PB, Wirth G, Shah R, Lloyd WE, *et al.* A critical approach for longitudinal clinical trial of stretch PTFE aortic grafts. *Cardiovasc Surg* 1997;5:414-8.
 117. Bogaert J, Dymarkowski S, Budts W, Gewillig M, Daenen W. Graft dilation after redo surgery for aneurysm formation following patch angioplasty for aortic coarctation. *Eur J Cardiothorac Surg* 2001;19:274-8.
 118. Goossens D, Weyers L, Engels P, Hamerlijnck R, Vermeulen F. 'In vivo' size of knitted Dacron prostheses (Gelseal) used in the thoracic aorta: a computed tomography study. *Cardiovasc Surg* 1996;4:205-6.
 119. Centola M, Rainer A, Spadaccio C, De Porcellinis S, Genovese JA, Trombetta M. Combining electrospinning and fused deposition modeling for the fabrication of a hybrid vascular graft. *Biofabrication* 2010;2:014102.
 120. Gui L, Zhao L, Spencer RW, Burghouwt A, Taylor MS, Shalaby SW, *et al.* Development of novel biodegradable polymer scaffolds for vascular tissue engineering. *Tissue Eng Part A* 2011;17:1191-200.
 121. Hibino N, McGillicuddy E, Matsumura G, Ichihara Y, Naito Y, Breuer C, *et al.* Late-term results of tissue-engineered vascular grafts in humans. *J Thorac Cardiovasc Surg* 2010;139:431-6, 6 e1-2.
 122. Khaladj N, Pichlmaier U, Stachmann A, Peterss S, Reichelt A, Hagl C, *et al.* Cryopreserved human allografts (homografts) for the management of graft infections in the ascending aortic position extending to the arch. *Eur J Cardiothorac Surg* 2013;43:1170-5.
 123. O'Hara PJ, Hertzner NR, Beven EG, Krajewski LP. Surgical management of infected abdominal aortic grafts: review of a 25-year experience. *J Vasc Surg* 1986;3:725-31.
 124. Goldstone J, Moore WS. Infection in vascular prostheses. Clinical manifestations and surgical management. *Am J Surg* 1974;128:225-33.
 125. Lorentzen JE, Nielsen OM, Arendrup H, Kimose HH, Bille S, Andersen J, *et al.* Vascular graft infection: an analysis of sixty-two graft

- infections in 2411 consecutively implanted synthetic vascular grafts. *Surgery* 1985;98:81-6.
126. Peck JJ, Eidemiller LR. Aortoenteric fistulas. *Arch Surg* 1992;127:1191-3; discussion 3-4.
 127. Plate G, Hollier LA, O'Brien P, Pairolero PC, Cherry KJ, Kazmier FJ. Recurrent aneurysms and late vascular complications following repair of abdominal aortic aneurysms. *Arch Surg* 1985;120:590-4.
 128. Bergqvist D, Alm A, Claes G, Drott C, Forsberg O, Larsson M, *et al.* Secondary aortoenteric fistulas—an analysis of 42 cases. *Eur J Vasc Surg* 1987;1:11-8.
 129. den Hoed PT, Veen HF. The late complications of aorto-ilio-femoral Dacron prostheses: dilatation and anastomotic aneurysm formation. *Eur J Vasc Surg* 1992;6:282-7.
 130. Szilagyi DE, Smith RF, Elliott JP, Hageman JH, Dall'Olmo CA. Anastomotic aneurysms after vascular reconstruction: problems of incidence, etiology, and treatment. *Surgery* 1975;78:800-16.
 131. Edwards JM, Teefey SA, Zierler RE, Kohler TR. Intraabdominal paraanastomotic aneurysms after aortic bypass grafting. *J Vasc Surg* 1992;15:344-50; discussion 51-3.
 132. Shingu Y, Aoki H, Ebuoka N, Eya K, Takigami K, Oba J. Late rupture of knitted Dacron graft. *Ann Thorac Cardiovasc Surg* 2005;11:343-5.
 133. Bachet JE, Termignon JL, Dreyfus G, Goudot B, Martinelli L, Piquois A, *et al.* Aortic dissection. Prevalence, cause, and results of late reoperations. *J Thorac Cardiovasc Surg* 1994;108:199-205; discussion -6.
 134. David T, Armstrong S, Manlhiot C, McCrindle BW, Feindel CM. Long-term results of aortic root repair using the reimplantation technique. *J Thorac Cardiovasc Surg* 2012;1-4.
 135. Khaladj N, Pichlmaier U, Stachmann A, Peterss S, Reichelt A, Hagl C, *et al.* Cryopreserved human allografts (homografts) for the management of graft infections in the ascending aortic position extending to the arch. *Eur J Cardiothorac Surg* 2013;43:1170-5.
 136. Thompson CS, Ramaiah VG, Rodriguez-Lopez JA, Vranic M, Ravi R, DiMugno L, *et al.* Endoluminal stent graft repair of aortobronchial fistulas. *J Vasc Surg* 2002;35:387-91.
 137. Kawamura M, Ogino H, Matsuda H, Minatoya K, Sasaki H, Kitamura S. Late-stage, nonanastomotic rupture of double-velour Dacron graft after descending aortic replacement. *J Thorac Cardiovasc Surg* 2006;132:961-2.

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