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Research Article

Extracorporeal Circulation and Venous Hemodynamics: A Literature Review on Physiological Foundations to Clinical Applications

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Abstract

The venous system constitutes a vital component of the human circulatory system, facilitating the return of deoxygenated blood from tissues and organs back to the heart. During cardiac surgeries while using cardiopulmonary bypass (CPB), a critical step involves diverting venous blood from a cannula through the heart-lung machine, where it undergoes oxygenation before re-entering the arterial circulation. This process demands careful control and management to ensure safe and effective perfusion throughout the body. This research paper offers an exploration of venous drainage strategies in the context of cardiac surgery and other applications of extracorporeal life support. The PRISMA method was employed as the guiding framework for conducting this review. The investigation utilized a qualitative research design to assess the artificial circulation and venous dynamics. Out of 85 selected journal publications, 63 peer-reviewed and evidence-based research works were shortlisted. Through an examination of existing evidence, the author underscores the significance of precise venous cannulation techniques and drainage approaches, underscoring the influence on hemodynamics, clinical outcomes, and potential complications. The study delves into advanced monitoring methods and future prospects within the realm of venous drainage. The insights presented in this review serve as a valuable resource for evidence-based decision-making, ultimately contributing to improved patient outcomes and elevated surgical practices.

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Keywords: Venous hemodynamics; Extracorporeal circulation; Venous system; Cardiac surgeries; Arterial circulation; Heart-lung machine.

Introduction

The venous system plays a pivotal role in the circulatory system by returning deoxygenated blood from tissues and organs to the heart. In the context of cardiothoracic surgery, redirecting venous blood into a heart-lung machine for oxygenation before it returns to arterial circulation is a critical procedure. This complex process requires careful management to ensure safe and effective perfusion throughout the entire body. This research paper aims to provide an understanding of the human venous system in conjunction with artificial venous circulation systems. It explores various applications of artificial circulation concerning the venous system, encompassing CPB, Extracorporeal membrane oxygenation (ECMO), Veno-Veno Bypass for liver transplantation, Ventricular Assist devices (VADs) for ventricular failure, and bridge to transplantation.

Additionally, it delves into the crucial role of monitoring during these applications. By examining existing evidence and insights, this paper underscores the critical importance of precise venous cannulation techniques, effective drainage strategies, potential venous complications, and the impact on patient outcomes. Furthermore, it discusses strategies for enhancing these procedures to improve overall patient care and results.

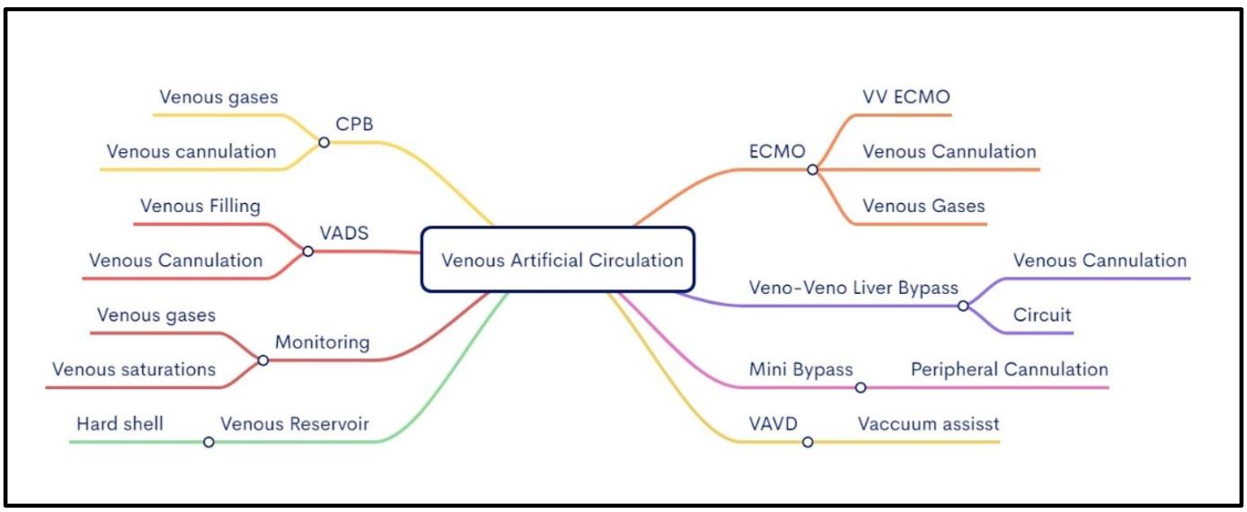

Figure 1: Illustration of venous aspects in perfusion.

Methods

The PRISMA method was employed as the guiding framework for conducting this review. The investigation utilized a qualitative research design to assess the artificial circulation and venous dynamics. Out of 85 selected journal publications, 63 peer-reviewed and evidence-based research works were shortlisted. The inclusion criteria involved empirical studies, observational research, and comprehensive reviews, resulting in 63 relevant research works.

The review process involved open-source journal publications and the Google Scholar database. Special attention was paid to the methods of facts collection and the validity of information garnered from secondary sources. The research engagement employed all the provisions of ethical conduct in research.

Themes/Factors	Authors/Year
Venous Anatomy	Saad AM, et al, 2020[1] Ismail A, et al, 2023[2] Wilson, et al, 2021[3]
Venous Physiology	Persichini R, et al, 2022[4] Tansey EA, et al, 2019[5] Skytioti M, et al, 2020[6]
Venous assist drainage	Fois M, et al, 2022[7] Datt B, et al, 2023[8] Narasaki S, et al, 2022[8] Sibel A, et al, 2020[22]
Cannulation	Pozzoli A, et al, 2022[10] Tovedal T, et al, 2010[11] Ceresa F, et al, 2023[12] Bennett MJ, et al, 2019[13] Goto T, et al, 2018[14]
Monitoring	Roberts A, et al, 2023[15] Ameloot K, et al, 2016[16] Svenmarker S, et al, 2016[17] Reagor J, et al, 2021[18] Osborne SC, et al, 2022[19]
Venous Reservoir and assisted venous drainage	Benim, et al, 2020[20] Saczkowski, et al, 2022[21] Daniel K A, et al, 2002[23] Élio Barreto de CF, et al, 2014[24] Kieron C P, et al, 2011[25] Norihiko S, et al, 2005[26] Masashi T, et al, 2016[27]
MIECC	Turki BA, et al, 2021[28] Raed AA, et al, 2012[29] Fernandes P, et al, 2009[30]
Veno- Veno bypass	Warangkana L, et al, 2020[33] Gianmarco G, et al, 2022[34] Chady S, et al, 2016[35] Fan SL, et al, 2022[36] Kurinchi SG, et al, 2011[37] Fan SL, et al, 2022[38] Kim HY, et al, 2018[39] Katrin H, et al, 2009[40]

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Extracorporeal Membrane Oxygenation	Banfi C, et al, 2016[41] Kim J H, et al, 2020[42] Lindholm J A , et al, 2018[43] Shaheen A, et al, 2016[44] Munshi L, et al, 2019[45] Menaker J, et al, 2018[46] Menaker J, et al, 2019[47] Tulman D, et al, 2014[48] Byun J H, et al, 2020[49] Banning A S, et al, 2021[50] Kanagarajan D, et al, 2023[51] Ius F, et al, 2015[52] Sohail S, et al, 2021[53] Winiszewski H, et al, 2022[54] Gugli, M, et al, 2019[55] Le Gall A, et al, 2017[56]
Ventricular Assist Device	Salna M, et al, 2020[57] Condello I, et al, 2020[58] Saito S, et al, 2012[59] Ricklefs M, et al, 2018[60] William Z, et al, 2018[61] Punjabi PP, et al, 2013[62] Ganushchak Y, et al, 2015[63]

Table 1: Illustration of studies to the related themes.

Human venous system

The human body pumps around 7,000 liters of blood each day, and the heart beats roughly 2.5 billion times in an average lifetime. The human venous system constitutes a vital component of the circulatory system, responsible for returning deoxygenated blood from tissues throughout the body back to the heart. Comprising a complex network of veins, these vessels play a crucial role in maintaining overall cardiovascular function. Veins are characterized by thin, flexible walls, which allow to handle changes in blood volume and pressure. Veins are equipped with one-way valves that prevent backflow of blood, ensuring a unidirectional flow towards the heart. The largest vein in the body, the superior and inferior vena cava, carries deoxygenated blood from the upper and lower body, respectively, into the right atrium of the heart, initiating the pulmonary circulation process. Overall, the human venous system serves as a vital conduit for efficient blood circulation, assisting in the transport of vital nutrients, waste products, and metabolic byproducts essential for maintaining homeostasis and sustaining human life [1].

Coronary veins drain blood from the heart's muscle. Which can be divided into two groups: greater (including the coronary sinus) and smaller veins. The coronary sinus is the largest and empties into the right atrium, crucial for retrograde cardioplegia delivery while monitoring pressures to prevent complications [2,3].

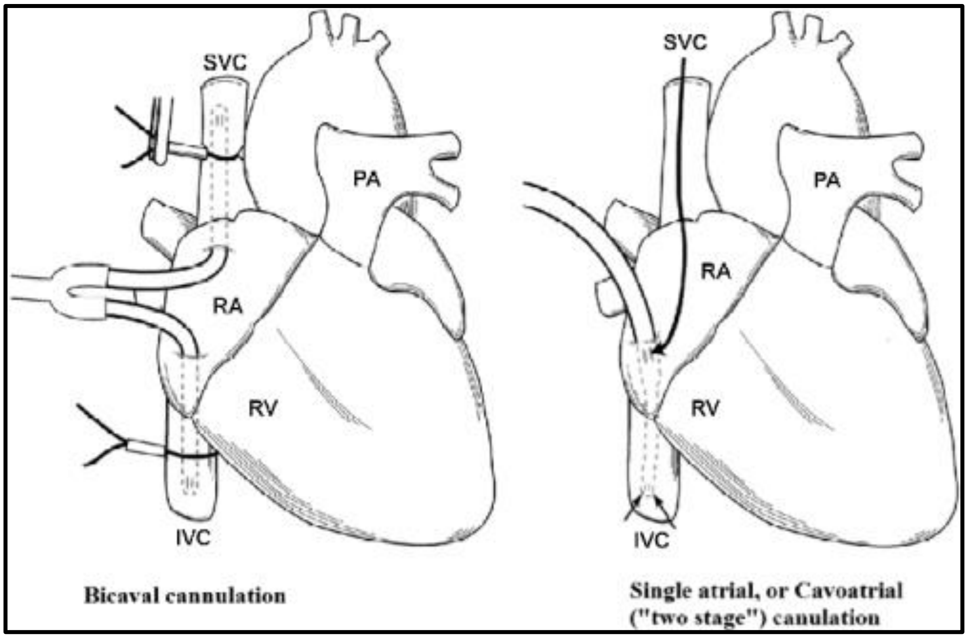

Figure 2: Illustration of single and bicaval venous cannulation for CPB [4].

The volume of blood returning to the right atrium depends on various factors, including systemic filling pressures, right atrial pressures, and vascular resistance [5].

Venous return =(Pmsf-RAP)/RVrVenous return =(Pmsf-RAP)/RVr

In the given formula, Pmsf (Mean Filling Pressure) represents the driving force for blood flow into the right atrium, originating from the elastic recoil potential stored in vein walls, influenced by vessel compliance and system volume. Conversely, right atrial pressures exert a counteracting force hindering venous return, influenced by factors like the weight of the blood column extending from the heart to the limbs when venous valves close, and the efficiency of the right ventricle as well as pleural pressure changes during ventilation. Additionally, resistance to venous return is a significant factor, determined by factors such as vein diameter controlled by the sympathetic nervous system and adrenergic tone [5]. Neurohumoral mechanisms play a pivotal role in regulating venous blood flow to maintain the right heart filling pressure. For instance, during exercise or hemorrhage, sympathetic activity triggers venoconstriction via adrenergic stimulation, reducing venous compliance, increasing peripheral venous pressure, and propelling blood forward. This venoconstriction and venodilation significantly impact total blood volume distribution and influence Central Venous Pressure (CVP), stroke volume (SV), and arterial blood pressure. Alpha-adrenergic-mediated venous constriction shifts blood from unstressed to stressed volume. In addition to neurohumoral mechanisms, the muscle pump system is another essential factor in promoting venous return during locomotion. Peripheral veins in the limbs feature one-way valves that direct blood flow towards the heart as surrounding muscles compress the veins during contraction, propelling blood in the heart's direction. Inspiration further enhances

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venous return as intrathoracic pressure drops, causing veins to compress during lung expansion. Studies suggest that respiratory pumps, such as spontaneous negative-pressure ventilation, contribute significantly to venous return and stroke volume, ameliorating reductions induced by hypovolemia [6,7].

Cardiopulmonary bypass and venous dynamics

During CPB, blood that would typically flow into the right atrium is redirected to the heart-lung machine via a cannula. This modification transforms the cardiovascular system from a closed to an open circuit, incorporating a venous reservoir. Cardiac output is controlled by the pump's flow, and the venous blood is efficiently drained into the heart-lung machine through a simple siphonage effect, sometimes with vacuum assistance. The lungs are deflated, neuromuscular blocking drugs are administered, and cardioplegia stops the heart's beating. Factors like patient's circulating volume, vacuum/kinetic assist, circuit setup (tubing sizes, gravity), and cannula placement all influence the return of blood into the reservoir.

Posture also plays a significant role in venous return during CPB (cardiopulmonary bypass). In the Trendelenburg position, gravity facilitates the pooling of blood in the right atrium, ensuring a greater volume is available for efficient flow down the venous cannula. Poiseuille's law underscores that the laminar flow rate of a fluid through a tube depends on several factors, primarily the diameter to the fourth power and resistance, encompassing fluid viscosity and tube length, while the pressure difference across the tube influences it as well. A study effectively demonstrated this principle by reducing priming volume, transitioning from a ½" to a 3/8" venous line, and compensating for the diameter reduction by shortening the tube's length, thereby maintaining optimal venous drainage. Given that blood viscosity typically remains within physiological limits during bypass, fine-tuning the diameter and length of the tubing can optimize venous return in a bypass circuit [8,9].

$$\Delta p = \frac{8\mu L Q}{\pi R^4}$$

Hagen-Poiseuille's equation

Various cannulas are strategically positioned within the veins to facilitate blood withdrawal, with studies emphasizing the critical nature of proper cannulation techniques [10-12]. However, beyond correct placement, the design of the cannula itself carries substantial significance. A recent study comparing smart cannulas to thin-walled counterparts indicates the advantages of using virtually non-walled cannulas, as it requires less suction assistance for achieving the same level of drainage efficiency. Furthermore, research underscores the importance of cannula diameter over the number of holes, revealing that the latter can lead to negative pressures. Similarly, another study highlights the adverse effects of increasing the number of holes while maintaining consistent surface area along the side of a cannula, as it induces flow separation from the tip-hole of the cannula [13-15].

Effective monitoring plays a pivotal role in ensuring proper venous drainage during all phases of CPB, from initiation to management and weaning. Inadequate

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venous drainage can result in suboptimal flow rates, cardiac distention, and potentially serious complications such as cerebral edema and lower-body congestion. Early detection of poor venous drainage can be achieved by monitoring the volume level in the venous reservoir and assessing Central Venous Pressure (CVP).

Furthermore, ultrasonography is a valuable tool for verifying correct cannula placement, while Transesophageal Echocardiography (TEE) proves especially useful in the context of peripheral venous cannulation. Near Infrared Spectroscopy (NIRS) has also been applied to identify lower cerebral oxygen saturation levels during venous congestion.

On the heart-lung machine, monitoring venous saturations becomes crucial as it offers insights into the balance between oxygen delivery and demand. These measurements, often employed in cardiac surgery, have a demonstrated impact on patient outcomes. Additionally, various devices, as discussed by Mark, et al., are available for real-time gas analysis, which serves as a comparable alternative to blood gas machines and aids in optimizing patient care during surgery [16-20].

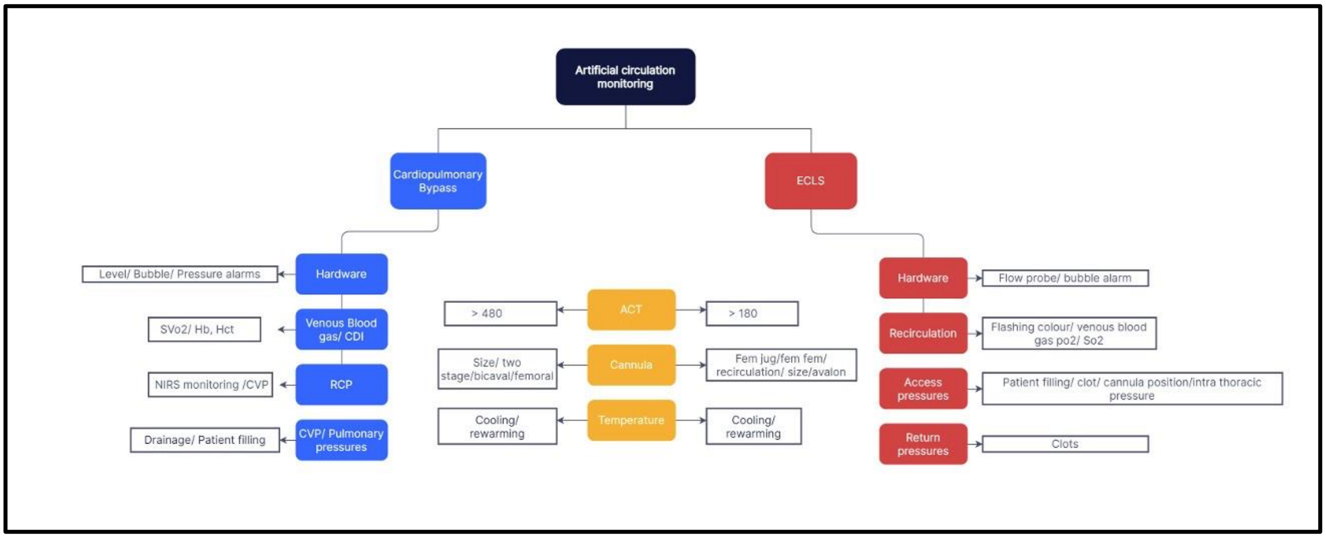

Figure 3: All aspects of venous monitoring in artificial Circulation.

Venous reservoirs and VAVD

The use of venous reservoirs, encompassing both soft shell and hardshell designs, is an integral aspect of CPB system, providing essential extracorporeal circulation support. To optimize patient outcomes, a deep comprehension of the distinct characteristics and impacts of these reservoirs is imperative.

An investigation by Benim, et al., delved into the hemodynamics of hardshell venous reservoirs in comparison to other components in extracorporeal circulation. Utilizing computational simulations, the authors analyzed flow patterns within two distinct hardshell reservoir designs. Notably, one design exhibited significant turbulence near the drainage tube connection, consequently elevating the Modified Index of Hemolysis (MIH) value due to its influence on blood damage potential [21]. Saczkowski, et al., undertook an evaluation of integrated

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pressure relief valves (IPRVs) in hardshell venous reservoirs, specifically in the context of Venous assisted venous drainage (VAVD). The findings underscored the variability of internal reservoir pressures based on different gas inflow rates. Additionally, the study highlighted the limitations of external secondary one-way valves (ESOVs) in mitigating reservoir pressurization events, thus emphasizing the need for improved communication regarding these devices' capabilities and limitations [22].

Addressing concerns of hemolysis in CPB, Almany, et al., explored the effects of VAVD and gravitational drainage (GD) on hemolysis during cardiac surgery. The observations revealed that despite applying lower negative pressure, VAVD offered a safe and effective means of improving venous drainage and cardiac decompression without exacerbating hemolysis or necessitating excessive fluid administration [23].

The limitations of positive pressure release valves (PPRVs) on hardshell venous reservoirs were investigated by Almany, et al. The study indicated varying levels of pressurization control among different PPRVs, highlighting the importance of comprehensive evaluation of reservoirs and associated PPRVs for maintaining safety under diverse clinical conditions [24].

Élio Barreto de Carvalho Filho's systematic review provided insight into the advantages and disadvantages of VAVD within CPB. This review showcased reduced transfusion rates and improved operative field visibility, ultimately suggesting that the benefits outweigh potential complications when implemented alongside appropriate technology and expertise [25].

Microbubble generation and air transmission within venous reservoirs were explored by Potger, et al. The in-vitro study underscored the critical necessity of preventing venous air entrainment during CPB procedures. Both closed soft-shell venous reservoirs (SSVR) and open hard-shell venous reservoirs (HSVR) demonstrated microbubble transmission at higher flow rates, emphasizing the importance of minimizing this phenomenon [26].

Shiiya, et al., introduced a modified closed-loop CPB system featuring a soft reservoir bag connected in parallel with a centrifugal pump to enable preload control during distal aortic perfusion. This innovative approach was proven effective in maintaining venous drainage, allowing for reduced heparin dosage, and avoiding abrupt increases in proximal aortic pressure during aortic cross-clamping [27].

Investigating the sterility and biocompatibility of stored open-reservoir CPB circuits, Tagaya, et al., found these standby circuits to be safe in terms of bacterial count, endotoxin presence, and chemical substances. These findings affirm the usability of such circuits without compromising safety during CPB procedures [28].

In essence, Venous reservoirs are pivotal in CPB systems. Studies probe diverse designs, highlighting turbulence-triggered blood damage in hardshell models. The effectiveness of pressure relief valves in these reservoirs varies and positive pressure release valves (PPRVs) show inconsistent pressurization control. VAVD emerges as a secure method for effective drainage and CPB decompression with reviews favor VAVD's

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benefits: less transfusions, improved surgery visibility. Finally, research confirms stored CPB circuits' safety, affirming sterility and biocompatibility.

Mini bypass circuit and venous drainage

The integration of mini bypass circuits has brought about transformative changes in cardiac surgery, yielding improved patient outcomes and refined surgical techniques. Within this context, the role of venous drainage has emerged as a pivotal factor in ensuring effective perfusion during CPB procedures.

Advanced venous cannulas tailored for mini bypass circuits have demonstrated the efficacy in optimizing venous drainage. These cannulas are designed with specialized attributes such as multiple drainage ports and optimized shapes to facilitate unhindered blood flow. By preventing stagnation and clot formation within the cannula, these innovations enhance the overall venous drainage process, consequently reducing the likelihood of complications during CPB [29].

Furthermore, the incorporation of venous reservoirs in mini bypass circuits is notable. These reservoirs serve as intermediate storage for blood during CPB, designed to ensure efficient venous drainage and mitigate the risk of air emboli. Enhanced bubble trapping mechanisms within these reservoirs offer an added layer of patient safety, minimizing the introduction of air into the circulatory system and its potential adverse effects [30].

The implementation of VAVD systems within mini bypass circuits represents a significant stride in optimizing venous drainage during CPB. VAVD has shown promise in diminishing blood trauma, reducing hemodilution, and enhancing cardiac performance during surgery [31]. Consequently, the integration of VAVD contributes to maximizing venous drainage efficiency, thereby improving patient outcomes.

The benefits of mini bypass circuits extend beyond enhanced venous drainage. Studies underscore the potential in reducing blood trauma-associated inflammatory responses. Notably, these circuits have been linked to decreased hemolysis, platelet activation, and complement system activation. By supporting smoother venous drainage, mini bypass circuits have the potential to minimize the deleterious effects on the patient's blood components, ultimately culminating in improved surgical outcomes [32].

However, challenges also accompany the utilization of mini bypass circuits in relation to venous drainage. The inherent characteristics of mini circuits, including smaller cannulae and tubing, may restrict the amount of blood that can be effectively drained. This could pose difficulties in managing patients with high venous return and potentially impact hemodynamic stability. Reduced blood flow rates might also compromise surgical field visibility, necessitating strategic collaboration between surgeons and perfusionists to optimize visualization techniques [33].

Another concern lies in the potential for venous stasis due to reduced flow rates in mini circuits. Venous stasis increases the risk of clot formation and thromboembolic events. Careful anticoagulation management and maintaining adequate flow velocities are essential to mitigate this risk. Additionally, the compact size of mini bypass circuits may

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present challenges during cannulation, particularly in cases of anatomical variations or limited access. Proficiency in cannulation techniques and comprehensive training are vital to ensure secure and effective placement of cannulae [34].

In pursuit of improved functionality and safety, a study addressed the limitations of mini CPB systems by developing a versatile minimized system (VMS). This VMS incorporated innovations such as a compliance chamber for pressure fluctuation reduction and bubble trapping. An open venous reservoir, adjustable level detector, and the potential for conversion to a vacuum-assisted system underscored its adaptability. By combining the advantages of mini circuits with the flexibility of conventional CPB systems, the VMS offers a means to effectively respond to intraoperative complications [35].

Veno venous bypass for liver transplantation

Veno-venous bypass (VVB) has been a longstanding technique in liver transplantation, evolving alongside technological progress and changing surgical practices. Notably, percutaneous techniques have gained prominence, allowing convenient access points such as the saphenofemoral junction, axillary vein, internal jugular vein, and femoral vein, enhancing patient comfort and accessibility [34].

The role of VVB has created debates within the field. The advent of the piggyback technique, preserving the recipient's retrohepatic inferior vena cava, has led to a decrease in routine VVB usage [36]. Nonetheless, controversy remains over its necessity, with studies suggesting comparable outcomes without routine VVB [38].

Alternative techniques, like utilizing a patent para-umbilical vein for VVB, highlight the adaptability of this approach in intricate scenarios [36,38]. Systematic reviews contribute to the discussion, comparing the benefits and drawbacks of VVB versus no VVB during liver transplantation [38].

Advancements in devices, exemplified by a magnetic levitation based VVB device, underscore the potential for technological innovations to enhance efficacy and safety [39].

Moreover, refining the weaning process of VVB is crucial, as the piggyback technique's popularity has altered its utilization. While the routine use of VVB is questioned, its selective benefits are explored. A review examining femoral-to-jugular VVB underscores the importance of tailored approaches based on patient-specific factors [40-42].

In summation, VVB's evolution in liver transplantation is marked by percutaneous techniques, changing surgical norms, and technological innovations. The ongoing debate regarding its routine use highlights the need for individualized decisions, considering patient characteristics and advancements in devices. Comprehensive research remains essential to define VVB's indications and benefits in the dynamic landscape of liver transplantation. Finally, in VVB, venous drainage is vital for maintaining blood flow. A venous bubble trap is used to remove air bubbles on the access line, preventing air embolisms and ensuring a safe procedure.

Extracorporeal membrane oxygenation

Extracorporeal membrane oxygenation (ECMO) is a life-saving therapy employed in critically ill patients facing severe respiratory failure. Specifically, veno-venous ECMO (VV-ECMO) has emerged as a vital variant, wherein venous blood is drained, oxygenated, and then returned to the venous system for respiratory support. In-depth studies have explored the outcomes, techniques, complications, and considerations inherent in VV-ECMO [43]. A systematic review by Kim, et al., delved into large case series and randomized trials to assess the outcomes and complications of VV-ECMO in adults, noting its increasing popularity in managing refractory respiratory failure, including pandemics such as the 2009 influenza and novel coronavirus [44]. Banfi, et al., examined cannulation techniques, highlighting VV-ECMO's comprehensive support but also underscoring potential risks like bleeding, thromboembolism, and infection [45]. Recirculation issues within the venous system were studied by Jonas, identifying cannula positioning and cardiac output as influencing factors [46]. Shaheen, et al., detailed indications, preprocedural considerations, and technique for placing VV-ECMO with a dual-lumen, single-cannula catheter, underscoring its role in refractory respiratory failure [47]. A systematic review and meta-analysis by Menaker, et al., sought to gauge VV-ECMO's effect on mortality in acute respiratory distress syndrome (ARDS) patients, scrutinizing its efficacy in severe ARDS [48]. Trauma patient outcomes on VV-ECMO were evaluated, illuminating demographic attributes, injury severity, and survival rates in adult trauma patients undergoing VV-ECMO [49]. Tulman, et al., deliberated on the challenges, controversies, and considerations encompassing VV-ECMO, noting its evolving role as a rescue therapy for acute respiratory distress syndrome [50]. Kang, et al., did a case report highlighting veno-arterial-venous ECMO's application in a critically ill patient with COVID-19, showcasing its use in cardiopulmonary failure [51].

In relation to Veno arterial ECMO (VA-ECMO) a randomized, multicenter trial, known as the EURO SHOCK trial, aims to assess the use of veno-arterial ECMO in patients with cardiogenic shock [52]. The trial's design and rationale focus on evaluating the potential benefits of this intervention in improving patient outcomes. Another study conducted a systematic review on preclinical investigations of pulsatile veno-arterial ECMO, aiming to overcome the limitations associated with continuous-flow devices [53]. This review highlights the importance of considering alternative techniques to enhance ECMO effectiveness. Venous cannula size is a critical determinant in VA ECMO, affecting the volume of blood that can be effectively drained from the patient. A larger cannula diameter facilitates higher flow rates, which is particularly crucial in cases of cardiogenic shock or severe respiratory failure. Appropriate sizing prevents excessive suction, minimizing the risk of vessel trauma, thrombosis, or hemolysis. Moreover, it helps maintain the desired oxygenation and hemodynamic parameters, contributing to overall patient stability. Cannula positioning is equally vital. Ensuring optimal placement within the right atrium or superior vena cava aids in efficient drainage and reduces the risk of recirculation. Inadequate positioning might lead to

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compromised blood flow and increased oxygenator workload. Correct placement also minimizes the potential for air entrainment, which could result in embolic events or reduced oxygen delivery. The choice of venous cannula types of further influences VA ECMO outcomes.

In summary Dual-lumen cannulas offer simultaneous venous drainage and oxygenated return, simplifying circuitry and enhancing patient comfort. Single-lumen cannulas are versatile and can be used for both VA and VV ECMO, but that might require additional circuit components.

The selection depends on patient-specific needs, anatomical considerations, and the intended level of support. Additionally, the concept of hypovolemia in VA ECMO warrants attention. Hypovolemia, or insufficient circulating blood volume, can lead to inadequate ECMO flow and compromised organ perfusion.

Monitoring and maintaining proper circulating blood volume through fluid administration and cautious ECMO management are paramount. Adequate perfusion pressure and flow must be sustained to prevent ischemic organ damage. Recent devices have incorporated built in venous pressure and flow monitoring, which is a great tool for measuring the patient's hypovolemic state. In addition, built in venous temperature monitoring also helps to maintain the patient's required temperature [54-58].

Ventricular assist device

Temporary Left Ventricular Assist Devices (LVADs) and Right Ventricular Assist Devices (RVADs) are pivotal in managing acute heart failure. Proper venous cannula size and positioning optimize drainage and function. Adequate blood volume is crucial to prevent hypovolemia-related complications for optimal performance and outcomes. Ventricular Assist Devices technology has evolved over time. LVADS such as the Impella device are on the rise, as the Protek Duo cannula (RVAD).

Salna, et al., explored this percutaneous dual-lumen cannula post-LVAD implantation, reporting favorable outcomes, suggesting its potential role in refractory RV failure [59]. Septic shock often leads to RV failure and poor fluid challenge response. The Protek duo also showed promise in mitigating invasive surgical interventions [60].

Saito, et al., demonstrated the effectiveness of a temporary centrifugal RVAD in severe biventricular failure [61], implying its value in managing right heart failure. An interesting case report presents a 72-year-old male with severe isolated end-stage right heart failure due to arrhythmogenic right ventricular cardiomyopathy.

Despite medical optimization, persistent symptoms and declining right ventricular function necessitated a singular right ventricular assist device (RVAD) implantation. The HeartMate 3™-VAD was chosen for its potentially lower thromboembolic risk. Implantation into the right atrium with outflow graft anastomosis to the pulmonary artery was successful. Post-implantation, the patient's condition improved, highlighting the feasibility of RVAD in isolated right heart failure as a last-resort option [62]. In another study addressing post-LVAD right ventricular failure, authors propose a novel technique for

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temporary RVAD placement that improves outcomes.

Unlike existing methods with delayed sternal closure or femoral catheters, the approach tunnels grafts from pulmonary artery and right atrium through intercostal spaces, allowing definitive chest closure. This enhances mobility, early extubation, and reduces reliance on vasoactives. Despite leaving grafts in the chest, minimal risk is argued due to required LVAD monitoring.

This strategy holds promise for better patient outcomes by addressing right ventricular failure without hindering recovery [63]. Venous drainage is essential in VADs, which help pump blood and support failing hearts.

It collects oxygen-depleted blood from the heart, allowing the VAD to assist in pumping and reducing the heart's workload. Proper venous drainage ensures stable circulation, prevents complications like clot formation, and is crucial for the success and safety of VAD therapy in patients with severe heart failure.

Future considerations for improved artificial circulation in relation to venous dynamics

Advanced cannula designs

The development of cannulae with improved flow dynamics, such as streamlined shapes and optimized drainage ports, can enhance venous drainage efficiency while minimizing the risk of stasis, clot formation, and complications.

Patient-specific cannulation techniques

Tailoring cannulation approaches based on individual patient characteristics and anatomy can optimize venous drainage while minimizing the risk of injury, recirculation, and other complications.

Real-time monitoring and feedback systems

Incorporating advanced monitoring technologies, such as ultrasonography, near-infrared spectroscopy (NIRS), and real-time hemodynamic monitoring, can provide continuous feedback on venous drainage performance and guide adjustments for optimal outcomes.

Robot-assisted cannulation

The integration of robotic systems for precise and controlled cannulation can improve the accuracy of cannula placement and reduce the risk of complications, leading to improved venous drainage.

Smart reservoirs

Developing reservoirs equipped with sensors and feedback mechanisms to monitor blood flow rates, pressures, and potential air entrainment can enhance the safety and efficiency of venous drainage during various applications.

Computational fluid dynamics (CFD) simulations

Utilizing CFD simulations can aid in optimizing cannula design and placement, as well as understanding flow patterns, turbulence, and pressure changes to achieve optimal venous drainage.

Biocompatible materials

Research into biocompatible materials for cannula construction can reduce the risk of thrombosis, clot formation, and

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inflammatory responses, thus improving long-term venous drainage efficacy.

Hemodynamic modeling and prediction

Developing sophisticated hemodynamic models and predictive algorithms can aid perfusionists and clinicians in predicting optimal drainage conditions, allowing for proactive adjustments to ensure effective venous drainage.

Minimally invasive techniques

Exploring minimally invasive approaches for cannula placement and drainage can reduce patient discomfort, enhance recovery, and improve patient outcomes.

Training and education

Continuously improving training programs and educational resources for perfusionists and healthcare professionals involved in artificial circulation procedures can ensure consistent and competent management of venous drainage techniques.

Collaboration between disciplines

Encouraging collaboration between cardiac surgeons, perfusionists, engineers, and researchers can lead to interdisciplinary innovations that advance the field of artificial circulation, specifically related to venous dynamics.

Multi-modal imaging

Integrating various imaging modalities, such as ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI), can provide comprehensive insights into venous anatomy and aid in optimal cannula placement.

Ethical considerations

As technology advances, ethical considerations related to patient consent, safety, and the responsible use of innovative techniques should be continuously evaluated and addressed.

Conclusion

In conclusion, precise venous drainage is critical during cardiac surgery and extracorporeal life support.

Advanced cannula designs, personalized techniques, real-time monitoring, and interdisciplinary collaboration hold promise for enhanced artificial circulation. Embracing these innovations will elevate patient care and surgical outcomes.

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