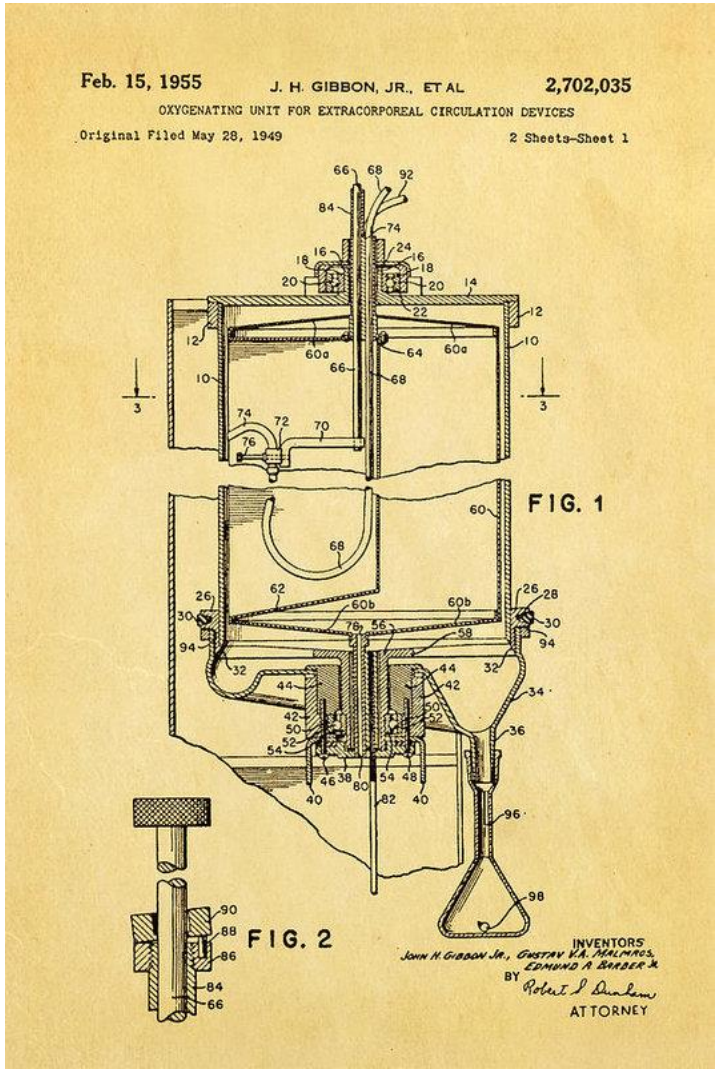
Basic of Cardiopulmonary Bypass

Kyo Seon Lee

Department of Thoracic and Cardiovascular Surgery
Chonnam National University Hospital
Chonnam National University Medical School

1st Cardiopulmonary Bypass

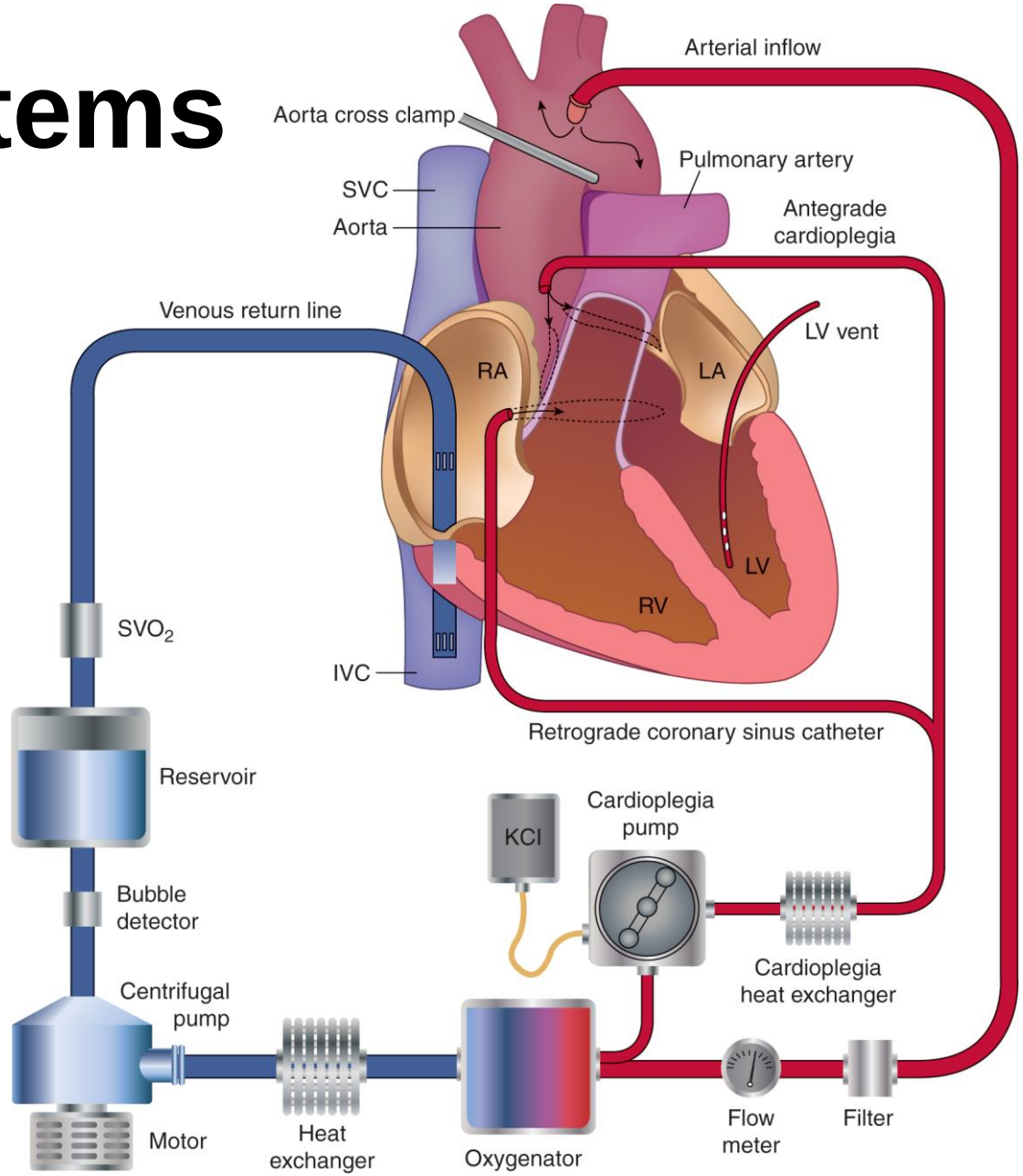
- ***John Gibbon*** - IBM engineer

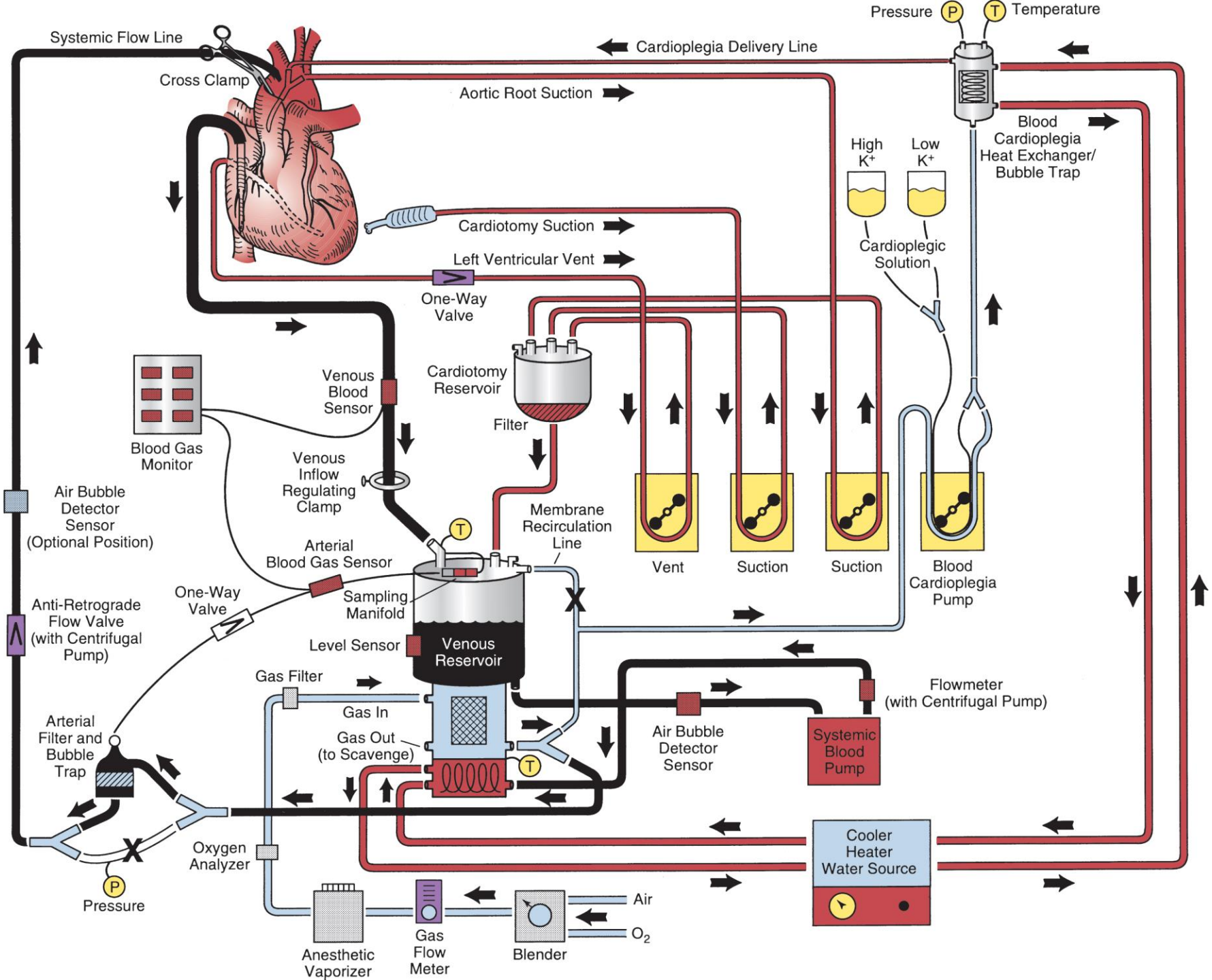


One of the most important biomedical inventions

Perfusion Systems

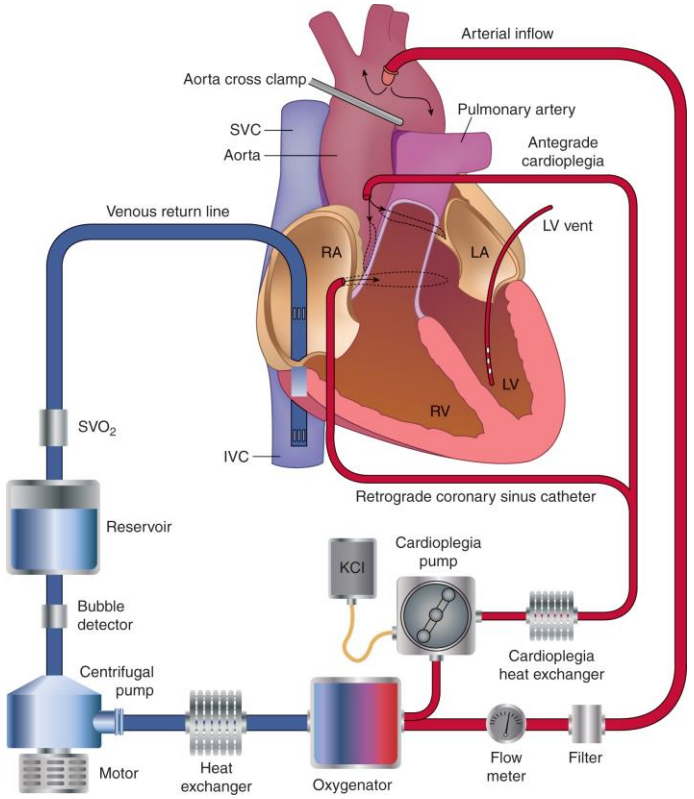
- Venous and arterial cannulation
- Venous reservoir
- Oxygenators
- Heat exchangers
- Pumps
- Filters and bubble traps
- Tubing and connectors
- Heparin-coated circuits
- Cardiotomy reservoir and field suction
- Venting
- Cardioplegia delivery systems
- Hemoconcentrators (Hemofiltration/ultrafiltration)
- Monitors and safety devices




Systemic Flow Line
Cross Clamp
Cardioplegia Delivery Line
Pressure
P
T
Temperature
Aortic Root Suction
Blood Cardioplegia Heat Exchanger/ Bubble Trap
High K+
Low K+
Cardioplegic Solution
Cardiotomy Suction
Left Ventricular Vent
One-Way Valve
Cardiotomy Reservoir
Filter
Venous Blood Sensor
Blood Gas Monitor
Venous Inflow Regulating Clamp
Air Bubble Detector Sensor (Optional Position)
Membrane Recirculation Line
Arterial Blood Gas Sensor
Vent
Suction
Suction
Blood Cardioplegia Pump
One-Way Valve
Anti-Retrograde Flow Valve (with Centrifugal Pump)
Sampling Manifold
Level Sensor
Venous Reservoir
Gas Filter
Gas In
Gas Out (to Scavenge)
Flowmeter (with Centrifugal Pump)
Air Bubble Detector Sensor
Systemic Blood Pump
Arterial Filter and Bubble Trap
Oxygen Analyzer
Cooler Heater Water Source
Pressure
Anesthetic Vaporizer
Gas Flow Meter
Blender
Air
O_2

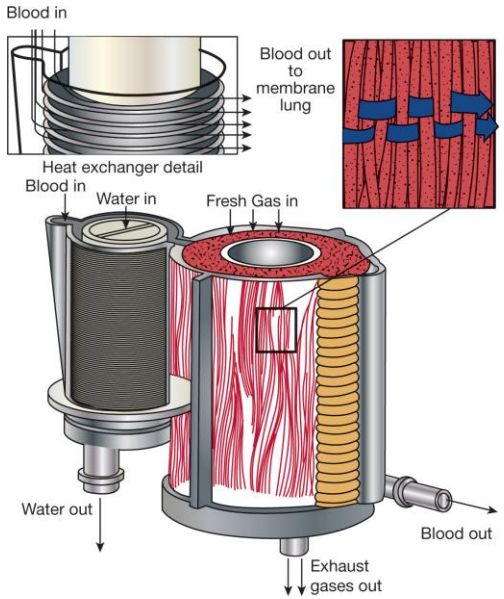
Venous Reservoir

- 1~3L of blood
- Store excess blood
- Bubble trap
- Access for drugs, fluids, or blood



- To provide time for the perfusionist to act if venous drainage is sharply reduced or stopped

Oxygenators



	PPL (polypropylene)	PMP (polymethylpentene)
Structure	Microporous	Non-porous
Mechanism of gas exchange	Plasma fills pores to form functional gas-exchange surface	True diffusion
Duration of use	Short-term (hours, CPB)	Long-term (days to weeks, ECMO)
Plasma leakage	Possible	None
Volatile anesthetic transfer	Possible (advantage for CPB)	Minimal/None (IV anesthesia required)
Cost	Lower	Higher
Biocompatibility	Relatively lower	Higher

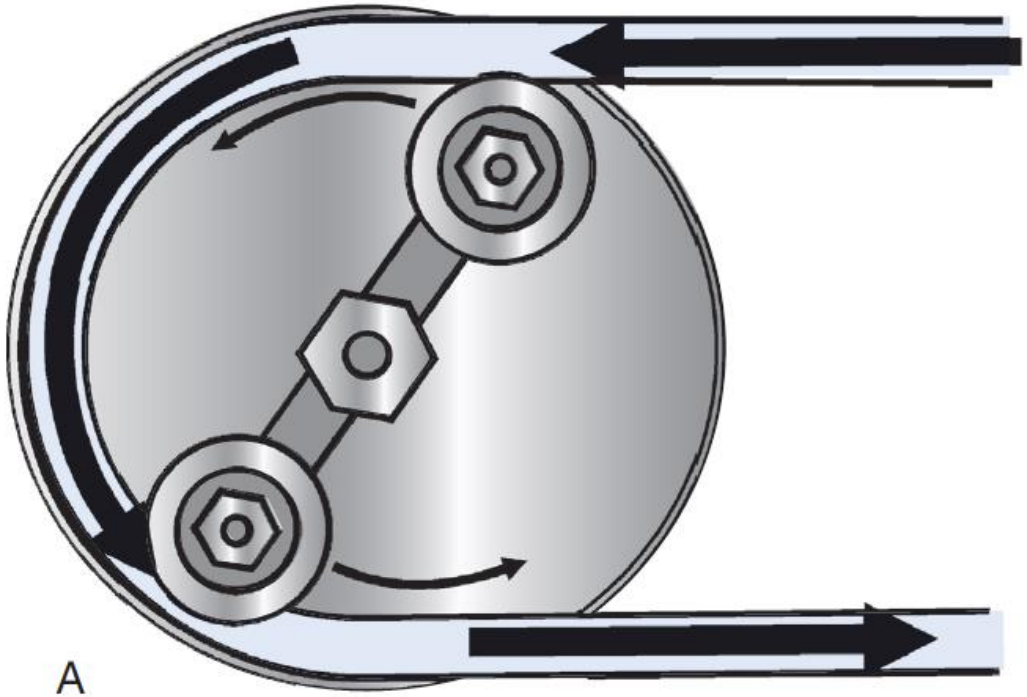
Recommendations	Class[a]	Level[b]
Microporous membrane oxygenators are recommended as the standard choice in the CPB procedure.	I	B
Polymethylpentene membrane oxygenators are not recommended when volatile anaesthetic agents are used during the CPB procedure.	III	B

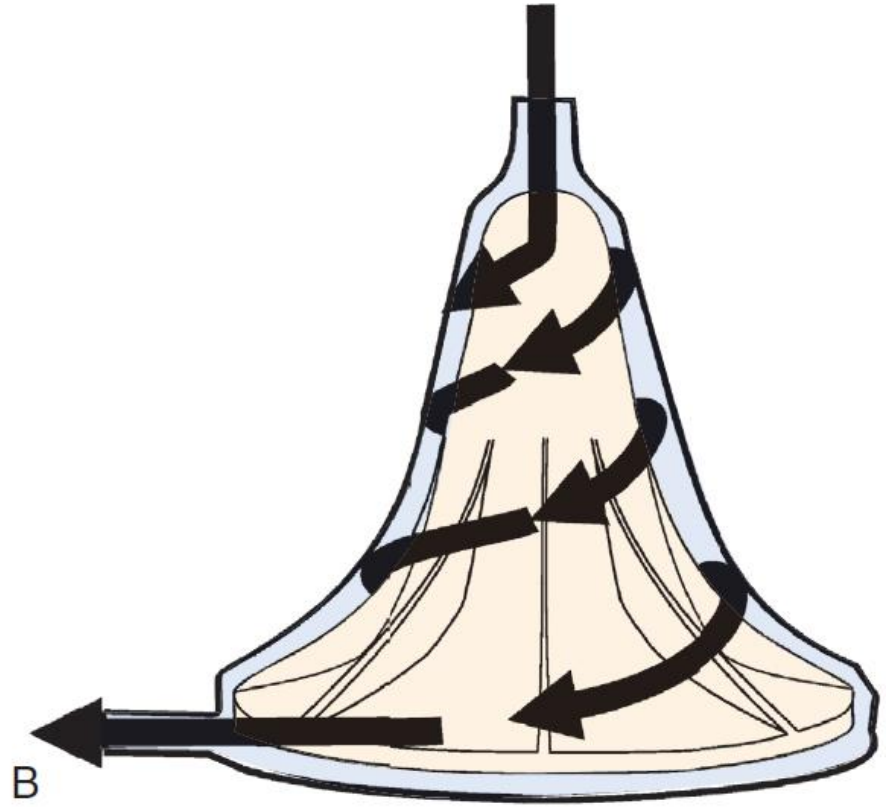
Eur J Cardiothorac Surg 2025;67:ezae354

Heat Exchangers

- Heated temperature < 40 °C
- Temperature gradient between body and circuit < 10 °C

Types of Pump





Roller vs Centrifugal Pumps

	Roller pump	Centrifugal pump
Description	Nearly occlusive Afterload independent	Nonocclusive Afterload sensitive
Advantages	Low prime volume Low cost No potential for backflow Shallow sine-wave pulse	Portable, position insensitive Safe positive and negative pressure Adapts to venous return Superior for right or left heart bypass Preferred for long-term bypass Protects against massive air embolism
Disadvantages	Excessive positive and negative pressure Spallation Tubing rupture Potential for massive air embolism Necessary occlusion adjustments Requires close supervision	Large priming volume Requires flowmeter Potential passive backward flow Higher cost

Centrifugal Pump and Roller Pump in Adult Cardiac Surgery: A Meta-Analysis of Randomized Controlled Trials

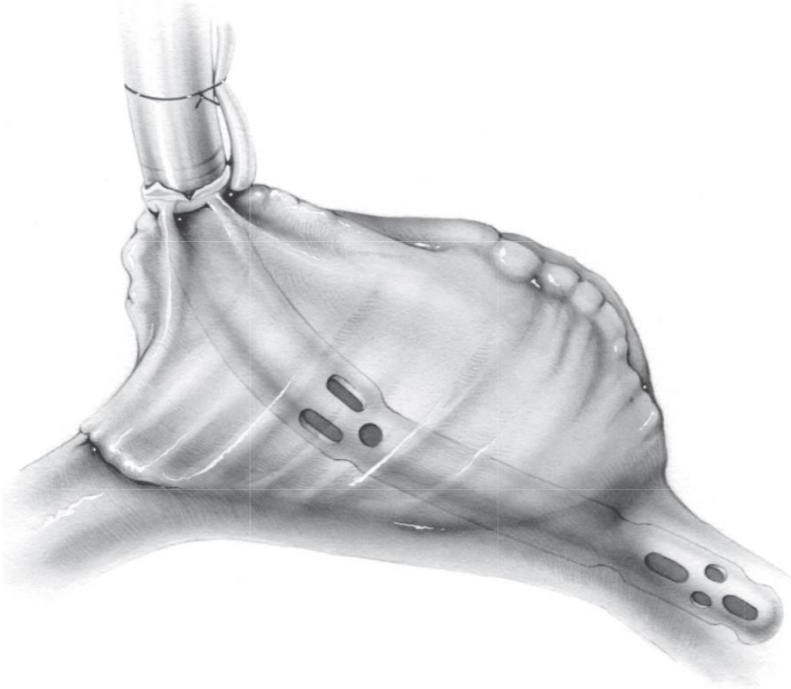
Richard Saczkowski, Michelle Maklin, Thierry Mesana, Munir Boodhwani, and Marc Ruel

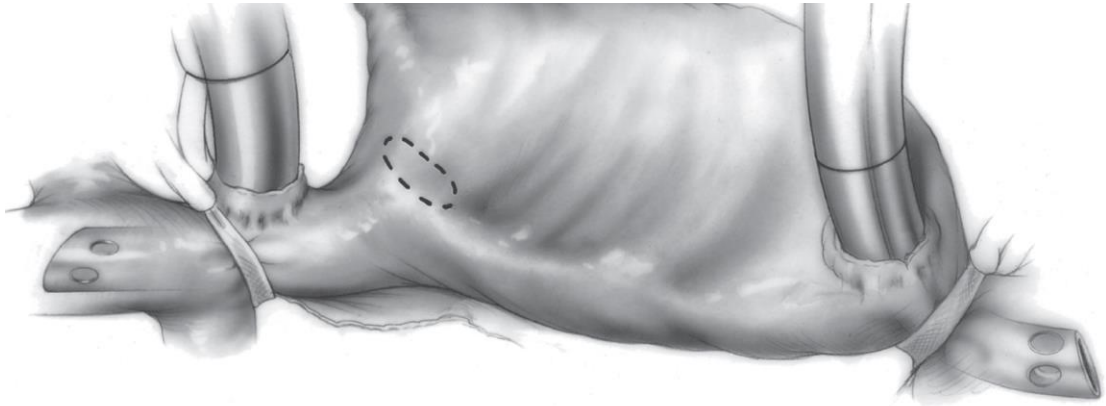
Department of Cardiac Surgery, Royal Columbian Hospital, New Westminster, British Columbia, Canada

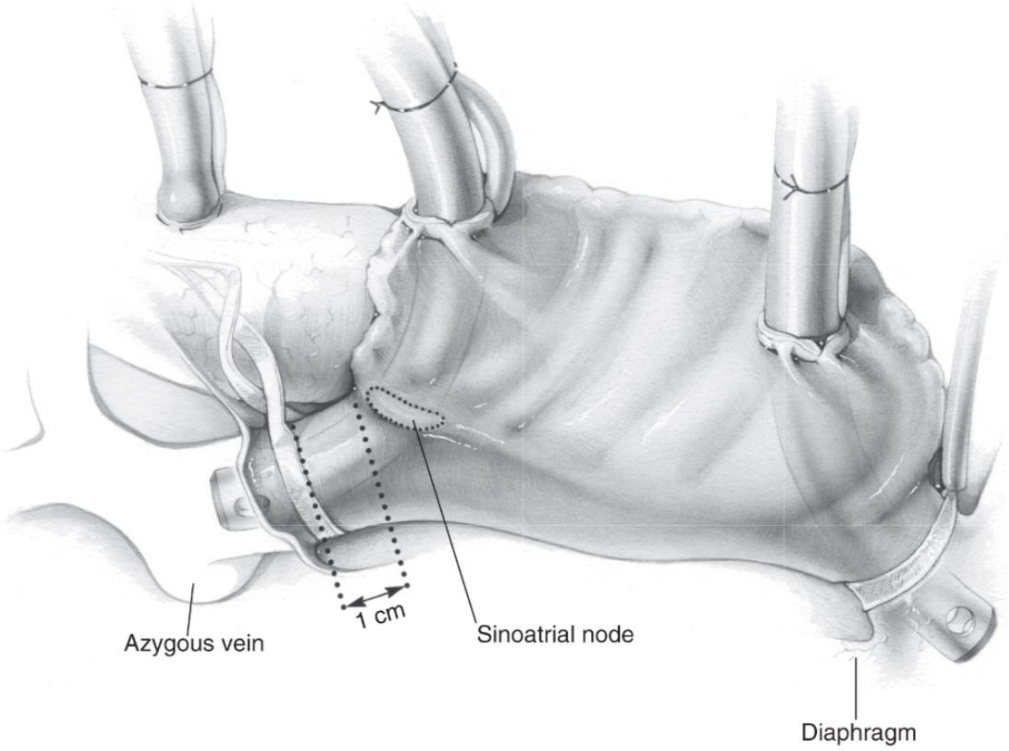
- 18 randomized controlled trials with 1868 patients
- Predominantly isolated CABG
- **No significant difference** for hematological variables, postoperative blood loss, transfusions, neurological outcomes, or mortality

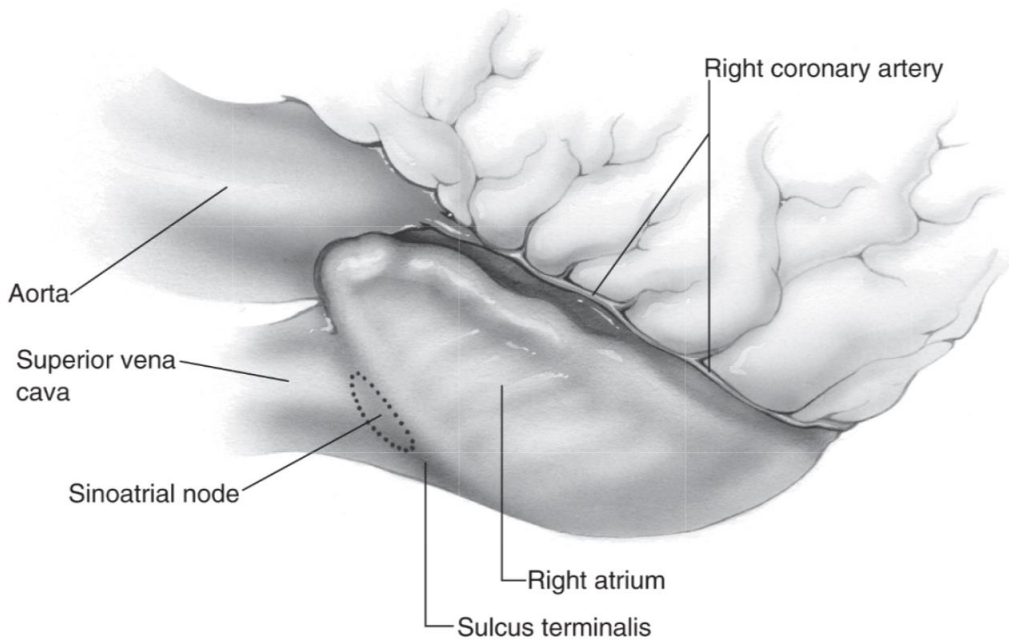
Artif Organs 2012;36:668-76

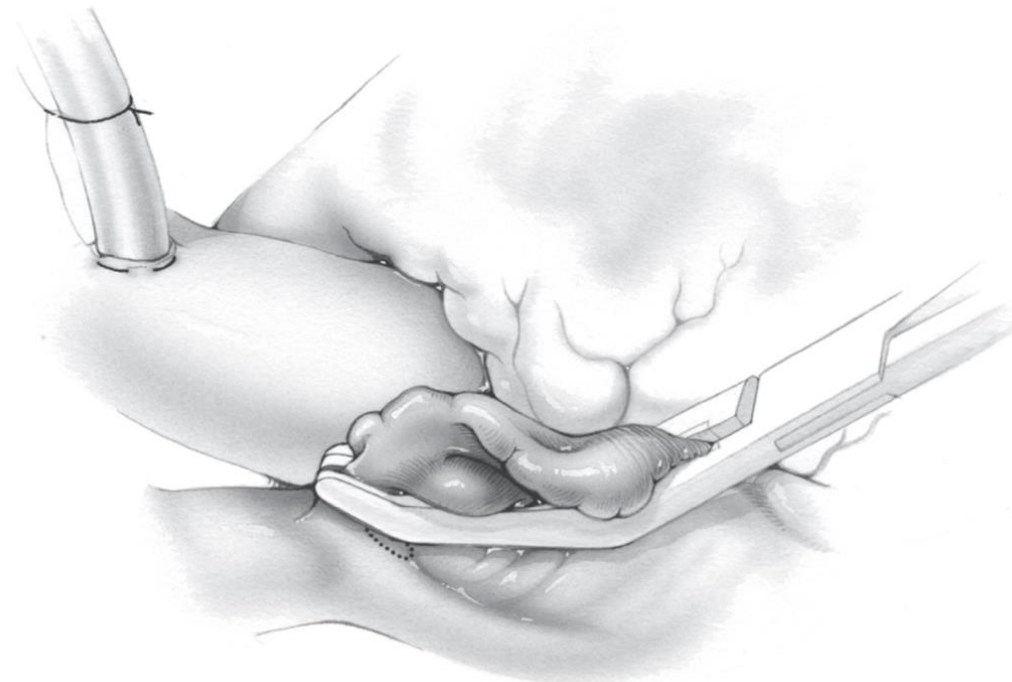
Venous Cannulation





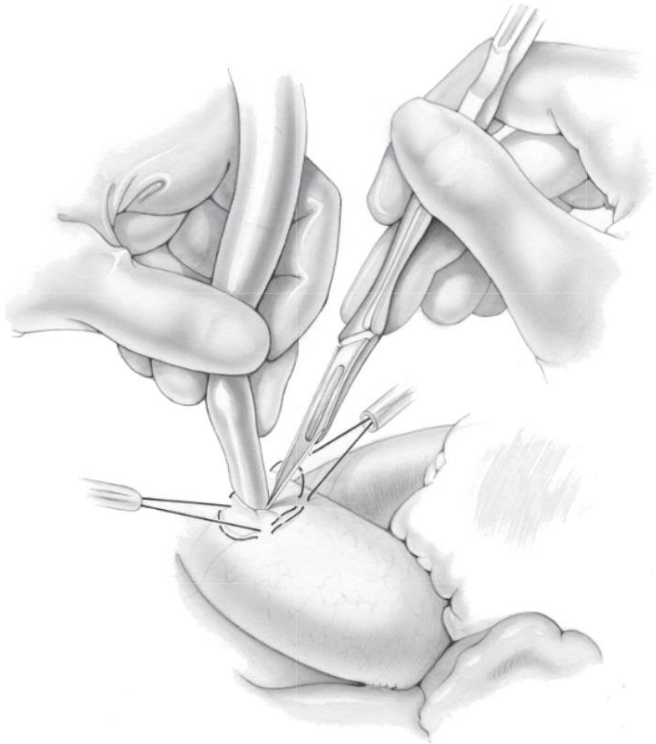



Right coronary artery
Aorta
Superior vena cava
Sinoatrial node
Right atrium
Sulcus terminalis

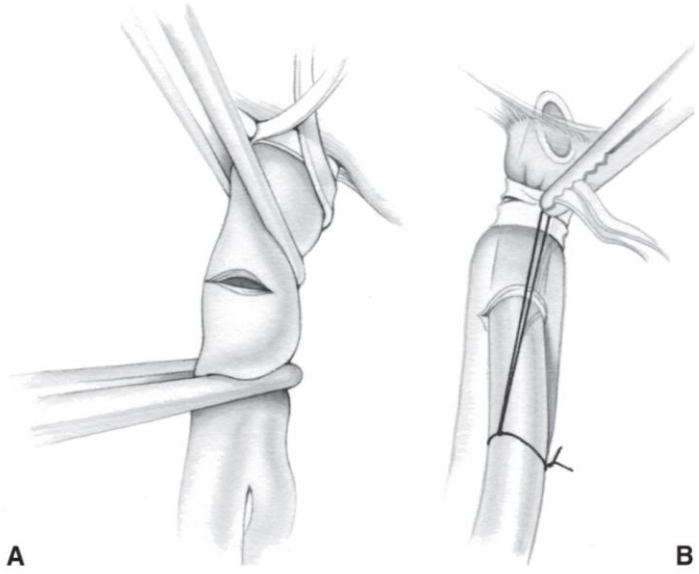


Arterial Cannulation

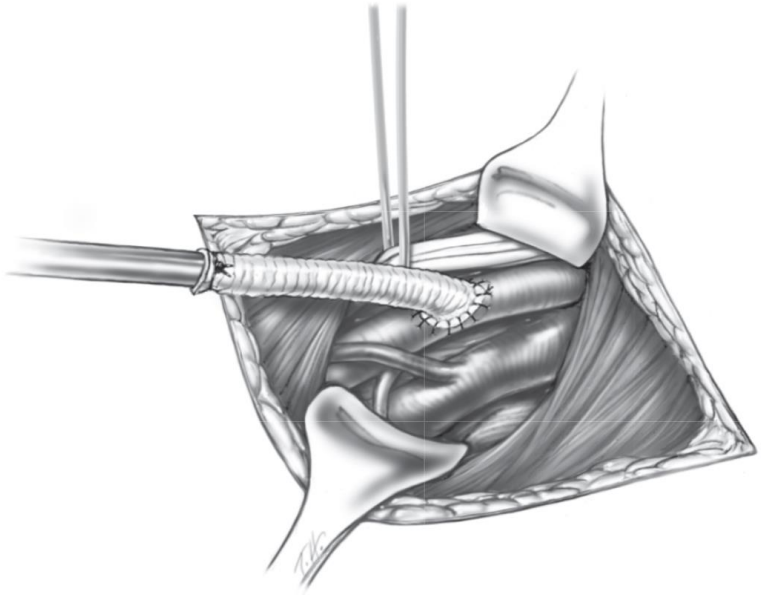
- Optimal arterial BP during cannulation
  - MAP 70~80mmHg, **sBP 100~120mmHg**



Ascending aorta

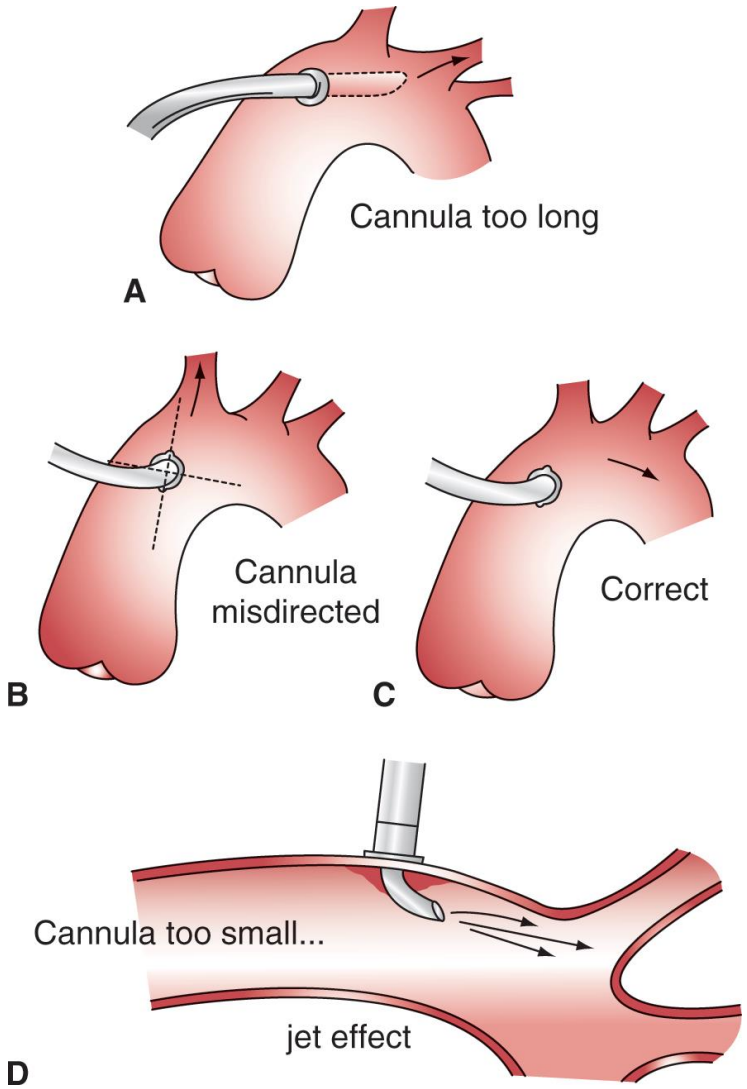


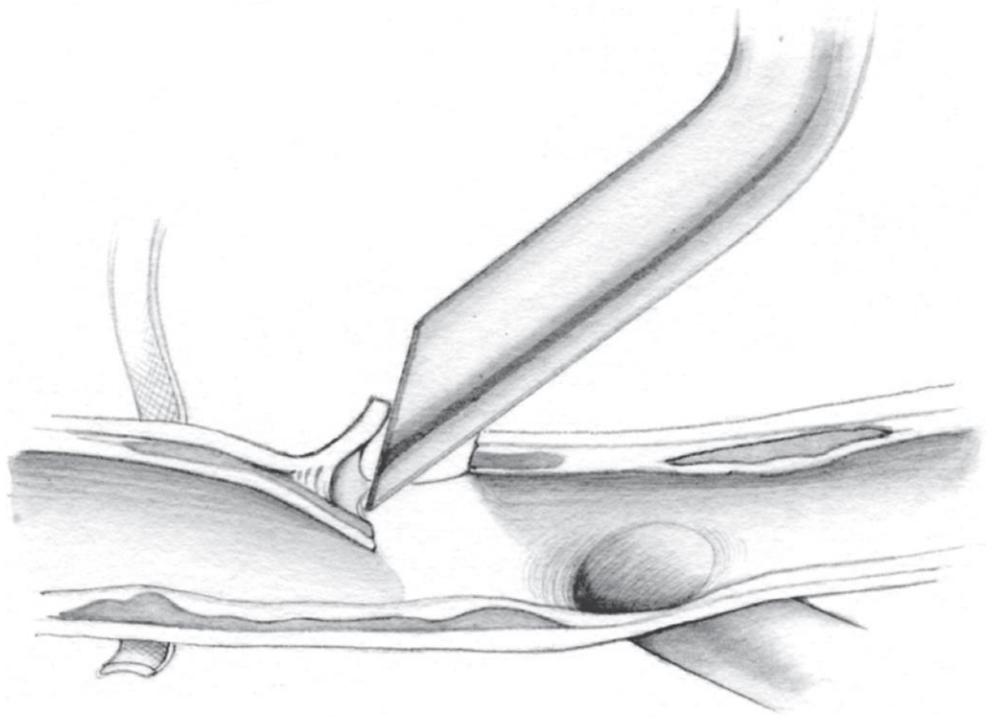
Femoral artery



Axillary artery

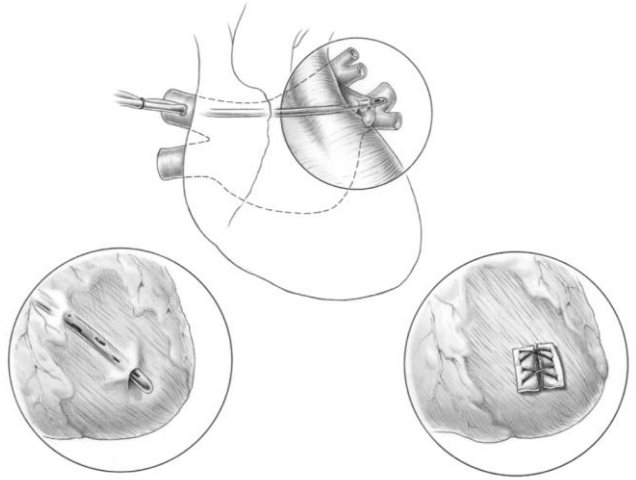
Aortic Cannulation Problems

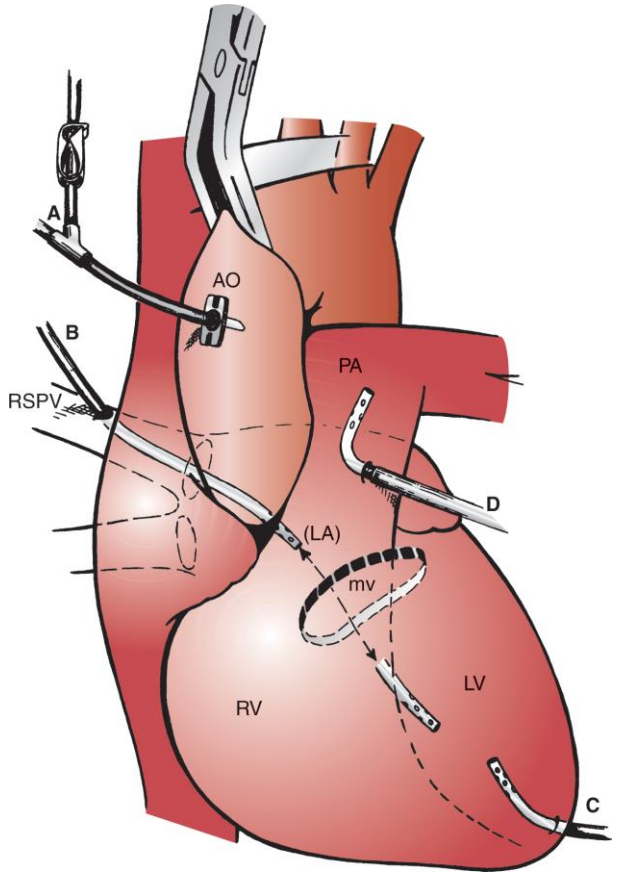




Purpose of Venting the Left Heart

- Preventing distension of the ventricle
- Reducing myocardial rewarming
- Preventing cardiac ejection of air
- Facilitating surgical exposure





Determinants of Safe Perfusion

Blood flow rate

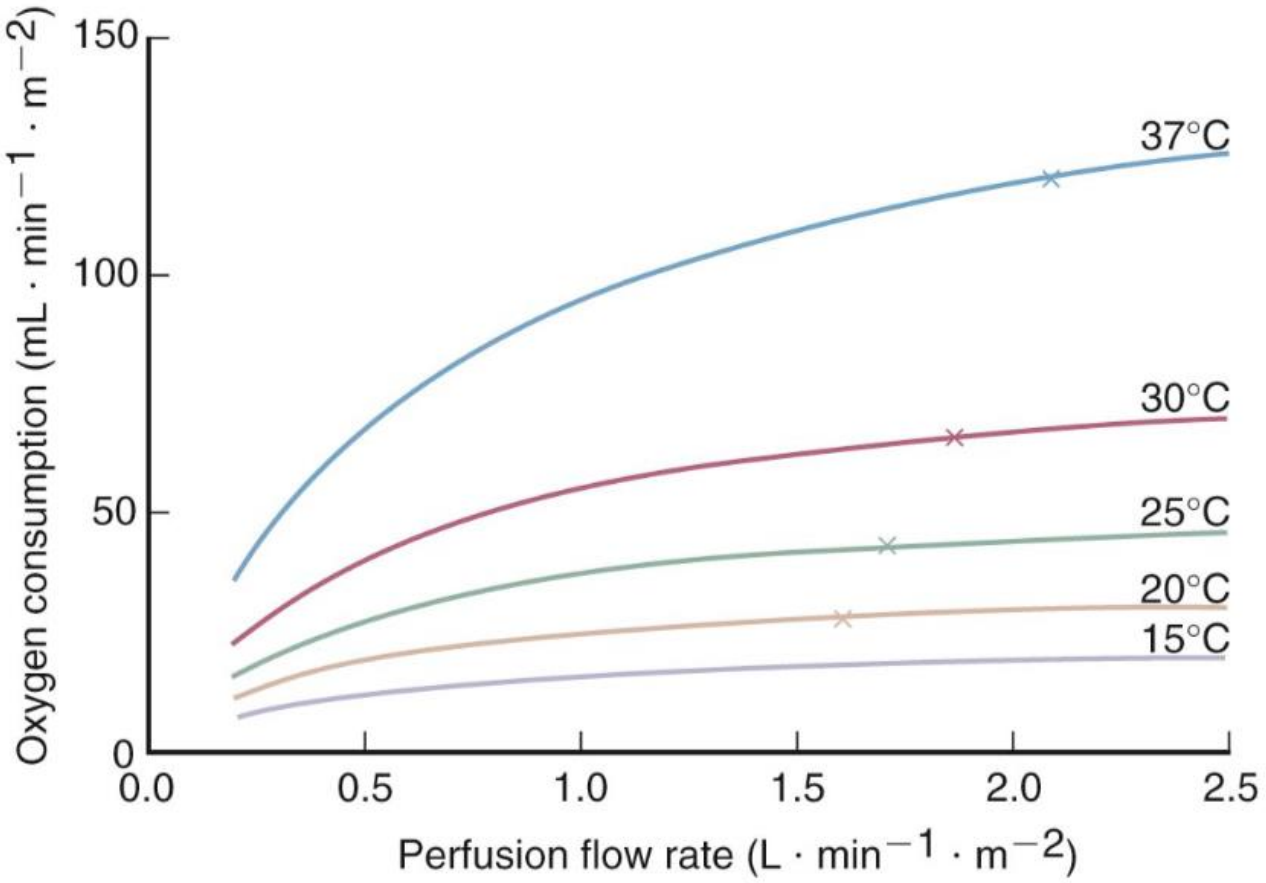
Arterial pressure

Hematocrit

Temperature

Acid/Base management

Blood Flow Rate



Accepted flow rate : 2.2~2.5L/min/m^2 at 35~37°C, Hct 25%

Kirklin/Barratt-Boyes Cardiac Surgery 4th edition, Chapter 2

2024 EACTS/EACTAIC/EBCP Guidelines on CPB in Adult Cardiac Surgery

Recommendation Table 41. **Recommendations for pump flow management during cardiopulmonary bypass**

Recommendations	Class[a]	Level[b]	Ref[c]
It is recommended that the estimated pump flow rate be determined before the initiation of CPB based on the BSA and the planned level of hypothermia.	I	C	-
The adequacy of the pump flow rate during CPB should be considered based on oxygenation and metabolic parameters (SVO_2, O_2ER, r_cSO_2, VCO_2, VCO_2/VO_2 and arterial blood lactate levels).[d] No validated threshold presently exists.	IIa	B	[213, 542, 543]
It is recommended that a minimal value of DO_2 of 280 ml/min/m^2 be used to reduce the risk of AKI stage 1.	I	A	[533–536, 545, 546]
Pump flow rates calculated on the basis of lean body mass may be considered as a suggested lower value in patients with obesity.	IIb	B	[528]

Eur J Cardiothorac Surg 2025;67:ezae354

Arterial Pressure

- Mean arterial pressure
  → near **70mmHg**

- Older patients with vascular disease or hypertension
  → **70~80mmHg**

Pressure Monitoring

Recommendation Table 40. **Recommendations for control of mean arterial blood pressure during cardiopulmonary bypass**

Recommendations	Class[a]	Level[b]	Ref[c]
It is recommended that the MAP be maintained between 50 and 80 mmHg with vasoconstrictors and vasodilators if required, having ensured that the depth of anaesthesia and pump flow rate are sufficient.	I	A	[381, 511]
The use of vasopressors to increase the MAP to values above 80 mmHg during CPB is not recommended.	III	B	[381, 510, 517]
Targeting the MAP during CPB within the limits of individualized cerebral autoregulation data, measured under normocapnic conditions before CPB, should be considered whenever the technical and human skills are available.	IIa	A	[222, 519, 520]
It is recommended that vasoplegic syndrome during CPB be treated with α1-adrenergic agonists and/or vasopressin.	I	C	[521, 523]
In refractory vasoplegic syndrome, alternative drugs (methylene blue or terlipressin) should be considered, alone or in combination.	IIa	B	[522, 523]
Hydroxocobalamin or angiotensin II may be considered to treat vasoplegic syndrome during CPB.	IIb	C	[524–527]

Eur J Cardiothorac Surg 2025;67:ezae354

Hematocrit

- Ideal hematocrit : controversial, but **usually 20~25%** during CPB

- Low hematocrit
  - Reduce blood viscosity and hemolysis
  - Reduce oxygen-carrying capacity
  - Increase cerebral blood flow

- Viscosity remains stable when percent Hct and blood temperature are equal (ex. Same viscosity : 37°C 37% Hct = 20°C 20% Hct)

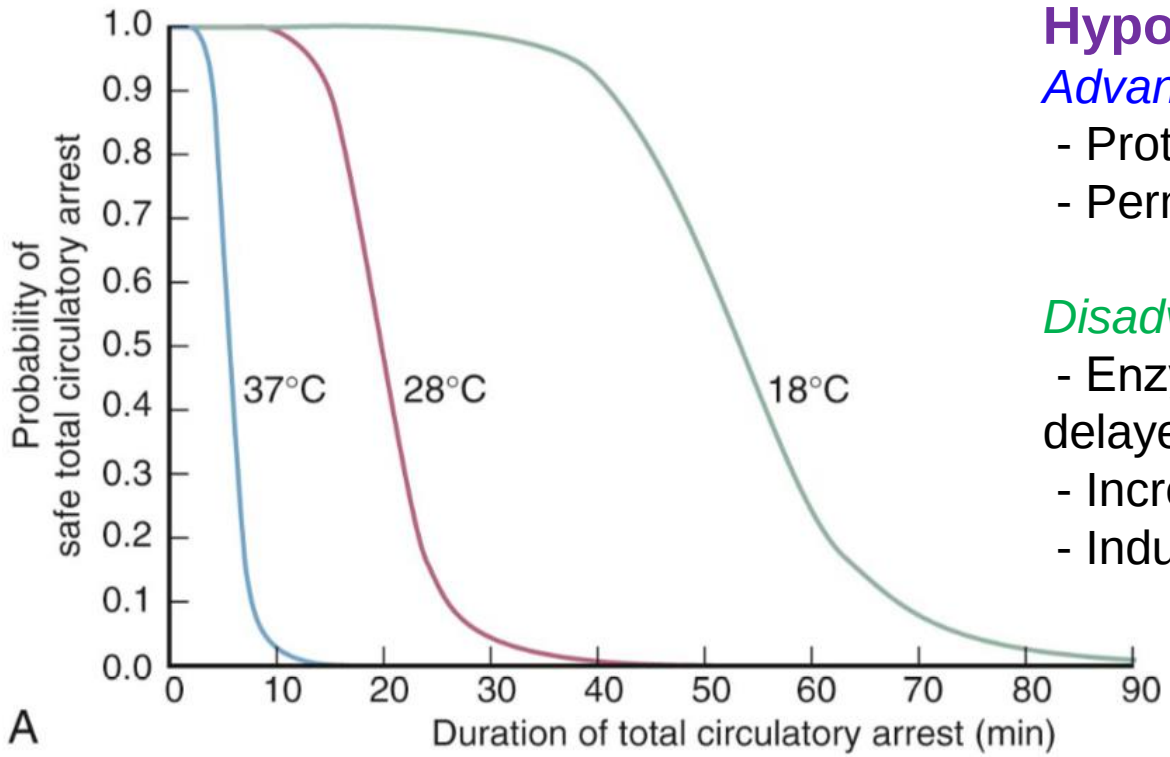
Transfusion Management

Recommendation Table 45. **Recommendations for transfusion management during cardiopulmonary bypass**

Recommendations	Class[a]	Level[b]	Ref[c]
Packed red blood cell transfusions			
It is recommended that PRBCs be transfused during CPB if the HCT value is <18% (Hb 6.0 g/dL).	I	C	-
For HCT values between 18% and 24%, PRBCs may be considered based on an assessment of the adequacy of tissue oxygenation.[d]	IIb	B	[592]
PRBCs are not recommended to be transfused during CPB if the HCT is >24% and DO_2 and extraction are acceptable.	III	C	[108, 587]
Fresh frozen plasma transfusions			
It is recommended that antithrombin concentrate be used as the primary treatment of antithrombin deficiency to improve heparin sensitivity.	I	B	[596–598]
If antithrombin concentrate is unavailable, FFP should be considered to treat antithrombin deficiency to improve heparin sensitivity.	IIa	C	-
FFP should not be used prophylactically during CPB to reduce perioperative blood loss.	III	B	[599, 600]

Eur J Cardiothorac Surg 2025;67:ezae354

Temperature



Hypothermia

Advantages

- Protect brain
- Permit lower flow perfusion and lower hematocrit

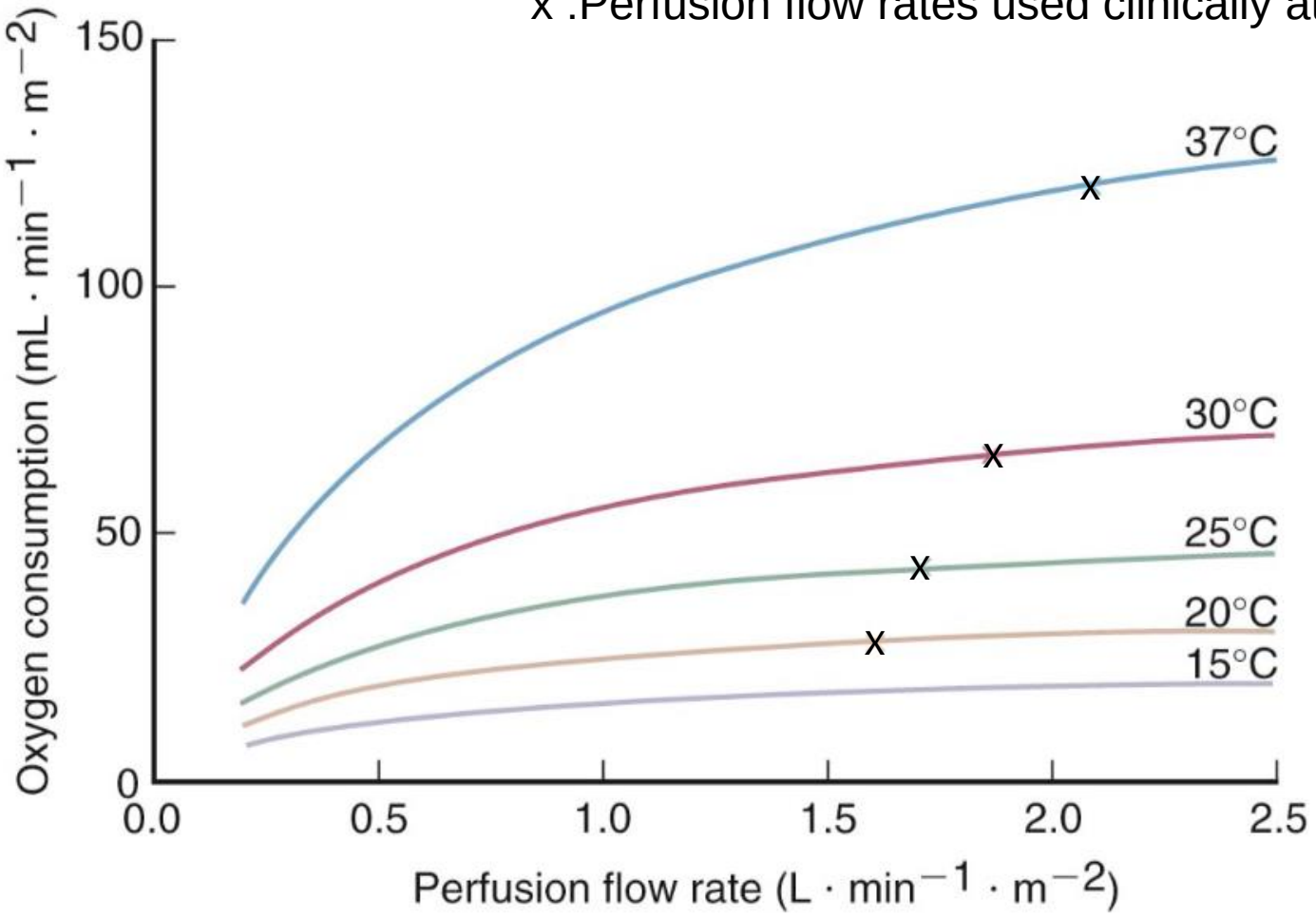
Disadvantages

- Enzyme and organ dysfunction (bleeding↑, SVR↑, delayed cardiac recovery)
- Increase viscosity
- Induce vasoconstriction

Circulatory arrest times of approximately 35 minutes at 18°C

Oxygen Consumption to Perfusion Flow

x :Perfusion flow rates used clinically at various temperature

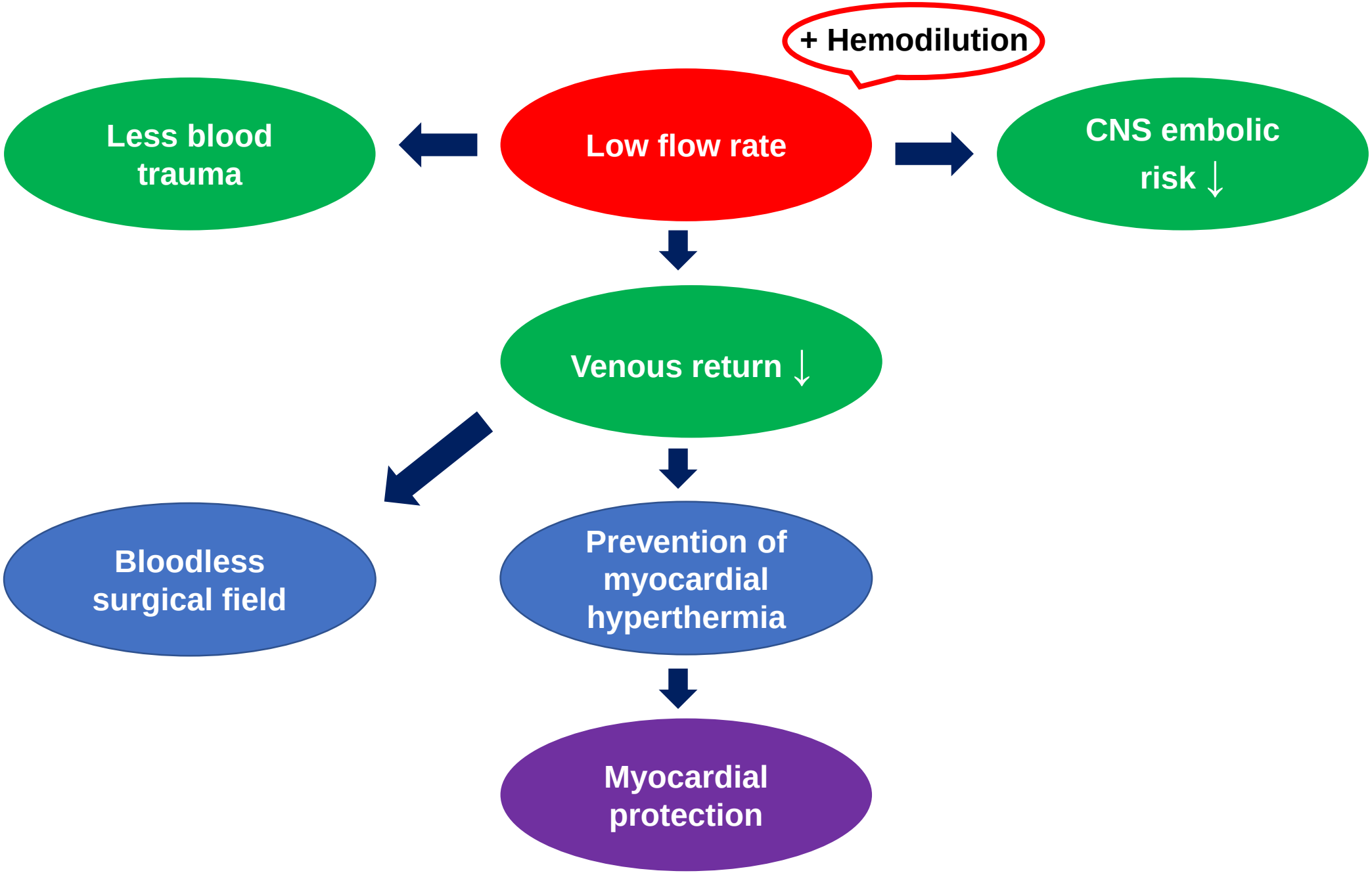


Hypothermia

⬇

Lower pump flow

Kirklin/Barratt-Boyes Cardiac Surgery 4th edition, Chapter 2


+ Hemodilution
Less blood trauma
Low flow rate
CNS embolic risk ↓
Venous return ↓
Bloodless surgical field
Prevention of myocardial hyperthermia
Myocardial protection

CPB with Systemic Hypothermia

Lower pump flows

Better myocardial protection

Less blood trauma

Better organ protection

Acid/Base Alteration

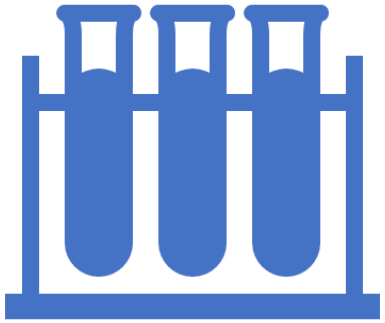
Temperature	pH	P_{CO2}
37°C	7.40	40mmHg
>37°C	↓	↑
<37°C	↑	↓

- At 40 °C → pH of 7.35 and higher P_{CO2}
- At 20 °C → pH of 7.65 and lower P_{CO2}

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$$

$$H_2O \Leftrightarrow H^+ + OH^-$$

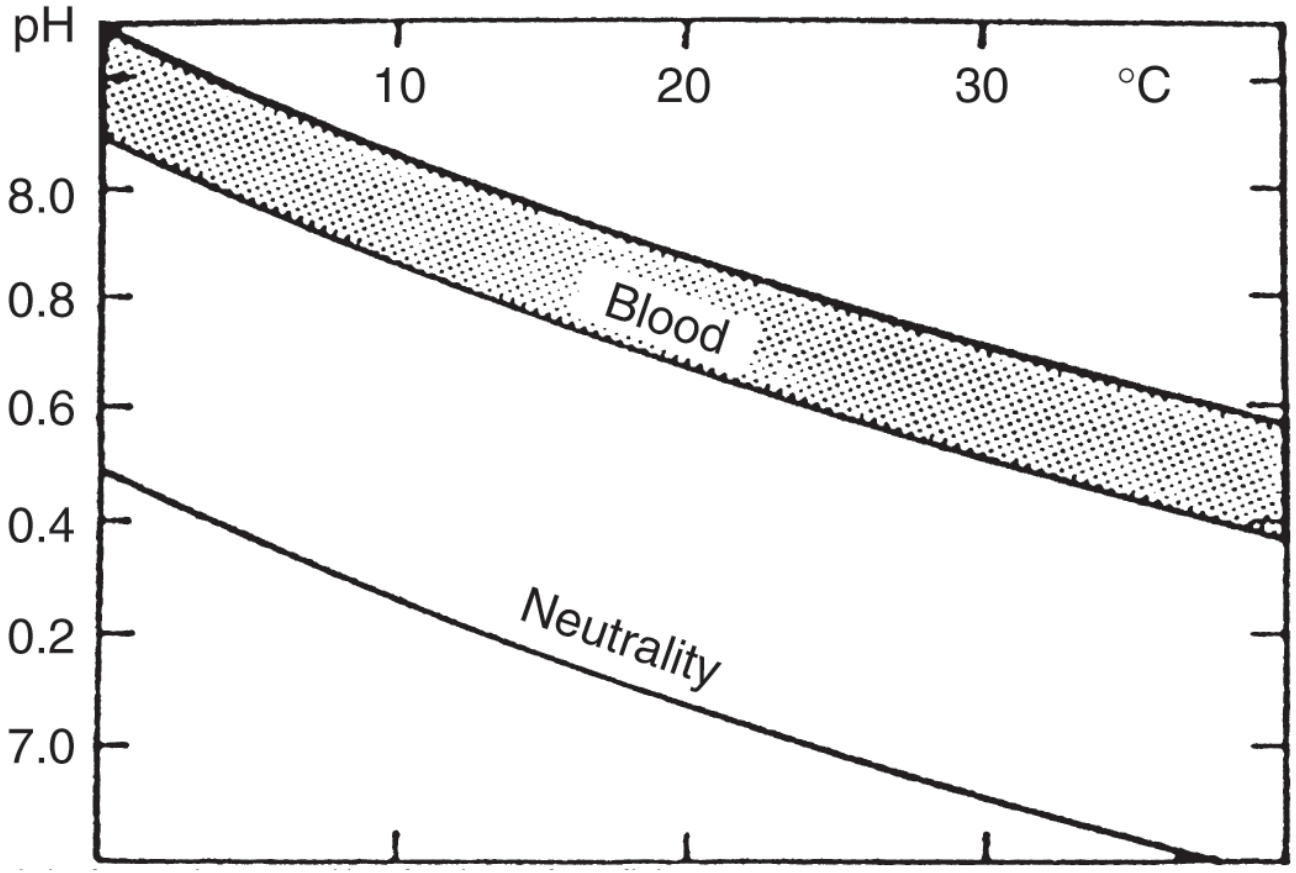
Acid/Base Management Strategies



Alpha-stat

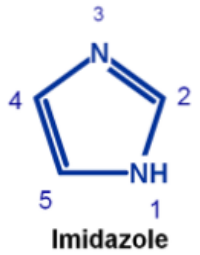
pH-stat

Alpha-stat Strategy

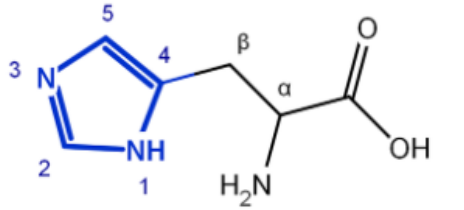


The pH of pure water at equilibrium at 25°C is 7

Buffering system
: Imidazole moiety of histidine



Imidazole



Histidine

Alpha : 특정 pH에서 histidine 의 이온화된 상태

Pneumonologie 1974;151:87-94

Alpha-stat Strategy

- The ratio of the unprotonated histidine imidazole groups to H^+
  - α (alpha)
- Maintenance of constant α
- Keeping total CO_2 content constant
- Allowing pH and $PaCO_2$ to varying temperatures

pH-stat Strategy

- Maintenance of pH at varying temperatures
- Addition of CO_2 at hypothermia to maintain $PaCO_2$ 40mmHg, pH 7.40

Alpha-stat vs pH-stat

	Alpha-stat	pH-stat
Blood pH	Alkalic	Normal
Intracellular pH	Normal	Acidic
Intracellular enzyme function	Maintained	↓
Technically demanding	No	Yes
Cerebral blood flow (CBF)	↓	Maintained

Cerebral Blood Flow (CBF)

- Hypothermia → Decreased CBF(↓) and cerebral metabolic rate(↓↓)
- Maintained response of cerebral circulation to changes in $PaCO_2$
- CBF : pH-stat > alpha-stat
- Enhanced CBF
  - Risk for microemboli, cerebral edema, high intracranial pressure
  - Improving cerebral cooling

Neurologic Complications after CPB

	Adults	Children
Mechanism	Emboli	Hypoperfusion Excitotoxic pathway
Favor strategy	Alpha-stat	pH-stat

Recommendations	Class[a]	Level[b]
Alpha-stat acid-base management should be considered in adult cardiac surgery patients with high-moderate hypothermia due to improved neurological and neurocognitive outcomes.	IIa	B

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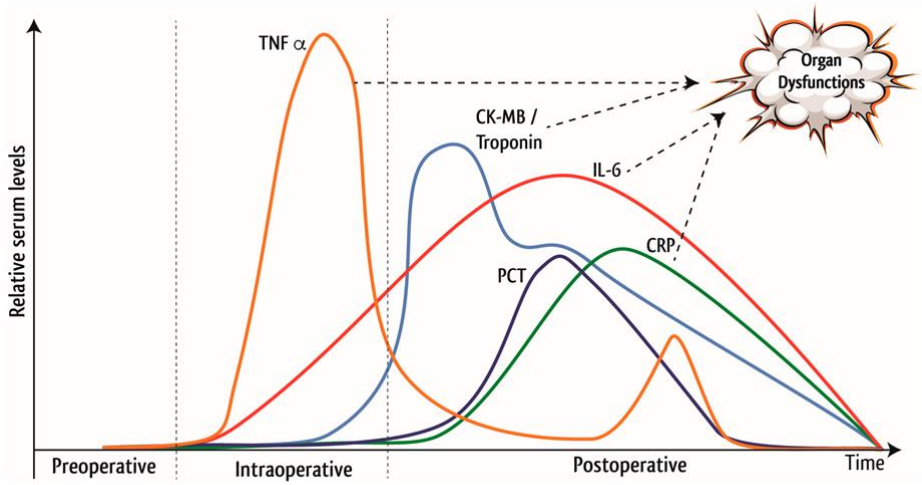
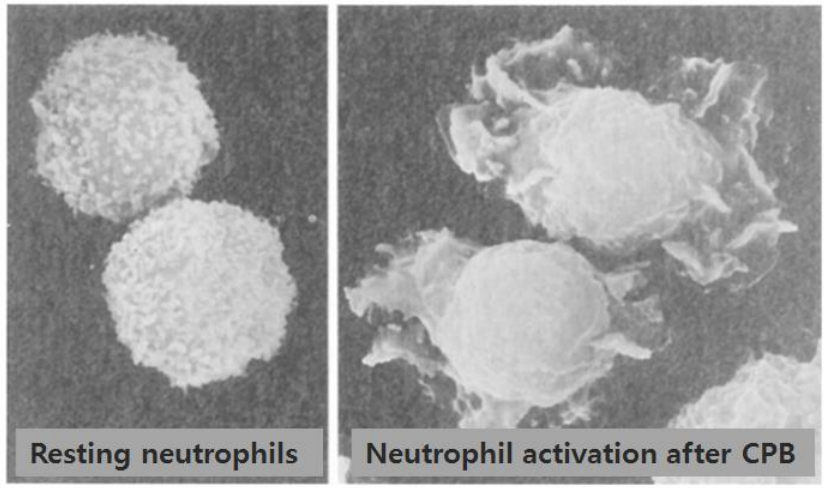
Inflammatory Responses to CPB



Aileen H., et al. Nutrients 2018



Baggiolini M. Nature 1998; 392:565.

Activation of inflammatory mediator and alteration of immune function

Coagulopathy Related to CPB

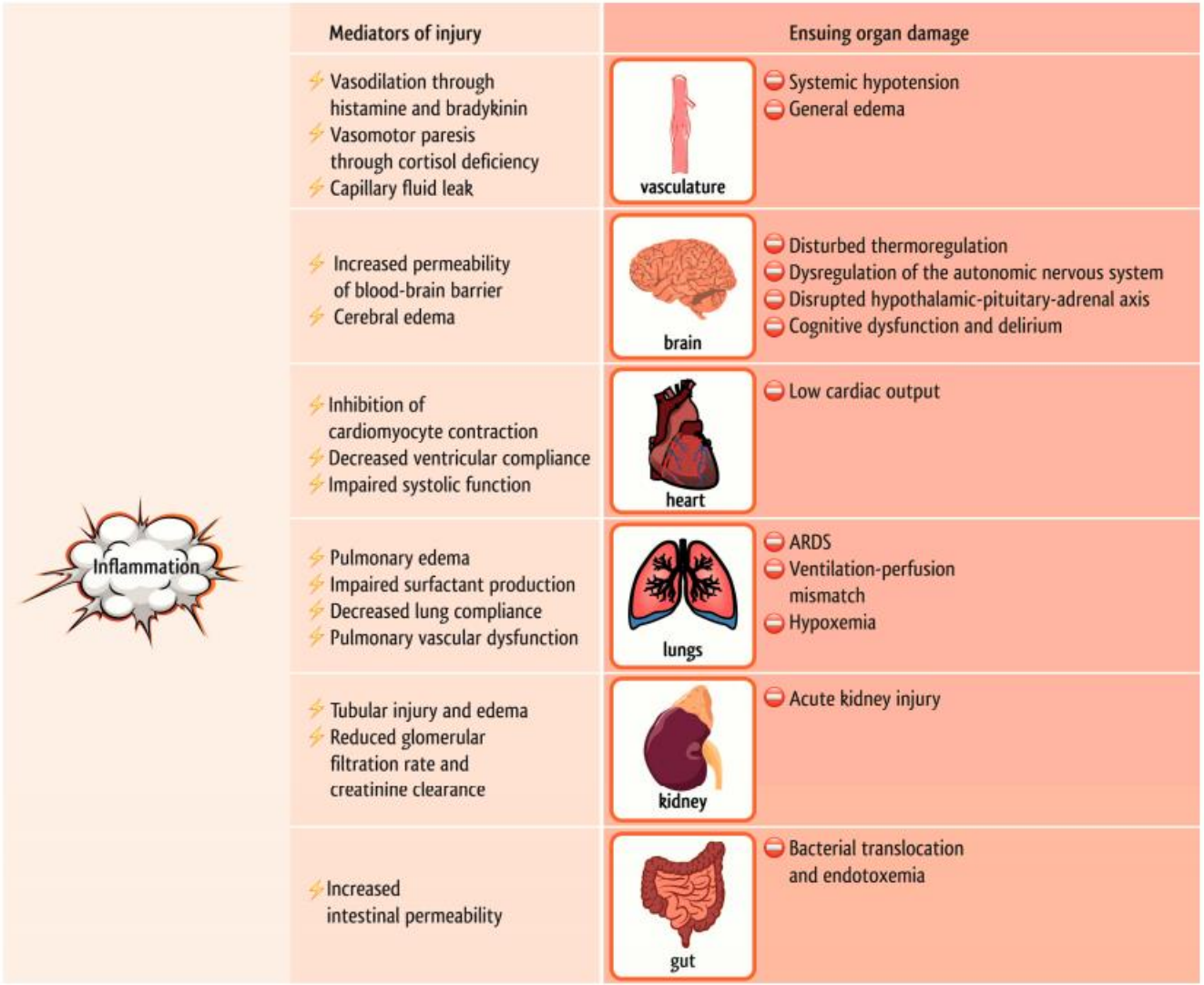
- Hemodilution
- Hypothermia
- Hemolysis
- Heparinization
- Activation of the coagulation system

Endocrine and Electrolytes Responses to CPB

- Antidiuretic hormone (vasopressin)↑
- Adrenocorticotropin↑
- T3 and T4 responses to TSH↓
- Adrenal responses↑
- Hyperglycemia and hypoinsulinemia
- Hypomagnesemia

Organ Damage Related to CPB

- Neurologic injury
  - Stroke
  - Delirium
  - Cognitive decine
- Lung injury
  - Atelectasis
  - ARDS
- Renal injury



Nutrients 2018;10:597

Heparin and Protamine

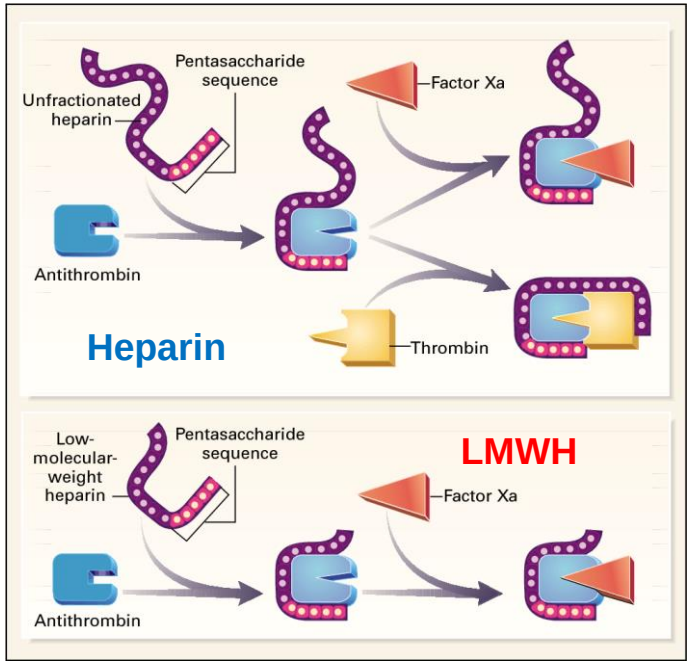
- Heparin dose : 300U/kg
- Target activated clotting time (ACT) : 400~480 sec
- Protamine dose : 1mg/100U of heparin

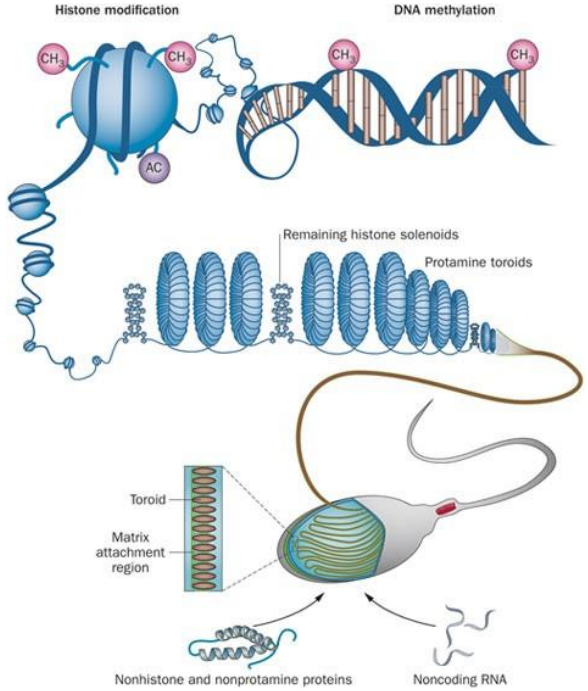
Protamine

- Derived from salmon sperm
- Strongly alkaline

- Polycationic protein
- High affinity for negatively charged sulfated glycosaminoglycans, such as heparin
- Cleared by the reticuloendothelial system (RES)

- Some anticoagulant activity





Protamine

Nat Rev Urol 2012;9:609-19

Problems related to Protamine

- Heparin rebound
- Hypotension
- Anaphylactoid reactions
- Pulmonary vasoconstriction
- Direct antiplatelet effect

Protamine Reactions

- Adverse cardiopulmonary response to protamine
- Catastrophic pulmonary vasoconstriction : ~0.6%
- Risk factors
  - Valvular heart disease
  - Preexisting pulmonary hypertension
  - Bolus protamine administration
  - Infusion rates > 50mg/min
  - Diabetes with prior NPH insulin exposure
  - Sterilization through ligation of the vas deferens
  - Fish allergy….

Management of Protamine Reactions

- Infusion rate : <5mg/min
- Prompt termination of protamine infusion at the first sign of any adverse effect
- Supportive care : Oxygen, fluids, Epi/NE
- Reinstitution of bypass
- Inhaled NO

- Prophylaxis with histamine blockers → no evidence for routine use

Recommendation Table 37. **Recommendations for heparin administration**

Recommendations	Class[a]	Level[b]
Individualized heparin and protamine management should be considered to reduce postoperative coagulation abnormalities and bleeding complications in cardiac surgery with CPB.	IIa	B
It is recommended that ACT checks be performed at regular intervals based on institutional protocols and that heparin doses be administrated accordingly, especially in the absence of individual heparin dosing services.	I	C

Recommendation Table 38. **Recommendations for protamine administration**

Recommendations	Class[a]	Level[b]
A protamine-to-heparin ratio < 1.0 is recommended to avoid overdosing of protamine.	I	B
Individualized heparin–protamine management should be considered to reduce postoperative coagulation abnormalities and bleeding complications after cardiac surgery with CPB.	IIa	B
Cardiotomy suction should be discontinued with the start of the administration of protamine.	IIa	C

Recommendation Table 39. **Recommendations for alternative anticoagulation**

Recommendations	Class[a]	Level[b]
Bivalirudin should be considered as the first-line anticoagulation treatment in patients with acute HIT type 2 who require cardiac surgery.	IIa	B
Anticoagulation with argatroban may be considered in patients with acute HIT type 2 who require cardiac surgery with CPB and have significant renal dysfunction.	IIb	C

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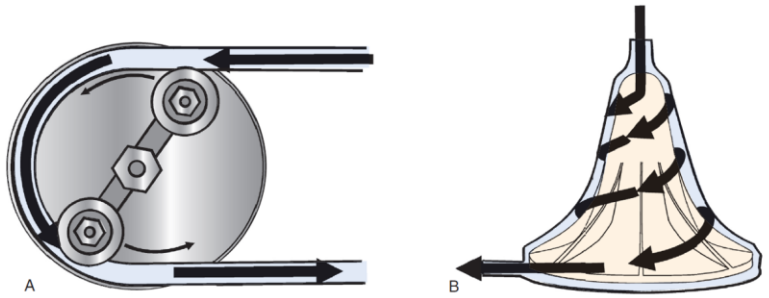
Summary

Types of Pump



Determinants of Safe Perfusion

- Blood flow rate
- Arterial pressure
- Hematocrit
- Temperature
- Acid/Base management

Neurologic Complications after CPB

	Adults	Children
Mechanism	Emboli	Hypoperfusion Excitotoxic pathway
Favor strategy	Alpha-stat	pH-stat

Recommendations	Class[a]	Level[b]
Alpha-stat acid-base management should be considered in adult cardiac surgery patients with high-moderate hypothermia due to improved neurological and neurocognitive outcomes.	IIa	B

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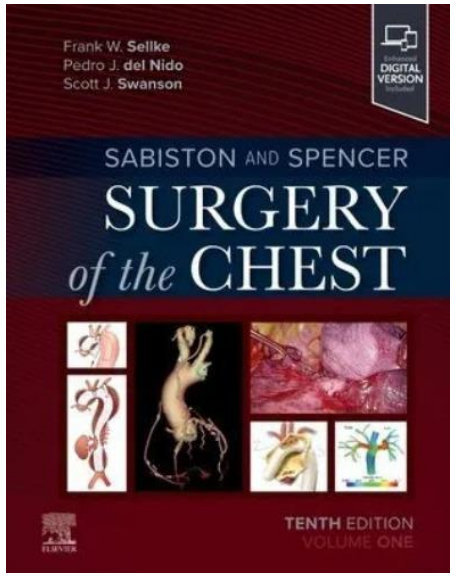
Management of Protamine Reactions

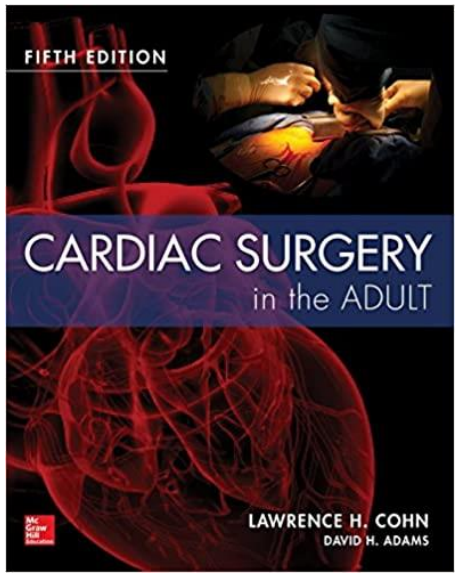
- Infusion rate : <5mg/min
- Prompt termination of protamine infusion at the first sign of any adverse effect
- Supportive care : Oxygen, fluids, Epi/NE
- Reinstitution of bypass
- Inhaled NO

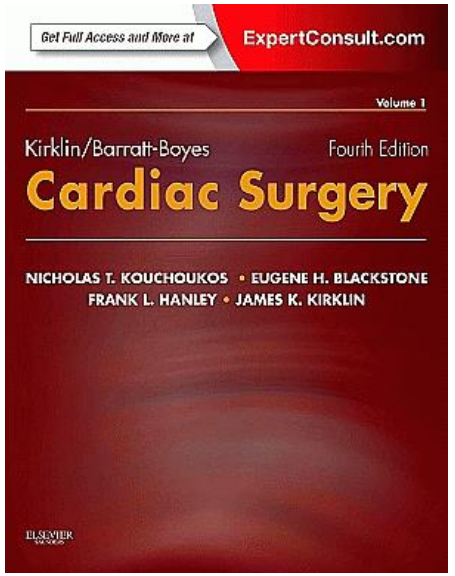
- Prophylaxis with histamine blockers → no evidence for routine use

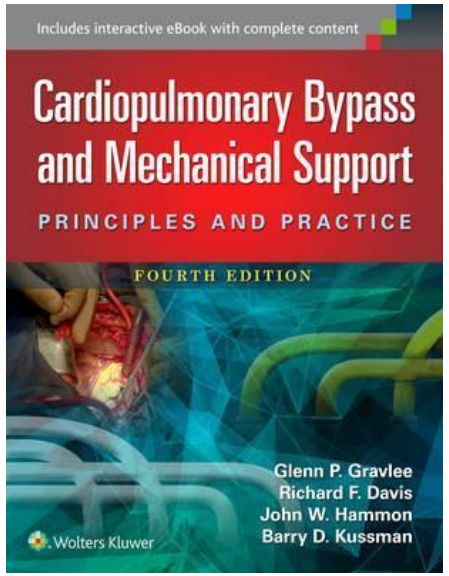
10:30~12:00	90'	Adult Cardiac Surgery Focused Session Ⅲ. CABG: My LITA to LAD Chair: Jun Sung Kim Kyo-Seon Lee Abstract	General Thoracic Session No. 25 Perioperative Chemotherapy and Immunotherapy in NSCLC Chair: In Kyu Park Yong Won Seong Abstract: 25-0~25-5	Intensive Care/ECMO/Trauma Focused Session Ⅰ. Management of Rib Fractures Chair: Hyun Koo Kim Sung Youl Hyun Panel: Junepill Seok, Wooshik Kim Abstract	Adult Cardiac Surgery Session No. 44 Aorta Ⅰ. From Bench to Bedside: Translating Research into Complex Aortic Repair Chair: Suk Won Song Suryeun Chung Abstract: 44-0~44-6

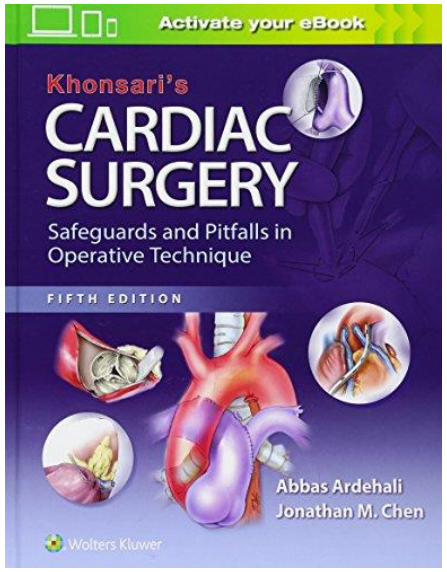
References











Thank you !