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Cardiopulmonary Bypass in Nursing Practice: Clinical Management, Patient Safety, and Perioperative Care

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Abstract

Background: Cardiopulmonary bypass (CPB) enables complex intracardiac surgery by temporarily substituting heart and lung function with an extracorporeal circuit, creating a motionless, blood-reduced field while maintaining systemic perfusion and oxygenation. Its benefits are counterbalanced by inflammatory activation, coagulopathy, and multisystem risks that demand meticulous perioperative management.

Aim: To outline CPB fundamentals and translate them into nursing practice—detailing clinical indications, equipment and roles, preparation, intraoperative technique, complications, and team-based strategies to enhance patient safety and outcomes.

Methods: Narrative synthesis of CPB physiology and workflow across the perioperative continuum, integrating device functions (pump, oxygenator, heat exchanger, reservoirs, cannulas, filters), anticoagulation protocols, cannulation strategies (central/peripheral; one-stage/two-stage; cavoatrial/bicaval), myocardial protection (antegrade/retrograde/ostial cardioplegia), and structured team roles.

Results: Effective CPB hinges on: (1) risk-informed patient selection; (2) standardized preparation (ACT targets, heparin resistance pathways); (3) precise cannulation and de-airing; (4) tightly controlled temperature, perfusion pressures, and blood chemistry; (5) vigilant nursing surveillance for bleeding, vasoplegia, neurologic, renal, and respiratory complications; and (6) disciplined, closed-loop communication among surgeons, anesthesiologists, perfusionists, nurses, and ICU teams.

Conclusion: CPB remains indispensable for coronary, valvular, congenital, and complex aortic surgery. Nursing practice is central to safety—operationalizing protocols, recognizing early deterioration, coordinating interventions, and ensuring error-resistant handoffs. Interprofessional standardization and continuous monitoring mitigate CPB's physiologic burdens, translating technical capability into improved recovery trajectories.

Keywords: cardiopulmonary bypass; nursing; perioperative care; perfusion; cardioplegia; anticoagulation; patient safety; vasoplegia; de-airing; team communication.

Introduction

Cardiopulmonary bypass (CPB) represents one of the most transformative achievements in the evolution of cardiac surgery, effectively resolving a question that long constrained operative innovation: whether the human heart could be safely operated upon without precipitating fatal interruption of circulation. Prior to the advent of extracorporeal support, surgeons were largely restricted to procedures that did not require entry into the cardiac chambers or prolonged interference with intracardiac blood flow. As a result, early operative efforts focused on comparatively limited conditions, including repairs of minor injuries involving the

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pericardium, myocardium, and major vessels, as well as certain extracardiac congenital abnormalities such as coarctation of the aorta and patent ductus arteriosus. The inability to arrest and open the heart while maintaining systemic perfusion represented a critical barrier to definitive treatment of complex structural and ischemic cardiac disease. The development of CPB constituted a revolutionary breakthrough by enabling temporary substitution of the heart and lungs with an extracorporeal circuit, thereby creating a controlled physiological environment that supports life during cardiac arrest. In practical terms, CPB allows the heart to be stopped, generating a motionless and largely bloodless operative field that is essential for precise intracardiac reconstruction, while simultaneously ensuring ongoing delivery of oxygenated blood to vital organs. This capacity to maintain perfusion and oxygenation during periods when native cardiac output and pulmonary gas exchange are intentionally suspended has been central to the expansion of surgical possibilities and has redefined standards of care in operative cardiology.[1][2][3][4]

At a functional level, the CPB circuit is designed to replicate core cardiopulmonary processes through coordinated mechanical components. A pump assumes the role of the heart by circulating blood through the system and back to the patient, while an oxygenator performs the gas exchange functions of the lungs, adding oxygen and removing carbon dioxide. Together, these elements establish extracorporeal circulation that can be adjusted to meet metabolic demands, support temperature management, and stabilize hemodynamics throughout the procedure. Since its emergence in the mid-twentieth century, CPB has served as a foundational platform for increasingly sophisticated operations, including coronary artery bypass grafting, valve repair and replacement, and the correction of complex congenital heart defects. These procedures, which were once either technically impossible or associated with prohibitive mortality, became feasible due to the physiologic control afforded by extracorporeal support. Despite its indispensable benefits, CPB is not a neutral intervention, as exposure of blood to artificial surfaces and nonphysiologic flow conditions can provoke significant systemic effects. These include inflammatory activation, alterations in coagulation pathways, and the potential for organ dysfunction involving the lungs, kidneys, brain, and other systems. Consequently, successful use of CPB requires meticulous planning, continuous monitoring, and coordinated decision-making among surgeons, perfusionists, anesthesiologists, and nursing personnel. Nursing practice is particularly integral to optimizing outcomes, as perioperative nurses contribute to surveillance for hemodynamic instability, bleeding, hypothermia-related changes, neurologic risk, and early signs of complications that may emerge both intraoperatively and during postoperative recovery. For healthcare professionals involved in cardiac surgery, a comprehensive understanding of CPB principles, techniques, and ongoing technological advancements is therefore essential, because these factors directly influence operative success, patient safety, and the trajectory of recovery.[1][2][3][4]

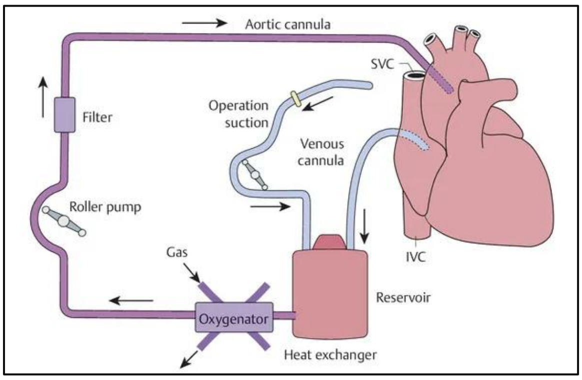

Fig. 1: Cardiopulmonary bypass.

Anatomy and Physiology

Cardiopulmonary bypass (CPB) functions as an integrated extracorporeal life-support system that temporarily assumes the essential circulatory and respiratory roles of the heart and lungs during cardiac surgery. Its physiologic purpose is to maintain systemic perfusion and gas exchange while creating operative conditions that permit safe manipulation of intracardiac structures. A principal mechanical function of CPB is decompression and "emptying" of the heart to facilitate a clear, bloodless surgical field. This is achieved by diverting venous blood away from the heart through venous cannulas, thereby reducing intracardiac volume and pressure and enabling the surgeon to perform complex repairs in a motionless environment. Once drained, the blood is routed into the extracorporeal circuit, where pump oxygenators provide oxygen uptake and carbon dioxide removal, effectively substituting for pulmonary function during the bypass period.[5] In this way, CPB establishes a controlled physiologic state in which circulation and ventilation are sustained independent of the patient's native cardiopulmonary activity. Beyond basic perfusion and oxygenation, CPB supports additional regulatory tasks that are critical to homeostasis during major surgery. Reservoir systems allow collection and staging of venous return, providing a site where volume can be managed and where elements of blood chemistry may be influenced through controlled mixing, filtration, and supplementation when required. Electrolyte and acid–base balance are closely tied to perfusion adequacy, hemodilution, and metabolic demand; thus, the circuit's design supports continuous monitoring and correction of physiologic parameters as clinical circumstances evolve. Temperature regulation is another defining feature of CPB physiology. Heat exchangers permit intentional cooling to reduce metabolic requirements and oxygen consumption, or rewarming to restore normothermia prior to separation from bypass. This capacity to modulate temperature adds an additional protective layer, particularly for the myocardium and central nervous system, and is integral to the broader physiologic strategy of minimizing ischemic injury [3][4][5].

The circuit completes systemic support by returning oxygenated blood to the patient through arterial cannulation, thereby sustaining perfusion to the brain, kidneys, and other organs throughout the operation. Hemodynamic adequacy depends not only on flow rates but also on the distribution of perfusion and maintenance of appropriate perfusion pressures, which require coordinated management by the perfusionist, anesthesiology team, and surgeons. CPB systems also incorporate mechanisms to reduce blood loss and conserve intravascular volume. Blood shed into the operative field can be collected through cardiotomy suction and returned to the circuit, supporting autologous blood recovery and potentially decreasing the need for allogeneic transfusion. To prevent cardiac distension that could impair myocardial protection and surgical exposure, cardiac vents are commonly employed to decompress cardiac chambers and maintain optimal intracardiac pressures during bypass. Additionally, CPB enables delivery of cardioplegia, a specialized solution designed to induce controlled cardiac arrest while protecting myocardial tissue by reducing metabolic activity and limiting ischemia during periods of interrupted coronary perfusion. These features are supported by adjunct pathways and standby safety mechanisms incorporated into a closed, pump-driven circuit interconnected by tubing, allowing redundancy, rapid correction of flow disruptions, and improved stability during the surgical intervention. Understanding the "physiology" of CPB also requires appreciation of the systemic inflammatory consequences that accompany extracorporeal circulation. Evidence indicates that CPB can precipitate a systemic inflammatory response syndrome mediated by multiple converging pathways. When blood contacts the nonendothelial artificial surfaces of the circuit, immune and coagulation cascades are activated, including complement activation, leukocyte stimulation, and endothelial dysfunction. This response is compounded by the physiologic stressors intrinsic to cardiac surgery, including tissue trauma, blood loss, and ischemia–reperfusion injury. Endotoxemia may also occur, attributed to translocation of gut-derived toxins into the circulation during periods of altered perfusion, further amplifying inflammatory signaling. Collectively, these processes promote release of pro-inflammatory cytokines, reactive oxygen species, and nitric oxide, producing oxidative stress that can contribute to postoperative organ dysfunction and has been associated with increased morbidity and mortality in susceptible patients.[6]

For clinicians, including perioperative and critical care nurses, these physiologic responses are not merely theoretical; they directly inform risk assessment, monitoring priorities, and preventive strategies. Reducing inflammatory activation and limiting blood loss are common goals, pursued through approaches such as employing more biocompatible circuit materials, using anti-inflammatory or immunomodulatory therapies when appropriate, refining operative techniques to minimize tissue injury, and maintaining meticulous hemostasis. Equally important is continuous, multidisciplinary vigilance to balance the benefits of extracorporeal support—namely, stable perfusion and a workable surgical field—against the systemic perturbations that CPB can generate. A detailed understanding of CPB anatomy and physiology therefore underpins safer operative management and supports improved short- and long-term outcomes for patients undergoing cardiac surgery [3][4][5].

Indications

Cardiopulmonary bypass (CPB) is indicated in cardiac surgery when the planned procedure cannot be performed safely under native cardiac output and pulmonary gas exchange, and when a controlled operative field requires temporary cessation of the heart's mechanical activity. In essence, CPB enables surgeons to bypass the heart and lungs, thereby sustaining systemic perfusion and oxygen delivery while intracardiac or major vascular structures are repaired under direct visualization. The decision to initiate CPB is therefore driven by both procedural requirements and patient-specific physiologic considerations, including the anticipated need for cardiac arrest, the complexity and duration of the repair, and the margin of safety afforded by the patient's baseline cardiopulmonary reserve. One of the most common indications for CPB is coronary artery bypass grafting (CABG), particularly when surgical exposure, hemodynamic stability, or the number and location of diseased vessels make off-pump strategies less suitable. In CABG, CPB supports circulation while grafts—typically harvested veins or arterial conduits—are anastomosed to bypass obstructed coronary arteries, thereby restoring myocardial perfusion. By providing a motionless and blood-reduced operative environment, CPB can facilitate accurate placement of grafts and support complex multi-vessel revascularization, especially in patients with reduced ventricular function or unstable coronary physiology. CPB is also a central requirement for many valve repair and replacement procedures. When valves are affected by stenosis, regurgitation, or combined pathology, definitive surgical correction often necessitates opening the heart chambers or great vessels, which is incompatible with continued intracardiac blood flow and vigorous cardiac motion. CPB enables controlled cardioplegic arrest and decompression of the heart, allowing surgeons to repair valvular structures, excise diseased leaflets, or implant prosthetic devices with precision. These operations frequently depend on stable perfusion parameters throughout the period of arrest to protect the myocardium and maintain end-organ oxygen delivery [3][4][5].

Congenital heart defect correction constitutes another major indication for CPB across pediatric and adult populations. Many congenital lesions involve septal defects, outflow tract abnormalities, or complex structural malformations that require intracardiac reconstruction. In these settings, CPB provides the physiologic platform for safe surgical exposure and repair, often under conditions requiring meticulous anatomic correction within small or uniquely configured cardiac structures. The ability to control temperature, flow, and perfusion pressures during CPB is particularly valuable in congenital surgery, where myocardial protection and neurologic safety are essential priorities. Complex aortic surgery, including repair of aneurysms involving the aorta, often also relies on CPB. When repair requires clamping or opening portions of the aorta, CPB can maintain systemic circulation while surgeons reconstruct or replace diseased segments of the vessel wall. In such operations, CPB supports perfusion to critical organs and can be adapted to the specific anatomic location of the aneurysm and the operative strategy chosen to manage circulatory interruption. Less frequent but clinically important indications include surgical removal of cardiac tumors, whether benign or malignant, when access requires opening cardiac chambers or when tumor location threatens hemodynamic stability during manipulation. CPB provides circulatory support and improves operative control, enabling careful excision while minimizing the risk of embolization or sudden compromise. Similarly, heart transplantation commonly requires CPB to sustain circulation during explantation of the failing heart and implantation of the donor organ, offering a stable hemodynamic bridge through periods of profound physiologic transition. Overall, CPB is employed when the complexity of the surgical intervention and the need for a bloodless, motionless field outweigh the physiologic burdens of extracorporeal circulation. By maintaining oxygenation and systemic perfusion throughout the procedure, CPB reduces intraoperative risk and expands the range of cardiac pathologies that can be addressed surgically, provided that careful patient selection and multidisciplinary management are applied [3][4][5].

Contraindications

Cardiopulmonary bypass (CPB) is a supportive technique rather than a stand-alone therapy, and for this reason it is generally understood to have no strict absolute contraindications. When a cardiac operation is life-saving or urgently required, CPB may be used despite significant comorbidity because the alternative—foregoing intervention—may carry a higher and more immediate risk. Nevertheless, in elective or semi-elective contexts, surgeons and the multidisciplinary team may decide to defer surgery when certain clinical conditions substantially increase the likelihood of perioperative complications or magnify the physiologic stress imposed by extracorporeal circulation. In practice, these circumstances function as relative contraindications, meaning that CPB is not prohibited, but proceeding without optimization may be unsafe. Acute renal impairment is one scenario in which postponement may be considered, as CPB can contribute to renal hypoperfusion, inflammatory activation, hemolysis, and fluid shifts that may worsen kidney function and increase the risk of postoperative acute kidney injury. Similarly, an acute cerebral stroke may prompt delay when clinically feasible because CPB is associated with embolic risk, anticoagulation requirements, and changes in perfusion and temperature that could exacerbate neurologic injury or complicate recovery. Respiratory compromise is another important consideration. A chest infection can increase perioperative pulmonary complications, prolong ventilation needs, and intensify inflammatory burden; delaying surgery allows time for antimicrobial therapy, respiratory optimization, and improved physiologic reserve. Severe asthma exacerbations represent a related concern, as poor airway control and heightened bronchial reactivity may complicate anesthesia and postoperative respiratory management, particularly in a setting where fluid shifts and inflammatory responses could worsen pulmonary function.[5][7][8][9] Accordingly, although CPB is not absolutely contraindicated, deferring surgery when possible allows targeted stabilization and optimization of organ systems, thereby reducing risk and improving the probability of favorable outcomes. The decision is ultimately individualized, balancing the urgency of the cardiac pathology against the potentially modifiable hazards posed by concurrent acute illness.[5][7][8][9]

Equipment

A cardiopulmonary bypass (CPB) system is an integrated extracorporeal circuit designed to temporarily replace the pumping function of the heart and the gas-exchange function of the lungs while providing the surgical team with a controlled, blood-reduced operative field. Although the circuit is often described as a "machine," it is more accurately a coordinated assembly of cannulas, tubing, pumps, reservoirs, an oxygenator, temperature-management devices, suction and venting mechanisms, and multiple safety monitors. Each component has a distinct physiologic purpose, and the overall reliability of CPB depends on how effectively these elements are selected, assembled, and managed to maintain stable flow, adequate oxygen delivery, appropriate pressure, and careful air handling throughout the procedure. Because patient anatomy, planned operation, and hemodynamic targets vary widely, many CPB components are available in multiple designs; thus, "best" equipment is generally contextual rather than universal, and selection is guided by operative goals and risk mitigation. Venous cannulas constitute the entry pathway of systemic venous blood into the bypass circuit. Their principal function is to divert deoxygenated blood away from the heart so that the cardiac chambers can be decompressed and opened safely while systemic perfusion is sustained extracorporeally. Clinically, venous cannulation commonly targets the right atrium, the superior vena cava, the inferior vena cava, or a combination of these sites, depending on whether single- or dual-stage drainage is desired and on the surgical exposure required. The design priorities for venous cannulas include promoting efficient drainage at low resistance, reducing the likelihood of cavitation and hemolysis, and minimizing the risk of entraining air. To address these aims, venous cannulas are manufactured in a range of sizes and shapes to match patient anatomy and operative needs, including pediatric and adult configurations, and variants intended for specific approaches. Selection must account for target flow requirements and venous return characteristics, because inadequate drainage can compromise circuit flow, elevate cardiac filling pressures, and reduce surgical visibility, while overly aggressive drainage can increase the risk of venous collapse or air entrainment [5][7][8][9].

Arterial cannulas form the return pathway by delivering oxygenated blood from the circuit to the patient's arterial system. The ascending aorta is the most common site for arterial cannulation in standard cardiac operations because it provides direct access to central circulation and enables robust systemic perfusion. In certain clinical contexts—such as reoperative sternotomy risk, aortic pathology, or when central cannulation is unsuitable—peripheral arteries like the femoral artery may be used. Regardless of site, the arterial cannula is engineered to minimize flow resistance and reduce vascular trauma, because excessive resistance elevates circuit pressures and increases hemolysis risk, while traumatic insertion can precipitate dissection or bleeding. Aortic cannulation is especially sensitive to these issues: the cannula should insert smoothly with an atraumatic tip and surface, and its outflow characteristics should avoid creating a high-pressure jet that might disrupt atheromatous plaque and increase embolic risk. Size selection is equally critical, as the cannula must permit sufficient flow to meet metabolic demands without generating prohibitive pressure gradients. Multiple arterial cannula designs exist because different shapes and tip geometries confer advantages in specific situations. For example, right-angled configurations can reduce the likelihood of posterior aortic wall perforation and may allow more selective perfusion strategies when arch branch flow is a concern, whereas straight cannulas may reduce the tendency toward selective arch vessel perfusion but can carry a higher risk of posterior wall penetration if placement is not optimal. Beveled tips may facilitate insertion and positioning, yet they can be associated with a higher pressure gradient at the outflow, while diffusion-tip designs are intended to lessen outflow pressure gradients and promote more uniform perfusion of arch branches, albeit with slightly increased structural complexity. Wire-reinforced cannulas can support higher flow through a smaller diameter and may be more resistant to iatrogenic dissection, whereas cannulas with flanges can enhance hemostasis and provide anchoring points for purse-string sutures. In practice, arterial cannula choice is individualized; different designs remain in routine use, and the surgeon's assessment of anatomy, aortic condition, and procedural goals ultimately determines the most appropriate option [5][7][8][9].

Thermal management during CPB is primarily achieved through the heat exchanger, which allows controlled cooling and warming of circulating blood. Temperature modulation is clinically important because hypothermia can reduce metabolic demand and oxygen consumption, offering protective effects for the brain and other organs during periods of altered perfusion, while rewarming is necessary to restore physiologic conditions before separation from bypass. Heat exchangers are typically constructed with a series of metal plates or tubular elements that provide a high surface area for heat transfer. Blood flows on one side of this exchange surface while a temperature-controlled fluid—most commonly water—flows on the other. By adjusting the temperature and flow rate of the circulating water, perfusionists can precisely influence blood temperature and thereby regulate patient temperature in a controlled, gradual manner. Effective heat exchange requires careful monitoring to avoid overly rapid temperature shifts, which can contribute to gas embolization risk or physiologic instability, and to ensure uniform warming prior to the conclusion of bypass. Oxygenators are the core gas-exchange component of the CPB circuit, functionally replacing pulmonary oxygen uptake and carbon dioxide elimination. Modern practice predominantly relies on membrane oxygenators, which use a semipermeable membrane to separate blood from the sweep gas. Blood flows along one side of the membrane while a controlled gas mixture flows along the other, enabling diffusion-driven oxygen transfer into blood and carbon dioxide transfer out of blood. Membrane systems are favored because they provide efficient gas exchange with comparatively lower blood trauma, reduced gaseous microembolism risk, and generally improved biocompatibility relative to older technologies. Bubble oxygenators, which oxygenate blood via direct contact with oxygen bubbles, represent an earlier approach that can be effective in achieving gas exchange but is associated with higher risks of blood trauma, embolic phenomena, and inflammatory activation. Although bubble oxygenators have been largely displaced by membrane oxygenators in most contemporary settings, understanding their design remains relevant historically and conceptually, as it highlights why current oxygenators emphasize separation of blood and gas and the reduction of blood–air interface exposure [5][7][8][9].

The reservoir container provides a volume-management interface within the circuit and supports stabilization of venous return and pump inflow. Reservoirs may be open or closed, and this distinction has important safety implications. Open reservoirs collect venous blood in a chamber where blood may interface with air, which can facilitate rapid access for adding fluids or medications and can simplify certain aspects of volume management. However, air exposure introduces a higher risk of air embolism and contamination, making meticulous air handling and aseptic technique essential. Closed reservoirs are designed to prevent direct blood–air contact, thereby reducing the risk of air embolization and limiting contamination potential. Closed systems also tend to support more stable maintenance of volume and pressure within the circuit, though they may offer less immediate access for interventions. The selection of reservoir type is influenced by institutional preference, case complexity, anticipated blood management needs, and safety priorities, particularly with respect to air control. The pump is the principal driver of blood flow through the CPB circuit, and pump selection shapes both hemodynamic performance and hemocompatibility. Roller pumps propel blood by compressing a section of tubing with rotating rollers, producing forward movement of blood through peristaltic displacement. This approach is mechanically simple and historically well established, which contributes to reliability in many settings. Nevertheless, roller pumps can increase blood trauma through mechanical compression and may carry risks such as tubing rupture and air embolism if the integrity of the tubing system is compromised. Centrifugal pumps, by contrast, use a rapidly rotating impeller to generate centrifugal force that moves blood through the circuit. This design is generally considered gentler on blood components, tending to reduce hemolysis and cellular trauma relative to compression-based pumping, and it avoids the same dependence on repetitive tubing compression that can contribute to rupture risk. Centrifugal systems can also provide a more consistent flow profile under many conditions, though accurate flow delivery still requires continuous monitoring, appropriate preload, and attention to circuit resistance. In practice, pump choice reflects a balance between institutional standards, case requirements, and the clinical team's preferences regarding hemolysis risk, pressure control, and operational familiarity [5][7][8][9]

Tubing forms the vascular "skeleton" of the CPB circuit, connecting all components into a continuous pathway capable of sustaining high flow rates with minimal leakage and appropriate visibility for safety checks. Standard CPB tubing is commonly made of polyvinyl chloride, valued for being nonallergenic, nonmutagenic, nontoxic, nonimmunogenic, pliable, flexible, and transparent. Transparency is not merely a convenience; it enables continuous visual surveillance for air bubbles, clot formation, discoloration, or abnormal flow patterns. Tube diameters are selected to match flow demands and pressure targets across different segments of the circuit. In the configuration described, the venous line is approximately one-half inch (12 mm), supporting high-volume drainage at low resistance, while the arterial line is approximately three-eighths inch (8 mm), balancing adequate return flow with manageable circuit priming volume. Smaller lines, such as vents and suction pathways, are approximately one-quarter inch (6 mm), reflecting their more localized roles in decompression and blood salvage rather than primary systemic flow. Tubing management requires careful attention to secure connections, prevention of kinking, appropriate routing, and confirmation that all clamps and one-way components function as intended, since tubing failures can rapidly evolve into critical safety events. Cardiotomy suckers are specialized suction devices used to remove blood from the operative field and return it to the CPB circuit, thereby preserving visibility for the surgical team and reducing net blood loss. Their role is especially important in procedures where bleeding into the pericardial space or operative site would otherwise obscure critical structures or increase the need for transfusion. Blood collected via cardiotomy suction is typically filtered before reinfusion to remove air, particulate debris, and potential microaggregates, addressing both embolic risk and inflammatory activation. While cardiotomy suction supports blood conservation, it also introduces blood that has been exposed to surgical surfaces and air, which can contribute to hemolysis and inflammatory mediator accumulation. Consequently, its use is coordinated with broader blood management strategies, including filtration and, when appropriate, adjunct cell-salvage approaches, to balance the benefits of conservation against potential physiologic burdens [5][7][8][9].

Vents are integral to cardiac decompression and air management during CPB, serving both mechanical and safety functions. Their primary purpose is to prevent distension of cardiac chambers, which can occur if blood accumulates within the heart despite venous drainage, and to reduce the risk that air will remain trapped in the heart and subsequently embolize when normal circulation resumes. Vent placement depends on the procedure and the surgeon's strategy but commonly targets the left ventricle, left atrium, or pulmonary artery, where venting can effectively reduce pressure and volume in left-sided chambers. By maintaining controlled intracardiac pressures, vents improve surgical exposure, support myocardial protection, and assist in de-airing maneuvers that are essential before the patient is separated from bypass. Effective venting also requires vigilance to ensure that suction is appropriate, that lines remain patent, and that one-way features prevent retrograde flow or inadvertent air introduction. Beyond the major circuit components, CPB systems incorporate a set of adjunct devices that collectively function as safeguards and performance monitors. A level detector helps track reservoir volume to reduce the risk of entraining air into the circuit when venous return fluctuates. Arterial line pressure monitoring provides real-time assessment of resistance and pressure load, enabling timely recognition of obstruction, cannula malposition, or excessive flow-related pressure that could harm blood elements or the patient’s vasculature. Bubble traps and arterial filters are critical defenses against gaseous and particulate emboli, capturing microbubbles and debris before blood returns to the patient. Pressure monitoring within the cardioplegia line supports safe delivery of myocardial protective solutions by preventing excessive pressure that could injure coronary circulation or compromise delivery efficacy. Gas line filters and flow meters ensure that the oxygenator receives clean, appropriately regulated sweep gas, promoting reliable gas exchange and reducing contamination risks. One-way valves on cardiac vents provide an additional layer of protection against backflow and air movement in the wrong direction, supporting consistent decompression and safer de-airing [5][7][8][9].

Taken together, the equipment of a CPB circuit reflects a deliberate engineering response to the physiologic requirements and hazards of extracorporeal circulation. Venous and arterial cannulas establish the patient–circuit interface, pumps and oxygenators provide the essential life-sustaining functions of circulation and gas exchange, the heat exchanger enables metabolic control through temperature management, reservoirs and tubing maintain volume integrity and continuity, and suction and venting systems support blood conservation and air control. Adjunct monitoring and safety devices unify these components into a system that can detect threats early and reduce the likelihood that technical problems escalate into clinical harm. For perioperative nurses and the broader cardiac surgical team, familiarity with CPB equipment is not simply technical knowledge; it directly informs patient safety practices, anticipatory monitoring, and effective interprofessional communication during one of the most physiologically demanding interventions in modern surgery [5][7][8][9].

Personnel

Successful implementation of cardiopulmonary bypass (CPB) depends on a highly coordinated, multidisciplinary team in which each professional contributes distinct expertise across the preoperative, intraoperative, and postoperative phases of care. Because CPB temporarily replaces core physiologic functions of the heart and lungs, even minor deviations in technique, monitoring, or communication can carry disproportionate clinical consequences. For this reason, patient safety and procedural success are optimized when roles are clearly defined, competencies are maintained through training and repetition, and interprofessional communication remains continuous, structured, and responsive to rapidly changing operative conditions. The cardiac surgeon functions as the procedural leader and bears ultimate responsibility for operative decision-making, including whether CPB is required and how it should be configured for the planned intervention. The surgeon oversees cannulation strategy and ensures that cannulas are placed accurately and securely, since correct venous drainage and arterial return are prerequisites for stable extracorporeal circulation. During bypass, the surgeon performs the central surgical repair—such as coronary revascularization, valve reconstruction, or congenital correction—within the physiologic environment created by CPB. This role also includes anticipating technical hazards, coordinating periods of cardiac arrest and myocardial protection, and managing transitions such as initiation of bypass and separation from bypass, which are high-risk moments requiring synchronized actions and real-time communication with anesthesia and perfusion personnel [10][11].

The anesthesiologist serves as the principal manager of anesthesia, physiologic monitoring, and hemodynamic stability before, during, and after CPB. In addition to providing anesthesia and analgesia, the anesthesiologist continuously assesses vital signs, cardiac rhythm, systemic perfusion markers, and ventilation parameters, translating these data into immediate interventions. Fluid balance management is particularly complex in cardiac surgery because CPB priming volume, hemodilution, blood loss, and transfusion requirements interact dynamically with vascular tone and cardiac function. The anesthesiologist therefore coordinates closely with the perfusionist and surgeon to adjust volume status, vasopressor or inotrope support, anticoagulation timing, and temperature targets, ensuring that the patient’s physiologic state remains compatible with both surgical needs and organ protection strategies. The perfusionist is the specialist responsible for assembling, operating, and continuously managing the CPB circuit. This role includes priming the circuit, ensuring the integrity of tubing and connections, verifying oxygenator performance, and confirming the readiness of safety features such as bubble detection, pressure monitoring, and arterial filtration. Once bypass is initiated, the perfusionist controls blood flow rates, perfusion pressures, oxygenation and ventilation parameters within the oxygenator, temperature management via the heat exchanger, and hematologic variables influenced by hemodilution. Anticoagulation management is a core responsibility, particularly monitoring and responding to parameters such as activated clotting time and coordinating with the team to ensure adequate anticoagulation for circuit safety while preparing for reversal when appropriate. The perfusionist also plays a central role in troubleshooting circuit-related complications, including inadequate venous return, rising arterial line pressures, air detection events, or oxygenator performance concerns, and must respond rapidly to protect the patient from catastrophic sequelae [10][11].

Surgical nursing personnel provide essential technical support and safety oversight within the operating room environment. The scrub nurse maintains the sterile field and supports the surgeon directly by preparing and passing instruments, managing suture materials, anticipating procedural steps, and ensuring that critical items required for cannulation, hemostasis, and closure are immediately available. The circulating nurse complements this function by managing the broader operating room environment, ensuring that supplies and equipment are available and functioning, maintaining sterility through adherence to aseptic protocols, coordinating documentation, and facilitating communication among team members. Because CPB cases often involve multiple device systems and time-sensitive transitions, nursing vigilance is central to preventing breaks in sterility, delays in equipment availability, and miscommunication during critical phases of bypass initiation and termination. Cardiovascular technicians frequently contribute to the preparation and operational readiness of CPB-related equipment. Their responsibilities often include assisting with setup and testing of components, supporting troubleshooting of mechanical or monitoring devices, and helping the perfusionist maintain equipment function during the procedure. This role can be particularly valuable in high-volume centers or complex cases where parallel tasks—such as assembling backup circuits, verifying alarm settings, or ensuring readiness of cardioplegia delivery systems—must occur efficiently without distracting the perfusionist from active patient management. Postoperative outcomes following CPB are heavily influenced by intensive care unit (ICU) teams, who assume responsibility for vigilant monitoring and targeted management during recovery. ICU staff—typically including critical care physicians, nurses, and advanced practice providers—monitor hemodynamic stability, bleeding, oxygenation, ventilation, renal function, neurologic status, and signs of infection or inflammatory complications. Because CPB can be associated with coagulopathy, fluid shifts, and organ dysfunction, ICU personnel must rapidly identify evolving complications and implement interventions such as titrating vasoactive medications, adjusting ventilator support, managing chest tube output, and coordinating transfusion or renal support when indicated. Their role extends beyond surveillance, encompassing structured recovery pathways, early mobilization planning when appropriate, and coordination of multidisciplinary follow-up [10][11].

Pharmacists contribute to both intraoperative and postoperative medication safety and efficacy. They prepare and supply medications required for anesthesia support, anticoagulation management, hemodynamic control, and infection prophylaxis, and they advise clinicians regarding dosing, compatibility, and interactions in a setting characterized by rapidly changing physiology. Pharmacists are particularly valuable when patients receive complex medication regimens, have renal or hepatic impairment, or require careful titration of vasoactive agents, sedatives, antimicrobials, or anticoagulant reversal strategies. Their expertise supports safer prescribing, reduces adverse drug events, and enhances standardization of medication protocols across the perioperative continuum. Biomedical engineers provide the technical assurance that CPB equipment is functioning properly, maintained according to safety standards, and repaired promptly when needed. Given the high-risk nature of extracorporeal circulation, preventive maintenance, calibration, and functional checks of pumps, monitors, oxygenators, and alarms are critical. Biomedical engineering oversight ensures that equipment-related failures are minimized and that the operating team can rely on accurate readings and reliable device performance during the procedure. Respiratory therapists play a complementary role in ventilation management before, during, and after bypass. Although gas exchange during CPB is handled by the oxygenator, respiratory therapists assist with optimizing ventilator settings pre-bypass and post-bypass, monitoring blood gases, and adjusting respiratory support during recovery. Their involvement is particularly important in patients with preexisting pulmonary disease, in those experiencing postoperative pulmonary dysfunction, or when complex ventilation strategies are required to support oxygenation and carbon dioxide clearance following separation from CPB. Echocardiographers, who often work through transesophageal echocardiography in the operating room, provide real-time imaging that guides surgical decision-making and physiologic management. Intraoperative echocardiography supports assessment of baseline cardiac anatomy and function, verification of repair adequacy, evaluation of ventricular performance during weaning from bypass, and detection of complications such as residual regurgitation, intracardiac air, or pericardial effusion. This imaging-based feedback loop strengthens clinical precision and supports timely correction when unexpected findings arise [10][11].

Clinical pathologists and laboratory personnel ensure rapid analysis of blood samples that inform anticoagulation, oxygenation, and metabolic management. Timely results for coagulation profiles, acid–base status, electrolytes, hemoglobin, and other parameters allow the team to respond to evolving physiologic needs during CPB and in the immediate postoperative period. Laboratory experts may also advise on interpretation of results in the context of hemodilution, hypothermia, or transfusion, supporting more accurate clinical decisions. Sterile processing technicians complete the safety chain by ensuring that surgical instruments and equipment are appropriately sterilized, assembled, and available when needed. CPB cases often require specialized trays and time-sensitive availability of sterile components, including cannulation instruments and accessories. Reliable sterile processing prevents delays, reduces infection risk, and supports smooth procedural workflow, particularly in urgent or complex operations. Collectively, CPB highlights the necessity of interprofessional collaboration: a shared mental model, consistent communication, and disciplined role execution allow the team to manage a high-risk physiologic intervention while maintaining the conditions needed for intricate cardiac repair. When each discipline contributes its expertise within a coordinated framework, CPB can be implemented safely and effectively, translating technical capability into improved surgical outcomes and more secure postoperative recovery [10][11].

Preparation

Preparation for cardiopulmonary bypass (CPB) is a structured, high-stakes process that integrates meticulous patient evaluation, coordinated anesthesia planning, careful positioning and sterile technique, and a technically precise cannulation strategy supported by rigorous anticoagulation management. Because CPB places the patient on a nonendothelial extracorporeal circuit and intentionally alters normal physiology, optimal outcomes depend on anticipating patient-specific risks, ensuring equipment readiness, and establishing clear interprofessional communication before critical transitions such as heparin administration, cannulation, and initiation of bypass. Preparation is therefore not a single step but a continuum that begins with preoperative assessment and extends through anesthetic induction and intraoperative setup, culminating in safe cannulation and verification that the circuit can support adequate perfusion and oxygenation. Preoperative assessment begins with a comprehensive history and physical examination designed to characterize the patient’s cardiovascular and pulmonary reserve, identify comorbid conditions that may amplify CPB-related risks, and clarify prior surgical history that may influence operative access or cannulation. A careful review of symptoms, functional status, and baseline limitations helps determine physiologic resilience, while targeted examination may reveal volume status abnormalities, signs of heart failure, pulmonary congestion, or peripheral vascular disease that could affect arterial cannulation choices. Prior operations, particularly previous sternotomy or thoracic procedures, warrant special attention because adhesions and scar tissue can complicate exposure, increase bleeding risk, and make central cannulation technically challenging. These factors influence not only surgical planning but also the selection of contingency strategies, including alternative cannulation sites and standby pathways should rapid initiation of bypass become necessary [11].

Diagnostic testing complements clinical assessment by defining anatomy, valve pathology, coronary disease, and ventricular function. Echocardiography is central in this phase, providing information on chamber size, systolic and diastolic performance, valve gradients and regurgitant severity, and the presence of intracardiac thrombus or shunt physiology. Coronary angiography or other relevant imaging modalities are used when ischemic disease is suspected or when operative planning requires precise delineation of coronary lesions. Additional imaging may be required to evaluate the aorta, peripheral vasculature, or congenital structures, depending on the planned intervention. These data shape both the surgical approach and the bypass plan, particularly regarding the safety of ascending aortic cannulation, the need for selective cerebral perfusion strategies, or the suitability of peripheral cannulation. Laboratory assessment supports risk stratification and establishes a baseline for intraoperative decision-making. A complete blood count informs anemia status and platelet adequacy, both of which affect transfusion planning and bleeding risk. Coagulation profiles are essential because CPB involves mandatory anticoagulation and is associated with coagulopathy; identifying baseline abnormalities allows proactive correction and reduces the likelihood of uncontrolled bleeding. Electrolyte and acid–base status provide insight into physiologic stability, while renal and hepatic function tests are particularly important because both organ systems influence drug handling, inflammatory response tolerance, and postoperative recovery. By integrating these laboratory data with clinical findings, the team can anticipate needs for blood products, adjust medication strategies, and prepare for more intensive monitoring in patients with limited reserve [11].

Anesthesia induction represents the physiologic transition from preoperative stability to a controlled intraoperative environment. General anesthesia is administered to ensure immobility, analgesia, and unconsciousness, creating the conditions required for sternotomy or minimally invasive access and for the hemodynamic manipulations associated with CPB. At the same time, anesthesia induction introduces hemodynamic vulnerability, especially in patients with severe aortic stenosis, advanced ventricular dysfunction, or pulmonary hypertension. Continuous monitoring is therefore expanded through both noninvasive and invasive modalities. Arterial lines provide beat-to-beat blood pressure measurement and facilitate frequent blood sampling, while central venous lines support vasoactive drug administration and volume assessment. In selected cases, pulmonary artery catheters may be used to quantify filling pressures and cardiac output, and transesophageal echocardiography provides dynamic imaging that helps guide volume management, confirms diagnosis, and supports assessment during weaning from bypass. These monitoring tools not only improve intraoperative safety but also enable rapid team responses during heparinization and cannulation, when sudden hemodynamic shifts can occur [11].

Patient positioning is typically supine and must balance operative exposure with prevention of pressure injuries and neurovascular compromise. Proper padding and alignment reduce the risk of peripheral nerve injury, skin breakdown, and musculoskeletal strain, particularly in lengthy CPB cases. Positioning also considers cannulation and line placement needs, ensuring that access points for central or peripheral cannulation are not obstructed and that the surgical field remains optimally accessible. Concurrently, operating room preparation focuses on strict sterility. The surgical site is cleansed with appropriate antiseptic solutions, and sterile drapes are placed to maintain an aseptic field. Sterile technique is not merely procedural formality; it is a primary defense against surgical site infection and mediastinitis, complications that can be devastating in cardiac surgery and can substantially prolong hospitalization and worsen outcomes. Heparinization is a pivotal preparatory step because CPB involves circulating blood through a nonendothelial circuit that strongly promotes activation of coagulation pathways. Without adequate anticoagulation, rapid and massive clot formation can occur within the circuit, threatening both the patient and the integrity of the bypass system. Accordingly, before going on bypass, a defined intravenous heparin dose is administered, commonly described as 300 units/kg or 3 g/kg in the provided protocol. Adequacy of anticoagulation is assessed in real time using the activated clotting time (ACT). ACT thresholds serve as operational safety gates: an ACT greater than 300 seconds is considered safe for cannulation, an ACT greater than 400 seconds is considered safe for initiating CPB, and an ACT greater than 480 seconds is considered safe for initiating deep hypothermic circulatory arrest. These thresholds support standardized decision-making and reduce variability during time-sensitive transitions. During the operation, ACT is rechecked at regular intervals, commonly every 30 minutes, to confirm sustained anticoagulation; if the value declines below 480 seconds, additional heparin—such as 500 units in the described approach—is administered to restore safety margins [11].

A failure of ACT to rise appropriately after full heparinization raises concern for heparin resistance, often linked to antithrombin III (AT3) deficiency. In such cases, escalation is coordinated with the surgeon and anesthesia team. If a cumulative heparin dose of 600 units/kg does not achieve an ACT above 480 seconds, recombinant AT3 concentrate may be considered to restore heparin responsiveness. Alternatively, fresh frozen plasma can be administered as a source of AT3. This structured approach emphasizes that anticoagulation during CPB is a dynamic physiologic process requiring ongoing assessment, prompt correction, and team-level agreement, as inadequate anticoagulation risks catastrophic circuit thrombosis, while excessive anticoagulation can contribute to bleeding complications. Arterial cannulation planning follows from both preoperative anatomic assessment and intraoperative findings. Arterial cannulas deliver oxygenated blood back to the patient, and they may be placed centrally or peripherally depending on anatomy, procedure type, urgency, and surgeon expertise. Central cannulation typically involves the ascending aorta for arterial return and the right atrium or vena cava for venous drainage. Its advantages include direct access to the heart and great vessels, the ability to achieve high flow rates with efficient CPB management, and a reduced risk of limb ischemia because peripheral arteries are not cannulated. Central access also tends to facilitate cardiac venting and decompression strategies, supporting improved operative exposure. However, central cannulation requires sternotomy or thoracotomy, increasing invasiveness and potentially prolonging recovery. Manipulation of the ascending aorta introduces a risk of aortic injury or dissection, and central cannulation can be challenging in reoperations where adhesions and scar tissue obscure anatomy and increase bleeding risk. While central cannulation is most commonly used, certain clinical circumstances reduce its attractiveness or increase its hazard. In aortic arch surgery, historical strategies involved cannulating the ascending aorta to achieve hypothermic circulatory arrest and then repositioning cannulas to provide antegrade cerebral perfusion, a sequence that increases manipulation and time. Cannulating the axillary artery using the same cannula can reduce these maneuvers and streamline cerebral perfusion strategies. In aortic aneurysm surgery, the ascending aorta may be dilated and fragile, and opening the chest before establishing bypass can carry rupture risk; initiating CPB via peripheral cannulation before sternotomy may therefore offer a safer approach in selected patients. In aortic dissection, distinguishing true and false lumens and ensuring reliable perfusion can be complex, and central cannulation may be compromised by distorted anatomy, making peripheral strategies more appealing depending on imaging and intraoperative findings [11].

Peripheral cannulation is often considered when less invasive access is desirable, when minimally invasive cardiac surgery is planned, or when prior sternotomy and complex chest anatomy complicate central exposure. Peripheral approaches may allow rapid initiation of bypass without opening the chest, which can be valuable in emergencies or in planned minimally invasive operations. However, peripheral cannulation introduces distinct risks. Limb ischemia is a major concern, particularly with femoral artery cannulation, and requires vigilant monitoring and, at times, use of distal perfusion catheters to preserve limb blood flow. Peripheral sites can be affected by atherosclerosis, increasing embolic risk and complicating cannula placement, and flow rates may be less optimal than central cannulation, potentially affecting the efficiency of CPB and organ perfusion. Local complications at cannulation sites—such as bleeding, infection, hematoma, and vessel injury—are also more common concerns with peripheral access and must be anticipated. Among peripheral arterial options, the axillary artery is often favored in selected cases because it generally carries a reduced risk of limb ischemia compared with femoral cannulation and can provide adequate flow for extended bypass periods. It is often less burdened by severe atherosclerotic disease, which may reduce embolic risk. Nonetheless, axillary cannulation can be technically demanding and requires careful dissection; proximity to the brachial plexus introduces a risk of nerve injury. The innominate artery can provide flow rates comparable to central cannulation and avoids femoral-associated limb ischemia, but it is technically complex and involves manipulation that may increase cerebrovascular risk, requiring careful technique and patient selection. Femoral artery cannulation remains common due to its accessibility and rapid deployment, making it useful in urgent scenarios or minimally invasive procedures. However, it carries a comparatively high risk of limb ischemia, is more often affected by atherosclerosis, and may yield lower flow performance than central or alternative peripheral sites, necessitating meticulous monitoring and supportive measures [11].

Venous cannulation completes the circuit interface by providing drainage of deoxygenated blood into the CPB system. Venous cannulas may be configured as one-stage or two-stage devices, selected according to the need for drainage efficiency and the requirement for cardiac isolation. One-stage venous cannulation typically involves placing a single cannula in the right atrium to drain blood from both the superior and inferior vena cava. The advantages are operational simplicity, faster insertion, fewer entry sites, and potentially reduced bleeding risk due to less manipulation. However, one-stage drainage may be limited in larger patients or in cases requiring maximal decompression, and it may be insufficient for complex procedures requiring complete isolation of the right atrium. In selective indirect bicaval strategies, one-stage cannulation can be used to provide adequate drainage while reducing complexity. In selective direct bicaval cannulation, a one-stage right-angled cannula may be used to avoid abutting and blocking against the back wall, improving drainage reliability in certain anatomic configurations. Two-stage venous cannulation refers either to placing two separate cannulas, one in the superior vena cava and one in the inferior vena cava, or to using a two-stage cannula with separate drainage ports designed to access both venae cavae. The principal advantage is superior venous return, more effective cardiac decompression, and increased versatility for complex operations where near-complete isolation of venous inflow is necessary, such as certain valve repairs or congenital reconstructions. Two-stage approaches also offer enhanced control over venous return, which can improve visualization and reduce the likelihood of blood obscuring critical structures. The trade-off is greater technical complexity and increased invasiveness, as additional cannulation sites and more extensive manipulation can elevate the risk of bleeding, vessel injury, and prolonged setup time. Two-stage cannulation is commonly referenced in cavoatrial venous cannulation strategies, where cannula design supports robust drainage through the cavoatrial junction [11].

Within venous cannulation strategies, three conceptual approaches are often described: cavoatrial cannulation, direct selective bicaval cannulation, and indirect selective bicaval cannulation. Cavoatrial cannulation involves placing a cannula at the junction of the inferior vena cava and right atrium. It is generally simpler than bicaval techniques and provides adequate drainage for many routine procedures, but it offers less granular control over separate superior and inferior vena caval drainage. This limitation can be significant in operations where complete isolation of the right atrium is needed to prevent blood return into the operative field. Direct selective bicaval cannulation places separate cannulas directly into the superior and inferior vena cava, enabling complete right atrial isolation, maximal venous return, and optimal decompression. This approach is particularly useful for procedures involving the tricuspid valve or certain congenital defects, where bloodless exposure of the right atrium is essential. However, it is technically demanding, consumes more time, and increases the number of cannulation sites, thereby elevating bleeding and vessel injury risk. Indirect selective bicaval cannulation seeks a compromise by using a two-stage cannula with separate drainage ports inserted through a single incision, simplifying the procedure while still providing effective drainage and partial isolation. The limitation is that isolation may be less complete than in direct bicaval cannulation, and drainage may be insufficient for certain complex repairs requiring full separation of venous return. Overall, preparation for CPB is a deliberate sequence of clinical evaluation and technical readiness checks designed to reduce uncertainty and control risk. Thorough preoperative assessment identifies vulnerabilities that may influence cannulation strategy, anticoagulation management, and monitoring intensity. Anesthesia induction and expanded monitoring create the physiologic framework for safe transitions. Sterile preparation and positioning protect the patient from avoidable harm. Heparinization and ACT-based verification provide the anticoagulation foundation required for extracorporeal circulation, including structured responses to heparin resistance. Finally, thoughtful selection of arterial and venous cannulation strategies—central or peripheral, one-stage or two-stage, cavoatrial or bicaval—aligns the bypass configuration with surgical requirements and patient anatomy. When these preparatory steps are executed as a coordinated team process, CPB can be initiated with greater safety, reduced complication risk, and improved likelihood of successful surgical repair and recovery [11].

Technique or Treatment

Once preoperative preparation has been completed, anticoagulation has been confirmed, and the arterial and venous cannulas have been placed securely, cardiopulmonary bypass (CPB) can be initiated. At this stage, the heart–lung machine assumes temporary control of systemic perfusion and gas exchange, allowing the surgical team to perform complex intracardiac or major vascular repair under conditions that would not be possible with native cardiopulmonary function alone. Although the overall concept of CPB is straightforward—divert venous blood to an extracorporeal circuit, oxygenate it, then return it to the arterial circulation—the technique requires meticulous sequencing, constant physiologic surveillance, and disciplined team communication. The process is best understood as a series of structured phases: initiation of bypass ("going on bypass"), confirmation that bypass is satisfactory, delivery of myocardial protection during the repair, and a controlled reversal process culminating in separation from bypass and dismantling of the circuit. At the start of CPB, venous drainage is established by inserting cannulas into the right-sided venous system, typically involving the right atrium and/or venae cavae. The purpose of venous cannulation is not only to route blood into the circuit but also to decompress the heart so that the surgical field becomes relatively bloodless and motion is minimized. In many standard configurations, venous return enters the circuit passively, driven primarily by gravity and the height differential between the patient and the venous reservoir; the reservoir is positioned lower than the patient so that venous blood siphons downward into the circuit. The blood entering the reservoir is then propelled by the pump through the oxygenator, where carbon dioxide is removed and oxygen is added, producing blood suitable for systemic circulation. From the oxygenator outlet, oxygenated blood is directed to the patient through an arterial cannula, most commonly positioned in the distal ascending aorta. This return stream is carefully regulated to provide perfusion pressures and flows adequate to sustain the brain, kidneys, and other vital organs throughout the operation [11][12].

A distinctive feature of CPB in cardiac surgery is the deliberate separation between systemic perfusion and myocardial perfusion. While one stream of oxygenated blood is returned to the systemic circulation, another stream is routed through a cardioplegia delivery system and mixed with cardioplegia solution for targeted myocardial protection. This cardioplegia stream is delivered to the aortic root through a dedicated cardioplegia pump, with the intent that the heart receives cardioplegia rather than normal perfusate. By ensuring that the myocardium is exposed to a protective arresting solution while the rest of the body continues to receive oxygenated blood, the circuit establishes two parallel physiologic goals: organ preservation through systemic perfusion and myocardial preservation through controlled electromechanical arrest. This functional separation is essential because the operative requirement for a motionless heart would otherwise conflict with the heart's need for oxygen delivery during ischemic periods. Aortic cross-clamping is central to intracardiac repair because it isolates the heart from the systemic circulation and enables the surgeon to work in a bloodless environment. However, cross-clamping inherently induces myocardial ischemia by interrupting coronary blood flow. Cardioplegia is therefore employed as a myocardial protection strategy that reduces metabolic demand and oxygen consumption by producing electromechanical arrest. In typical configurations, the cardioplegia cannula is placed proximal to the cross-clamp, while the systemic arterial cannula lies distal to the clamp. Cardioplegia may be administered antegrade through the aortic root into the coronary ostia, retrograde through the coronary sinus, or as a combined strategy. Retrograde delivery often uses a balloon-tipped cannula inserted into the coronary sinus; transesophageal echocardiography can assist placement by confirming position and reducing the risk of maldeployment. Clinically, retrograde cardioplegia alone is recognized as insufficient for complete right ventricular protection, which is why antegrade or combined approaches are commonly preferred when feasible. Nevertheless, retrograde delivery can be particularly important when antegrade delivery is compromised, most notably in the presence of aortic insufficiency. When the aortic valve is incompetent, antegrade cardioplegia may regurgitate into the left ventricle rather than perfusing the coronary circulation effectively, resulting in inadequate myocardial protection and pathological ventricular distension. Under such conditions, retrograde cardioplegia may be required in addition to antegrade or direct ostial cardioplegia. In cases of severe aortic regurgitation, ostial cardioplegia—direct infusion into the coronary ostia—may be used to achieve reliable myocardial protection.[10]

While myocardial protection proceeds, CPB supports whole-body homeostasis through integrated control of temperature and blood chemistry. The heat exchanger provides controlled cooling and rewarming, allowing the team to modulate metabolic requirements and protect organs during the ischemic phases of surgery. The circuit also permits correction of acid–base status and electrolytes based on serial blood gas analyses and laboratory monitoring, ensuring that systemic perfusion remains physiologically effective rather than merely mechanical. Simultaneously, cardiotomy suction devices retrieve blood from the operative field and return it to the circuit after filtration, supporting visibility and reducing transfusion requirements. Cardiac vents maintain optimal intracardiac pressures by decompressing chambers and assisting in de-airing, thereby limiting distension-related myocardial injury and reducing the risk of air embolism when circulation is restored. In practice, the transition to CPB is a high-risk juncture because it involves rapidly changing hemodynamics, potential arrhythmias, and the possibility of blood loss or air introduction. A structured approach to "going on bypass" therefore emphasizes sequencing, verification, and shared readiness. The surgeon performs arterial and venous cannulation and connects the cannulas to the circuit tubing. Connecting the arterial cannula first can provide a safety advantage: if the patient becomes hemodynamically unstable during venous cannulation, the perfusionist can rapidly transfuse circuit volume into the circulation through the arterial line. This is particularly relevant because venous manipulation can irritate the atrium and precipitate supraventricular arrhythmias such as atrial fibrillation, which may be poorly tolerated in certain physiologic states including left ventricular hypertrophy or severe aortic stenosis. In addition, atriotomy for venous cannula placement can produce blood loss that compromises hemodynamics. Having the arterial cannula connected and ready allows immediate volume support and can prevent deterioration while cannulation is completed [9][10][11][12].

Before the team proceeds, the surgeon confirms readiness with both the anesthetist and the perfusionist, and only after all parties report that conditions are safe does the surgeon give the order to initiate bypass. A critical technical step is dividing the lines, which refers to opening continuity between the patient cannulas and the circuit tubing in a controlled manner. Before doing so, two confirmations are essential with the perfusionist: that the pump is off, and that the venous line is clamped. If the pump is running against a closed clamp, pressure can build rapidly and cause circuit damage; if the venous line is not clamped, fluid may siphon back into the reservoir and destabilize volume management. Prior to final connection, de-airing maneuvers are performed. The perfusionist may push fluid into the arterial cannula to expel air from the connection ("come around"), while venous adjustments may include pulling back fluid, shortening tubing length, and ensuring the cannula sits appropriately to promote drainage and reduce the risk of air entrainment. After the arterial line is connected to the aortic cannula, the team confirms both "good swing" and "good pressure," which reflect that the cannula is within the lumen and in continuity with the bloodstream and that there is no evidence of malposition, obstruction, posterior wall abutment, or placement into a dissection lumen. Once bypass is initiated, confirming that CPB is satisfactory is an ongoing process rather than a single checkpoint. Adequate venous drainage is assessed by observing consistent flow into the reservoir without excessive negative pressure, resistance, or air entrainment, all of which may suggest malposition or insufficient preload. Arterial line pressure monitoring is used to ensure that blood is being delivered safely and effectively into the arterial system; abnormal elevations may indicate outflow obstruction, kinking, cannula malposition, or systemic resistance changes, whereas unusually low pressures may reflect inadequate flow or circuit leaks. Blood gases and oxygenation parameters are checked repeatedly to verify oxygenator performance and to ensure that carbon dioxide removal is appropriate. Hemodynamic stability is monitored through arterial pressure, heart rhythm, filling pressures, and other markers of perfusion adequacy, recognizing that the patient's native heart is decompressed and that systemic circulation is now largely determined by pump settings and vascular tone. Flow rates are adjusted based on patient size and physiologic needs to maintain organ perfusion while minimizing excessive hemodilution and shear stress. Temperature is monitored at multiple points to confirm that the heat exchanger is maintaining safe targets and that rewarming and cooling occur at controlled rates. In parallel, a visual inspection of the circuit is continuously performed to identify leaks, air bubbles, abnormal reservoir levels, or device malfunction. Throughout, communication among the surgeon, anesthetist, and perfusionist remains essential, particularly for confirming cannula function, maintaining appropriate pressures, and ensuring that cardioplegia delivery is achieving reliable myocardial arrest and protection [9][10][11][12].

Separation from CPB, or weaning, is the controlled reversal of extracorporeal support, requiring the heart and lungs to resume their physiologic roles. The process typically begins with rewarming, de-airing, and restoration of ventilation. Rewarming is necessary because myocardial function and normal metabolic activity depend on achieving physiologic temperature. The rewarming process is intentionally slower than cooling, commonly described at approximately 0.3–0.5 °C per minute, reflecting the thermal properties of body tissues and the need to avoid complications related to gas solubility and microbubble formation. Systemic rewarming is accomplished through the heat exchanger, and external warming devices such as forced-air warming may be used to support peripheral temperature normalization. Rewarming must be controlled to avoid overheating, which can contribute to protein denaturation and metabolic stress, and to avoid rapid temperature gradients that favor microbubble formation in accordance with gas laws. De-airing is one of the most critical safety steps in weaning because residual air within the heart or great vessels can embolize to any organ, with the coronary and cerebral circulations being especially vulnerable due to their proximal aortic branching. Particular concern is often noted for the right coronary artery given its anterior position, as air embolization can precipitate right ventricular ischemia and distension. De-airing involves coordinated surgical maneuvers, vent management, and controlled changes in pump flow and pressure to displace air and ensure that the heart and aorta are cleared before the heart assumes full circulatory responsibility. In difficult cases, additional measures may be required, including temporary return to full bypass or specialized perfusion strategies. Because surgical breaches and open cardiac chambers introduce ambient air, the entire pathway—from venous cannulation through the right heart and pulmonary circulation to the left heart and aorta—may contain air when the heart is decompressed. Potential sources include surgical openings such as atriotomy and aortotomy, anesthetic lines such as central venous catheters, circuit-related issues such as low reservoir levels or cavitation, and natural anatomic dead space. Successful de-airing therefore depends on systematic technique and cross-disciplinary vigilance [10][11][12].

Once ventilation is restored and de-airing is judged adequate, the team must confirm that heart and lung function are sufficient to tolerate separation. This includes assessment of arterial blood gases, electrolyte status—particularly potassium—temperature within the physiologic range of approximately 35–37 °C, and hemodynamic indices that reflect cardiac output and perfusion adequacy. Echocardiography often plays a decisive role at this moment by assessing ventricular filling and contractility, valve competence, and the presence of residual intracardiac air. The surgeon and anesthetist also confirm the absence of correctable surgical problems, such as graft failure, valve leak, dissection, or residual air, and verify that pacing and ventilation are satisfactory before proceeding further. Gradual weaning from the pump proceeds by shifting volume back to the heart and progressively reducing extracorporeal flow. The perfusionist typically begins by partially clamping the venous line, which reduces venous drainage and allows more blood to remain in the patient, thereby filling the heart. This controlled filling supports restoration of myocardial stretch and contractility along the Frank–Starling relationship, aiming to achieve effective contraction at an optimal filling point. As cardiac ejection becomes stable, the perfusionist reduces pump flow in coordination with the surgeon's instructions until the pump is fully stopped and the venous line is completely clamped. During this period, the heart and lungs are closely observed for hemodynamic stability, adequate oxygenation, and absence of arrhythmias or ventricular distension. Even after the pump is off, arterial and venous lines may remain clamped but connected for a short observation period to ensure stability, recognizing that rapid return to bypass may be necessary if instability develops. Circuit dismantling occurs only once the team is confident that cardiopulmonary function is stable and that immediate return to bypass is unlikely. At this point, anticoagulation is reversed with protamine, commonly dosed at 1 mg per 100 units of heparin administered. Protamine reverses heparin through ionic binding and formation of complexes, restoring coagulation capacity. However, protamine administration carries recognized risks, including hypotension, pulmonary vasoconstriction, bronchoconstriction, reduced cardiac output, and in rare cases anaphylaxis, with hypotension being particularly dependent on the speed of administration. Consequently, protamine is given with careful monitoring and controlled infusion rate. Dismantling is performed stepwise, commonly removing the venous cannula first while maintaining readiness of purse-string sutures, followed by removal of vents, and finally removal of the aortic cannula after adequate reversal and satisfactory filling. During this process, precautions are maintained to facilitate rapid recannulation if needed. For example, the venous line may be filled with crystalloid to permit rapid reprime, reservoir levels are monitored, and the atrial purse strings may be left positioned for reuse. The perfusionist confirms circuit readiness parameters, including adequate reservoir volume and the functional capacity to reinitiate flow if the patient decompensates. Across every phase of CPB technique, the core principle is controlled transitions supported by redundancy and communication. Going on bypass demands sequencing that anticipates instability and prioritizes air control. Confirming satisfactory bypass requires continuous surveillance of drainage, pressure, oxygenation, temperature, and circuit integrity. Weaning requires physiologic restoration of temperature, ventilation, and myocardial function coupled with rigorous de-airing, incremental transfer of flow responsibility back to the heart, and careful reversal of anticoagulation. When these steps are executed as an integrated team process, CPB provides a safe physiologic bridge that enables complex cardiac repair while protecting end organs and maximizing the likelihood of stable recovery [11][12].

Complications

Cardiopulmonary bypass (CPB) has enabled modern cardiac surgery to progress from limited extracardiac interventions to complex intracardiac reconstruction; however, the physiologic price of extracorporeal circulation is a distinct spectrum of complications that may influence both short-term stability and long-term recovery. These adverse effects arise from multiple mechanisms, including exposure of blood to nonphysiologic surfaces, altered flow patterns and shear forces, hemodilution, temperature manipulation, anticoagulation requirements, and ischemia–reperfusion phenomena. Because many complications are multifactorial, prevention and management depend on continuous monitoring, coordinated interprofessional decision-making, and the use of evolving technologies and evidence-informed strategies. A prominent and widely recognized complication is systemic inflammatory response syndrome (SIRS), which can be triggered when circulating blood contacts the nonendothelial surfaces of the CPB circuit. This interface activates complement pathways, leukocytes, and endothelial cells, initiating a cascade of inflammatory signaling that may be amplified further by surgical trauma, ischemia–reperfusion injury, and, in some cases, endotoxemia related to altered splanchnic perfusion. Clinically, this inflammatory activation may manifest as fever, leukocytosis, and capillary leak syndrome, the latter of which can contribute to generalized edema, intravascular volume depletion, pulmonary dysfunction, and difficulty maintaining hemodynamic stability. One clinically challenging downstream expression of this inflammatory milieu is vasoplegic syndrome, characterized by profound systemic vasodilation and low systemic vascular resistance despite adequate or elevated cardiac output. Pharmacologic approaches with antioxidant properties have been described as potentially beneficial in attenuating inflammatory and oxidative pathways during CPB, with emerging evidence suggesting promise in reducing CPB-related complications, including vasoplegic syndrome.[6] Although such strategies do not eliminate risk, they reflect an important direction in perioperative optimization: targeting the biological mechanisms that underlie CPB-associated inflammation rather than treating consequences alone.

Hemostatic derangements represent another major complication domain. CPB is frequently associated with coagulopathy arising from hemodilution, platelet activation and dysfunction, consumption of clotting factors, and activation of fibrinolytic pathways. Exposure of blood to the circuit and suctioned blood returned from the surgical field can further impair platelet function and disturb coagulation balance. Clinically, these changes may manifest as excessive postoperative bleeding, increased chest tube output, and an elevated requirement for transfusion of blood products such as platelets, plasma, or cryoprecipitate. Bleeding complications are not solely a matter of volume loss; they may increase the risk of tamponade, prolong mechanical ventilation, delay wound healing, and contribute to infection risk. Prevention therefore requires careful anticoagulation monitoring during bypass, meticulous surgical hemostasis, judicious use of blood conservation strategies, and targeted correction of coagulation abnormalities guided by laboratory or point-of-care testing. Neurologic complications remain among the most feared adverse outcomes after CPB because they can impose profound and lasting disability. Stroke can occur due to embolic events, including atheromatous debris or gaseous microemboli, as well as due to cerebral hypoperfusion, disturbances in autoregulation, or inflammatory effects on cerebral microcirculation. Even in the absence of overt stroke, CPB has been associated with postoperative cognitive dysfunction and delirium, outcomes influenced by age, comorbidity burden, perfusion pressures, temperature management, and inflammatory activation. Consequently, contemporary practice places strong emphasis on minimizing embolic load through filtration and air management, maintaining appropriate perfusion pressures, and using monitoring techniques to support cerebral protection when indicated [6].

Renal complications, particularly acute kidney injury, are also clinically significant and may result from altered renal perfusion, nonpulsatile flow, inflammatory activation, hemolysis-related pigment nephropathy, and perioperative hypotension or vasoplegia. Even modest postoperative increases in creatinine can be associated with prolonged hospitalization and increased morbidity. Electrolyte disturbances may accompany CPB due to hemodilution, transfusion practices, temperature shifts, and changes in acid–base balance, and they can contribute to arrhythmias, hemodynamic instability, or delayed recovery if not promptly corrected. Finally, CPB can be associated with transfusion-related complications. Hemolysis may occur due to mechanical shear stress, suction effects, or circuit-related factors, while transfusion itself carries risks including immunologic reactions, volume overload, and infectious transmission, albeit rare with modern screening. Taken together, these potential complications underscore why CPB management is inseparable from vigilant surveillance and proactive mitigation strategies. Through refined circuit design, improved biocompatibility, optimized perfusion techniques, and targeted pharmacologic interventions, contemporary cardiac surgery aims to preserve the lifesaving benefits of CPB while reducing the incidence and severity of its physiologic burdens.[6]

Clinical Significance

Cardiopulmonary bypass (CPB) occupies a central position in contemporary cardiac surgery because it enables definitive correction of cardiac pathology under conditions that would otherwise be physiologically untenable. The essential clinical value of CPB lies in its ability to temporarily replace the pumping function of the heart and the gas-exchange function of the lungs, thereby sustaining systemic perfusion and oxygenation while the operative team gains controlled access to intracardiac and proximal great-vessel structures. By decompressing the heart and allowing electromechanical arrest, CPB creates a largely bloodless and motionless surgical field, which is critical for meticulous reconstruction of valves, septa, and complex congenital anatomy, as well as for procedures that require precision suturing and delicate tissue manipulation in confined anatomic spaces. In this environment, surgeons can perform interventions with improved visibility and technical control, reducing the likelihood of errors related to poor exposure or uncontrolled bleeding and enabling procedures that demand extended operative time and structural precision. The clinical impact of CPB is particularly evident in conditions for which alternative strategies are limited or inadequate. In congenital heart disease, CPB permits repair of septal defects, outflow tract obstructions, and complex structural malformations that would be incompatible with uninterrupted intracardiac blood flow. In coronary artery disease, CPB supports coronary artery bypass grafting in patients with complex multivessel disease, reduced ventricular function, or anatomy that makes off-pump approaches more technically challenging. Similarly, in valvular heart disease, CPB enables repair or replacement of stenotic or regurgitant valves under controlled conditions, facilitating durable correction and hemodynamic restoration. Through these roles, CPB has contributed substantially to improved survival, expanded surgical candidacy, and enhanced long-term quality of life, making it a foundational technology for modern cardiothoracic practice [6][7][10].

Nevertheless, the same mechanisms that make CPB effective—extracorporeal circulation, blood contact with artificial surfaces, anticoagulation, and deliberate physiologic manipulation—also introduce clinically significant hazards. CPB is associated with inflammatory activation, coagulopathy, neurological risk, renal injury, and other organ dysfunctions that can prolong recovery or, in severe cases, threaten life. These risks elevate the clinical importance of careful perfusion management, robust monitoring, and evidence-based protocols designed to prevent avoidable harm. The requirement for continuous oversight is not limited to perfusion variables alone; it extends to temperature regulation, acid–base and electrolyte control, anticoagulation targets, air management, and hemodynamic stability during initiation and separation from bypass. Consequently, the clinical significance of CPB is inseparable from the requirement for vigilant management, because outcomes depend not only on the ability to place the patient on bypass but also on the ability to maintain physiologic stability throughout a dynamic operative course and to mitigate known complications. In recognition of CPB-associated morbidity, some surgeons increasingly employ off-pump cardiac surgery in selected cases, particularly for coronary revascularization, as a strategy to avoid the systemic effects of extracorporeal circulation. Off-pump techniques aim to preserve the benefits of surgical repair while reducing CPB-related inflammatory, hematologic, and neurologic burdens.[11][12][13][14] However, off-pump approaches may not be appropriate for all patients or procedures, and the need for CPB remains essential in many complex operations. Thus, CPB continues to be clinically indispensable, providing a reliable physiologic platform for intricate repairs while demanding a high level of procedural expertise, patient selection, and intraoperative vigilance to ensure that its benefits outweigh its risks.[11][12][13][14]

Enhancing Healthcare Team Outcomes

Optimizing outcomes in procedures involving cardiopulmonary bypass requires a comprehensive interprofessional strategy that integrates technical expertise, anticipatory planning, disciplined communication, and coordinated care across the perioperative continuum. Because CPB transforms the patient's physiology and introduces risks that can evolve rapidly, successful management depends on a shared understanding of goals and contingencies among surgeons, anesthesiologists, perfusionists, nurses, pharmacists, and critical care teams. High performance in this setting is not solely a function of individual competence; it emerges from the reliability of the team system, including standardized processes, clear role delineation, and an environment in which concerns can be raised promptly and acted upon without delay. Physicians and surgeons are responsible for determining the appropriateness of CPB, selecting cannulation strategies, and executing the operative repair under bypass conditions. Their decisions must incorporate not only anatomy and procedural complexity but also patient-specific risk factors that influence perfusion targets, myocardial protection strategy, and the likelihood of complications such as bleeding or neurologic injury. Anesthesiologists provide continuous physiologic management, translating hemodynamic signals into real-time interventions, coordinating with perfusion to align pump flows and pressures with systemic requirements, and facilitating safe transitions during initiation and weaning. Perfusionists, who operate the heart–lung machine, sustain the patient's perfusion and oxygenation throughout bypass and must continuously adjust flow, temperature, gas exchange parameters, and anticoagulation monitoring in response to clinical conditions. Their role is both technically demanding and safety-critical, as circuit issues such as air entrainment, abnormal pressures, or oxygenator dysfunction require rapid detection and decisive corrective action .[11][12][13][14]

Nursing personnel and advanced practice providers are equally vital to outcomes, contributing to preoperative assessment, intraoperative surveillance, and postoperative recovery management. Preoperatively, nurses support risk identification through careful assessment, verification of allergies and comorbidities, and readiness checks that reduce preventable delays and omissions. Intraoperatively, scrub and circulating nurses maintain sterility, ensure availability of critical equipment, and provide continuous situational awareness that supports safe workflow during high-risk moments such as cannulation, cross-clamping, and separation from bypass. Postoperatively, intensive care nurses and advanced practitioners monitor for bleeding, vasoplegia, arrhythmias, respiratory compromise, renal dysfunction, and neurologic changes, implementing protocols and escalating care promptly when deterioration is suspected. This continuity across phases is essential because many CPB-related complications emerge after the patient leaves the operating room, and early detection often determines severity and reversibility. Pharmacists strengthen outcomes by optimizing medication management in a context characterized by anticoagulation, hemodynamic instability, and polypharmacy. Their input is particularly important for dosing heparin and protamine, managing vasopressors and inotropes, ensuring appropriate antimicrobial prophylaxis, and monitoring for adverse drug reactions or clinically important drug interactions. They also contribute to protocol standardization and stewardship practices that improve reliability across cases. Biomedical engineers and technical staff further support safety by ensuring that CPB equipment is maintained, calibrated, and functionally reliable, thereby reducing the risk that device failure becomes a clinical emergency .[11][12][13][14]

Effective communication is the operational thread that binds these contributions into coherent care. Structured intraoperative dialogue, closed-loop communication, and clearly defined checkpoints—such as confirming anticoagulation adequacy, readiness to initiate bypass, and criteria for safe weaning—reduce error risk and improve shared situational awareness. Care coordination extends this teamwork beyond the operating room. Preoperative conferences and individualized planning align team expectations and establish contingency plans for high-risk features such as difficult cannulation, severe ventricular dysfunction, or anticipated bleeding. Intraoperatively, continuous coordination ensures that changes in patient status or surgical strategy are communicated instantly so perfusion, anesthesia, and nursing actions remain synchronized. Postoperatively, coordinated handoffs, consistent monitoring priorities, and early multidisciplinary rehabilitation planning support recovery, reduce complications, and enhance patient-centered outcomes. Through this collaborative model—grounded in shared expertise, timely information exchange, and coordinated decision-making—healthcare teams can improve the safety and effectiveness of CPB, delivering complex cardiac surgery with fewer complications and more predictable recovery trajectories .[11][12][13][14]

Conclusion:

Cardiopulmonary bypass has transformed cardiac surgery by decoupling systemic perfusion from myocardial activity, permitting precise intracardiac reconstruction under controlled conditions. Yet the very mechanisms that confer this advantage—extracorporeal circulation, anticoagulation, hypothermia, and deliberate hemodilution—introduce predictable, potentially severe hazards, including systemic inflammation, coagulopathy, neurologic events, renal injury, and air or particulate embolization. Nursing practice is the continuous safety net across these phases. Before bypass, nurses operationalize readiness: comprehensive assessment, equipment verification, sterility, and anticoagulation targets. Intraoperatively, they sustain situational awareness—tracking reservoir levels, line pressures, bleeding, temperature changes, rhythm disturbances, and early signs of vasoplegia or inadequate oxygenation—while facilitating closed-loop communication during high-risk transitions (going on bypass, cross-clamp, reperfusion, weaning, protamine reversal). Postoperatively, ICU nursing surveillance detects evolving complications and coordinates timely interventions (ventilator adjustments, vasoactive titration, transfusion stewardship, renal support). Outcomes improve when these nursing actions are embedded within standardized, team-based pathways: clear role delineation; echo-guided checks for ventricular filling and residual air; protocolized ACT monitoring and heparin-resistance rescue; structured de-airing and controlled rewarming; and disciplined handoffs that carry forward risk cues from the OR to the ICU. In sum, CPB's clinical value is maximized—and its risks minimized—when nursing practice leads the reliability agenda: anticipatory monitoring, rapid escalation, and uncompromising communication that make complex cardiac surgery safer and recovery more predictable.

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