CHAPTER 1

Equipment for bypass

The cardiopulmonary bypass plan starts with basics of patient height, weight, allergy history, original diagnosis, previous surgeries, and current indications for surgery. The perfusionist must select and assemble an array of equipment matched to the patient's size, expected pump flow rates, and other factors related to diagnosis. The following is an overview of the major components of a bypass circuit. Please refer to *Chapter 6* for equipment considerations in addition to patient size. Figure 1.1 is provided as a reference to basic equipment arranged for cardiopulmonary bypass.

Oxygenators

The contemporary "oxygenator" is actually several integrated items that in addition to the oxygenating membrane may include the arterial line filter (ALF), venous reservoir and filter, cardiotomy filter, and heat exchanger. Figure 1.2 depicts the components of the Terumo CAPIOX FX series of "oxygenators." Figure 1.3 depicts typical components of an oxygenator system.

The oxygenator membrane

- Membrane oxygenators allow for diffusion of gas, oxygen and carbon dioxide most importantly, across a material separating the blood path from the gas flow path (also called the blood and gas phases).
- True membrane oxygenators allow for diffusion of gases through a membrane separating the blood and gas phases (see Figure 1.4). The type and thickness of the membrane, as well as blood and gas flow characteristics on opposing sides, determines overall diffusion rates.
- Microporous membrane oxygenators allow for diffusion of gases through microscopic holes in the membrane material (see Figure 1.4). The gas transfers directly through these micropores and is therefore less impacted by the membrane material. However, blood and gas flow characteristics on opposing sides still impact diffusion capacity.
- The vast majority of oxygenators for cardiopulmonary bypass are microporous membrane oxygenators. True membrane oxygenators have limited applications today including the use for ECMO at some institutions.
- The membrane oxygenator size chosen for a particular patient should be the smallest which will allow for safe perfusion with some degree of functional reserve in case of decreasing efficiency during extended bypass runs or to account for markedly increased pump flows due to aortopulmonary connections (MAPCAs, surgical or other central shunts) or significant aortic regurgitation. Increased pump flow rates in these situations may be required to maintain adequate effective systemic perfusion.
- Using an oxygenator above its manufacturer recommended maximum flow rate may increase arterial line GME transmission and is not recommended.
- It is recommended to define the patient BSA and select an oxygenator based on the maximum expected pump flows. It is important to note that for neonates and infants in particular, their relatively higher metabolic requirement may require markedly increased pump flows during normothermic bypass (i.e., rewarming). Flows of 3.0–3.5 L/min/m^2 are not uncommon and should be considered for equipment selection.
- Primary consideration is given to the manufacturer-recommended maximum flow rate that is based on gas

Perfusion for Congenital Heart Surgery: Notes on Cardiopulmonary Bypass for a Complex Patient Population, First Edition. Gregory S. Matte.

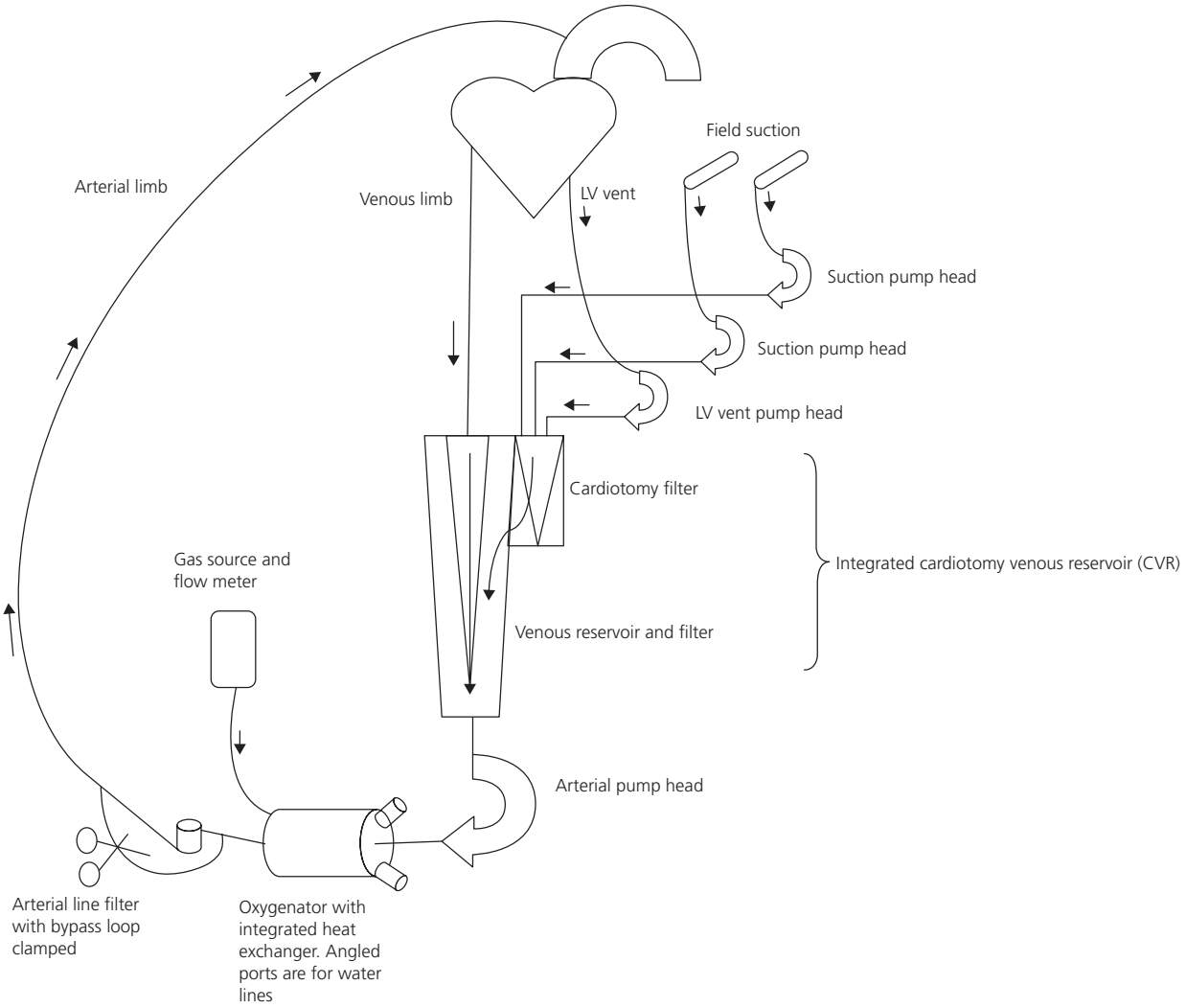


Figure 1.1 Simplified schematic for basic cardiopulmonary bypass equipment (excludes cardioplegia system).

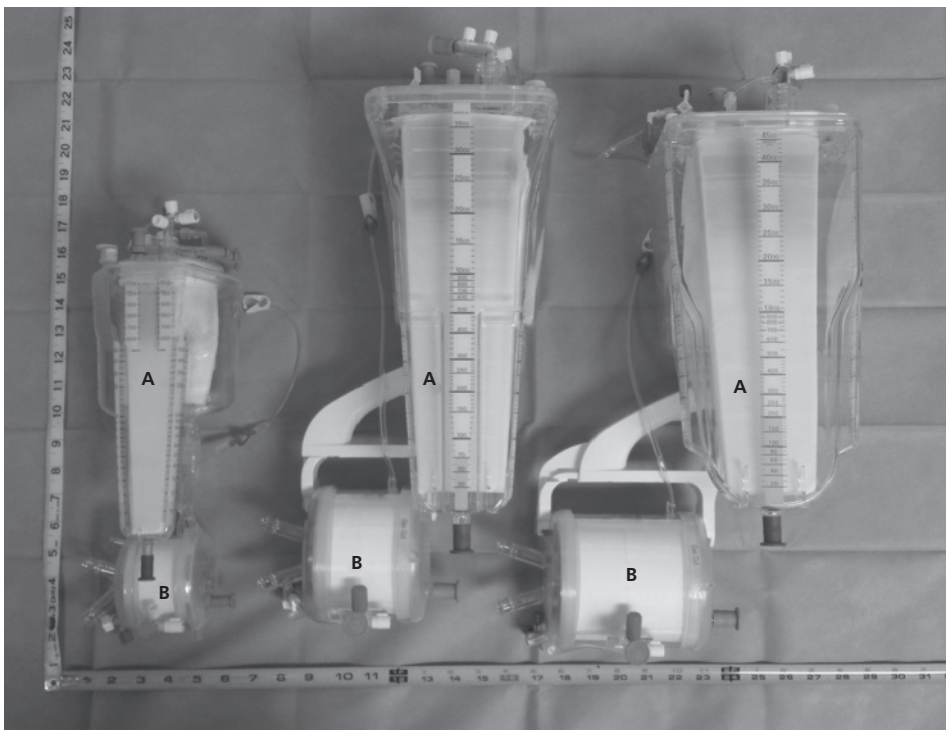


Figure 1.2 Terumo CAPIOX FX series of oxygenators. *Left to right: Terumo CAPIOX FX05, Terumo CAPIOX FX15-30, Terumo CAPIOX FX25. A—cardiotomy venous reservoir and B—oxygenator membrane with integrated arterial line filter and heat exchanger.* (*See insert for color representation of the figure.*)

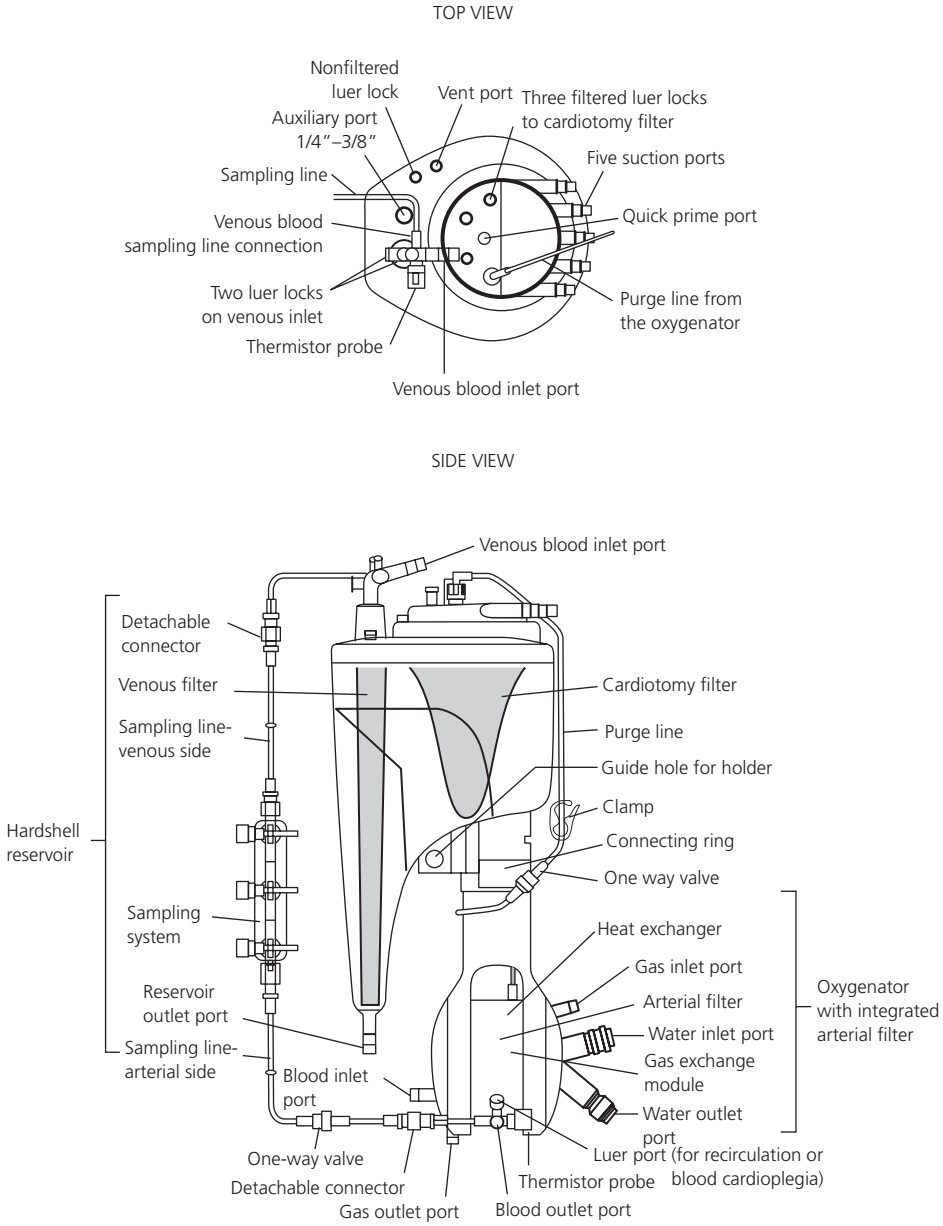
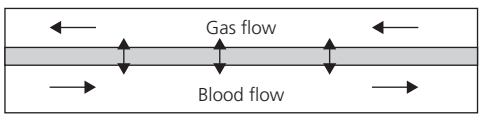
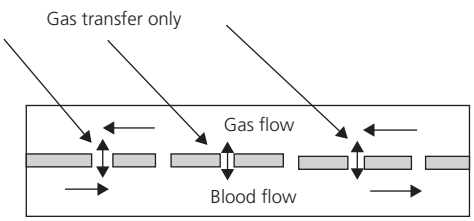


Figure 1.3 Typical components of an oxygenator system. Reproduced with permission from Terumo Cardiovascular Group, Ann Arbor, MI. All rights reserved.

True membrane oxygenators

Gas diffuses through a solid membrane (shown in gray). There are no direct communications between the gas and blood compartments.





Microporous membrane oxygenators

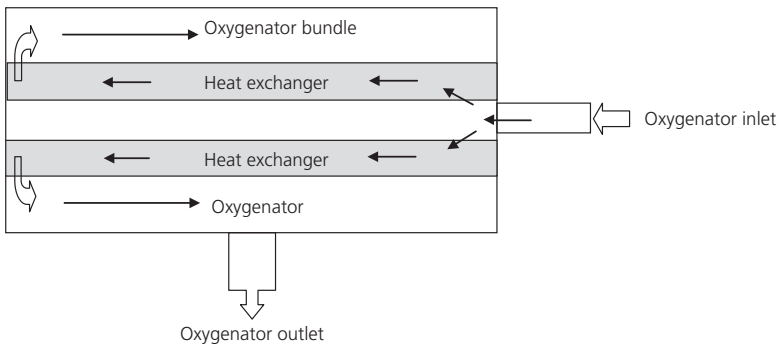
Gases diffuse through tiny holes in the membrane material (shown in gray). There are direct communications between the gas and blood compartments. Microair in the blood compartment may pass into the gas compartment to facilitate removal of gaseous microemboli in the blood. Blood cannot pass.

Figure 1.4 Primary types of oxygenators currently in use.

exchange and other aspects of oxygenator, heat exchanger, and reservoir performance. The American Association of Medical Instrumentation (AAMI) standard reference values are usually not relied solely upon since they may not take into account additional factors that the manufacturer evaluates for overall performance.

- Increased oxygenator bundle size does not linearly relate to performance since characteristics of the blood and gas flow paths vary among devices.
- Oxygenators have either radial or axial blood flow paths that affect performance in competing ways in regards to oxygenating efficiency, pressure drop, microemboli removal, and heat exchanger performance (see Figure 1.5).
- Microporous oxygenator bundles are important in the removal of air from the blood path. Some centers, particularly outside of the United States, deem the microporous oxygenator effective enough at air removal that they do not utilize a standalone ALF.
- One oxygenator on the market, the Medtronic Affinity Fusion, has taken advantage of the air handling capabilities of microporous oxygenators, and unique bundle wrapping technology, to be FDA approved for use as an ALF as well as an oxygenator.
- The perfusionist must be familiar with the *manufacturer* recommendations for treating an oxygenator suspected of "wetting out." These values are listed in Tables 1.1 to 1.4.
- Oxygenators are usually qualified for use by the manufacturer for up to 6 h. Use beyond this limit does occur and most often there is not a significant decrease in performance. However, safe use beyond this limit is not guaranteed. Consideration should be given to changing out an oxygenator after a long case in which an additional bypass run is a serious possibility. Elective change out while off bypass can be accomplished in a controlled manner and can eliminate several concerns of emergently resuming bypass with a product at the end of its rated performance limit.
- Blood proteins coat a membrane oxygenator's surface area, including the micropores through which gas exchange occurs.
- Microporous membranes may experience increased protein coating and subsequent decrease in oxygen transfer during extended bypass runs. It is important to note that this protein coating may also decrease the air handling capabilities of the membrane.
- The pressure drop across an oxygenator membrane is frequently listed as a specification. It may be measured in real time during bypass. A change in this value over time is important to consider during bypass as it can be an indicator of change in function.
- Pressure drop is frequently equated with shear stress where a lower pressure drop is considered beneficial with lower shear stress. That is not always the case since

Axial blood flow path
Blood travels along the axis of the heat exchanger first and then along the axis of the oxygenator bundle before exiting a low point in the device.



Radial blood flow path
Blood enters and radiates through the heat exchanger and oxygenator bundle before exiting a low point in the device. Some oxygenators preferentially have blood exit the heat exchanger top before flowing through the oxygenator bundle.

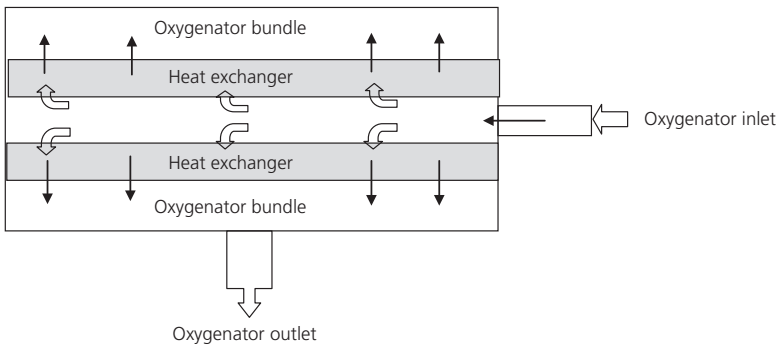


Figure 1.5 Simplified schematic of blood flow paths through an oxygenator.

Table 1.1 Oxygenators rated up to ~2 LPM.

Manufacturer	Oxygenator (microporous polypropylene except as noted)	Oxygenator bundle (m^2)	Oxygenator prime volume	Manufacturer recommended blood flow range (LPM)	Heat exchanger size (cm^2)	Heat exchanger performance factor at manufacturer maximum recommended blood flow rate	Reservoir capacity (mL)	Compatible with vacuum assisted drainage	Integrated arterial filter/pore size/surface area	Minimum operating volume	Gas flow range (LPM)	Maximum temporary gas flow for suspected wetting out of oxygenator
Sorin	D100	0.22	31	Up to 0.7	300	0.65	500	Yes	No	10	Up to 1.4 LPM with a max V/Q of 2:1	Up to 2.8 LPM with a max V/Q of 4:1
Sorin	Liiliput D901	0.34	60	0.8	200	0.72	675	Yes	No	15	Up to 1.6 LPM with a max V/Q of 2:1	None specified
Maquet	Quadrox-i Neonatal	0.38	38	0.2–1.5	700	0.62	800	Yes	No	15	0.1–3.0	None specified
Maquet	Quadrox-i Neonatal with integrated ALF	0.38	40	0.2–1.5	700	0.62	800	Yes	Yes/33 μm/20 cm^2	15	0.1–3.0	None specified
Terumo	Capiox RX05	0.5	43	0.1–1.5	350	0.65	1000	Yes	No	15	0.05–5, minimum 0.2 V/Q	5 LPM for 10s, do not repeat
Terumo	Capiox FX05	0.5	43	0.1–1.5	350	0.65	1000	Yes	Yes/32 μm/130 cm^2	15	0.05–5, minimum 0.2 V/Q	5 LPM for 10s, do not repeat
Sorin	D101	0.61	87	Up to 2.5	600	0.6	1500	Yes	No	30	Up to 5 LPM with a max V/Q of 2:1	Up to 10 LPM with a max V/Q of 4:1
Medtronic	Pixie	0.67	48	0.1–2.0	Not specified	0.65	1200	Yes	No	20	Up to 4.0 LPM with a max V/Q of 2:1	None specified

Table 1.2 Oxygenators rated ~2 to ~5 LPM.

Manufacturer	Oxygenator (microporous polypropylene except as noted)	Oxygenator bundle (m^2)	Oxygenator prime volume	Manufacturer recommended blood flow range (LPM)	Heat exchanger size (cm^2)	Heat exchanger performance factor at manufacturer maximum recommended blood flow rate	Reservoir capacity (mL)	Compatible with vacuum assisted drainage	Integrated arterial filter/pore size/ surface area	Minimum operating volume	Gas flow range	Maximum temporary gas flow for suspected wetting out of oxygenator
Sorin	Lilliput D902	0.64	105	Up to 2.3	200	0.48	1800	Yes	No	200	Up to 4.6 LPM with a max V/Q of 2:1	None specified
Maquet	Quadrox-i Pediatric	0.8	81	0.2–2.8	1500	0.62	1700	Yes	No	30	0.1–5.6	None specified
Maquet	Quadrox-i Pediatric with integrated ALF	0.8	99	0.2–2.8	1500	0.62	1700	Yes	Yes/33 μm/55 cm^2	30	0.1–5.6	None specified
Maquet	Quadrox-iD Pediatric (polymethylpentene)	0.8	81	0.2–2.8	1500	0.62	1700	Yes	No	30	0.1–5.6	None specified
Medtronic	Minimax	0.8	149	0.5–2.3	Not specified	0.45	2000	No	No	150	None specified	None specified
Maquet	Quadrox-i Small Adult	1.3	175	0.5–5.0	3000	0.62	4200	Yes, with VHK 2001 reservoir	No	300	Up to 15	None specified
Maquet	Quadrox-i Small Adult with integrated ALF	1.3	295	0.5–5.0	3000	0.62	4200	Yes, with VHK 2001 reservoir	Yes/40 μm/430 cm^2	300	Up to 15	None specified
Sorin	Inspire 6 (optional integrated arterial filter)	1.4	184/284 with ALF	Up to 6.0	4300	0.6	4500	Yes	Optional/38 μm/68 cm^2	150	Up to 12 LPM, not to exceed 2:1 V:Q	Up to 12 LPM, not to exceed 2:1 V:Q
Terumo	Capiox RX15, 30	1.5	135	0.5–4, 5 LPM with assisted venous drainage	1400	0.6	3000	Yes	No	70	0.5–15	15 LPM for 10s, do not repeat
Terumo	Capiox RX15, 40	1.5	135	0.5–5.0	1400	0.6	4000	Yes	No	200	0.5–15	15 LPM for 10s, do not repeat
Terumo	Capiox FX15, 30	1.5	144	0.5–4, 5 LPM with assisted venous drainage	1400	0.6	3000	Yes	Yes/32 μm/360 cm^2	70	0.5–15	15 LPM for 10s, do not repeat
Terumo	Capiox FX15, 40	1.5	144	0.5–5.0	1400	0.53	4000	Yes	Yes/32 μm/360 cm^2	200	0.5–15	15 LPM for 10s, do not repeat

Table 1.3 Oxygenators rated up to 8 LPM (Part I of II).

Manufacturer	Oxygenator (microporous polypropylene except as noted)	Oxygenator bundle (m^2)	Oxygenator prime volume	Manufacturer recommended blood flow range (LPM)	Heat exchanger size (cm^2)	Heat exchanger performance factor at manufacturer maximum recommended blood flow rate	Reservoir capacity (mL)	Compatible with vacuum assisted drainage	Integrated arterial filter/ pore size/surface area	Minimum operating volume	Gas flow range	Maximum temporary gas flow for suspected wetting out of oxygenator
Sorin	Inspire 8 (optional integrated arterial filter)	1.75	219/351 with ALF	Up to 8.0	4300	0.53	4500	Yes	Optional/38 μm/ 97 cm^2	150	Up to 16 LPM, not to exceed 2:1 V:Q	Up to 16 LPM, not to exceed 2:1 V:Q
Maquet	Quadrox-i Adult	1.8	215	0.5–7.0	4000	0.6	4200	Yes, with VHK 2001 reservoir	No	300	Up to 15	None specified
Maquet	Quadrox-i Adult with integrated ALF	1.8	335	0.5–7.0	6000	0.62	4200	Yes, with VHK 2001 reservoir	Yes/40 μm/430 cm^2	300	Up to 15	None specified
Maquet	Quadrox-iD Adult (polymethylpentene)	1.8	215	0.5–7.0	4000	0.6	4200	Yes, with VHK 2001 reservoir	No	300	Up to 15	None specified
Terumo	SX18	1.8	270	0.5–7.0	2200	0.5	4000	Yes	No	200	0.5–20	20 LPM for 10 s, do not repeat
Sorin	PrimO2X	1.87	250	Up to 8	1400	0.44	4300	Yes	No	250	Up to 16 LPM, not to exceed 2:1 V:Q	Up to 16 LPM, not to exceed 2:1 V:Q
Sorin	Apex HP	1.87	250	Up to 8	1400	0.48	4000	Yes	No	200	Up to 16 LPM, not to exceed 2:1 V:Q	Up to 16 LPM, not to exceed 2:1 V:Q
Sorin	Synthesis	2	500 with integrated ALF	Up to 8	1400	0.36	4300	Yes	Yes/40 μm/400 cm^2	300	Up to 16 LPM, not to exceed 2:1 V:Q	Up to 16 LPM, not to exceed 2:1 V:Q

Table 1.4 Oxygenators rated up to 8 LPM (Part II of II).

Manufacturer	Oxygenator (microporous polypropylene except as noted)	Oxygenator bundle (m^2)	Oxygenator prime volume	Manufacturer recommended blood flow range (LPM)	Heat exchanger size (cm^2)	Heat exchanger performance factor at manufacturer maximum recommended blood flow rate	Reservoir capacity (mL)	Compatible with vacuum assisted drainage	Integrated arterial filter/pore size/surface area	Minimum operating volume	Gas flow range (LPM)	Maximum temporary gas flow for suspected wetting out of oxygenator
Medtronic	Affinity NT	2.5	270	1.0–7.0	Not specified	0.45	4000	Yes	No	200	1.0–7.0	None specified
Medtronic	Affinity Fusion	2.5	260	1.0–7.0	4000	0.55	4500	Yes	Yes/25 μm via oxygenator bundle	200	None specified	None specified
Terumo	Capiox RX25	2.5	250	0.5–7.0	2000	0.53	4000	Yes	No	200	0.5–20	20 LPM for 10s, do not repeat
Terumo	Capiox FX25	2.5	260	0.5–7.0	2000	0.53	4000	Yes	Yes/32 μm/600 cm^2	200	0.5–20	20 LPM for 10s, do not repeat
Terumo	SX25	2.5	340	0.5–7.0	2200	0.5	4000	Yes	No	200	0.5–20	20 LPM for 10s, do not repeat

shear is not only related to pressure. Additionally, pressure drop plays an important role in microembolic air removal in microporous systems [1]. Today's FDA-approved oxygenators have shear values well within acceptable limits, and pressure drop across the device should not simply be minimized. Since pressure drop values may be misleading for initial consideration of a device, they are not listed in Tables 1.1 to 1.4.

The integral ALF (select models only)

- An ALF is a screen filter with a pore size generally in the 25–40 μm range.
- The ALF generally serves as the last safeguard in a cardiopulmonary bypass circuit to trap and/or remove particulate and air emboli from the blood before return to the patient.
- An integrated ALF, if used, must meet or exceed the maximum oxygenator flow rate. One should not "push" an oxygenator with an integrated arterial filter beyond its recommended flow, even if gas exchange is acceptable, without manufacturer confirmation that the filter can safely handle a higher flow.
- For additional information, *see section "Arterial Line Filters."*

The venous reservoir

- Most pediatric centers use open hard-shell reservoirs. The term "open" refers to the reservoir being open to atmosphere for use in a system using gravity siphon drainage. The reservoir must be properly vented to prevent pressurization and the risk of air embolization to the patient. Pressure in the reservoir can result from sucker, vent, and venous inflow if air is not allowed to escape through a vent port or vacuum system. (*See section "Massive air embolism" in Chapter 8 and section "Standard and augmented venous return" in Chapter 3.*)
- "Closed" bypass systems commonly incorporate a bag design for the venous reservoir, which significantly limits the blood:air interface. Closed systems have been shown to have a decreased inflammatory response and fewer hematologic disruptions. However, closed systems have less precise visual monitoring of venous return, require additional systems for purging venous bag air, and are not readily converted to vacuum-assisted venous drainage (which comes with its own set of additional concerns for safe use).
- The venous reservoir contains the venous filter.
- The venous reservoir generally collects venous blood and cardiotomy blood. Both venous blood and cardiotomy blood get filtered separately via different flow paths in the reservoir. The reservoir may therefore be referred to as the cardiotomy venous reservoir (CVR) (see Figure 1.6).
- The reservoir capacity needs to handle the patient blood volume in cases of planned or unplanned low-flow or circulatory arrest.
- The venous reservoir is an extremely important air removal device. The vast majority of air in the cardiotomy and venous blood flow paths is removed in their respective filtration systems (see Figure 1.7).
- Venous reservoirs have inflows either near the top (top feeders) or bottom (bottom feeders). Both incorporate an extension tube (venous straw) which runs low in the reservoir to help maintain a continuous column of fluid for gravity siphon drainage.
- Venous (and cardiotomy) filters are normally coated, at least in part, with a chemical compound to help prevent the formation of foam and to eliminate foam that has been introduced to the filter. Antifoam products containing silicone, simethicone, and methylcellulose are currently used for this application.

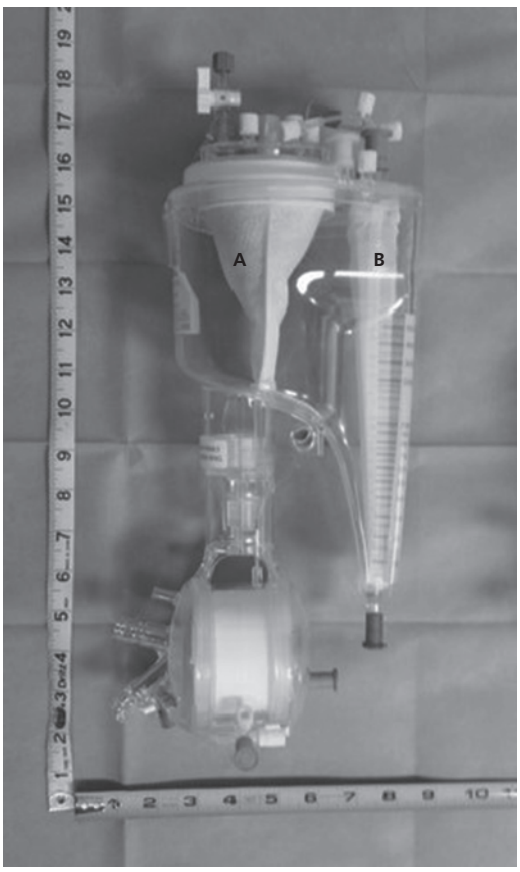


Figure 1.6 Filters in the Terumo CAPIOX FX05 oxygenator. *A—cardiotomy filter in the CVR. B—venous filter in the CVR.* (*See insert for color representation of the figure.*)

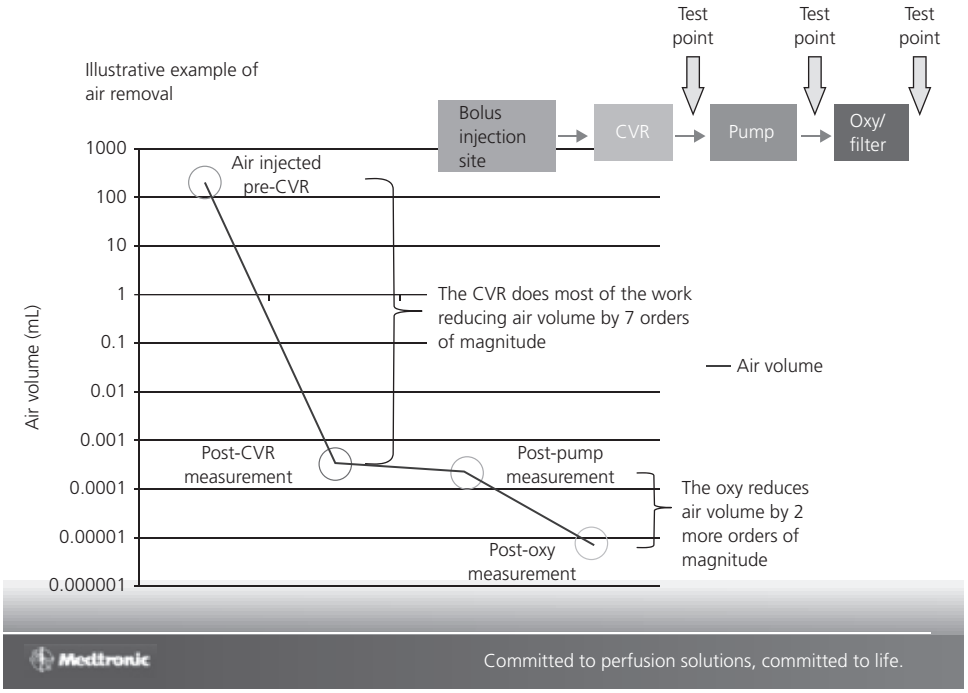


Figure 1.7 Air removal in the CVR and oxygenator. Reproduced with permission from Medtronic, Inc., Minneapolis, MN. All rights reserved. (*See insert for color representation of the figure.*)

- It is common for defoaming agents to coat only the upper levels of a filter system. This results in a system whereby it is not mandatory for the blood to pass through the defoamer. The blood/foam will only come in contact with the defoamer when it is more likely to be needed (i.e., foam rising above a certain reservoir level during periods of high sucker flow) and during periods when the reservoir level is high. If foam is seen in a CVR during bypass, the perfusionist should maintain a higher reservoir level to aid in the defoaming process. This aids in the removal of gaseous microemboli by allowing for an increased reservoir transit time.

The cardiotomy filter

- The cardiotomy filter has its own flow rating that is generally less than the maximum oxygenator flow but well within the needs for field suction and left ventricular vent flow.
- The cardiotomy filter generally provides more filtering capacity than the venous filter. Venous blood tends to be much "cleaner" with less air and particulate emboli, while cardiotomy blood generally has more.
- An integrated cardiotomy filter is normally located higher than and behind the venous reservoir. This arrangement allows cardiotomy blood to passively flow into the venous reservoir after passing through the cardiotomy filter.
- Consideration should be given to a secondary stand-alone cardiotomy reservoir if there is concern that the integrated CVR would overflow in cases of pump low-flow or circulatory arrest. The secondary reservoir can be used to temporarily store blood volume.
- A secondary cardiotomy reservoir with filter should also be considered for cases with an expected high sucker flow (reoperations, patients with significant MAPCAs, very large patients with high pump flow, surgery in or around the liver). The additional filtration, or prefiltering, of shed blood provided by a secondary cardiotomy filter may increase the useful life of the primary CVR. When utilized, a secondary cardiotomy is usually set up to process vent and sucker return with drainage to the primary cardiotomy reservoir.
- Cardiotomy (and venous) filters are normally coated, at least in part, with a chemical compound to help prevent the formation of foam and to eliminate foam that has been introduced to the filter. Antifoam products containing silicone, simethicone, and methylcellulose are currently used for this application.
- It is common for defoaming agents to coat only the upper levels of a filter system. This results in a system whereby it is not mandatory for the blood to pass through the defoamer. The blood/foam will only come into contact with the defoamer when it is more likely to be needed (i.e., foam rising above a certain reservoir level during

periods of high sucker flow) and during periods when the reservoir level is high. If foam is seen in a CVR during bypass, the perfusionist should maintain a higher reservoir level to aid in the defoaming process. Of course, this would also aid in the removal of gaseous microemboli by allowing for an increased reservoir transit time.

The heat exchanger

- An oxygenator's integrated heat exchanger must be water tested prior to the addition of crystalloid solutions for priming. Running water through the heat exchange system at a flow and pressure comparable to the operating room values and inspecting for leaks to the blood compartment are important steps in the process of setting up a heart–lung machine for bypass.
- The water pathway through an oxygenator helps dissipate static electricity charges that may develop in the roller head pumps and be transmitted through the blood pathway. This feature is especially important in preventing static electricity discharge through the heart–lung machine circuitry that can cause damage.
- Heat exchanger specifications are qualified by a "performance factor" defined as the difference of inlet (venous) and outlet (arterial) blood temps divided by the difference of inlet (venous) blood and inlet water temperatures.

$$\text{Performance factor} = \frac{(\text{arterial blood temperature} - \text{venous blood temperature})}{(\text{water inlet temperature} - \text{venous blood temperature})}$$

- The performance factor is frequently in the range of 0.4–0.7 at a device's maximum rated flow.
- The gradient between the venous blood and the water inlet temperature is usually limited to 10 °C (though some manufacturers allow for a gradient of up to 15°C). This is to prevent excessive gradients where there is potential for gas to come out of solution if warmed too rapidly (due to the decrease in gas solubility at higher temperatures). Limiting the temperature gradient also helps to evenly cool and warm a patient. A more homogenous warming may result from limiting the gradient during rewarm which can help prevent after-drop (whereby core patient temperature falls in the early post bypass period).
- Some manufacturers may explicitly state that the gradient should be less than 10 °C (an 8°C maximum for example), which would be an important factor in evaluating a product for use in a congenital cardiac program that uses moderate-to-profound hypothermia. Lower gradients can increase the length of a bypass case since rewarming times will be longer. (*See section "Temperature management" in Chapter 3.*)
- It is commonly accepted that limiting temperature gradients is important in preventing gas from coming out of solution. However, an animal study by Nollert *et al.* found no correlation between temperature gradient and emboli count [2]. Manufacturer-recommended gradient limits should not be exceeded.
- The minimum acceptable heat exchanger performance factor is not defined by the manufacturer or AAMI. This leaves the practitioner to decide if heat exchange performance is acceptable at the intended bypass flow and/or up to the maximum recommended oxygenator flow. This assessment comes with clinical experience. To note, an oxygenator may provide acceptable gas exchange but unacceptable heat exchange for a planned deep hypothermic circulatory arrest case. This situation, for example, would encourage the perfusionist to upsize the oxygenator and therefore the integral heat exchanger.
- It is important to note that there have been oxygenators manufactured with different oxygenator bundle sizes wrapped around the same-sized heat exchanger. Therefore, the perfusionist must be familiar with product line specifications.
- The heat exchanger performance factor must be evaluated carefully. The value stated by the manufacturer is not standardized to a heat exchanger water flow rate. Furthermore, the value must be obtained from a chart that looks at the spectrum of performance factors over the entire rated flow range. Therefore, performance factors are ideally evaluated at the expected pump flow rate for a given case. To note, the values listed in Tables 1.1 through 1.4 are performance factors at the maximum rated blood flow as stated by the manufacturer but are not always standardized to 10 LPM water flow since that information is not always available.
- Heat exchanger performance will be least efficient at the upper flow rating for a device.
- Increased heat exchanger surface area does not always equate to increased performance. The blood flow path through the oxygenator (axial vs. radial), the heat exchanger material, and characteristics of the water system will affect performance.
- It is important to consider that the rates of cooling and warming on cardiopulmonary bypass are impacted by systemic vascular resistance management and pump flow.

Tables 1.1, 1.2, 1.3, and 1.4 list devices currently on the market. Adult-sized oxygenators are included since

congenital cardiac perfusion programs must be able to accommodate patients of all sizes. Users are encouraged to trial oxygenators and evaluate all aspects of performance in their own operating room environment. Then, along with this thorough understanding of the oxygenators to be used, custom tubing packs can be created. Ultimately, a perfusion group should develop a chart identifying the components to be used for different expected pump flow ranges. (*See section "Comprehensive experience-based equipment chart" in Chapter 12.*)

Arterial line filters

The cardiopulmonary bypass circuit contains filters in several systems: the cardiotomy reservoir, venous reservoir, oxygenator bundle, bypass arterial line, prebypass, gas line, crystalloid line, blood transfusion line, cardioplegia system, and others. The ALF tends to receive the most attention since it serves as the last system in a cardiopulmonary bypass circuit to trap and/or remove particulate and air emboli from the blood before return to the patient. It is important to note that one of the most important aspects of a bypass circuit is its ability to remove (and not create) particulate and air emboli. Several authors have conclusively shown that microair emboli are delivered to patients on bypass [3–8]. These emboli can result in microvasculature blockages with the downstream effects of hyoperfusion or ischemia. Air in particular is disruptive to the endothelial glycocalyx which has important implications for vascular permeability and the potential for edema throughout the body with cardiopulmonary bypass [9–11]. The cardiotomy reservoir, venous reservoir, and oxygenator bundle are all important air handling and removal devices in a cardiopulmonary bypass circuit. The ALF is the last removal device before blood reenters the body. Figure 1.8 depicts four commonly used external ALFs. The ALF must be properly deaired with a crystalloid priming solution before bypass. If a blood prime is used, blood should only be added after crystalloid priming and thorough ALF deairing.

- ALFs are most commonly standalone add-ons to a perfusion circuit.
- ALFs are screen filters with a pore size ranging from 25 to 40 μm.
- Filter housings are preferably clear to visually facilitate deairing during crystalloid priming.
- External ALFs most commonly have folded or wrapped filter medium that is not fully visible. The filter should be carbon dioxide flushed prior to crystalloid priming. Then, with fluid flowing through at the manufacturer's recommended rate for priming, the filter should be adequately tapped to ensure no air is trapped (more precisely, any microbubbles present *should be* carbon dioxide).
- Air emboli during bypass are generally purged from the filter by its flow characteristics and venting system with the flow velocity decreasing in the external ALF encouraging any bubbles to rise and exit via the top-mounted purge line.
- The external ALF most often has a bleed line continuously returning a low flow back to the cardiotomy reservoir. Less commonly, hydrophobic material located at

Figure 1.8 External arterial line filters. **(a)** *Sorin Group D736*. **(b)** *Sorin Group D733*. **(a)** and **(b)** Reproduced with permission from Sorin Group USA Inc., Arvada, CO. All rights reserved. **(c)** *Terumo Capiox AF02*. Reproduced with permission from Terumo Cardiovascular Group, Ann Arbor, MI. All rights reserved. **(d)** *Medtronic Affinity Pixie*. Reproduced with permission from Medtronic, Inc., Minneapolis, MN. All rights reserved. (*See insert for color representation of the figure.*)

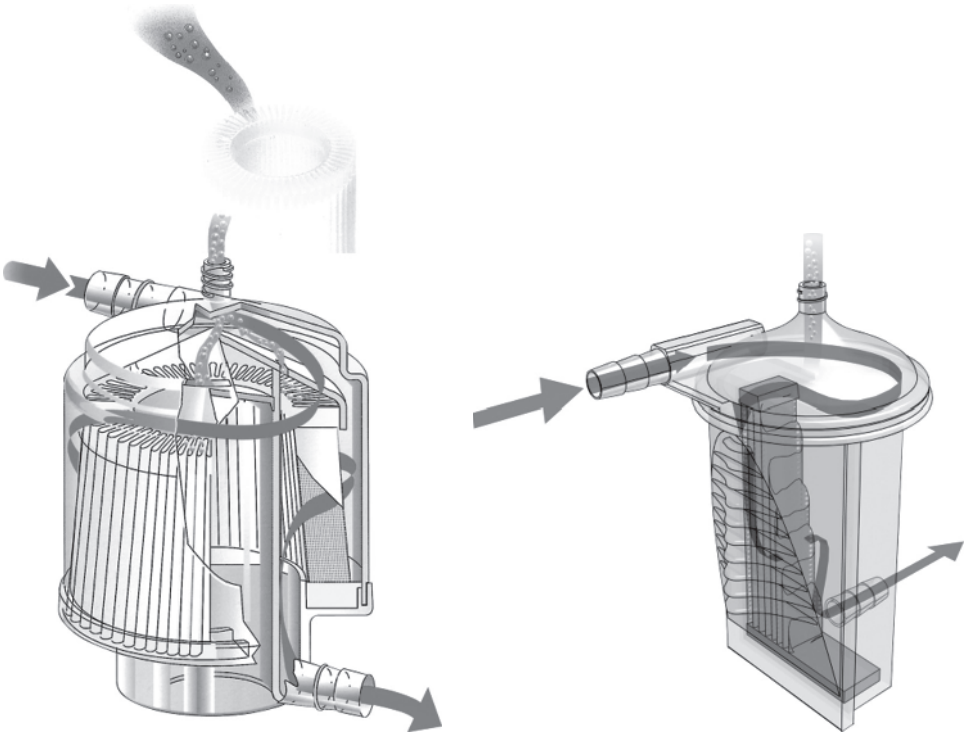


Figure 1.9 Typical flow path through external arterial line filters. The top luer connector purges continuously via a line connected to the CVR. Reproduced with permission from Sorin Group USA Inc., Arvada, CO. All rights reserved. (*See insert for color representation of the figure.*)

the top of the filter allows air to be directly vented to the atmosphere. Figure 1.9 shows the typical blood flow path through two external ALFs with top-mounted purge lines.

- Some oxygenators now have integrated screen filters wrapped around the oxygenator bundle. These integrated, or internal, ALFs additionally promote the removal of air in the blood by purging air directly through the microporous oxygenator fibers to be vented out the gas phase of the oxygenator. This is facilitated by the back pressure the internal filter provides and the proximity of the potential air to the oxygenator bundle's micropores.
- Oxygenator-integrated ALFs decrease circuit priming volume since the additional filtering medium and space usually adds less volume than a standalone external ALF to the overall prime.
- Future oxygenators may employ microporous membrane wrapping technology to serve dual function as oxygenator and arterial filter. However, the use of oxygenator membranes serving the additional role of filter medium has not been adequately validated in the literature. The adult-sized Medtronic Affinity Fusion is currently the only oxygenator on the market FDA approved for this dual role.
- The pressure drop across an ALF is an important factor to evaluate. However, filters today tend to have a generous surface area with rated flows well within acceptable values for sheer stress and turbulence.

Table 1.5 lists commonly used external ALFs. The charts in Tables 1.1 to 1.4 can be used to compare the integrated ALFs some oxygenator models offer against the external model characteristics listed in Table 1.5.

Tubing packs

Custom tubing packs for cardiopulmonary bypass circuits are commonly created by the perfusion team to aid in quick and efficient setup of the heart–lung machine (HLM). A congenital cardiac program may have 3–5 different oxygenators as well as 3–5 tubing packs with overlap between oxygenators and tubing packs. This creates numerous options that come with several considerations when choosing equipment for bypass. Table 1.6 is an example of tubing pack specifications based on anticipated maximum pump flow rates. In addition to these items, an institutional comprehensive experience-based equipment chart is helpful in defining the options for nearly all common components

Table 1.5 External arterial line filters.

Manufacturer	Model	Maximum flow (LPM)	Prime volume (mL)	Pore size (μm)
Sorin	KiDS D130	0.7	16	40
Sorin	KiDS D131	2.5	28	40
Terumo	Capiox AF02	2.5	40	32
Sorin	D736	2.5	47	40
Sorin	D735	2.5	47	27
Pall	AL3	3	28	40
Medtronic	Affinity Pixie	3.2	39	30
Sorin	D731	6	100	27
Sorin	D733	6	100	40
Terumo	Capiox AF125X	7	125	37
Maquet	QUART	7	180	40
Terumo	Capiox AF200X	7	200	37
Medtronic	Affinity	7	212	20
Medtronic	Affinity	7	212	38
Pall	AL6	8	100	40
Pall	AL8	8	170	40
Sorin	D732	8	195	27
Sorin	D734	8	195	40
Pall	AV6SV	8	220	40

Table 1.6 Example of equipment selection based on anticipated maximum pump flow rate.

	Total circuit prime (mL)	Oxygenator with integrated 32 μm ALF	Primary tubing pack components	Milliliters of prime for oxygenator (O), reservoir (R), arterial limb (A), boot (B), venous limb (V), centrifugal venous head and tubing (CH)
Up to 1.2	215	Terumo Capiox FX05 rated to 1.5 LPM	3/16 arterial 3/16 boot 1/4 venous	(O) 43, (R) 75, (A) 30, (B) 15, (V) 52
1.2–1.5	230		3/16 arterial 1/4 boot 1/4 venous	(O) 43, (R) 75, (A) 30, (B) 30, (V) 52
1.5–1.8	460	Terumo Capiox FX15-30 rated to 5 LPM (with assisted drainage)	1/4 arterial 1/4 boot 1/4 venous	(O) 144, (R) 150, (A) 75, (B) 30, (V) 61
1.8–2.1	535		1/4 arterial 1/4 boot 3/8 venous	(O) 144, (R) 150, (A) 75, (B) 30, (V) 136
2.1–3.15	570		1/4 arterial 3/8 boot 3/8 venous	(O) 144, (R) 150, (A) 75, (B) 65, (V) 136
3.15–3.6	675		3/8 arterial 3/8 boot 3/8 venous	(O) 144, (R) 150, (A) 175, (B) 65, (V) 141
3.6–4.4	750		3/8 arterial 3/8 boot 3/8 venous, Centrifugal venous assist head	(O) 144, (R) 150, (A) 175, (B) 65, (V) 141, (CH) 75
4.4–5	775		3/8 arterial 1/2 boot step up 3/8 venous, Centrifugal venous assist head	(O) 144, (R) 150, (A) 175, (B) 90, (V) 141, (CH) 75
5.0–7.0	980	Terumo Capiox FX25 rated to 7 LPM	3/8 arterial 1/2 boot step up 3/8 venous, Centrifugal venous assist head	(O) 250, (R.) 250, (A) 175, (B) 90, (V) 140, (CH) 75

for bypass. (*See section "Comprehensive experience-based equipment chart" in Chapter 12.*)

- A cardiovascular team must define their maximum acceptable flows through the various sizes of available tubing: 3/16″, 1/4″, 3/8″, and 1/2″ (other sizes are available but are less commonly used).
- Institutions vary in regards to standard bypass tubing length, table height, venous reservoir height, and typical venous cannulae style and size which all impact achievable flow rates.
- Tubing used for venous return may be evaluated with gravity versus augmented drainage.
- Boot (arterial pump raceway) tubing should be evaluated for flow based on head RPMs since spallation and the potential for failure are a function of the number of tubing compressions over time. Maximum RPMs used are commonly in the 160–170 RPM range even though roller heads may be capable of 250 RPMs.
- Smaller raceway lengths (i.e., mini-heads) increase the compression rate for a given pump flow rate.
- Table 1.7 outlines an *example* of the maximum flows used for various tubing sizes.
- Each tubing size has a prime volume that can be calculated with a known length (Table 1.8).
- The objective in defining custom tubing pack line sizes is to achieve the smallest prime volume while ensuring adequate and safe flow rates and pressures.
- Consideration must be given to the range of operative table movement since rolling the bed away in an up position may require several inches of pump tubing to safely accommodate.
- The venous line must have some slack in it to allow for "walking" air out if an air lock develops on bypass with gravity siphon drainage.
- The total system prime volume will include the tubing pack, oxygenator, starting reservoir level, dynamic volume holdup (if significant), and hemoconcentrator (if primed before bypass).
- The starting reservoir volume may be higher for surgeons who tend to give more pump volume during the cannulation process.
- Tubing lengths will vary for each case based on how much of the arterial-venous loop is discarded before connection to the bypass cannulae. Excess tubing in the pack is important to accommodate varied pump positions, particularly variances for femoral bypass.
- Some pediatric centers will claim a much lower prime volume with the use of retrograde arterial priming and venous antegrade priming. It is debatable whether these autologous priming strategies have a net positive effect since young congenital heart disease patients frequently do not have much volume to "donate" to the bypass circuit in the immediate prebypass period. In fact, these patients are frequently more sensitive to overall volume loss during cannulation. It is also debatable whether it is appropriate to use alpha agents such as phenylephrine immediately before bypass to aid in autologous priming techniques.
- The prime volume of a custom tubing pack is simply the various line lengths multiplied by the volume contained. The volume of tubing cut off at the field may be subtracted only if it is accounted for in the starting reservoir level since blood-primed circuits will have this volume returned via the pump suckers before bypass.
- Future efforts toward circuit prime reduction will focus primarily on tubing size and length since the bulk of the prime is now either there or in the venous reservoir. The use of vacuum-assisted venous drainage has allowed some centers to move the oxygenator apparatus closer to the patient since the kinetic potential requirement between the patient relative to the reservoir is eliminated. Vacuum-assisted venous drainage though is not without risk and must be carefully implemented into a congenital cardiac perfusion practice. (*See section "Standard and augmented venous return" in Chapter 3.*)

Table 1.6 is offered as an *example* of an overview for equipment selection. The maximum flow rate anticipated on

Table 1.7 Typical tubing sizes with flow maximums.

Tubing size	Max flow boot line in standard raceway (mL/min)	Max flow arterial line (mL/min)	Max flow venous line with gravity siphon drainage (mL/min)	Max flow venous line with assisted drainage (mL/min)
3/16″	1200	1500	600	800
1/4″	2100	3150	1800	2500
3/8″	4400	>3150	3750	>3750
1/2″	>4400	NA	>3750	>6000

Table 1.8 Tubing prime volume.

Internal tubing diameter	1/8″	3/16″	1/4″	5/16″	3/8″	1/2″
Milliliters per foot	2.4	5.0	9.7	15.5	21.7	38.6

bypass is identified on the left with prime volumes and circuit components required listed to the right. An individual bypass plan may require a maximum flow of 2.5–4.0 L/min/m^2, which usually corresponds with an absolute flow of 0.4–7.0 LPM. There is overlap between the ranges listed. When the anticipated maximum flow straddles two oxygenator brackets, it is important to consider whether the functional reserve built into this estimate is worth the additional prime volume, and possibly the additional minimum operating volume, which importantly affects how a bypass case is run. This chart does not list ALFs since the oxygenators in this example have integrated 32 μm screen filters wrapped around the oxygenator bundle. This chart also includes the option of kinetic-assisted venous drainage for pump flows greater than 3.6 LPM since 1/2″ venous tubing is not utilized. Perfusion programs providing the option of vacuum-assisted venous drainage for all patients may be able to further decrease priming volumes by moving the oxygenator assembly closer to the patient. Gravity drainage requires the assembly to be closer to the floor for sufficient kinetic potential.

Cardioplegia systems

There are dozens of congenital cardiac surgery cardioplegia formulas, delivery methods, and protocols that are heavily based on institutional experience and surgeon preference. In fact, a recent North American survey of the Congenital Heart Surgeon's Society showed that while 86% of respondents used blood-based cardioplegia, the crystalloid component of those solutions varied; 38% del Nido, 34% custom, 16% St Thomas/Plegisol/Baxter, 7% Custodial, and 5% microplegia [12]. Additionally, there were wide variations noted regarding dosage, delivery method, temperature, and time interval between doses. It is clear that while excellent clinical outcomes have been achieved at numerous centers, consensus regarding optimal myocardial protection for congenital cardiac surgery patients has not been reached.

Cardioplegia *systems* can broadly be categorized as recirculating, nonrecirculating, and continuous. Each system will require either a custom tubing pack or a commercially available option. It is beyond the scope of this chapter to describe the dozens of cardioplegia formulas and delivery methods in use. The following are types of cardioplegia *systems.* Articles regarding *types* of cardioplegia are listed in the reference section at the end of this chapter [12–25].

Recirculating cardioplegia system

- The recirculating circuit has an outlet, ideally near the aortic root needle, to which cardioplegia is directed during delivery (the return limb is clamped and the outlet line unclamped during cardioplegia delivery). Otherwise, the flow is recirculated (the outlet line is clamped and the recirculation limb is unclamped) (see Figure 1.10).
- Contains cardioplegia (crystalloid or blood-based) in a system in which the final product for delivery is kept flowing, well mixed, and at the desired temperature (see Figure 1.11).

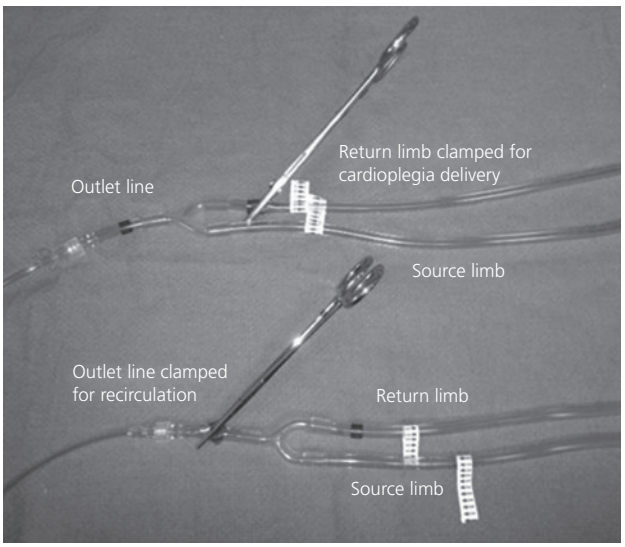


Figure 1.10 Recirculating cardioplegia system table lines. Top: Recirculating delivery system with table line return limb clamped for cardioplegia delivery. Bottom: Recirculating delivery system with table line outlet limb clamped for recirculation. (*See insert for color representation of the figure.*)

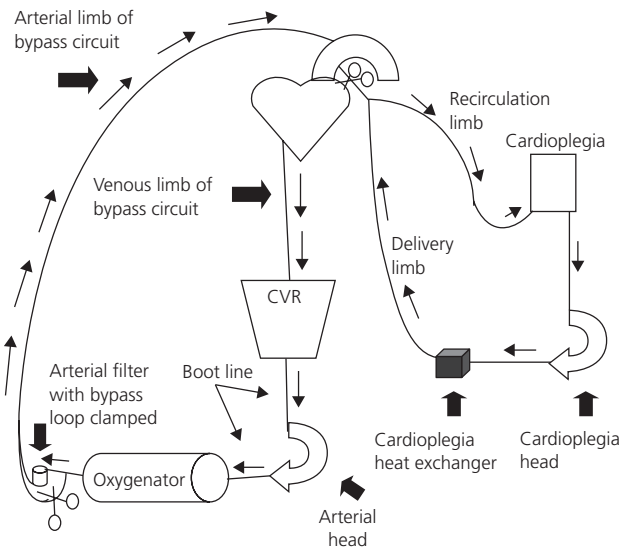


Figure 1.11 Recirculating cardioplegia schematic. Note the table line outlet limb is clamped for recirculation.

- An active cooling coil or ice bath coil is used to adjust the cardioplegia delivery temperature.
- An ideal system has minimal dead space volume. The dead space volume in a recirculating system is that which is not part of the active flow but integral to the delivery pathway. Generally, this would be the volume of the aortic root needle proximally back to the return limb of the flow path.
- The dead space volume must be kept to a minimum since it can warm to room temperature and contain poorly mixed cardioplegia solution.
- Cardioplegia in the dead space can be flushed through a vented aortic root before delivery if that volume is deemed significant.
- Recirculating systems may be used for single-dose and multidose cardioplegia strategies.
- A recirculating system is by its nature a closed system and is therefore not vented to the atmosphere. A recirculating system should not be flushed with carbon dioxide before priming unless there is a mechanism to remove the excess carbon dioxide which will be dissolved in the cardioplegia solution with priming.
- 1/8″ to 3/16″ tubing is commonly used to minimize the cardioplegia circuit prime volume.

Nonrecirculating cardioplegia system

- Generally pulls arterialized blood from a post-oxygenator source that is mixed with a crystalloid component (see Figure 1.12).

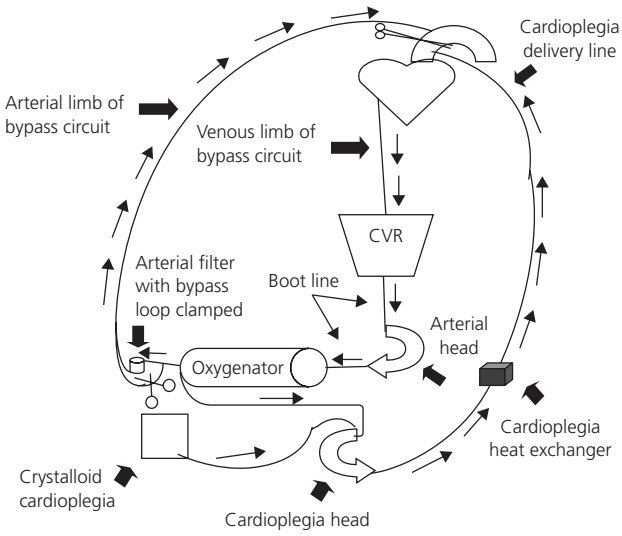


Figure 1.12 Nonrecirculating cardioplegia schematic. The cardioplegia head draws a crystalloid component together with a blood component to be delivered through a cardioplegia heat exchanger to the patient.

- May also be referred to as a single-pass system.
- The mixed cardioplegia solution flows through an active coiling coil or ice bath coil and on to the aortic root needle.
- This system inherently has more dead space volume. This volume extends from the aortic root needle back to the blood and crystalloid component sources. The cardioplegia in the dead space portion of the circuit may be at room temperature during initial and/or subsequent doses if it is not flushed from the system in some fashion.
- The dead space volume may equate to a significant portion of the intended dose volume in neonates and infants.
- Can be employed for single-dose and multidose cardioplegia strategies.
- 1/8″ to 3/16″ tubing is commonly used. The crystalloid and blood components may have different tubing sizes, which run through the same roller head to effect the desired ratio between the two components. Alternately, the crystalloid and blood components may run through different roller heads to allow for a variable and adjustable ratio of components during a bypass run.

Continuous cardioplegia system

- Continuous cardioplegia, also known as microplegia, is primarily arterialized blood drawn from a post-oxygenator source that is mixed with an arresting agent and other additives.
- It is given via continuous or cyclic low flow.
- The concentration of additives may be adjusted for effect in real time.
- The delivery temperature may be cold or warm and may vary throughout the arrest period; warm or cold induction, warm or cold maintenance, and warm terminal reperfusion dose (aka hot shot).
- Continuous cardioplegia systems are not commonly used for congenital cardiac surgery, and there are few published reports for its use in neonates and infants.

The heart–lung machine

The HLM needs several basic items for safe cardiopulmonary bypass. Most importantly, periodic preventative maintenance as recommended by the manufacturer is essential. Such checks go a long way toward

preventing the need for emergency procedures (hand cranking, arterial head change-out, etc.). Today's HLMs minimally have arterial head servoregulation for system pressure, reservoir-level sensing, internal checks for over/under-speed of the head, a calibrated system for calculating pump flow based on tubing size and raceway length, bubble detection, and master/follower head assignments (i.e., cardioplegia head should not flow more than the arterial head in systems drawing cardioplegia blood from a post-oxygenator source). It is strongly encouraged to have HLMs that can quickly and easily be adapted to any size patient. Then, knowledge of patient specifics allows one to select and set up any available HLM for the bypass run, particularly in an emergency. Figure 1.13 depicts a customized HLM configuration.

The HLM, in my opinion, has seen five significant advances over the past decade:

1 The layout of the hardware has become more customizable.
   - HLMs formerly existed as 4–6 standard pump heads on a mobile base. Today's HLM allows for regular-sized heads and mini-heads to be pole mounted, rotated toward the field, and even placed in a somewhat stacked fashion to decrease the overall console footprint and minimize the circuit prime volume. The roller pump heads may also rotate in their housings which can decrease line lengths and prevent hard angles as the tubing makes its way through the system. However, it is important to note that pump consoles still follow the law of conservation of mass. When a HLM decreases its width side-to-side, it tends to increase its front-to-back dimension. This is an important consideration for programs that occasionally use their HLMs in areas of the hospital outside of the cardiac operating rooms. Not all doorways in an institution may allow for passage of the newer style HLM as easily as the cardiac operating room doorways.

2 Belt-driven systems have been replaced with electric field motor drives.
   - This technology requires less maintenance with increased reliability since there are fewer parts (belts, brushes, bushings, etc.) to wear out over time.

3 Basic LCD displays have been replaced with touch screen color systems.
   - This advance has decreased the number of display pages that need to be scrolled through, and therefore has increased efficiency. Color systems also aid with quick detection of specific alarms and alerts.

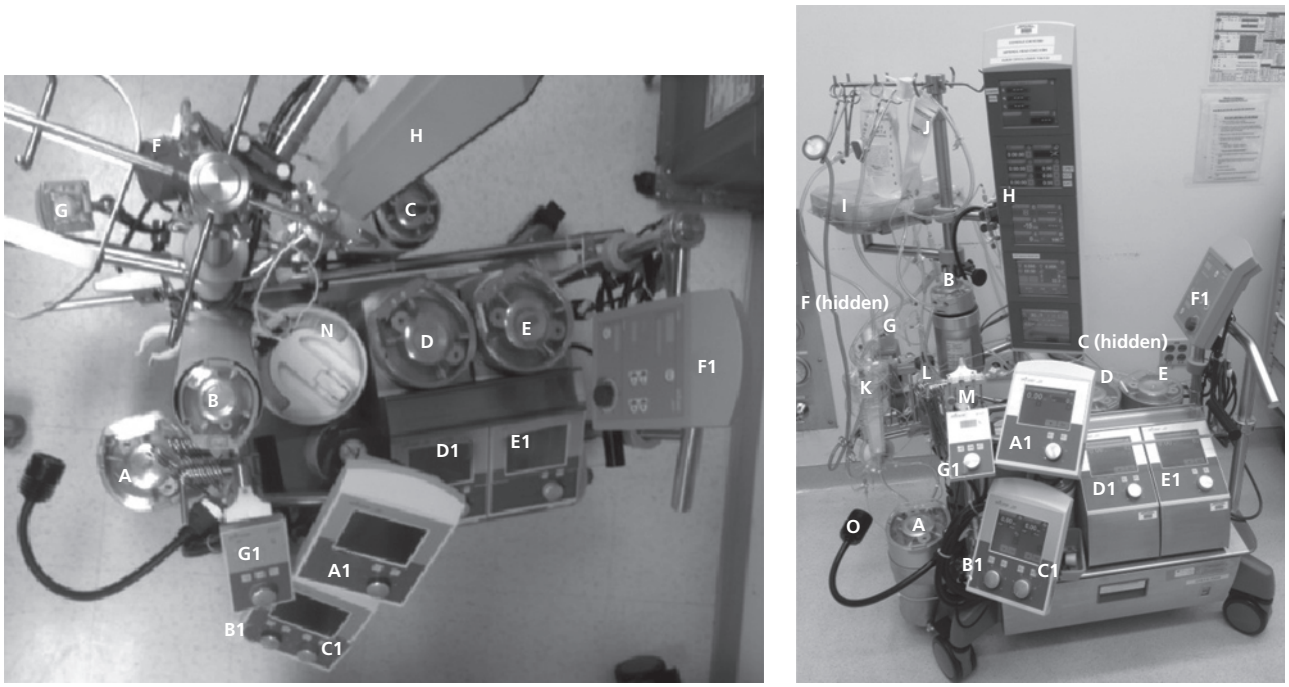


Figure 1.13 Top and side views of a customized Stockert S5 heart–lung machine. *A—Arterial head and its controller A1, B—cardioplegia head and its controller B1, C—vent head and its controller C1, D—field sucker and its controller D1, E—field sucker and its controller E1, F—centrifugal head motor (for kinetic venous-assisted drainage) and its controller F1, G—electronic venous occluder and its controller G1, H—master display tower, I—sterile custom tubing pack, J—custom cardioplegia tubing set, K—oxygenator, L—hemoconcentrator, M—blood gas sampling manifold, and N—ice bucket for cardioplegia cooling coil.* (*See insert for color representation of the figure.*)

4 Display systems and head assignments are more customizable.
   - The control and alarm displays can be assigned to different locations on the display tower to meet the needs of a perfusion program. These computerized systems have also eliminated the requirement of older systems where servoregulation was controlled by individual component power plug placement. Current systems allow for user assignment of servoregulation and alarm systems to individual pumps. This is an important safety improvement since older systems risked running without servoregulation if a replacement head could not be plugged into the one designated outlet on the console for that feature (i.e., the arterial head was servoregulated for pressure and level solely based on its power supply location in the base).

5 Internal HLM batteries are nearly universal and more powerful.
   - These upgraded batteries can power the console for an extended period of time. This is an essential feature even in hospitals with backup power systems because those systems can experience brief temporary loss of output. Loss of output in computerized systems without battery backup can result in extended boot-up processes complicating the reinstitution of bypass. Computerized systems generally do not allow for hand cranking during the startup systems-check, which adds unnecessary risk to the patient. An integrated battery backup system alleviates any concerns regarding temporary loss of hospital power and allows for transport in the unlikely event of an operating room environment emergency requiring evacuation.

The arterial pump head

HLMs for congenital heart surgery most often use roller heads for the arterial pump. Roller head pumps allow for precise control over flow and are not afterload sensitive. Centrifugal heads are less commonly used for congenital cardiac surgery, especially in younger patients. Centrifugal heads may have theoretical (and oft-cited) advantages in regards to decreasing blood trauma and preventing massive air infusion, but studies have shown that centrifugal heads can produce more hemolysis than roller pumps and they transmit gaseous microemboli just as roller heads do [26–28]. However, the inability to finely control blood flow for extended periods of time, especially when weaning support, and the inability to provide exceptionally low blood flow rates for neonates or during regional cerebral perfusion, essentially limits their utility in congenital cardiac surgery. Additionally, it is less than ideal to have a perfusion group switching between roller heads and centrifugal heads depending on the day's case mix and having more custom pack options on the shelf to accommodate such. Therefore, most congenital cardiac surgery programs utilize roller head pumps in the arterial position on their HLMs.

The heater-cooler system

The heater-cooler system is an essential cardiopulmonary bypass component. It is the piece of hardware that interfaces with the heat exchanger that is integrated in today's oxygenator housing. It may also have the capability to provide separate water flow to a cardioplegia system or surface cooling/warming blanket. The heater-cooler system may also be referred to as the thermocirculator.

A heater-cooler system comes in two varieties. The most common system is a standalone mobile unit that is capable of heating and cooling up to three water baths (Figure 1.4). One water bath is connected to the oxygenator heat exchanger with water lines capable of providing 10–18 LPM of water flow and temperatures of 15–41 °C. The other water bath(s) are generally used to provide temperature management to the cardioplegia system. These baths are sometimes separate to allow for rapid temperature change between the following cardioplegia strategies: cold (2–15 °C), tepid (28–32 °C), and warm (32–37 °C). Alternately, the other water bath(s) may be used to provide water flow through a surface cooling/warming blanket under the patient.

The standalone heater-cooler unit is a rather simple device. It provides water flow based on pump power and system resistance. Different oxygenators and different water connection lines, lengths, and hardware will result in varying water flow rates. A water flow rate of 10–18 LPM is commonly used by manufacturers to test oxygenator heat exchangers. The unit should provide flow in this range. If a flow quantifier is not included with the unit, an aftermarket product should be added. It is important to have the ability to monitor water flow since it is an important factor in cooling and warming a patient. The ability to readily quantify water flow is important when ruling out issues related to the temperature management of a patient. Suboptimal water flow, due to a kinked line for example,

can significantly decrease the ability to properly manage a patient's temperature on bypass.

A less common type of heater-cooler system is termed "wall water." This system utilizes the traditional hot and cold water supplies, or a designated system for such, specifically for the cardiac operating rooms. These systems usually have the advantage of high water flow and the ability to rapidly change temperature. Recall that standalone systems usually only have one water bath for oxygenator heat exchanger management that requires active warming and cooling when changes are required. The wall water system, on the other hand, allows for immediate temperature change since there are no recirculating baths. Wall water systems use fresh water at the desired temperature, which is then sent to a drain system. For this reason, wall water systems tend to have higher operating costs. Reliance on wall water systems also requires standalone units as backup in case of system failure, increasing operative costs.

Most perfusion programs use standalone heater-cooler systems. These systems have proven to be reliable, cost-effective, easy to maintain, and mobile. Their evolution over the past decade has decreased their size and made them quieter, both important in the operating room environment. Additionally, remote-operating control systems have allowed the units to be located away from the HLM console. This may be an advantage to the operating room layout, but it should be noted that significant water line length decreases system efficiency since more water must be heated or cooled. This is an important consideration in congenital cardiac programs regularly utilizing moderate-to-deep hypothermia.

Figure 1.14 Stockert heater-cooler system 3T (three-tank system). *A—Cold cardioplegia circuit. The first tank instantly provides 2–10°C water to the cardioplegia system. B—Warm cardioplegia circuit. The second tank instantly provides 15–41°C water to the cardioplegia system. It can also be fitted for a water-based patient surface cooling/heating blanket. C—Oxygenator circuit. The third tank provides 15–41°C water to the oxygenator heat exchanger. It has a second pump and circuit to provide water flow from the same tank to a water-based patient blanket if desired.* (*See insert for color representation of the figure.*)

Cannulae

Patients with congenital heart disease can be cannulated for bypass in a variety of ways. The ascending aorta is most commonly cannulated for arterial inflow. Some congenital cardiac defects require arterial inflow via the main pulmonary artery with flow through the ductus arteriosus to provide systemic perfusion (with branch pulmonary arteries controlled). Venous cannulation is most commonly via the superior and inferior vena cavae when intracardiac work is needed. A single right atrial venous cannula is commonly used when intracardiac work is not needed. Additionally for cannulation, a left ventricular vent may be placed via the right superior pulmonary vein and advanced across the mitral valve. Figure 1.15 depicts a structurally normal heart to illustrate cannulation sites relative to the general cardiac anatomy. Figures 1.16 and 1.17 illustrate normal left aortic arch and central venous anatomy for reference.

Regarding cannulae, is it cannulae or cannulas? These terms are used interchangeably for the plural of cannula. The term "cannulas" is more common in conversation, whereas the term "cannulae" seems to be more common in written form. Both are used in this text.

There are literally hundreds of different cannulae available for cardiopulmonary bypass. The range of cannulae that need to be readily available for a congenital cardiac program is quite extensive to cover patients of all sizes from 1 to 200 kg! One must have on hand aortic root needles of various sizes, retrograde coronary sinus and coronary perfusers, left ventricular vents, and of course connectors and tubing to incorporate these items into the

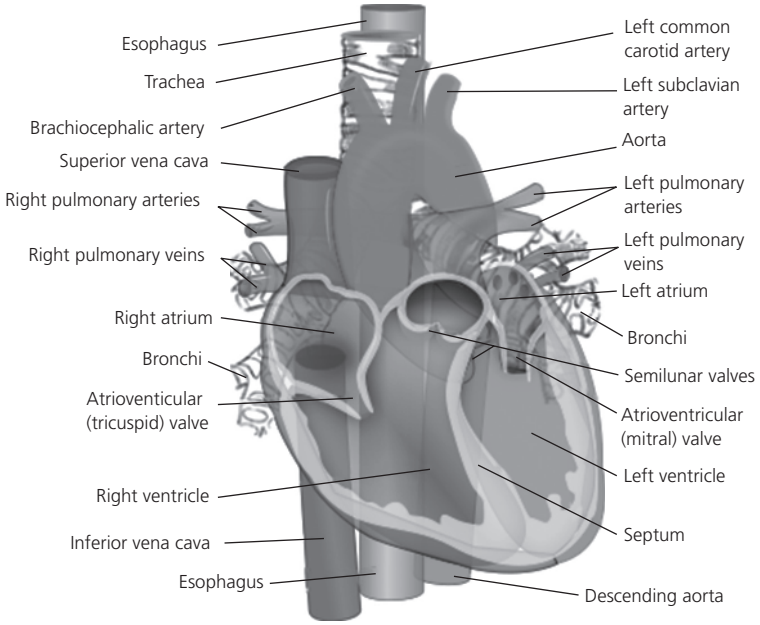


Figure 1.15 General cardiac anatomy. http://en.wikipedia.org/wiki/File:Relations_of_the_aorta,_trachea,_esophagus_and_other_heart_structures.png via Wikipedia. Reproduced with permission from under the Creative Commons Attribution-Share Alike 3.0. Unported license (accessed January 7, 2014). (*See insert for color representation of the figure.*)

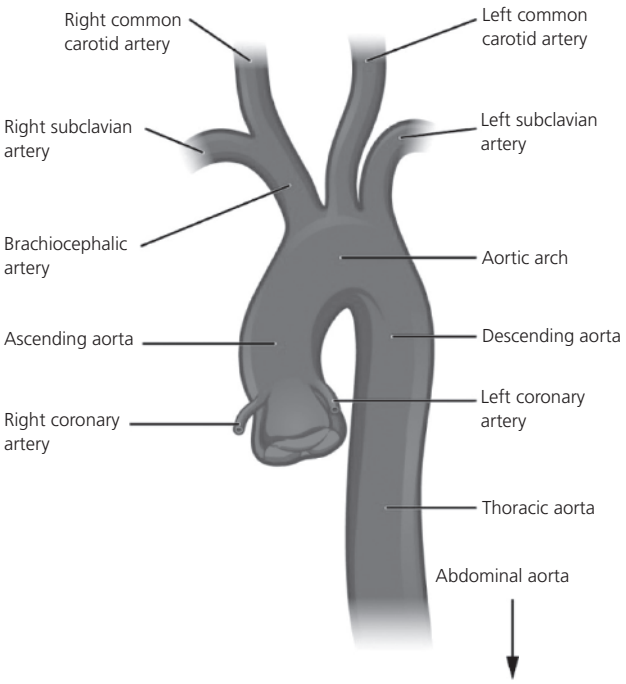


Figure 1.16 Aortic arch anatomy. http://cnx.org/content/m46646/latest/2121_Aorta.jpg. Reproduced with permission from OpenStax College on Wikimedia Commons under the Creative Commons Attribution-Share Alike 3.0. Unported license (accessed January 7, 2014). (*See insert for color representation of the figure.*)

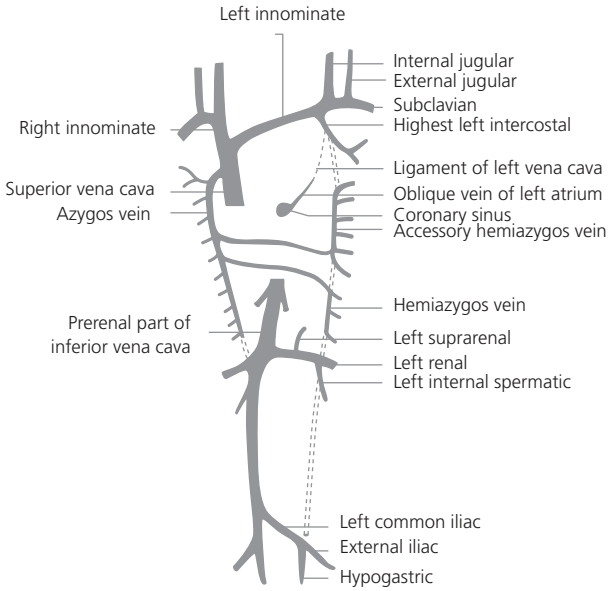


Figure 1.17 Central venous anatomy. Reproduced with permission from Gray's Anatomy of the Human Body, 1918 edition (http://en.wikipedia.org/wiki/File:Gray480.png) via Wikipedia. (*See insert for color representation of the figure.*)

bypass circuit. Arterial and venous cannulae are the most important to consider since they are required to place a patient on traditional cardiopulmonary bypass.

It is an underappreciated fact that cannulae do not come from the manufacturer with specific rated flows, as do oxygenators and ALFs. Rather, cannulae come with charts depicting flow versus pressure drop (also called pressure loss). These charts are based on manufacturer-based measurements using water flow at room temperature and may

therefore be referred to as "water charts." These charts do not factor in tubing length connecting the cannula to the bypass equipment, temperature changes during a case, hematocrit, or several other factors that may impact the actual flow capability of a specific cannula. It is therefore imperative that a perfusion program develop their own charts rating flow capabilities for cannulae within their cardiopulmonary bypass system. These experience-based charts are essential in a congenital cardiac surgery program where dozens of options exist due to considerable variation in patient and vessel size. An overview of factors determining cannulae size is provided with examples of sizing charts to follow.

Venous cannulae

Venous cannulae are graded based on their French size (Fr). Most manufacturers use the outer diameter (OD) to determine French size. It is generally accepted that with gravity drainage through a venous cannula, the pressure drop across the cannula should be limited to 35–40 mmHg. A venous cannula with a larger internal lumen will obviously have a lower pressure drop and increased flow capacity. However, there are other important considerations. Venous cannulae are made with different materials and have variable tip designs usually consisting of additional side port holes. Different cannula designs, tip materials (metal, polycarbonate, plastic, silicone), and construction methods result in different ratios between the inner and outer diameter of the cannula. All of these differences may be important to the cannulating surgeon. Metal tips tend to have the benefit of maximized inner to outer (I/O) ratios but are rigid. Silicone tips have less favorable (I/O) ratios as compared to metal tips but are less rigid and tend to have more conical tips that may aid insertion into the cavae. It is important to note that while venous cannulae are graded based on OD, flow capabilities will vary due to these factors. The choice of venous cannulae, as with all cannulae, usually comes down to surgeon judgment. Examples of pediatric venous cannulae are shown in Figure 1.18. The pediatric perfusionist must be familiar with available options for outlier cases such as difficult cannulations or LSVC, hepatic, axillary, or femoral cannulation.

In adult coronary artery surgery, the right atrium is most commonly cannulated with a single dual-stage venous cannula. This right atrial cannula has a low likelihood of occluding its side port holes since the right atrium is considerably larger than the cannula itself. In congenital cardiac surgery, patients are more likely to require bicaval cannulation since intracardiac work is more common. It is important to note that a larger venous cannula inserted into a cava does not always result in a higher expected flow rate. If the side port holes are occluded, venous return can be limited to a single hole at the tip, which may decrease overall performance. Furthermore, the IVC cannula must not occlude the hepatic venous drainage. The Eustachian valve is also of consideration for IVC cannulation since it can hinder proper cannula placement.

Table 1.9 lists recommended cannulae sizing for Medtronic DLP right-angle metal-tip cannulae and is based on one institution's experience using gravity drainage. The

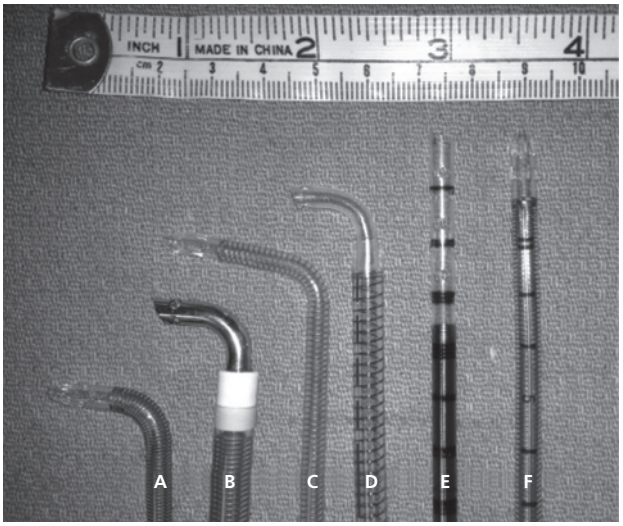


Figure 1.18 Select pediatric venous cannulae. *A—14 Fr. Terumo Tenderflow right angle PVC tip. B—14 Fr. Medtronic DLP right angle metal tip. C—12 Fr. Medtronic DLP right angle PVC tip. D—12 Fr. Edwards Lifesciences Thin-Flex right angle plastic tip. E—14 Fr. Medtronic Bio-Medicus straight with multiple side port holes. F—14 Fr. Medtronic DLP malleable straight PVC tip.* (*See insert for color representation of the figure.*)

Table 1.9 Venous cannulae for bicaval cannulation.

Medtronic DLP angled metal tip venous cannulae		
Weight (kg)	**SVC (Fr.)**	**IVC (Fr.)**
<3	12	12
3–6	12	14
6–8	12	16
8–12	14	16
12–16	14	18
16–22	16	18
22–30	16	20
30–34	18	20
34–46	18	20 or 22
46–58	20	22
58–75	20	24
75–100	22	24
>100	22 or 24	24 or 28

Table 1.10 Water chart flow rates for select venous cannulae.

Venous Cannula Size (Fr.)	Manufacturer	Water chart flow (LPM)
12	Medtronic DLP angled metal	0.8
	Medtronic DLP angled PVC	0.6
	Medtronic DLP straight PVC	0.6
	Terumo angled tenderflow	0.7
14	Medtronic DLP angled metal	1.6
	Medtronic DLP angled PVC	0.8
	Medtronic DLP straight PVC	0.8
	Terumo angled tenderflow	1.1
16	Medtronic DLP angled metal	1.9
	Medtronic DLP angled PVC	1.4
	Medtronic DLP straight PVC	1.4
	Terumo angled tenderflow	1.5
18	Medtronic DLP angled metal	2.6
	Medtronic DLP angled PVC	1.8
	Medtronic DLP straight PVC	1.8
	Terumo angled tenderflow	2.0
20	Medtronic DLP angled metal	3.0
	Medtronic DLP angled PVC	2.4
	Medtronic DLP straight PVC	2.4
	Terumo angled tenderflow	2.4
22	Medtronic DLP angled metal	3.7
	Medtronic DLP angled PVC	3.1
	Medtronic DLP straight PVC	3.1
	Terumo angled tenderflow	2.7
24	Medtronic DLP angled metal	4.2
	Medtronic DLP angled PVC	3.5
	Medtronic DLP straight PVC	3.5
	Terumo angled tenderflow	4.1
28	Medtronic DLP angled metal	5.3
	Medtronic DLP angled PVC	5.2
	Medtronic DLP straight PVC	5.2
	Terumo angled tenderflow	Cannula size not available

Table 1.11 Water chart flow rates for select femoral venous cannulae.

Weight (kg)	Size (Fr.)	Brand	Water chart flow (LPM)
<4.5	10	Edwards Lifesciences Fem-Flex	0.8
	10	Biomedicus, 7.5″	0.7
4.5–10	12	Edwards Lifesciences Fem-Flex	1.25
	12	Biomedicus, 7.5″	1.25
10–14	14	Edwards Lifesciences Fem-Flex	1.80
	14	Biomedicus, 7.5″	1.75
14–28	15	Biomedicus, 30″	1.2
28–40	17	Biomedicus, 30″	1.7
40–55	19	Biomedicus, 30″	2.5
55–75	21	Biomedicus, 30″	3.0
75–90	23	Biomedicus, 30″	3.8
>90	25	Biomedicus, 30″	4.7
	27	Biomedicus, 30″	5.5
	29	Biomedicus, 30″	>6.0

- Kinetic-assisted venous drainage or VAVD increases achievable flows.
- Significant differences in femoral vessel size can be seen in similarly sized patients. Cannula used will primarily be determined by vessel size.
- Water chart flows may overestimate achievable flows with femoral cannulation in particular since the venous line may end up being longer to accommodate connection to the bypass circuit.
- For quick reference in emergent situations, femoral venous cannula size is frequently 2 Fr. greater than the femoral arterial size (15 Fr. femoral arterial cannula will result in a 17 Fr. femoral venous cannula).
- The achievable flows with a single femoral venous cannula using gravity drainage are rarely able to support full flows on bypass.
- Femoral cannulation may simply support circulation until full cardiac exposure is achieved and central cannulation is possible. Alternately, an SVC or right atrial cannula may be added to the femoral venous circuit to allow for full flow on bypass.

use of vacuum or kinetic assist would allow for the use of smaller venous cannulae (and possibly a smaller venous line). As discussed, cannulae are rated by pressure drop and the achievable flows within an accepted pressure range. Table 1.9 is based on weight and there is overlap between the ranges. Experience-based sizing based on weight has been shown to be more useful than water flow charts, especially during emergent cannulations. The overlap encourages the clinician to consider other patient variables when contemplating stepping up or down the size of a cannula.

Tables 1.10 and 1.11 exemplify some of the options and flow differences between manufacturers and venous cannulae designs. Referencing more comprehensive charts such as these is less than ideal in emergent situations. And, these flow charts are based on water flows and so may not accurately reflect achievable flows in a bypass system. A weight based chart works well in most instances, while water flow charts may be helpful in unique situations. The water charts are useful when determining cannula size for single venous and alternate cannulation strategies. These charts are offered only as an example since different perfusion programs will have different bypass line lengths and equipment, which may affect cannulae performance. Additionally, cannula position importantly affects achievable flows. Experience-based charts should be an excellent guide resulting in proper sizing with rare exception. Ultimately, the patient's anatomy, anticipated flows on bypass, surgical needs, and surgeon judgment determine venous cannulae size.

Arterial cannulae

Arterial cannulae are graded based on their French size. Table 1.12 lists an example of weight-based arterial cannulae sizing for central aortic cannulation. Generally speaking, as with venous cannulae, arterial cannulae French size refers to the outer diameter (OD). It is generally accepted that the pressure drop across an arterial cannula should be limited to 100 mmHg to prevent excessive jetting, shear forces and damage to the formed elements of the blood. An arterial

Table 1.12 Arterial cannulae for central aortic cannulation.

Weight (kg)	Size (Fr.)	Brand	Water chart flow (LPM)
<2.5	6	Medtronic DLP	0.4
2.5–4.5	8	Biomedicus	0.7
4.5–10	10	Biomedicus	1.3
10–14	12	Biomedicus	2.1
14–28	14	Biomedicus	2.8
25–35	16	Medtronic One-Piece	3.8
28–35	18	Medtronic EOPA CAP	2.6
35–50	18	Medtronic EOPA	4.8
50–75	20	Medtronic EOPA CAP	4.1
75–100	20	Medtronic EOPA	5.7
75–90	22	Medtronic EOPA CAP	5.4
>90	22	Medtronic EOPA	>6
>90	24	Medtronic EOPA	>6

cannula with a larger internal lumen will have a higher flow capacity at the acceptable pressure drop. However, the cannula cannot be so large that it significantly blocks flow around it which is particularly important for ascending aortic cannulation. Native cardiac output ideally is not significantly impacted with arterial cannulation, particularly during the initiation, rewarming, and weaning phases of bypass or when the patient is cannulated but not on bypass. Additionally, the length of the cannula with smallest diameter, and whether the cannula is compressible (likelihood to kink or be restricted by the purse strings), will impact performance. Figure 1.19 depicts some commonly

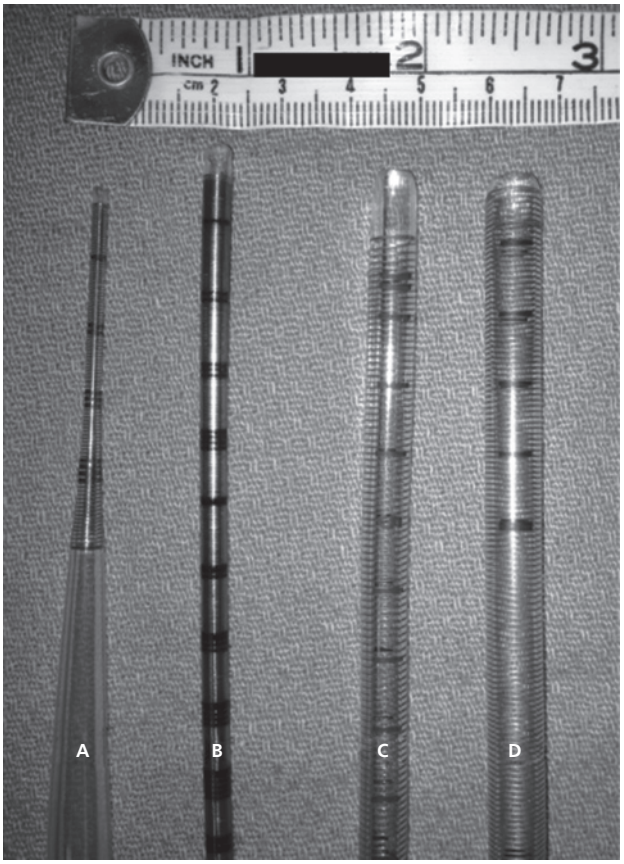


Figure 1.19 Select arterial cannulae for central cannulation. *A-6 Fr. Medtronic DLP One Piece. B-12 Fr. Medtronic Bio-Medicus. C-20 Fr. Medtronic EOPA. D-22 Fr. Medtronic EOPA CAP.* (*See insert for color representation of the figure.*)

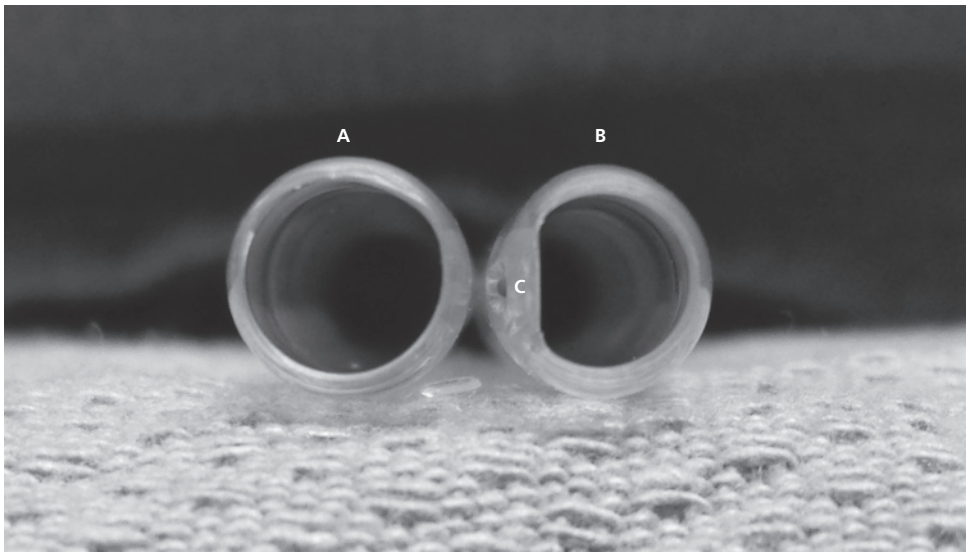


Figure 1.20 Luminal variation between types of arterial cannulae. *A-Standard round lumen for a 22 Fr. Medtronic arterial cannula. B-D-shaped lumen for a 22 Fr. Medtronic arterial cannula with central aortic pressure (CAP) monitoring capability. C-Left of "C" is the central aortic pressure monitoring port.* (*See insert for color representation of the figure.*)

Table 1.13 Arterial cannulae for femoral cannulation.

Weight (kg)	Size (Fr.)	Brand	Water chart flow (LPM)
<4.5	8	Edwards Lifesciences Fem-Flex	0.8
4.5–10	10	Edwards Lifesciences Fem-Flex	1.3
10–14	12	Edwards Lifesciences Fem-Flex	2.0
14–28	14	Edwards Lifesciences Fem-Flex	2.4
28–40	15	Biomedicus	3.0
40–55	17	Biomedicus	4.0
55–75	19	Biomedicus	5.3
>75	21	Biomedicus	6.5

*Most arterial cannulae can be used for femoral cannulation with a cut down procedure.
†The cannulae listed here come with appropriate supplies for Seldinger technique insertion.

used arterial cannulae. Furthermore, some arterial cannulae have a port at the tip which can be used to monitor central aortic pressure (not cannula lumen pressure) before and after bypass. If the monitoring line for this feature runs through the lumen, overall flow capabilities will be lower since the effective lumen size is decreased. This means that two arterial cannulae with the same French size (same OD) can have different flow capabilities (see Figure 1.20). Some arterial cannulae come with a side port allowing for stopcock placement. This is useful for monitoring patient arterial pressure post bypass (on bypass, it only reflects bypass circuit pressure) and as a means for deairing during cannulation (prebypass and emergently). Finally, Table 1.13 lists weight-based arterial cannula options for femoral cannulation.

References

Oxygenators and emboli

1 Desomer FM, Dierickx P, Dujardin D, *et al*. Can an oxygenator design potentially contribute to air embolism in cardiopulmonary bypass? A novel method for the determination of the air removal capabilities of neonatal membrane oxygenators. Perfusion. 1998;13:157–63.
2 Nollert G, Nagashima M, Bucerius J, *et al*. Oxygenation strategy and neurologic damage after deep hypothermic circulatory arrest. I. Gaseous microemboli. J Thorac Cardiovasc Surg. 1999;117:1166–71.

Gaseous microemboli on bypass

3 Lou S, Ji B, Liu J, *et al*. Generation, detection and prevention of gaseous microemboli during cardiopulmonary bypass procedure. Int J Artif Organs. 2011;34(11):1039–51.
4 Liu S, Newland RF, Tully PJ, *et al*. In vitro evaluation of gaseous microemboli handling of cardiopulmonary bypass circuits with and without integrated arterial line filters. J Extra Corpor Technol. 2011;43(3):107–14.
5 Kurusz M, Butler BD. Bubbles and bypass: an update. Perfusion. 2004;19:S49–55.
6 Wang S, Woitas K, Clark JB, *et al*. Clinical real-time monitoring of gaseous microemboli in pediatric cardiopulmonary bypass. Artif Organs. 2009;33(11):1026–30.
7 Myers GJ, Voorhees C, Haynes R, Eke B. Post-arterial filter gaseous microemboli activity of five integral cardiotomy reservoirs during venting: an in vitro study. J Extra Corpor Technol. 2009;41(1):20–7.
8 Groom RC, Quinn RD, Lennon P, *et al*. Detection and elimination of microemboli related to cardiopulmonary bypass. Circ Cardiovasc Qual Outcomes. 2009;2(3):191–8.
9 Myers GJ. Gaseous Microemboli during Cardiopulmonary Bypass. Italy: Sorin Group; 2011.
10 Lindner JR, Ismail S, Spotnitz WD, *et al*. Albumin microbubble persistence during myocardial contrast echocardiography is associated with microvascular endothelial glycocalyx damage. Circulation. 1998;98(20):2187–94.
11 Barak D, Katz Y. Microbubbles: pathophysiology and clinical implications. Chest. 2005;128(4):2918–32.

Cardioplegia in general

12 Kotanin Y, Tweddel J, Bruber P, *et al*. Current cardioplegia practice in pediatric cardiac surgery: a North American multiinstitutional survey. Ann Thorac Surg. 2013;96(3):923–9.
13 Allen BS. Pediatric myocardial protection: where do we stand? J Thorac Cardiovasc Surg. 2004;128:11–13.
14 Doenst T, Schlensak C, Beyersdorf F. Cardioplegia in pediatric cardiac surgery: do we believe in magic? Ann Thorac Surg. 2003;75(5):1668–77.
15 Jacob S, Kallikourdis A, Selke F, Dunning J. Is blood cardioplegia superior to crystalloid cardioplegia? Interac Cardiovasc Thorac Surg. 2008;7(3):491–8.
16 Dobson GP, Faggian G, Onorati F, Vinten-Johansen J. Hyperkalemic cardioplegia for adult and pediatric surgery: end of an era? Front Physiol. 2013;4:228.

del Nido cardioplegia solution

17 Matte GM, del Nido PJ. History and use of del Nido cardioplegia solution at Boston Children's Hospital. J Extra Corpor Technol. 2012;44:98–103.
18 Charette K, Gerrah R, Quaegebeur J, *et al*. Single dose myocardial protection utilizing del Nido cardioplegia solution during congenitalheart surgery procedures. Perfusion. 2012;27:98–103.
19 O'Blenes SB, Friesen CH, Ali A, Howlett S. Protecting the agedheart during cardiac surgery: the potential benefits of del Nidocardioplegia. J Thorac Cardiovasc Surg. 2011;141:762–9.
20 O'Brien JD, Howlett SE, Burton HJ, *et al*. Pediatric cardioplegia strategy results in enhanced calcium metabolism and

lower serum troponin T. Ann Thorac Surg. 2009;87: 1517–24.
21 Ginther RM Jr, Gorney R, Forbess JM. Use of del Nido cardioplegia solution and a low-prime recirculating cardioplegia circuit in pediatrics. J Extra Corpor Technol. 2013;45(1): 46–50.
22 Govindapillai AG, Hua R, Rose R, *et al.* Protecting the aged heart during cardiac surgery: use of del Nido cardioplegia provides superior functional recovery in isolated hearts. J Thorac Cardiovasc Surg. 2013;146(4):940–8.

Microplegia

23 Durandy Y. Perfusionist strategies for blood conservation in pediatric cardiac surgery. World J Cardiol. 2010;2(2):27–33.
24 Durandy Y. Warm pediatric cardiac surgery: European experience. Asian Cardiovasc Thorac Ann. 2010;18(4):386–95.
25 O'Rullian JJ, Clayson SE, Peragallo R. Excellent outcomes in a case of complex redo surgery requiring prolonged cardioplegia using a new cardioprotective approach: adenocaine. J Extra Corpor Technol. 2008;40(3):203–5.

Arterial pump heads

26 Rawn DJ, Harris HK, Riley JB, *et al.* An under-occluded roller pump is less hemolytic than a centrifugal pump. J Extra Corpor Technol. 1997;29(1):15–18.
27 Wang S, Kunselman AR, Myers JL, Undar A. Comparison of two different blood pumps on delivery of gaseous microemboli during pulsatile and nonpulsatile perfusion in a simulated infant CPB model. ASAIO J. 2008;54(5):538–41.
28 Yee S, Qiu F, Su X, *et al.* Evaluation of HL-20 roller pump and Rotaflow centrifugal pump on perfusion quality and gaseous microemboli delivery. Artif Organs. 2010;34(11):937–43.