

Original Article

A Clinical Evaluation of the Terumo Capiox SX18R Hollow Fiber Oxygenator

Perry A. Dekkers, BS, CCP; D. Scott Lawson, BS, CCP; Gregory R. Smigla, BS, CCP; Ian R. Shearer, BS, CCP

Perfusion Services, Duke University Medical Center, Durham, North Carolina

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ABSTRACT

The Terumo Capiox SX18R is a commercially available, low prime, reverse phase, hollow fiber membrane oxygenator. The oxygenator consists of a 1.8 m² microporous polypropylene hollow fiber bundle, a 2200 cm² tubular stainless steel heat exchanger, and an open hard shell venous reservoir with integral cardiotomy filter.

The Terumo Capiox SX18R oxygenator was evaluated to determine its clinical oxygenating performance. Blood samples were drawn from 25 patients yielding 114 data points. The following parameters were recorded: blood flow, cardiac index, gas flow, gas to blood flow ratio, and oxygen fraction. Samples were assayed for hematocrit, hemoglobin, arterial and venous blood gas values, and venous oxygen saturation. The data and assay results were used to calculate arterial, venous, and membrane gas oxygen content, oxygen transfer, shunt fraction, and oxygen diffusion capacity.

The Terumo Capiox SX18R oxygenator performed adequately with sufficient oxygen transfer reserve and carbon dioxide clearance under a variety of clinical conditions for the tested population.

Address correspondence to:
Perry A. Dekkers, BS, CCP
Perfusion Services
Duke University Medical Center
Box 3082
Durham, North Carolina 27710

INTRODUCTION

Recently a generation of low prime, reduced surface area membrane oxygenators has become available for the adult population. These oxygenators have newly engineered blood channeling pathways that reduce the blood to gas barrier between hollow fibers, allowing a greater amount of venous blood to be in contact with the oxygenating surface (1). The utilization of new hollow fiber weaving patterns, stitched mats, and tighter external shell configurations acts to decrease the blood boundary layer. The resulting decrease in surface area can provide a decrease in priming volume.

Hollow fibers are produced by two different methods: extrusion or microphase separation. Most fibers are extruded from polypropylene, stretched to form micropores, and then heated for stabilization. This method creates pores of irregular size that traverse to the gas side of the fiber. These extruded fibers are approved for 6 hours of use. The Terumo series of oxygenators is unique because of its microphase separation method for hollow fiber production. This process yields an indirect continuous channel through a thicker (50 micron) hollow fiber with smaller average pore sizes of 0.05 microns. This feature gives rise to more durable hollow fibers designed to prevent plasma leakage for up to twenty hours of use. However, the Federal Drug & Administration (FDA) has approved the oxygenator for six hours of use. Instead of a hollow fiber bundle that is weaved or matted, Terumo uses a polycarbonate housing that is narrowed at the center of the fiber bundle. This decreases the distance between fibers and helps maintain their position under stress.

This paper examines the clinical oxygenating performance of the Terumo Capiox SX18R by focusing on oxygen transfer (VO_2), shunt fraction (Q_s/Q_t), membrane oxygen diffusion capacity (DmO_2), and carbon dioxide removal.

MATERIALS AND METHODS

The Terumo Capiox SX18R^a oxygenator consists of a 4.0 L polycarbonate venous hard shell reservoir with an integral 20 μ cardiomy filter, venous side stainless steel heat exchanger, and polypropylene fiber bundle. The oxygenator has a static prime volume of 270 ml and a rated blood flow range of 2.0-7.0 L/min. The venous side heat exchanger consists of a series of stainless steel tubes (2200 cm²) in which blood flows inside and water outside. The oxygenator employs a 1.8 m² reverse phase fiber bundle configuration (blood flows externally to the fibers and gas internally). The blood pathway enters at the top of the oxygenator, flows perpendicularly, continues down and parallel to the fiber bundle, and exits perpendicularly at the bottom of the oxygenator. This pathway has been termed "Z" flow. Ports are also available for blood cardioplegia and pressure monitoring.

Equipment

The extracorporeal circuit consisted of an oxygenator^a, roller

pump^b, cardiomy reservoir^c, arterial filter^d, custom tubing pack^e, in-line blood gas monitor^f, and hemoconcentrator^g. The prime included: 1200 ml Lactated Ringers^h, 250 ml Hetastarchⁱ, 300 ml 20% mannitol^h, 50 ml 8.4% sodium bicarbonate^h, and 5 ml heparinⁱ (1000 units/ml). Arterial and venous blood gas values and blood temperatures were continuously monitored. Blood gas analysis was performed on a calibrated analyzer^k. A calibrated CoOximeter^l provided venous blood saturations (SvO₂) and hemoglobin levels (Hgb). Hematocrit levels (Hct) were measured using a microhematocrit centrifuge^m.

Perfusion Technique

The extracorporeal circuit was set up in accordance with the manufacturer's instructions, CO₂ flushed, primed with \approx 1600 ml of crystalloid fluid, and fully debubbled before initiating bypass. Alpha-stat acid-base management was utilized for blood gas analysis (2, 3). Perfusion blood flows were maintained at cardiac indices (CI) between 1.7 to 2.4 L/min/m² maintaining SvO₂ greater than 60%. Activated clotting timesⁿ were kept greater than 400 seconds for anticoagulation.

Data Collection

Samples were drawn from 25 patients yielding 114 data points. The following parameters were recorded at the time assays were performed: blood flow rate (Q_b), CI, gas flow rate (Q_g), $Q_g:Q_b$, and FiO₂. The blood samples were drawn every 20-30 minutes and assayed for Hct, Hgb, arterial and venous blood gas values, and SvO₂. The data and assay results were used to calculate arterial oxygen content (CaO₂), venous oxygen content (CvO₂), membrane gas oxygen content (CgO₂), VO₂, Q_s/Q_t, and DmO₂. Oxygen tension levels were corrected to actual temperatures before calculations were performed (4).

Oxygen Content

Arterial oxygen content, CvO₂ and CaO₂ are used in calculating VO₂, Q_s/Q_t, and DmO₂ (5). The values are expressed in milliliters per deciliter (ml/dl) and derived from the following formulas:

$$CaO_2 = [(1.34 \text{ ml/g})(\text{Hgb mg/dl})(\% \text{ sat})] + [(0.003 \text{ ml/dl/mmHg})(PaO_2 \text{ mmHg})]$$

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- a Terumo Corporation, Tokyo, Japan
 - b Model 063800-011, Cobe Cardiovascular, Inc. Arvada, CO 80004
 - c Model H-4700, Bard Cardiopulmonary Division, Tewksbury, MA 01876
 - d Model SP 3840, Pall Biomedical Inc., Fardardo, PR 00738
 - e Model 6873, Gish Biomedical, Inc., Irvine, CA 92714
 - f Model 300, CDI/3M Health Care, Irvine, CA 92714
 - g Model H-8732, Bard Cardiopulmonary Division, Tewksbury, MA 01876
 - h Abbott Laboratories, North Chicago, IL 60064
 - i McGaw, Inc., Irvine, CA 92714
 - j Elkins-Sinn, Inc., Cherry Hill, NJ 08003
 - k Model 1400, Instrumentation Laboratory, Lexington, MA 02173
 - l Model 382, Instrumentation Laboratory, Lexington, MA 02173
 - m Model C-70, Separation Technology, Inc., Salt Lake City, UT 84119
 - n Model 801, Hemochron/International Technidyne Corporation, Edison, NJ 08820

$$CvO_2 = [(1.34 \text{ ml/g})(\text{Hgb mg/dl})(\% \text{ sat})] + [(0.003 \text{ ml/dl/mmHg})(PvO_2 \text{ mmHg})]$$

$$CgO_2 = [(1.34 \text{ ml/g})(\text{Hgb mg/dl})(\% \text{ sat})] + [(0.003 \text{ ml/dl/mmHg})(PgO_2 \text{ mmHg}^*)]$$

$$*PgO_2 = (FiO_2)(\text{barometric pressure} - 47 \text{ mmHg})$$

Oxygen Transfer

Oxygen transfer is a quantitative test that assesses the total amount of oxygen that is transferred across a respiratory membrane (6,7). The ability of the hollow fibers to oxygenate the venous blood can be assessed by measuring the amount of oxygen transfer at various oxygen fractions. The values are expressed in ml of oxygen transferred per minute (ml/min).

$$VO_2 = (CaO_2 - CvO_2)(Q_b)(10)$$

Shunt Fraction

Shunt Fraction is the portion of the total venous blood flow that passes through the hollow fiber bundle but does not become involved in gas exchange (Q_s). It is expressed as a percentage of the total blood flow (Q_t) (6,8). Shunting occurs in areas between fibers and around non ventilated hollow fibers. Compliance in the membrane, improper hollow fiber configuration at production, and hollow fiber shifting can lead to increased shunting. At a given FiO_2 shunt fraction is the oxygen content that was not transferred divided by the maximum available oxygen content.

$$\frac{Q_s}{Q_t} = \frac{CgO_2 - CaO_2}{CgO_2 - CvO_2}$$

Oxygen Diffusion Capacity

The membrane oxygen diffusion capacity evaluates the ability of the membrane oxygenator to conduct oxygen to the blood through the hollow fibers and, therefore, evaluates the efficiency of the hollow fiber configuration (9). By definition, it is the volume of oxygen that diffuses across a membrane per minute for a gas pressure gradient of 1 mmHg (6,10). Factors that affect the rate of oxygen diffusion across a membrane are its thickness, surface area, gas pressure gradient, and diffusion coefficient of oxygen in the membrane material (10). The value is expressed in ml/min/mmHg.

$$DmO_2 = \frac{VO_2}{PgO_2 - PvO_2}$$

RESULTS

The patient and operative data are shown in Table 1. The observed and assayed data are shown in Table 2. The oxygen transfer data from the patient population was graphed against

Table 1: Patient Population Data

N=25	CABG	AVR	AVR/CABG
	22	2	1
	Mean	SD	Range
Weight (kg)	72.6	13.3	48.0-99.0
Height (cm)	166.9	9.7	146.0-185.0
BSA (m2)	1.8	0.2	1.4-2.2
Age (yrs)	64.6	11.6	38.0-84.0
Bypass Time (min)	107.2	39.4	61.0-218.0
Hospital Stay (days)	12.0	5.3	6.0-25.0

Table 2: Average laboratory values

N = 114	Mean	sd	Range
Art. Temp. (°C)	32.67	4.70	21.0-39.1
Q _b (L/min)	4.28	0.63	3.00-6.00
Cl (L/min/m ²)	2.40	0.24	1.81-3.12
Q _g (L/min)	3.20	1.11	1.50-7.00
Q _g (L/min) : Q _b (L/min)	0.74 : 1	0.22 : 1	0.43:1-1.52:1
FiO ₂ (%)	61.0	12.0	35.0-90.0
Hct (%)	21.09	2.87	13.00-28.60
Hgb (mg/dl)	7.24	1.18	4.10-10.80
pH	7.40	0.05	7.28-7.52
PaCO ₂ (mmHg)	36.56	3.14	28.00-46.00
PaO ₂ (mmHg)	233.22	37.51	154.00-406.00
PaO ₂ corr(mmHg)	215.07	35.93	138.00-313.98
BE (mmol/l)	-1.05	2.50	-6.60-5.70
vPH	7.37	0.04	7.24-7.48
PvCO ₂ (mmHg)	41.57	3.78	33.00-52.00
PvO ₂ (mmHg)	43.61	8.14	31.00-74.00
PvO ₂ corr(mmHg)	30.42	5.30	13.06-42.23
SvO ₂ (%)	77.0	9.0	50.0-94.0
VO ₂ (ml/min)	118.59	46.04	40.3-223.41
Q _g /Q _t (%)	21.75	4.47	12.26-38.95
DmO ₂ (ml/min/m2)	0.28	0.07	0.12-0.47

various oxygen fractions and a regression line was calculated (Figure 1). The maximum oxygen transfer that the population demanded was measured at a FiO_2 of 0.80. The regression line was extrapolated to a FiO_2 of 1.00 to determine a predicted maximum oxygen transfer using the following formula:

Figure 1: Oxygen transfer slope. Extrapolated maximum oxygen transfer was 295.45 ml/min ($m=0.0022$, $intercept=0.35$, $r^2=0.67$, $n=114$).

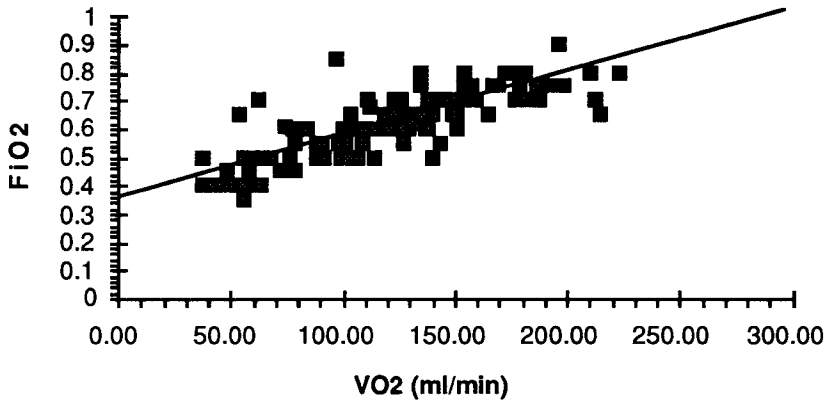
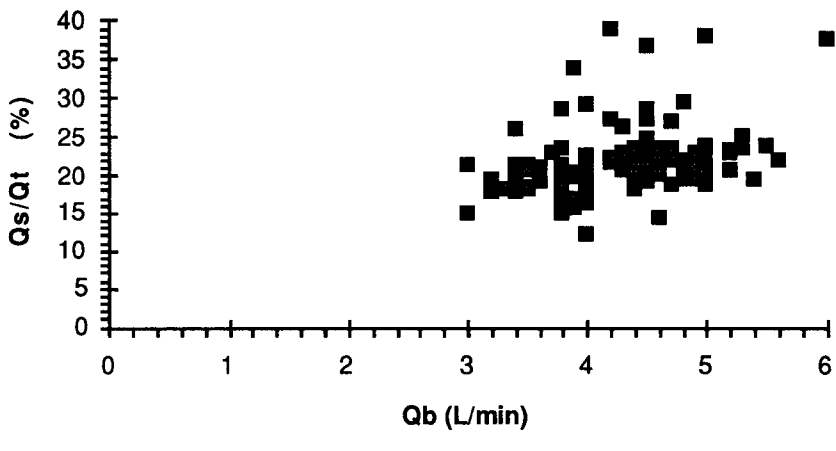


Figure 2: Shunt fractions (n=114).



$$\text{Maximum oxygen transfer} = \frac{(1.0 - \text{Intercept})}{\text{Slope}}$$

The slope (m) was 0.0022 with an intercept of 0.35. The strength of a linear relationship for the regression line, r^2 , was 0.67. The maximum measured oxygen transfer was 223 ml/min at a FiO_2 of 0.80. The predicted maximum oxygen transfer at a FiO_2 of 1.0 was 295.45 ml/min or 164.14 ml/min/m² when indexed to membrane surface area.

All shunt fractions at various blood flow rates are shown in Figure 2. The average shunt fraction for all 114 data points was 21.75% or 12.08% per m² when indexed to membrane surface area. The minimal shunt was 13% corresponding with a PaO_2 of 244 mmHg (Q_b of 4.0 L/min, FiO_2 of 0.65, and SvO_2 51%). The maximum shunt was 39% corresponding with a PaO_2 of 221 mmHg (Q_b of 4.2 L/min, FiO_2 of 0.65, and SvO_2 88%). Five shunt fractions greater than 35% occurred between 4 and 6 L/min.

Individual regression line analysis shows the relationships between shunt fractions and Q_b for each oxygenator in Figure 3.

Graphing average blood flow rates and average shunt fraction at their respective FiO_2 in Figure 4 shows the FiO_2 requirements for increasing blood flow rates.

The oxygen diffusion capacity was graphed against FiO_2 in Figure 5. The same procedure used to determine the maximum predicted oxygen transfer was used to determine the maximum predicted DmO_2 . A regression line for DmO_2 was calculated and extrapolated to a FiO_2 of 1.00. The slope and intercept were 0.928 and 0.36, respectively. The strength of linear relationship, r^2 , was 0.27. The maximum extrapolated oxygen diffusing capacity for all 114 data points was calculated to be 0.69 ml/min/mmHg or 0.38 ml/min/mmHg/m² when indexed to the membrane surface area.

The carbon dioxide tension levels were maintained at normal levels with gas to blood flow rate ratios as low as 0.43:1.0 increasing to a maximum ratio of 1.52:1.0.

DISCUSSION

This evaluation concentrates on the clinical oxygenating performance and carbon dioxide removal of the Terumo Capiox SX18R. Other aspects of overall oxygenator performance and design need to be addressed and studied (5, 11-14). However, adequate oxygen transfer and carbon dioxide clearance are the primary indicators for safe clinical oxygenator performance.

The oxygen transfer for the Terumo Capiox SX18R was sufficient to meet the maximum oxygen demands of the tested population and had further reserve to increase oxygen transfer. The maximum oxygen transfer was 223 ml/min at a FiO_2 of 0.80 and a Q_b of 5.0 L/min. By increasing FiO_2 and Q_b , oxygen transfer can be further increased. Therefore, oxygen transfer was adequate and in excess for the tested population. A larger sized patient population could be challenged.

In comparison, average shunt fractions of 21.75% for the Terumo Capiox SX18R remained unchanged to past generation oxygenators. Last generation oxygenators had shunt fractions of 27.0-15.6% (11, 15). Reviewing the combined shunt fractions, most shunt fractions were near the average and did not vary with blood flow rates as past designs in oxygenators have revealed (Figure 2) (11). When reviewing each oxygenator individually many shunt fractions were inconsistent in relation to Q_b (Figure 3). Several oxygenators had shunt fractions that either increased, decreased, or remained unchanged with increased Q_b while other oxygenators had changes in shunt fractions when Q_b was con-

stant. Through regression analysis, no significant increasing relationship between shunt fraction and Q_b was seen for 24 oxygenators. One of the 25 oxygenators had significant increasing shunt fractions with increasing Q_b ($p < 0.05$). However, there was insufficient data from each oxygenator to make the assertion that any relationship exists. In summary, shunt fraction was unpredictable. The suspected reason for the variabilities in shunt fractions is an intermittent shifting of hollow fibers due to the external shell design.

Factors that affect DmO_2 for each oxygenator either vary or remain constant during the clinical use of each oxygenator. The thickness of the membrane and the diffusion coefficient of oxygen are constant variables. The membrane surface area participating in gas exchange and the gas pressure gradient across the membrane are non constant variables. The changes in surface area are reflected in shunt fraction measurements. Therefore, increasing shunt fractions are associated with decreasing surface areas for oxygen to be transferred resulting in a decrease in DmO_2 . The opposite is true with decreasing shunts. Increasing FiO_2 creates a larger gas pressure gradient across the membrane. The result is an increase in DmO_2 . With higher oxygen concentrations, there is a greater number of oxygen particles striking the membrane surface and thus having a greater likelihood of diffusion across the membrane. The difference between the venous and membrane gas partial pressure of oxygen is the *net tendency* for oxygen to diffuse across the membrane (10). Increasing DmO_2 can be falsely associated with increasing Q_b and/or temperatures because they are associated with increasing FiO_2 . The DmO_2 for the Terumo Capiiox SX18R is improved from the past generation oxygenators (15, 16). Past DmO_2 were less than 1.5 ml/min/kPa/m² and the Terumo Capiiox SX18R had a maximum predicted DmO_2 of 0.38 ml/min/mmHg/m² or 2.85 ml/min/kPa/m² (16). Therefore, the hollow fiber configuration transferred oxygen more efficiently and was responsible for the successful reduction in the surface area.

Carbon dioxide clearance for the Terumo Capiiox SX18R was satisfactory. Normal carbon dioxide partial pressures were maintained with membrane gas flow rates that never exceeded 1.52 times Q_b .

Figure 3: Individual regression lines for each oxygenator analyzing shunt fractions at increasing blood flows (n=114).

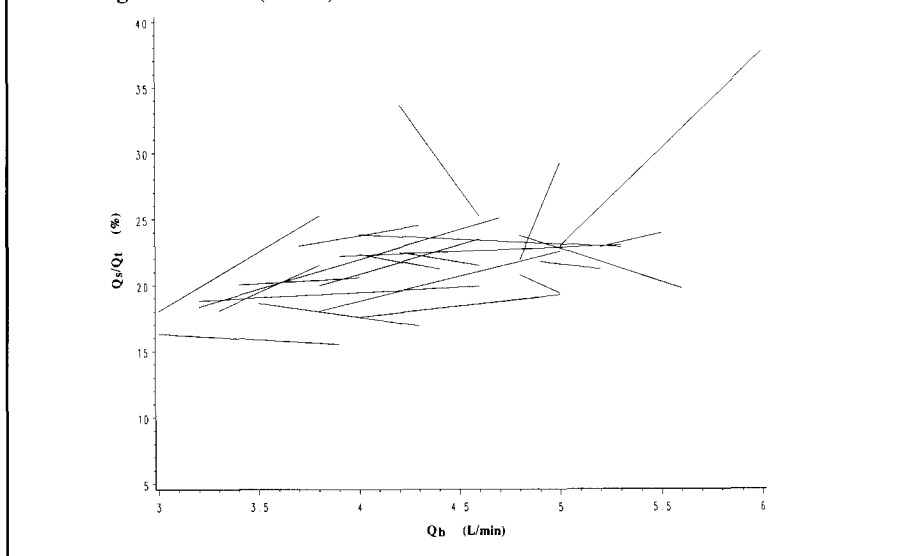


Figure 4: Average blood flow rates (bars) and average shunt fractions (dot line) at respective oxygen fractions.

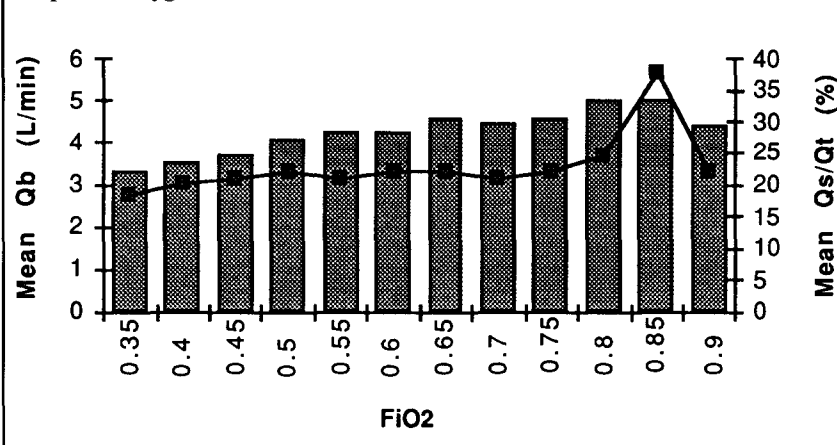
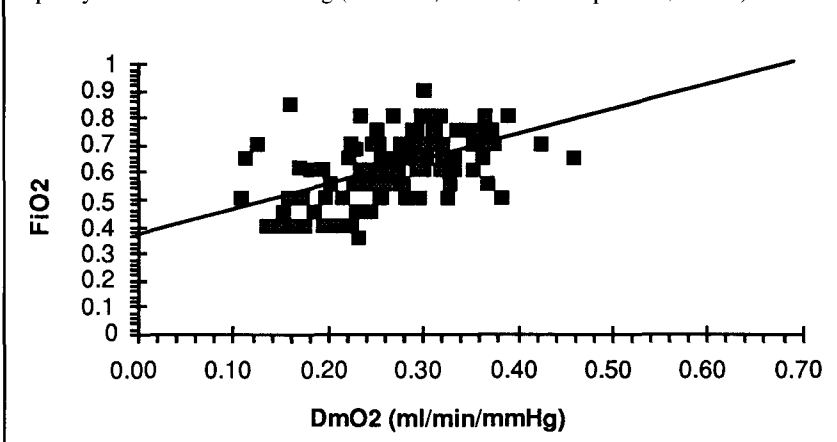


Figure 5: Oxygen Diffusion Capacity slope. Extrapolated maximum oxygen diffusion capacity was 0.69 ml/min/mmHg ($m=0.928$, $r^2=0.27$, intercept=0.36, $n=114$).



The new hollow fiber oxygenators have a smaller surface area when compared to past designs. Any change from the designed blood flow pathways through the hollow fiber bundle could result in a large decrease in oxygenating performance. Therefore, oxygen transfer reserve is crucial in an oxygenator's performance and accomplished by maximizing oxygen transfer, lowering shunt fractions, and designing efficient hollow fiber configurations. The Terumo Capiox SX18R met the physiological demands of the patient population. When comparing the oxygenator to the past generation of oxygenators, there are marked improvements. Yet, there were inconsistent shunt fractions which affect VO_2 and DmO_2 performance. Further comparisons to updated studies of the present generation oxygenators can provide further insights into the performance factors of the Terumo Capiox SX18R.

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