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Review Article

The Evolution of Aortic Cannula Modification: A Mini Review

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ABSTRACT

Aortic cannulation is a surgical technique used in cardiac surgery to establish extracorporeal circulation, enabling the surgeon to bypass the heart's function temporarily during procedures such as coronary artery bypass grafting (CABG), valve replacement, aortic aneurysm repair, and congenital heart defect corrections. This technique involves accessing the aorta, the largest artery in the body, and connecting it to a cardiopulmonary bypass (CPB) machine, which takes over the pumping function of the heart and provides oxygenated blood to the body's organs and tissues. Aortic cannulation is a critical step in cardiac surgery, providing the necessary access to the heart and vasculature while ensuring adequate perfusion of vital organs during surgical interventions. Careful attention to patient selection, cannula placement, and intraoperative monitoring is essential to optimize outcomes and minimize complications. To appreciate the contemporary landscape of aortic cannulation, it is imperative to embark on a historical journey through its evolution. The roots of aortic cannulation trace back to the pioneering efforts of early cardiac surgeons. Their ingenuity and perseverance laid the foundation for the refined techniques in practice today. Over the years, aortic cannulation techniques have undergone a metamorphosis, driven by advances in surgical instruments, technology, and a deepening understanding of cardiovascular physiology.

INTRODUCTION

According to the 2020 update of "Heart Disease and Stroke Statistics" (Virani et al., 2020), cardiovascular disease (CVD) remains the most common and complex medical condition, accounting for 859,125 deaths in 2017, making it the leading cause of death in the United States. 36% of all fatalities in 2014 were due to morbidity and mortality resulting from CVD. Despite incredible advancements in medical treatment, heart failure (HF), a progressive illness with an unclear etiology that is sometimes accompanied by or made worse by acute cardiomyopathy or chronic hypertension, was directly responsible for 9.4% of these fatalities (Miller et al., 2007). It is the most expensive diagnostic category globally, with costs exceeding $213.8 billion between 2014 and 2015 because to its intricate process and ongoing care (Benjamin et al., 2019). With a rate as high as 2-5%, stroke is a fatal side effect of cardiopulmonary bypass (CPB) surgery (Houlind et al., 2012).

The quality of life is significantly impacted by aortic illness (De Lazzari et al., 2023). The most dangerous signs of aortic illness are aneurysmatic dilatation and acute aortic dissection involving the aortic arch. There are existing methods for treating these disorders by endovascular or surgical means. While a successful complete arch repair yields a good result, there is a chance of catastrophic postoperative consequences. Most patients can be offered conventional aortic arch replacement, while hybrid and

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endovascular methods are becoming more and more common. However, stroke and endo-leaks are early limiting factors and have less favourable mid- to long-term results; hence, a less invasive method can sometimes be as technically demanding as open surgery (Bachet et al., 2018). Both hybrid and traditional aortic arch surgery have variable mid-term results and rates of intraoperative complications, which are influenced by patient appropriateness and centre experience (Chakos et al., 2018).

Additionally, an epiaortic echogram was used to demonstrate the atheromatous plaque breakup caused by the jet from the aortic cannula (Fukuda et al., 2007). An epiaortic echogram is an ultrasound imaging technique used to visualize the aorta, particularly its ascending portion, during cardiac surgery. It provides detailed images of the aortic wall, aortic valve, and nearby structures. This technique is especially useful for detecting atherosclerotic plaques, thrombi, or other abnormalities in the aorta that could complicate surgical procedures like coronary artery bypass grafting (CABG) (Fukuda et al., 2007). Jet flow detection in an epiaortic echogram refers to identifying abnormal blood flow patterns, such as high-velocity jets, which may indicate pathological conditions like aortic valve regurgitation or stenosis (Fukuda et al., 2007).

A possible reason for the development of lesion and rupture of the existing atheroma has been identified as the sandblasting effect, which is the quick and highly focused blood flow from typical end-hole aortic cannula (Schnurer et al., 2011). Several researches have attempted to improve the aortic cannula's design in order to give the best possible blood perfusion, in an attempt to prevent this deadly consequence. By altering the tip, inserting a spiral rib inside the cannula tube, integrating the stator, and changing the internal profile of the tube at the cannula's body part, later designs of the single stream cannula have evolved to multiple streams, dispersed stream cannulas, and the current spiral flow stream (Kauffman et al., 2014; Scharfschwerdt et al., 2013). It has been demonstrated that modified cannulas, in particular spiral flow aortic cannulas, provide superior hemodynamics when compared to commonly used normal end-hole cannulas (Kauffman et al., 2014; Menon et al., 2013).

In the meanwhile, it has been demonstrated that the blood flow within the aorta naturally exhibits spiral flow features. Using Magnetic Resonance Imaging (MRI), ultrasound, and angiography, the healthy spiral flow motion was verified from the imaging of thoracic aortic diseases (Tanaka et al., 2010). Spiral flow is thought to offer a number of benefits, including shielding the arterial wall from harm, creating a steady flow through a curved pathway, lessening the intensity of turbulence, preserving flow mechanical forces like wall shear stress level, and clinically reducing thrombosis and intimal hyperplasia (Ha et al., 2014; Linge et al., 2013; Stonebridge et al., 2012). Additionally, previous study also found that by increasing the oxygen flux to the arterial wall, a spiral arrangement of blood flow is more effective in transporting oxygen (Liu et al., 2010).

This paper aims to provide a comprehensive mini-review on the evolution of aortic cannula modifications. It will present the outcomes from previous studies, offering insights into the advancements and effectiveness of these modifications in clinical practice. By examining the progression of design and technological improvements, this review will highlight the impact of these modifications on surgical outcomes, patient safety, and overall procedural efficiency. Additionally, it will discuss the challenges encountered and the solutions developed over time, offering a thorough understanding of the current state and future directions of aortic cannula technology.

Problems Associated with the Aortic Cannula

The extracorporeal circuit's thinnest segment is the aortic cannula. Using a conventional end-hole of 24 Fr (8 mm in tip diameter) and a simple calculation at 5 L/min, the outflow velocity immediately following the cannula tip could theoretically reach 1.66 m/s as blood shoots into the aortic arch. The highest velocity in the aortic root throughout a cycle is 0.7 m/s, in comparison to the healthy situation (Levick et al., 2003). When there is a discrepancy more than twice, there may be unfavorable pressure gradients, high jet flow velocities, turbulence, and cavitation. This unfavorable pressure gradients occur when the pressure difference between two points in a fluid flow system is not conducive to smooth and efficient flow. In the context of cardiovascular physiology and jet flow within the arteries, unfavorable pressure gradients can have significant implications.

Aortic manipulation and changed flow conditions inside the aortic arch have been implicated in several clinical investigations as the primary causes of intra-operative stroke seen in on-pump CPB patients (Selnes et al., 2012). Nonetheless, it has been stated that the primary cause of the sandblasting effect is the typical end-hole aortic cannula (Gerdes et al., 2002). The endothelial lesions at the cannulation location opposite to the 40 healthy aorta specimens in a swine CPB model resulted from a jet that struck the aortic wall straight from the cannula's tip to (Schnurer et al., 2011). This move raises the risk of atherosclerosis formation, this is a chronic vascular inflammatory disease, which preferentially develops at sites under disturbed blood flow with low speeds and chaotic directions, and atheromatous embolisation refers to the process where pieces of atherosclerotic plaque break off from the arterial wall and travel through the bloodstream. This can lead to serious complications (Wang. L et al, 2020).

Remarkably, individuals with atheromathous aorta and those who are elderly experience a considerably more severe sandblasting impact. This is due to the aortic wall's stiffness as well as the possibility of a jet flow striking the plaque and causing atheroembolism (Laumen et al., 2010; Minakawa et al.,2010). Meanwhile, investigations have demonstrated that the jet from the aortic cannula clearly demonstrated the breakdown of the atheromatous plaque (Fukuda et al., 2007), and it has been documented in several studies that the perfuse jet flow from the tip of the aortic cannula is one of the main causes of atheroembolism (Tenenbaum et al., 2001; Weinstein et al., 2001).

Moreover, the ascending aorta is the source of 30–50% of perioperative strokes identified by brain imaging during surgery (Djaiani et al., 2004). Following coronary artery bypass graft surgery, other investigator successfully investigated the mechanism causing strokes. They discovered that 62.1% of strokes were caused by embolic mechanisms, which are derived from atrial fibrillation and atherosclerotic plaque, and 8.8% were caused by hypoperfusion mechanisms (Likosky et al., 2003).

Aortic Cannula Modification

Many studies have attempted to design an aortic cannula that can passively induce spiral flow due to the benefits of spiral flow that have been documented. These techniques include inserting a spiral guide inside the cannula tube, integrating a stator, and altering the internal profile of the tube at the cannula's body part (Kauffman et al., 2014; Menon et al., 2013). Aortic cannulas with dispersive mesh-like tips and funnel shapes that induce spinning stators (Assmann et al., 2015) and pentagonal tips with obtuse angles that create flame-like streams (Goto et al., 2015) are among the most recent described modifications.

While Joubert-Huebner et al. (2000) devised a dispersion tip that resulted in a disperse stream type, Gerdes et al. (2002), innovated by inserting a stator at the cannula body to achieve a spiral flow stream. This was followed by Scharfschwerdt et al. (2004) who created an angled circular lamellae tip, yielding multiple streams. Later, White et al., (2009) introduced an expanded angle funnel-tip that produced a single stream type. Avrahami et al. (2013) designed a backward suction cannula, also producing a single stream. Other researcher (Kaufmann et al., 2014) incorporated an internal profile at the cannula body along with a diffuser tip to generate a spiral flow. Finally, (Darlis et al., 2015) added an internal groove profile at the cannula body with variations of 2, 3, and 4 grooves, which resulted in a spiral flow stream type.

In the meanwhile, Menon et al. (2013) have investigated the design of a four-lobed groove profile for a swirl inducer in conjunction with a diffuser tip. Positive results showed that by utilising this feature, the pressure drop in the aortic cannula was further reduced. Additionally, the dye-flow visualisation experiment verified that the swirl inducer grooves' size and prominence play a significant role in improving the coherence of the outlet jet at high speeds. However, they recommended that more research be done on the impact of pitch length, number of turns, and swirl inducer diameter because the study was restricted to variations in groove depth.

Zhan et al. (2010) developed a spiral guider that can be utilised to supply spiral flow during small-caliber artery graft bypass operations, despite the need to modify a body component to produce spiral flow. The guider's outer radius was the tangential location for the intake section. Inside the guider, the angular flow motion was created from the linear flow motion coming from the intake. When compared to the inner radius of the guider, the peripheral speed was greater at the outside radius. This is comparable to the notion of force vortex flow. According to this theory, some of the rotational energy of the rotating object will be transferred to the fluid within. A rising tangential velocity for increasing values of radius is its defining characteristic (Philip et al. 2011). To provide passively induced flow, the spinning device function was substituted by tangentially positioning the input flow at the spiral guider's outer radius. Because of this, the spiral guider concept was applied in this work to modify the aortic cannula at its entrance.

Current and Future Perspective of Aortic Cannula

The future of aortic cannula design and technology in cardiac surgery looks promising, driven by ongoing advancements in biomedical engineering, materials science, and surgical techniques. One key area of development is the use of advanced materials, including biocompatible and antithrombotic coatings like heparin-bonded surfaces and novel biopolymers that promote better blood compatibility (Darlis et al., 2018). Additionally, flexible and durable materials will enhance the ease of cannula insertion and reduce the risk of vascular damage and minimize the clinical risk of the cannulation site. Innovations in flow dynamics, such as spiral flow technology, will improve blood flow patterns and reduce shear stress through sophisticated internal designs and computational fluid dynamics (CFD) (Darlis et al., 2018).

Besides, minimizing jet flow through multi-orifice tips and novel geometries will further mitigate complications like endothelial damage and hemolysis. Minimally invasive and hybrid approaches will benefit from smaller, more versatile cannulas, enabling less invasive surgical techniques and reducing patient recovery times (Goto et al., 2021). The prior researcher used CARDIOSIM©, a numerical simulator, in conjunction with smart cannulas. The impact on energetic and hemodynamic parameters, as well as the benefit in terms of organ perfusion pressure and flow, were analysed using the CARDIOSIM© cardiovascular simulation platform. A three-way cannulation method for aortic arch surgery is theoretically supported by a simulation technique based on lumped-parameter modelling, pressure–volume analysis, and modified time-varying elastance, which is correlated with actual clinical practice (De Lazzari et al., 2023). Automated deployment systems and robotically assisted cannulation will increase precision and safety by lowering the need for manual methods and minimising human error.

Next, personalized and patient-specific cannulas, enabled by 3D printing technology, will allow for the creation of anatomically tailored cannulas, improving fit and function. Data-driven design using machine learning algorithms will optimize next-generation cannulas for various clinical scenarios. Enhanced training tools, such as virtual reality (VR) and augmented reality (AR), will provide realistic simulations for complex procedures, improving surgical proficiency. Advanced simulation environments will test and refine new cannula designs under various physiological conditions, ensuring safety and efficacy before clinical use (Darlis et al., 2018).

Hybrid methods combining femoral and direct aortic access will optimize patient-specific approaches and improve outcomes (Choudhary et al., 2023). In some situations, the pathology's unique needs can necessitate using a different cannulation site. The most important first step in type A aortic dissection is selecting the appropriate cannulation site. The choice of cannulation sites needs to be unique to each patient. Femoral, right axillary, innominate, carotid, central aortic, transapical, trans-atrial, and direct true lumen cannulation are among the several cannulation procedures. Cannulation should be simple, fast, and appropriate for all clinical situations. It ought to let CPB to proceed normally without cerebral embolisation or malperfusion. In addition, the cannulation technique needs to provide the choice of selective antegrade cerebral perfusion and be devoid of difficulties related to the local site or neurovascular system (Choudhary et al., 2023).

From the authors point of view, the multidisciplinary collaboration between cardiac surgeons, biomedical engineers, materials scientists, and computational experts will foster innovation and accelerate the development of cutting-edge solutions. Ensuring new technologies meet regulatory standards and addressing ethical considerations related to patient safety and data privacy will be crucial for their adoption. In summary, the future of aortic cannulas in cardiac surgery is set to be shaped by technological innovations, advanced materials, personalized medicine, and enhanced surgical techniques, all aimed at improving patient outcomes, reducing complications, and expanding the possibilities of cardiac surgery.

CONCLUSION

Cannulas are often used extensively in medical procedures, either in the operating room or on the ward, to transfer fluids between the patient and the machine. There are several varieties of cannula, each intended for a specific purpose. Cannulas are usually used in pairs, one for drainage and one for return. During CPB, a variety of commercially available cannula types are utilised, such as arterial, which restores oxygenated blood to the body, venous, which drains deoxygenated blood from the body, and cardioplegia, which provides a cardiac arrest supply solution. Given that CPB involves a significant surgical operation, it has been demonstrated to be a very essential method in cardiac surgery. This technique's greatest strength is its ability to give the surgeon a clean field for manipulating the heart while maintaining pulmonary and hemodynamic stability. The field is also immobile and largely bloodless.

The historical development and evolution of aortic cannulation techniques underscore the relentless pursuit of excellence in cardiac surgery. From the pioneering efforts of early cardiac surgeons to the cutting-edge technologies of today, the journey of aortic cannulation reflects the progress of cardiac surgery as a discipline. By embracing innovation, collaboration, and evidence-based practice, cardiac surgeons continue to push the boundaries of what is possible, ensuring better outcomes for patients undergoing cardiac interventions. Modern aortic cannulas incorporate advanced flow dynamics to reduce shear stress and jet flow, enhancing patient outcomes. Techniques such as spiral flow technology, which induces beneficial helical blood flow patterns, have been integrated into cannula design to minimize complications. The shift towards minimally invasive and hybrid surgical approaches has driven the development of smaller, more versatile cannulas, enabling procedures with reduced recovery times and lower risks.

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