CHAPTER

Cannula design

18

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INTRODUCTION

The anatomical interaction between mechanical circulatory and respiratory support and the patient is achieved using cannulae, grafts, or cuffs. Inflow connections remove blood from the native venous system to the mechanical device, while outflow connections deliver blood from the device to the native circulatory system (Fig. 18.1). Ventricular assist devices (VADs) are primarily attached via an inflow cannula and an outflow graft. Extracorporeal membrane oxygenation (ECMO) usually employ infusion and drainage cannulae, while total artificial hearts (TAHs) typically use inflow cuffs and outflow grafts. For ease of reference in this chapter, cannulae, grafts, and cuffs are grouped into a single term "cannula," or "cannulae" as plural, unless specifically stated otherwise.

It is crucial that an optimal anatomical interaction is achieved between the device and patient. Suboptimal anatomical interaction can lead to postoperative hemorrhage (bleeding), thrombus formation, cardiac distension, and/or reduced cardiac output, which can result in significant complications including reduced quality of life, readmittance for surgery, or even death. Most vascular access systems used in current practice are adapted from clinical cardiac surgery. Further research is needed for optimizing cannula design and obtaining FDA approval for situations that are disease- or physiology-specific, so that a gold standard can be established.

This chapter begins by discussing the key complications associated with suboptimal anatomical interactions for mechanical circulatory and respiratory support,

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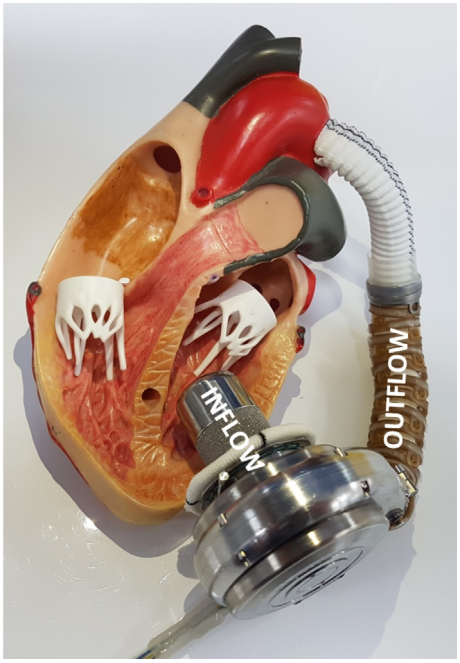


FIG. 18.1

Example model of inflow and outflow cannulation for a left ventricular assist device.

including thrombus formation, bleeding, and perfusion. Different cannula designs and their placement, orientation, and fixation techniques for VADs, TAHs, and ECMO are then discussed. Finally, a summary is presented along with future considerations for improving anatomical interaction.

THROMBUS FORMATION

Neurologic complications remain one of the most serious adverse events for mechanical circulatory and respiratory support [1]. Virchow's triad described the three key predisposing factors to thromboembolic complications: vessel wall abnormalities (endothelial injury), abnormal flow, and coagulation state (Fig. 18.2). If any of the mentioned features are not optimal, the subsequent flow dynamics may result in abnormal flow, thrombosis, thromboembolic and potentially neurologic or other end-organ ischemic complications. The geometrical design, placement, and alignment of the cannula all contribute to normal or abnormal blood flow, while incorrect design, placement, or alignment may result in circulatory stasis or turbulence. Insertion and surgical fixation of the cannula will undoubtedly result in some endothelial injury as the cannula penetrates the vessel; however, the surgical technique and cannula design may be altered to reduce endothelial injury. Meanwhile, pre-operative abnormal coagulation is common in heart

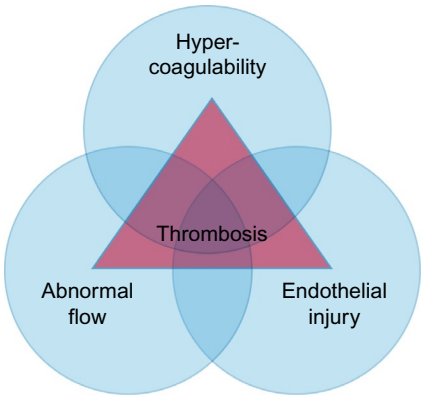


FIG. 18.2

Virchow's Triad describing the three predisposing factors for thrombosis.

failure patients due to hepatic dysfunction and the use of anti-coagulant or anti-platelet medications. Therefore, patients receiving mechanical circulatory or respiratory support are exposed to perturbations of all three elements of Virchow's triad. Ventricular thrombus formations have been reported in several previous studies [2,3]. These may release, potentially traveling to the brain and causing a stroke. Therefore, it is important to reduce or eliminate the effect of vessel wall abnormalities, abnormal flow, and a coagulation state when implementing mechanical circulatory or respiratory support. This may be achievable through changes in cannula design, insertion length, insertion site, and orientation.

POSTOPERATIVE BLEEDING

The incidence of thrombotic events is actually much lower than bleeding events [4]. The most frequent complication during ECMO is significant bleeding, reported to occur in 10%–30% of patients [5]. Often occurring at the site of cannulation and potentially due to systemic heparinization, platelet dysfunction, and clotting factor hemodilution, bleeding is often managed by decreasing or stopping heparin infusion, which then exposes the patient to thrombus formation. Meanwhile, bleeding is the most common complication during VAD support and is a major contributing factor of operative mortality during VAD implantation and explantation [4,6–8]. Previous studies have shown up to 76% of patients experience excessive bleeding in the acute phase following VAD implantation with as many as 60% requiring operative intervention [8–11]. Kirklin et al. [12] found that in the first month of destination therapy of 385 patients from the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) database, 11% of deaths were attributed to postoperative, surgery-related hemorrhage. Decades of improvements to medical therapy, particularly focusing on anticoagulation regimes, has done little to overcome this complication [13,14]. This is evident by a more recent INTERMACS report demonstrating

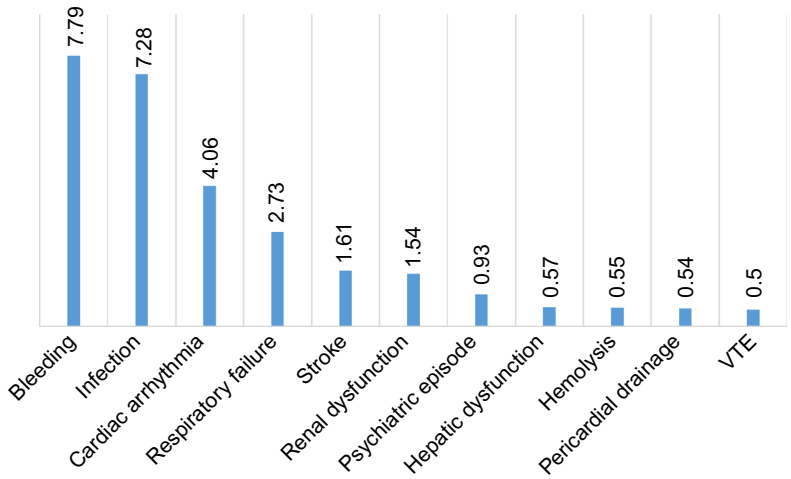


FIG. 18.3

Adverse event rates (events/100 patient months) in the first 12 months post-implant between 2012 and 2014 for continuous flow left ventricular assist devices and biventricular assist devices. VTE—venous thrombotic event. Note: only adverse event rates equal to, or above, 0.5 are shown.

Data taken from Kirklin JK, Naftel DC, Pagani FD, et al. Seventh INTERMACS annual report: 15,000 patients and counting. J Heart Lung Transplant 2015;34(12):1495–1504.

the continued significance of postoperative bleeding, with 4420 events (7.79 per 100 patient months) reported in the era between 2012 and 2014 (Fig. 18.3) [15].

Postoperative bleeding is a particularly significant problem during the acute phase of mechanical circulatory and respiratory support (first 24–48 h), occurring at suture lines and cannulation sites, and can be difficult to localize [8]. Hemodynamic instability is common during the early postoperative period, most frequently due to low flow rates due to cannula obstruction, tamponade and hypovolemia from hemorrhage [16]. Risk factors for significant hemorrhage include coagulopathy due to hepatic congestion, compromised nutritional status, preoperative anticoagulation, previous cardiac surgeries, extended cardiopulmonary bypass (CPB) time, and extensive surgical dissection [16]. Surgery-induced bleeding may also be due to hemodilution of clotting factors during CPB and device-induced coagulopathies [8].

PERFUSION

Suboptimal inflow or outflow cannula design or placement may result in cannula obstruction, subsequent suction events, and pump flow stoppages [17]. Inlet cannula obstruction is quite common and is often due to occlusion by the surrounding tissue, such as the ventricular free wall or septum [16,18]. This can lead to adverse events including ventricular arrhythmias, endocardial damage, and reductions in device flow. Goerbig-Campbell et al. [19] observed serious adverse events in 17 consecutive patients who received an axial flow LVAD. Eight patients experienced dynamic

inflow occlusion events, defined as near or complete cessation of flow in systole or diastole, with 19 separate serious adverse events (including bleeding requiring blood transfusion or invasive intervention, intractable ventricular arrhythmia, stroke (CVA), thromboembolic event other than CVA, pump thrombosis, surgical pump revision, admissions in which the principle diagnosis was heart failure) occurring in seven of those patients. Only nine serious adverse events were recorded in the nine patients who did not experience dynamic inflow occlusion events, indicating that inflow occlusion may result in additional postoperative complications.

VENTRICULAR ASSIST DEVICES

VADs are used to support the left and/or right ventricles in parallel to the native circulatory system. For more information on VADs, please refer to Chapters 3-5. VADs are attached to the native circulatory system via inflow (to the pump) and outflow (to the patient) cannulae.

INFLOW

Several characteristics influence the hemodynamic performance of a VAD inflow cannula, including cannula design, insertion site, orientation, insertion length, and fixation techniques.

Cannula design

There is currently no "gold standard" cannula design. Each device has its own cannula design, while some extracorporeal devices have several for selection. For instance, the first-generation extracorporeal Abiomed BVS5000 device can be implanted using inflow cannulae with a rounded tip or a chamfered straight tip, both with different side hole arrangements [20]. The extracorporeal Medos HIA-VAD uses a kink-resistant inflow cannula with a polyester velour to encourage tissue integration (as an infection barrier) and a suture ring to assist with surgical fixation [21], with the atrial cannula including a cage to prevent inflow occlusion. Malleable inflow tips are also available to adjust the cannula tip angle during insertion. The Thoratec PVAD, also an extracorporeal device, has side holes in the cannula tip (Fig. 18.4)

FIG. 18.4

The Thoratec PVAD atrial (left) and ventricular (right) inflow cannulae.

to improve blood flow and a polyester velour to promote endocardial healing and reduced thrombus formation [22].

Of the newer generation rotary devices, each has its own cannula design. The HeartWare HVAD has a thick-walled inflow cannula with a filleted tip and a sintered component at the base to encourage tissue ingrowth at the apex, while the smooth upper portion prevents tissue overgrowth (Fig. 18.5). The addition of the sintered component has reportedly reduced pump thrombosis to 4% of patients, compared to 15% with the earlier generation, non-sintered device [23]. Others have also reported reduced thrombus formation with inflow cannulae wrapped with titanium mesh [24]. The Berlin Heart INCOR also incorporates a partially textured inflow; however, the tip shape is distinctively different with four equally spaced protruding tips forming a "castle-like" shape (Fig. 18.6). Conversely, the HeartMate II has a fully textured (internal and external surfaces) straight inflow cannula with incorporated bend relief (Fig. 18.7). Trumpet-shaped cannulae have also been used clinically with the Ventracor VentrAssist (Fig. 18.8) and shown experimentally to improve ventricular washout and reduce the severity of ventricular suction [25].

FIG. 18.5

HeartWare HVAD with sintered inflow cannula.

Various cannula tip designs have been evaluated in silico [26,27], in vitro [28,29], and in vivo [30]. The influence of side holes on cannula and ventricular flow dynamics has received some attention, with reports of reduced LVAD flow rate due to the side holes disturbing the cannula flow streamline [26]. The addition of side holes may also decrease maximum fluid velocity, shear rate, and cannula pressure drop

FIG. 18.6

The "castle-like" shaped Berlin Heart INCOR inflow cannula.

Courtesy of Berlin Heart GmbH.

FIG. 18.7

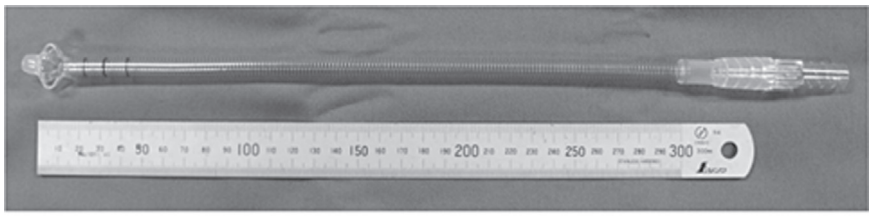
The Thoratec HeartMate II with textured inflow cannula and bend relief.

[27]. Novel cannula designs, including the Lantern cannula (Fig. 18.9), have included side holes and demonstrated (in silico and in vivo) reduced pressure drop across the cannula [31].

Inflow cannula bend relief may also be an important characteristic for VAD support to maintain the cannula axis in the center of the ventricle, thus reducing the risk of contacting the septum or free walls and causing potential occlusion events and myocardial damage [16]. Devices such as the HeartMate II include inflow cannula bend relief, while smaller devices that can be placed pericardially

FIG. 18.8

The Ventracor VentrAssist with trumpet-shaped inflow cannula.



(A)

(B)

FIG. 18.9

The Lantern cannula in (A) the pre-implant and implanted configuration and (B) the elongated configuration (via a stylet) used during insertion.

Reprinted with permission from Sumikura H, Toda K, Takewa Y, et al. Development and hydrodynamic evaluation of a novel inflow cannula in a mechanical circulatory support system for bridge to decision. Artif Organs 2011;35(8):756–64.

(i.e., Jarvik 2000, HeartWare HVAD) may avoid the need for bend relief as they can be correctly oriented during implantation without the need for placement in a pump pocket. However, movement of the VAD and myocardial remodeling during support has been reported [32]. Thus rigid inflow cannulation may be more susceptible to ventricular suction. Flexible inflow cannulae have been developed to overcome this problem, while complete collapse of the inflow cannula due to negative pressure can be prevented through semi-flexible wire-reinforcement [32]. Adjustable inflow cannula position mechanisms have also been proposed; however, their feasibility in long-term VAD support must be evaluated before clinical acceptance [33].

Tissue overgrowth for both the LVAD and RVAD must also be considered when selecting suitable cannulae or designing new cannulation systems. Ootaki et al. [30] evaluated seven different inflow cannula designs implanted into the right ventricle in healthy calves, demonstrating reduced tissue overgrowth with an open-ended titanium cannula with side holes and sintered titanium beads. Conversely, an angled titanium inflow with a caged tip showed severe obstruction by endocardial tissue growth, which was also observed with an open-ended titanium cannula, a flanged titanium cannula, and a flexible polyurethane-coated polyvinyl chloride cannula with wire reinforcement. Coatings have been applied to cannulae to encourage tissue growth and potentially reduce the impact of the vessel wall abnormalities. For instance, the Thoratec HMII inflow cannula has a textured titanium microsphere surface to prevent thrombus formation [34]. Yamada et al. [35] coated the portion of inflow cannula that protrudes into the ventricle with a titanium mesh to create an autologous neointima to prevent wedge thrombus formation. The mesh included fine titanium wire and protruded up to 20 mm from the apex. Four bovine experiments with an LVAD revealed no thrombus formation in the pump or the inflow cannula, while the mesh was enveloped with neointima tissue which had grown from the ventricular myocardium. Thus cannula design, coating, and insertion site must all be considered to prevent tissue overgrowth and potential inflow obstruction.

Insertion site

VAD inflow cannulation is, in most cases, achieved via the atrium or ventricle. The choice of inflow cannulation site is often dependent on the preference of the surgeon and can be limited by anatomical constraints or the presence of thrombus within a vessel. Ventricular cannulation is often regarded as the preferred site for implantable LVADs [36,37]. This is due to improved LVAD inflow conditions resulting from remnant heart activity, which in turn increases pump flow and reduces the risk of thromboembolism [22]. Therefore, ventricular cannulation may reduce the risk of stroke, which has been found to decrease with increased ejection fraction [38,39]. Ventricular cannulation has also been shown to improve valvular washout [40].

Atrial cannulation, on the other hand, may allow easier surgical insertion and improved potential for cardiac ventricular recovery by alleviating ventricular workload and preserving remaining cardio-myocytes [36,41]. However, increased pressure

and volume loading with atrial cannulation may have the opposite effect and be detrimental to myocardial recovery [42]. Atrial cannulation typically results in reduced ventricular ejection fraction and may increase the risk of thrombus formation within the unloaded ventricle. This is particularly important as the reduced ejection fraction often encountered in heart failure patients creates a condition of relative stasis within the ventricle that may predispose it to the risk of thromboembolic events [37,43].

Left atrial cannulation may be achieved via the dome of the atrium (between the superior vena cava and aorta), behind the interatrial groove, through the left atrial appendage, or even between the left and right superior pulmonary veins. Left ventricular cannulation is usually achieved via the apex of the left ventricle; however, rates of infection and ventricular arrhythmias have been reduced with cannulation via the left ventricular free wall [44].

Right ventricular assist devices (RVADs) can also be implanted via the atrium or ventricle. The right atrial free wall or appendage may be used for atrial cannulation [20], while the right ventricular free wall (halfway between the right ventricular base and apex) may also be used [14,45]. Increased ejection fraction (and thus potentially increased washout) has been reported with right ventricular cannulation compared to right atrial cannulation with rotary blood pumps in a severe biventricular heart failure simulation [46]. However, right atrial cannulation recorded increased pulmonary valve flow and reduced right ventricular stroke work in a mild biventricular heart failure condition, which may be preferential if myocardial recovery is anticipated.

Orientation and insertion length

The cannula tip length and orientation influences the flow dynamics within the chamber and the interaction between the cannula and surrounding tissue. Positioning of the cannula tip within the left atrium is vital, with a small angle possibly resulting in impingement upon the left atrial roof, while a larger angle may extend the cannula across the mitral valve [47]. If placed in the left ventricle, care must be taken to ensure minimal interaction between the cannula and mitral valvular or sub-valvular apparatus and to ensure the cannula is not placed in the left ventricular outflow tract, left atrium, or directly against the left ventricular wall.

The left ventricular inflow cannula should be directed posteriorly toward the mitral valve to prevent obstruction. Improper positioning of the LVAD inflow cannula may alter the left ventricular geometry and potentially place more strain on the right ventricle, promoting right ventricular failure [48]. Changes in inflow cannula orientation (i.e., reduced angle between inflow cannula and pump axis) with the Thoratec HeartMate II have been shown to increase the risk of serious adverse events, including pump thrombus formation, and subsequently reduce survival [49,50]. The placement of the inflow cannula should also accommodate anticipated reductions in left ventricular chamber size [4]. Movement of the inflow cannula may occur over time due to pericardial changes or suboptimal intraoperative preparation. This movement may lead to partial occlusion of the cannula with subsequent hemolysis, low pump flow, arrhythmias, and chronic inadequate LV

unloading, potentially resulting in right heart failure. Sub-optimal LVAD inflow cannula position following implantation and chest closure, or changes in position during support, may also contribute to pump thrombosis requiring device exchange or surgical repositioning [11].

Inflow cannula orientation and insertion length has been shown to influence ventricular flow dynamics and patient outcomes. In a study of 216 patients receiving the Berlin Heart INCOR (Berlin Heart GmbH, Berlin, Germany), Schmid et al. [51] compared short (24 mm, $n = 138$) and long (34 mm, $n = 78$) inflow cannulae (Fig. 18.10). Patients with the longer cannula demonstrated improved one- and two-year survival rates of 61% and 53%, respectively, compared to 50% and 33%, respectively, for the short cannula. Only three patients with the long cannula (3.8%) had a thromboembolic adverse event, compared with 32 (23.2%) with the short cannula. The relative risk of stroke was 6.03 times higher with the short cannula compared to the longer cannula, while the incidence of cerebral bleeding was also higher with the shorter cannula (0.21 vs. 0.11 events per patient year). The difference in patient outcomes could potentially be explained by the longer cannula extending further into the ventricle and improving blood flow dynamics, while also having increased clearance above the ventricular trabeculae and thus less tissue growth around the inflow orifice.

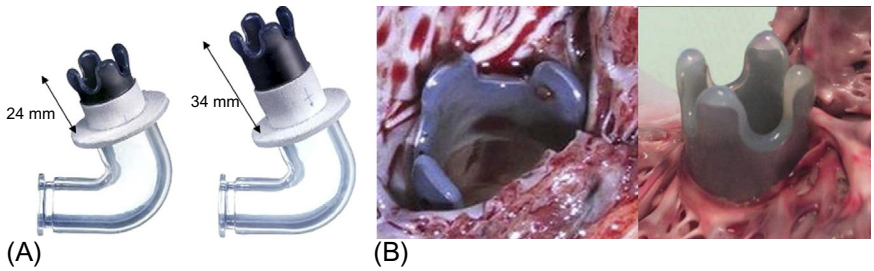


FIG. 18.10

The long and short Berlin Heart INCOR cannula showing (A) the difference in cannula design and (B) the resultant change in cannula protrusion within the ventricle.

Reprinted with permission from Schmid C, Jurmann M, Birnbaum D, et al. Influence of inflow cannula length in axial-flow pumps on neurologic adverse event rate: results from a multi-center analysis. J Heart Lung Transplant 2008;27:253–60.

Fixation

Insertion and fixation of LVAD and RVAD inflow cannulae can vary between devices and the surgical team, with a more detailed review of VAD surgical implantation procedures provided in Chapter 15.

Recent data from the INTERMACS database reports bleeding as the most common (highest events/100 patient months) adverse event with VAD support [15]. Although not exclusively occurring at the cannulation sites, it is vital to employ an optimal cannulation system to match the VAD recipient to reduce the rates of

postoperative bleeding. In one study, 87% of patients experienced severe bleeding after rotary blood pump support with atrial cannulation [52]. Atrial cannulation can be difficult due to the thin-walled vessel and is usually reinforced with felt pledgets, while others have reported reinforcing the atrial wall with a Dacron sleeve [53]. Alternative LVAD inflow cannulation sites, such as the right superior pulmonary vein, may be used [54]. Novel fixation techniques may also be applied for right atrial cannulation where RVAD support is required, such as using the right atrial venous cardiopulmonary bypass cannula for RVAD inflow [55].

The thickness of the ventricular myocardium may allow improved VAD fixation compared to the thin-walled atrium. Inflow cannulation is typically achieved using cardiopulmonary bypass, with several sources recommending inspection of the left ventricle for thrombus before VAD inflow cannula insertion [22,34]. The clinically available rotary pumps usually incorporate a sewing ring either attached directly to the inflow cannula (e.g., Berlin Heart INCOR) or as a separate mechanism that can be sutured to the ventricular apex and then fastened to the inflow cannula (e.g., HeartWare HVAD) [56]. The small HeartWare HVAD sewing ring consists of an inner titanium C-clamp, which can be tightened against the inflow cannula and silicone O-ring by turning a screw inside the clamp, attached to an outer Dacron polyester that is sutured to the apex (Fig. 18.11). Felt pledgets may also be used in combination with the inflow sewing ring to provide additional reinforcement [22,57]. With complications such as increased risk of bleeding, end-organ dysfunction, and stroke associated with extended time on CPB, several institutes have attempted off-bypass VAD implantation [58,59]. This is typically achieved by suturing the sewing ring to the apex, coring the myocardium, and manually occluding the apical orifice before inserting the inflow cannula and tying the sutures.

FIG. 18.11

The HeartWare HVAD with sewing ring and tightening driver.

OUTFLOW

The success of outflow cannulation from VADs can be influenced by the material, size, anastomosis location, patient state, and potential complications.

Outflow graft material and size

The outflow graft aims to return blood into the systemic or pulmonary circulation with sufficient patency while preventing bleeding. In the past, certain LVAD manufacturers used porous Dacron (polyethylene terephthalate) grafts that required preclotting to achieve hemostasis [60]. However, preclotting of porous Dacron grafts is sometimes not possible if the patient is already heparinized for a range of reasons. Even if preclotting is successfully performed, blood oozing can occasionally still occur, which requires surgeons to wrap an existing graft with a pre-sealed graft [61]. This led manufactures to move toward nonporous grafts such as Hemashield (collagen-impregnated) and Vascutek (gelatine-sealed) grafts [61,62]. Outflow graft diameters can range from 10 to 25 mm but have been optimized to around 10 mm to minimize blood stasis while maintaining unrestricted flow [60,61]. A study has shown that using a 14 mm Hemashield (collagen-impregnated woven polyester) graft resulted in the formation of excessive neointimal tissue when used with an RVAD (DexAide, Arrow International, Reading, USA) [63]. This excessive tissue growth was eliminated using a 14 mm GoreTex standard walled, ringed vascular PTFE graft. However, using the same 14 mm Hemashield collagen-impregnated woven polyester graft in an LVAD (CorAide) did not result in excessive neointimal tissue. The reason for the differences is unknown, but it is speculated that they may be due to differences in pressure, flow, and shear stress or blood oxygen levels between the systemic and pulmonary circulations.

Outflow graft location and fixation

The outflow graft of an LVAD is often anastomosed to either the ascending or descending aorta (Fig. 18.12), each having advantages and disadvantages. Perfusion of vessels branching from the aorta can be affected by the location of the outflow graft. However, other locations, such as the supraceliac abdominal aorta, brachiocephalic artery, and subclavian artery grafting, have been explored as alternative options [64]. These options can be used for patients with complex medical conditions, where standard anastomosis of the ascending aorta is not possible. A study that used calves to assess the difference in myocardial perfusion between ascending and descending anastomosis reported there were no changes between the two locations [65]. Anastomosis of the descending aorta has the benefit of LVAD implantation in a less invasive matter, although retrograde flow and blood stasis may occur [66]. Due to the retrograde and disturbed flow, there are higher areas of disturbed wall shear stress, which has the possibility of increasing atherosclerosis and thrombogenesis [67]. It has been suggested that when transaortic valve flow is low, anastomosis close to the aortic valve is advantageous to prevent blood stagnation; but if sufficient transaortic flow exists, then anastomosis of the outflow graft distal to the aortic root is

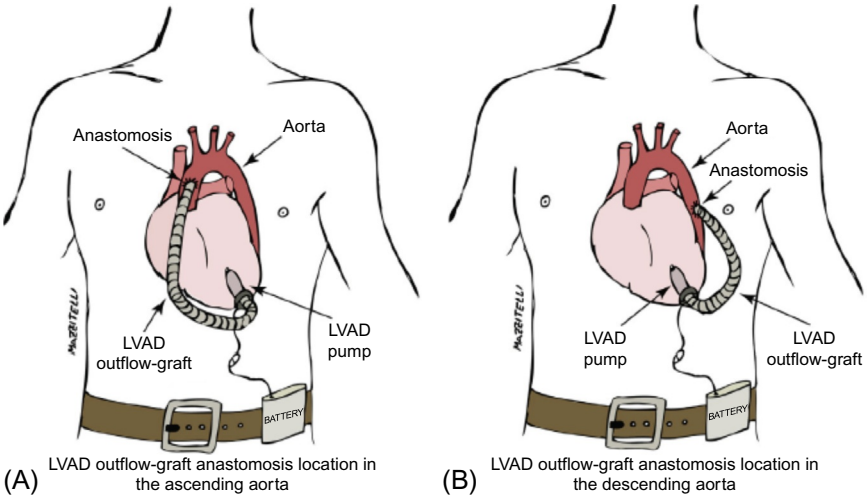


FIG. 18.12

Location of common outflow graft locations including the ascending (A) and descending (B) aorta.

Reprinted with permission from Mazzitelli R, Boyle F, Murphy E, et al. Numerical prediction of the effect of aortic Left Ventricular Assist Device outflow-graft anastomosis location. Biocybern Biomed Eng 2016;36(2):327–43.

acceptable when less invasive surgery is required [68]. Outflow grafts anastomosed to the subclavian arteries, independent of grafting angles, have been reported to provide comparable coronary and cerebral flow rates compared to conventional grafting locations [69]. Studies have reported that the reduction in anastomosis angle can reduce wall shear stresses [69,70]. When the outflow graft is anastomosed to the ascending aorta, a lower grafting angle could reduce blood residence time to the brachiocephalic, subclavian, and carotid arteries, potentially decreasing the risk of cerebrovascular accidents [70].

RVAD outflow graft anastomosis to the main pulmonary artery can be technically challenging. Thus an alternative is to use the right pulmonary artery between the ascending aorta and superior vena cava [71]. Anastomosis location for the pulmonary circulation is studied significantly less compared to the systemic circulation.

Incorrect selection or placement of the outflow graft can lead to kinking, tissue ingrowth, or graft thrombosis, which may reduce VAD flows. Although VAD recipients are usually carefully treated with anticoagulants, it has been shown that Dacron grafts have a surface with some resistance to anticoagulation, which may be a cause for thrombogenicity [72]. Dislodgement of thrombus from the outflow graft has the potential to cause cerebrovascular accidents and should be carefully monitored [73]. In general, recommendations can be provided for the location of anastomosis, but considerations must be made with the patients state in mind. As a result, the location of outflow graft anastomosis is highly dependent on patient condition, surgical constraints, and preference of the surgeon.

Banding

LVADs have been used to support the right ventricle as specifically designed RVADs are not common (refer to Chapter 6); however, due to differences in SVR and PVR, these afterload sensitive LVADs are operated at reduced speeds, often outside the design point. Operation of LVADs off-design can lead to, but is not limited to, increased risk of thrombosis. An alternative to operating LVADs off-design is the use of outflow graft banding. It has been reported that RVAD banding of 5–8 mm in diameter is suitable for LVADs to operate within the original design specifications [74]. An increase in length of the outflow graft could provide similar results to banding, but may come with an increased risk of graft kinking [75].

TOTAL ARTIFICIAL HEART

Currently, there are only two TAH devices with FDA approval: the SynCardia TAH (SynCardia Systems, Inc. Tusco, AZ, USA) and the AbioCor TAH (ABIOMED Inc., Danvers, MA, USA). The principal use of a TAH is in patients with end-stage heart failure with irreversible left and right ventricular failure for whom heart transplant is the only option. The implantation procedure can take from 5 to 9 h, and TAHs are currently used in only a small number of patients due to their complexity and associated complications. As there are very few clinically available devices and the heart is removed, there are very few options for unique cannula designs for TAHs. A brief outline of the cannula design and implantation procedure is provided in this section. For more information on TAHs, please refer to Chapter 7.

SYNCARDIA TOTAL ARTIFICIAL HEART

The SynCardia is the only TAH currently approved for use in the United States, Canada, and Europe. During the implantation procedure, both ventricles and the four heart valves are removed, leaving the atria, aorta, and pulmonary artery intact. The inflow connections are atrial cuffs that are trimmed and cut in a circular fashion to leave about 3–5 mm of sewing cuff for attachment to the left and right atria. The outflow connectors are large grafts that are prepared and preclotted or sprayed with CoSeal (Baxter, Deerfield, Illinois, USA) using a special applicator. The grafts are stretched while sprayed and allowed to dry [76]. The outflow connectors are trimmed to size, with the pulmonary artery graft usually slightly longer (5–6 cm) than the aortic graft (3–4 cm). The inflow and outflow connections contain quick-connects that are sewn into the atria, aorta, and pulmonary artery (Fig. 18.13). The TAH is then implanted and attached using the four quick-connects.

ABIOCOR TOTAL ARTIFICIAL HEART

The AbioCor TAH (Fig. 18.14) was designed to be fully implantable and has a similar graft and cuff design to the Syncardia device. The ventricles and valves are excised for graft and cuff attachment. The inlet cuffs consist of a quick-connect

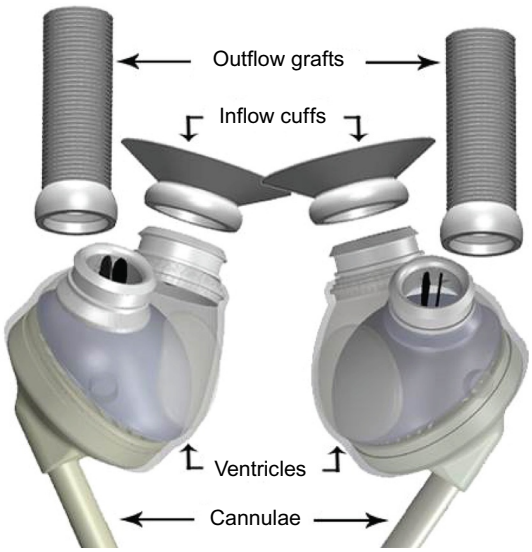


FIG. 18.13

The SynCardia Total Artificial Heart showing the inflow and outflow quick-connects.

Courtesy of syncardia.com.

system for rapid device attachment and are surrounded by a sewing ring that is trimmed to an appropriate size for the individual patient. Wide grafts attached to quick-connects are used for the outflow connections and attached directly to the aorta and pulmonary artery. The preferred order for attachment of the quick-connects, given the small space available for implantation, is the left atrial connection, followed by the aortic, pulmonary artery, and right atrial connections [77].

ALTERNATIVE TOTAL ARTIFICIAL HEART OPTIONS

Dual rotary LVADs have been used to provide TAH support in humans, with custom inflow and outflow connections developed for this specific purpose [78]. Customized cuffs have been fabricated from polypropylene hernia mesh, Dacron cardiovascular patches and medical silicone to attach the dual devices to the patient. The HeartMate II was used for this application, with the inflow cannulae removed and replaced with the customized cuffs, while short segments of the 14 mm standard outflow grafts were attached to the aorta and pulmonary artery. Although this LVAD/TAH cannula design has been used only in a few patients, it provides a novel solution to achieve TAH support with durable rotary blood pumps and demonstrates how a simple change in cannula design can repurpose reliable VAD technology for other applications.

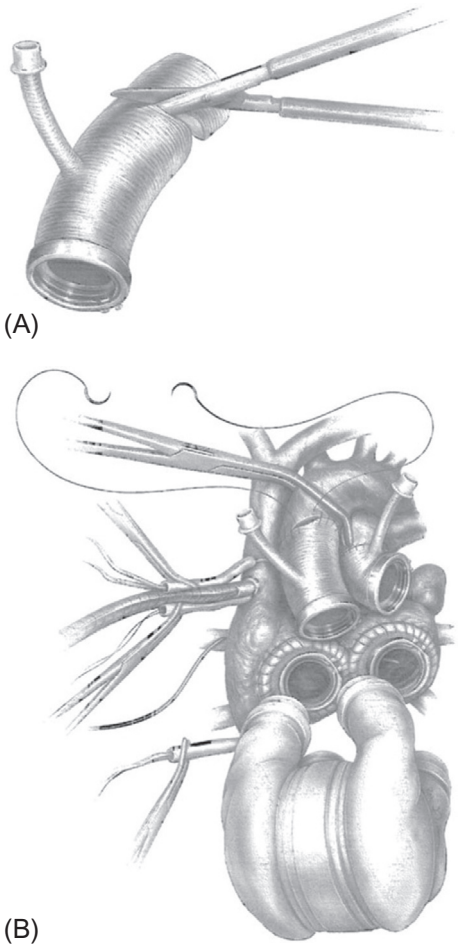


FIG. 18.14

The AbioCor Total Artificial Heart implantation showing the quick-connect systems.

Reprinted with permission from Dowling RD, Etoch SW, Gray LA, Jr. Operative techniques for implantation of the AbioCor total artificial heart. Oper Tech Thorac Cardiovasc Surg 2002;7(3):139–51.

EXTRACORPOREAL MEMBRANE OXYGENATION

ECMO is characterized by the ability to provide long-term heart-lung support (days, weeks, even months), usually by peripheral vascular access as a bridge-to-recovery or to transplant. The term ECMO is also increasingly used to describe shorter-term cardiopulmonary support (days) by central vascular access when unable to wean from CPB after cardiac surgery as a bridge-to-recovery, transplant, or decision. The cannula is one of three critical components of ECMO, along with a blood pump

and gas exchanger. The cannula is the only ECMO component implanted inside the patient's body. Cannulation is the only surgery required to put a patient on ECMO, which can be challenging. Most ECMO complications and circuit malfunctions are related to the cannula and the cannulation procedure.

Peripheral ECMO cannulae are classified as "drainage" cannula for blood withdrawal from the patient to the ECMO circuit and "infusion" cannula for blood delivery from the ECMO circuit to the patient. In the literature, some authors refer to the drainage cannula as the "inlet cannula." This terminology is confusing. If we focus on the ECMO pump/gas exchanger, then the inlet cannula refers to the drainage cannula, as in VADs. However, if we focus on the patient, as often seen in previous publications, then the inlet cannula refers to the infusion cannula. Obviously, the outlet cannula suffers the same confusion. Therefore, the terms infusion cannula and drainage cannula are used to more precisely describe flow through the ECMO circuit in this section. These terms are especially important when describing flow through veno-venous (VV) ECMO double lumen cannulae.

The basic problems facing ECMO is how much gas exchange, how much circulatory support, the projected length of time for needing support, and whether to ambulate the patient. Extracorporeal CO_2 Removal, IVOX (obsolete), and A-V CO_2R are rarely used currently, but they show the spectrum of characteristics and choices for cardio-respiratory support. Table 18.1 outlines the differences between venoarterial (VA) ECMO, VV ECMO, CPB, $ECCO_2R$, IVOX, A-V CO_2 removal and total artificial lung; it also summarizes the different cannulation configurations, required blood flow, and common complications. For more detail on ECMO configurations, please refer to Chapter 8.

CANNULA DESIGN

In ECMO cannula design and manufacture, minimal blood resistance, long-term durability, and high flexibility are desirable properties. Minimal blood resistance is required for high hemodynamic performance and low sheer stress. Poiseuille's Law describes where length is directly proportional to resistance but inversely proportional to the cannula radius to the 4th power. The maximal cannula inner diameter (ID) minimizes blood resistance, while cannula outer diameter (OD) is limited by the peripheral vessel size. Therefore, minimal cannula wall thickness is the only way to maximize cannula ID for minimal blood resistance. The drainage and infusion cannulae, therefore, become the blood flow bottleneck with the highest resistance in the ECMO circuit. Since the flow through the infusion cannula is driven actively by positive pressure using a pump, the resistance to flow is less critical than on the drainage side, where flow is by gravity drainage (CPB) or suction (ECMO). The ECMO physician must choose the access that allows maximum cannula diameter relative to the vessels available.

Higher resistance generates higher shear stress, potentially causing blood trauma. A sudden change of the cannula lumen geometry could also cause blood recirculation/stagnancy, generating thrombosis. Smooth tapering helps mitigate this blood recirculation/stagnancy. During cannula design, computational fluid dynamics are used to

Table 18.1 Comparison of Support, Cannula Characteristics and Outcomes With Various Extracorporeal Membrane Oxygenation (ECMO) and Cardiopulmonary Bypass (CPB) Configurations

	VA ECMO	VV ECMO	CPB	$ECCO_2R$	IVOX/IMO	$AVCO_2R$	Total Artificial Lung
Setting	Respiratory and/or cardiac failure	Respiratory and ambulatory	Cardiac surgery	Respiratory failure	Respiratory failure (investigational)	Respiratory failure (investigational)	Respiratory failure (experimental)
Location	Extrathoracic	Extrathoracic	Intrathoracic	Extrathoracic	Intravenacaval	Extrathoracic	Extrathoracic
Type of support	Cardiac	Respiratory	VA (total bypass)	VV (respiratory) (CO_2)	Partial respiratory (O_2 & CO_2)	AV (respiratory) (CO_2)	PA-PA or PA-LA
Cannulation	Neck or groin 2 cannulae (surgical or percutaneous)	Neck and groin 2 cannulae (surgical or percutaneous) 1 cannula (VVDL)	Direct cardiac 2 cannulae (surgical)	Neck and groin 2 cannulae (surgical or percutaneous) 1 cannula (VVDL)	Groin (femoral vein insertion)	Groin 2 cannulae (percutaneous)	Transthoracic to major vessels
Blood flow	High (70%–80% CO)	High (70%–80% CO)	Total (100% CO)	Medium (30% CO)	Variable (passive) (IVC/SVC/RA flow external to membrane)	Low (10%–15% CO)	Total (100%)
Ventilatory support	Pressure-controlled 10–12 breaths/min	Pressure-controlled or tracheotomy with spontaneous breathing. 10–12 breaths/min	None (anesthesia)	2–4 breaths/min High FiO_2	4–6 breaths/min FiO_2 for $PaO_2 > 60$	4–6 breaths/min FiO_2 for $PaO_2 > 60$	None necessary

Continued

Table 18.1 Comparison of Support, Cannula Characteristics and Outcomes With Various Extracorporeal Membrane Oxygenation (ECMO) and Cardiopulmonary Bypass (CPB) Configurations —cont'd

	VA ECMO	VV ECMO	CPB	$ECCO_2R$	IVOX/IMO	$AVCO_2R$	Total Artificial Lung
Blood reservoir	Small (50 mL)	Small (50 mL)	Large (>1 L)	Small (50 mL)	No	No	No
Arterial filter	No	No	Yes	No	No	No	No
Blood pump	Roller or centrifugal	Roller or centrifugal	Roller or centrifugal	Roller or centrifugal	None (pulsed fibers may ↑ gas exchange	None	None
Heparinization	ACT 200–260	ACT 200–260	ACT >400	ACT 200–260	ACT 200–260	ACT 200–260	ACT 200–260
Average length of extracorporeal support	Days to weeks	Days to weeks to months	Hours	Days to weeks	Days	Days to weeks	Days
Unique complications	Arterial emboli. Bleeding	Bleeding	Arterial emboli. Bleeding	Bleeding	Insertion and positioning. Bleeding	Vascular access. Bleeding	Thoracotomy. Bleeding
Unique causes of death	Air embolism. Circuit failure	Circuit failure	Air embolism. Circuit failure	Inadequate support	Inadequate support	Inadequate support	Right heart failure

LFPPV-$ECCO_2R$, low-flow positive pressure ventilation with extracorporeal carbon dioxide removal; IVOX, intravenacaval oxygenation; IMO, intravenous membrane oxygenator; $AVCO_2R$, arteriovenous carbon dioxide removal; VA, venoarterial; VV, venovenous.

evaluate blood velocity and shear stress, minimizing high sheer stress-induced blood trauma and uneven blood flow-associated thrombosis formation. The goal of cannula design is to create as little resistance and turbulence as possible to enhance flow and reduce the potential for hemolysis, circuit rupture, and system afterload.

Peripheral ECMO cannulae are vulnerable to kinking. Minimal cannula wall thickness will facilitate flow but compromise cannula strength, resulting in collapse, kinking, and less durability. A stiff cannula decreases kinking and lumen collapse, maintaining cannula integrity for consistent blood flow for days to months of ECMO duration. However, a rigid cannula cannot be curved along the blood vessel during insertion due to potential for increasing vessel damage. High flexibility plus strong construction is required to prevent blood vessel damage/penetration and cannula kinking.

In peripheral ECMO cannula design and manufacture, a balance between minimal blood resistance, wall thickness, strength, and rigidity is required for high performance, long-term durability, and high flexibility. To achieve this, thin polymer reinforced with stainless steel wire winding is usually used to make the peripheral cannula. The stainless steel wire coil functions as a backbone to ensure a strong cannula with flexibility, preventing kinking and collapsing. The thin polymer provides a smooth biocompatible surface for easy insertion and minimal thrombogenicity.

Double lumen cannulae

The AvalonElite (Maquet, Rastatt, Germany) and Origen (OriGen Biomedical, Austin, TX, USA) double lumen cannulae (DLC) were developed for highly efficient VV ECMO through single site cannulation [79–81] (Fig. 18.15). The Origen is a simple

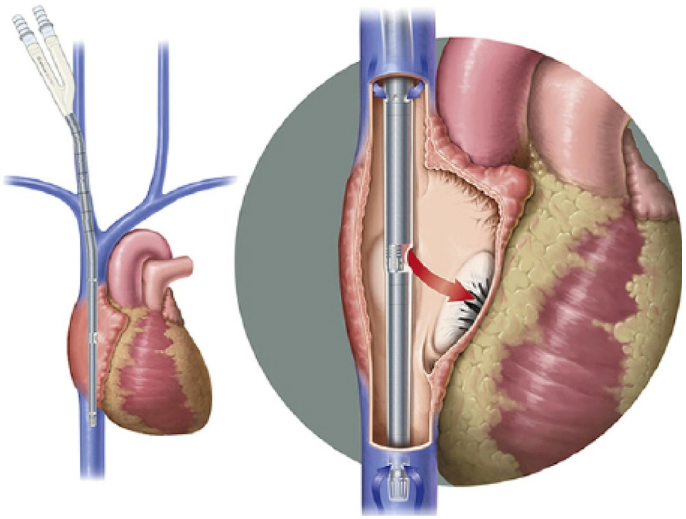


FIG. 18.15

The AvalonElite double lumen cannula.

Reprinted with permission from Lazar DA, Cass DL, Olutoye OO, et al. Venovenous cannulation for extracorporeal membrane oxygenation using a bicaval dual-lumen catheter in neonates. J Pediatr Surg 2012;47(2):430–4.

double barrel design. The AvalonElite consists of a long drainage lumen with two separate groups of drainage holes, one group in the superior vena cava (SVC) and one group in the inferior vena cava (IVC). The infusion lumen is a collapsible membrane sleeve with the infusion hole in the right atrium between these two groups of drainage holes. The AvalonElite DLC outer wall is made of high silicone content polyurethane copolymer with flat wire wound stainless steel reinforcement. The infusion lumen membrane sleeve is made of a thin silicone-polyurethane. The infusion lumen collapses to allow an introducer to fit inside the drainage lumen, smoothing percutaneous insertion. The AvalonElite DLC is designed to be inserted from the right jugular vein. When the AvalonElite DLC is properly positioned, the drainage end holes are located in the IVC, upper drainage holes are in the SVC, and infusion hole is toward the tricuspid valve. Therefore, the AvalonElite DLC withdraws blood from both the SVC and IVC through the same drainage lumen, allowing up to total cardiac output blood drainage. Infusion blood is delivered into the right atrium toward the tricuspid valve. The drainage and infusion hole(s) are spaciously and anatomically separated, mitigating recirculation [82].

The AvalonElite DLC-based VV ECMO is characterized by: (1) withdrawal of blood from both SVC and IVC through a single drainage lumen, achieving up to total venous blood drainage for total gas exchange performance, (2) negligible recirculation achieved if positioned properly, and (3) only one cannula and single-site cannulation. However, the AvalonElite DLC has flaws. Image guidance is required for: (1) DLC placement in order to prevent damage of heart and IVC and (2) properly positioning the DLC for outflow with opening toward tricuspid valve for minimal recirculation.

The Origen is less complex and drains from the SVC, while reinfusing more distally to minimize recirculation. This DLC is easier to insert, may not require image guidance, and is less expensive, but recirculation is greater than the AvalonElite.

The AvalonElite DLC has a stronger outer construction, minimizing the potential of cannula kinking. The AvalonElite DLC-based VV ECMO requires only one site cannulation from the right jugular vein (RJV), avoiding femoral cannulation, which prevents patient ambulation. Therefore, the AvalonElite DLC-based VV ECMO has enabled patient ambulation.

CANNULA PLACEMENT

The drainage cannula is usually placed into a major vein such as the SVC or IVC. Currently, a centrifugal blood pump is preferred for most adult peripheral ECMO. This pump generates significant negative pressure (up to negative 100 mmHg; when alarms sound) to draw blood out through the drainage cannula. This negative pressure could also suck the vessel wall against the drainage hole or collapse the vessel, resulting in insufficient or no drainage blood flow. To address this problem, a large bore and long drainage cannula is placed into the right atrium. The right atrium serves as a large compliance chamber to allow up to total cardiac output drainage from both the SVC and IVC. Multi-stage drainage holes make this cannula less likely

to obstruct and, therefore, more efficient. Unfortunately, if proximal drainage holes predominantly withdraw the blood, then blood flow in the distal cannula may be low and stagnant, increasing the risk of thrombosis. Therefore, size and arrangement of the drainage holes should be carefully designed to balance between minimizing blood resistance and ensuring an acceptable blood flow rate throughout the distal cannula.

In VV ECMO, blood is withdrawn from and delivered into a major vein such as the SVC and IVC. VV ECMO could be achieved by a single lumen cannula through two-site cannulation, or double lumen cannula through one-site cannulation. No matter which cannula is used and which site is cannulated, oxygenated infusion blood into the SVC/IVC is easily picked up by the drainage cannula and sent back to the ECMO circuit, resulting in recirculation [83–86]. For more detail on ECMO cannula placement and securement, please refer to Chapter 15.

CANNULA PROBLEMS

Venous cannula insertion can cause tearing of the internal jugular vein and/or SVC, resulting in massive intrathoracic bleeding. Even after appropriate venous cannula placement, cannula obstruction due to kinking is a common problem; therefore, adequate flow is extremely dependent on patient neck positioning and cannula fixation. High arterial return pressures may indicate kinking internally or by sutures. After insertion, effective placement is confirmed by unobstructed flows ranging from 120 to 150 mL/kg/min. An inability to achieve full flow on ECMO requires repositioning. Likewise, during VV ECMO, cannula malpositioning may cause increased recirculation with peripheral hypoxia.

Arterial cannulation can cause intimal dissection of the common carotid (or femoral) artery, potentially leading to lethal aortic dissection. The catheter can be inserted too far into the ascending or descending aorta, thus decreasing coronary and cerebral oxygenated blood. If returned blood flow selectively enters the right subclavian artery, the upper extremity is infused with hyper-oxygenated blood flow, while the rest of the body is hypoxic and cyanotic. A cannula in the ascending aorta can cause increased afterload to left ventricular outflow with left ventricular distension and failure. In addition, the cannula can cross the aortic valve, causing aortic insufficiency and distension. Finally, the cannula can be inserted against the left ventricular endothelium with the potential for left ventricular disruption or perforation.

Accidental decannulation can cause massive bleeding externally and internally, as well as the loss of ECMO support. The preventative measure is appropriate securing of the cannulae to the patient and a secure object. Relying solely on sutures and/or tape on the surgical site can result in them becoming loose with time. The ECMO specialist should observe and record the depth of insertion of each neck and/or groin cannula at the incision site. Comparing each previous shift can identify placement changes and alert the ECMO physician. Even with all precautions in place,

accidental decannulation may occur. Every program should have a policy and procedure in place to deal with the situation. For more information on complications with ECMO, please refer to Chapter 16.

SUMMARY AND FUTURE CONSIDERATIONS

Almost all clinically available devices for mechanical circulatory or respiratory support come with their individually designed cannulae. Perhaps the cannulae are designed for the specific device, or perhaps the field of cannula design has been left behind the development of the pump. There is no "gold-standard" cannula design available; thus further research is required to optimize cannula designs for VAD, ECMO, and TAH applications to reduce significant complications such as bleeding and thrombus formation.

Much effort and development is dedicated toward miniaturization, less power requirement, battery design, ambulation, blood-surface interactions, longevity, and eventual implantation of artificial organs. Unfortunately, cannula design is largely limited by physics. The major opportunity for design improvement is specific design for a specific application. For example, congenital heart lesions are characterized and labeled, but each patient has anatomic variability. A limited set of cannulae that are size specific will always be a compromise during application. In the future, design variability must be patient specific to accomplish needed support.

It is established that minimizing bypass time during VAD implantation decreases the risk of bleeding and end-organ dysfunction [59]. However, VAD inflow cannulation is particularly difficult off CPB as the heart is often enlarged in congestive heart failure, making access to the left ventricular apex and left lateral atrial wall mechanically difficult. In fact, insertion of the LVAD inflow cannula is almost always completed with CPB support [22]. Meticulous surgical procedures to ensure hemostasis lengthen the CPB time, which has been shown to be a significant predictor of patient survival to transplant [87]. The state of the patient's heart and surrounding vessels must also be considered when planning for mechanical circulatory or respiratory support. Insertion of cannulae cannot be hurried as the vessel is often in a condition where suboptimal fixation will almost certainly result in postoperative bleeding. Cannula design and implantation techniques can clearly influence the rates of postoperative bleeding and thrombus formation and should be considered for future developments. Particular focus should be placed on rapid cannulation techniques that can be completed without the requirement for CPB, with some devices currently under development [88,89].

CONCLUSION

Cannula-related complications, including bleeding and thrombus formation, are significant after VAD, TAH, or ECMO implantation. Despite the advances in cannula design and various techniques for placement and securement, mechanical circulatory and

respiratory support remains riddled with the same complications seen in previous decades. Continued cannula development with a focus on rapid implantation and patient-specific designs is vital to improve the outcomes of these critically ill patients.

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