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Lean Flow: Optimizing Cardiopulmonary Bypass Equipment and Flow for Obese Patients—A Technique Article

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Abstract: The goal of this chart review was to investigate the use of down-sized cardiopulmonary bypass (CPB) circuits for obese patients. The effects of transitioning from larger to smaller oxygenators, reservoirs, and arteriovenous tubing loops were evaluated through a retrospective review of 2,816 adult non-congenital procedure perfusion records. This technique report and case series is a continuation of our original prescriptive CPB circuit quality improvement project. An algorithm was derived to adjust body surface area (BSA) to lower body mass index (BMI) to provide down-sized extracorporeal circuit components capable of meeting the metabolic needs of the patient. As a result of using smaller circuits, decreased priming volumes led to significantly increased hemoglobin (HB) nadirs ($p < .05$) leading to significant decreases in homologous donor blood product exposures ($p < .05$). Patients with large BSAs were supported safely with smaller circuits by using lean body mass (LBM)–adjusted BSA and target blood flow algorithm. Based on this case series, large BMI patients may be safely supported with smaller circuits selected based on BSAs adjusted more toward LBM. Use of smaller circuits in high BMI patients led to higher HB nadirs and less donor blood components during the surgical procedure. Renal function and hospital stay were not affected by this approach. *J Extra Corpor Technol. 2017;49:30–5*

The minimization of cardiopulmonary bypass (CPB) circuit size to reduce prime volume and hemodilution is a national care guideline (1). In our original quality improvement project, we used smaller CPB circuits for patients based on their native body surface area (BSA) and a cardiac index (CI) of 2.4 (2). Based on analysis of the data from the previous study, however, it was believed that lean body mass (LBM) could be used to better predict blood flow (BF) requirements for obese patients, allowing for the use of smaller circuits on larger BSA patients.

The National Institutes of Health estimate greater than one-third of the U.S. population to be obese, whereas just over 6% is considered extremely obese. Body mass index (BMI) is often used as an indicator of obesity (BMI >30 kg/m^2) and morbid obesity (BMI >40) in patients, indicating a high fat to LBM ratio. Increases in BMI are strongly associated with cardiovascular disease, hypertension, hyperlipidemia, type II diabetes, dysmetabolic syndrome, and decreases in maximum oxygen consumption (VO_2) (3). Adjusting body weight for high BMI can provide a more accurate estimate of a patient's LBM, creating a better representation of the patient's metabolic need, and thus BF requirements (4). Ideal weight has been used successfully to adjust BF needs for patients, without compromising safety (4,5).

We propose creating new (lean) target flow limits based on LBM, derived from adjusted BMIs. In an equation proposed by Cunningham et al., fat-free mass (FFM) is approximated as the LBM at a BMI of 25 plus 1/4 the excess weight (FFM = LBM at [BMI = 25] + 1/4 excess weight) (6). In this technique, morbidly obese patients will be readjusted to a BMI of 28, as this can be an effective estimation of Cunningham's equation, whereas obese patients will be adjusted to a BMI of 25. The patient's BSA is then recalculated using the adjusted weight, as height remains unchanged. Target CPB BFs can be calculated by multiplying the new BSA by a CI of 2.4 $L/min/m^2$. Cooling can be used to further reduce metabolic needs, and the oxygen delivery (DO_2) index (mL $O_2/min/m^2$),

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based on the patient's native BSA, will help guide additional BF needs (7).

The use of smaller circuits on obese patients has been demonstrated to reduce red blood cell (RBC) transfusions, while providing optimal flow to support these patients (5).

METHODS

Perfusion Circuit

Livanova S5® heart-lung machines (HLM) were used in all bypass procedures with an arterial 1/2-inch ID tubing roller pump (Livanova, London, UK). The Connect Data Management System® (Connect, Livanova) was connected to the S5 HLM to collect pertinent data. Terumo Capiox® FX oxygenators with integrated arterial filters (Terumo Cardiovascular Systems, Ann Arbor, MI), were used with W30 (3 L) and W40 (4 L) reservoirs and X-Coating® (Terumo, Ann Arbor, MI) with either 3/8″ × 1/2″ or 3/8″ × 3/8″ arterial-venous (AV) loops. Cardiotomy suction was returned to the oxygenator venous reservoir.

Procedure Guideline

Patient cooling ranged from 28°C to normothermic, depending on the procedure. Alpha-stat management was used when patient temperature was above 32°C and during rewarming, whereas pH-stat was used during the cooling phase below 32°C. Heparin loading doses of 350–450 U/kg were used to achieve an activated clotting time >480 seconds, as measured by iSTAT® Celite® Activated Clotting Time test (Abbott Point of Care, Princeton, NJ). A one-to-one reversal dose of protamine to heparin was used for reversal of anticoagulation. Retrograde and antegrade autologous priming were frequently used to reduce crystalloid load with hemodilution.

Estimating Lean Flow

An algorithm (Figure 1) was created to expand on the original "right-sizing" flowchart (Figure 2) to allow for further downsizing and circuit miniaturization for patients. This algorithm was based on data from the previous "right-sizing" quality improvement project, and was placed in the perfusion work area for daily use. There are three major points at which the diagram branches. First, the use of circulatory arrest would automatically default to the use of the FX25 oxygenator because of its increased surface area, allowing for more efficient warming of the patient. This was agreed upon by our team before implementation. Second, gender is considered as women tend to have a higher percentage of body fat than do men, causing a lower absolute resting metabolic rate (8). Finally, men over the age of 60 can be safely downsized based on decreasing metabolism due to decreases in FFM with age (9).

If the patient is determined by the algorithm to be downsized based on LBM, the perfusionist can estimate a new BSA based on a weight equivalent to a BMI of 25 for obese patients, and 28 for morbidly obese patients.

Table 1 outlines the steps to determine the lean BSA for high BMI patients, allowing for an approximation of their "lean flow," or CPB target BF based on LBM.

The parameters of the algorithm were translated into a modifiable Microsoft Excel® (Microsoft Corporation, Redmond, WA) spreadsheet allowing for immediate adjustment of BSA based on BMI recalculation, BF recommendations, and appropriate circuit component selection.

Group Analysis

Lean flow requirements were based on patient lean BSA and a target CI of 2.4 L/min/m^2. Minimum BF was set at the patient's native BSA at a CI of 1.8 L/min/m^2, as agreed upon by the team. Patients were divided into two groups: BMI-adjusted BSA (n = 224) and native-BMI BSA not adjusted (n = 963). For BMI-adjusted patients, the smaller FX15W30 oxygenator reservoir combination with a 3/8″ × 3/8″ AV loop was used; whereas

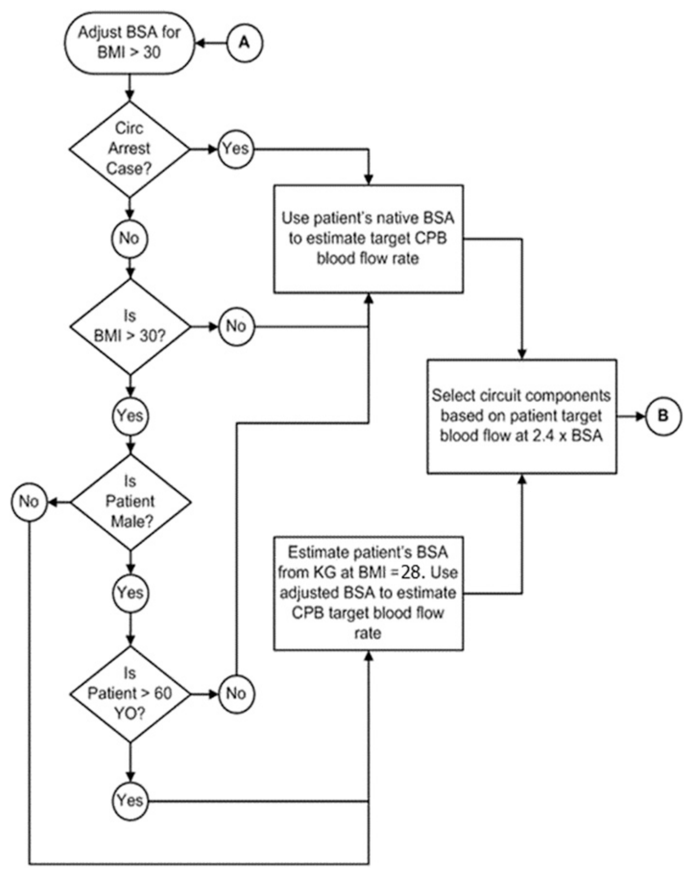

Figure 1. The decision algorithm used to adjust the high BMI patient's BSA toward LBM to estimate a new target BF rate. The adjusted BSA and target BF rate are used to select a right-sized circuit. "B" connects to the algorithm in Figure 1.

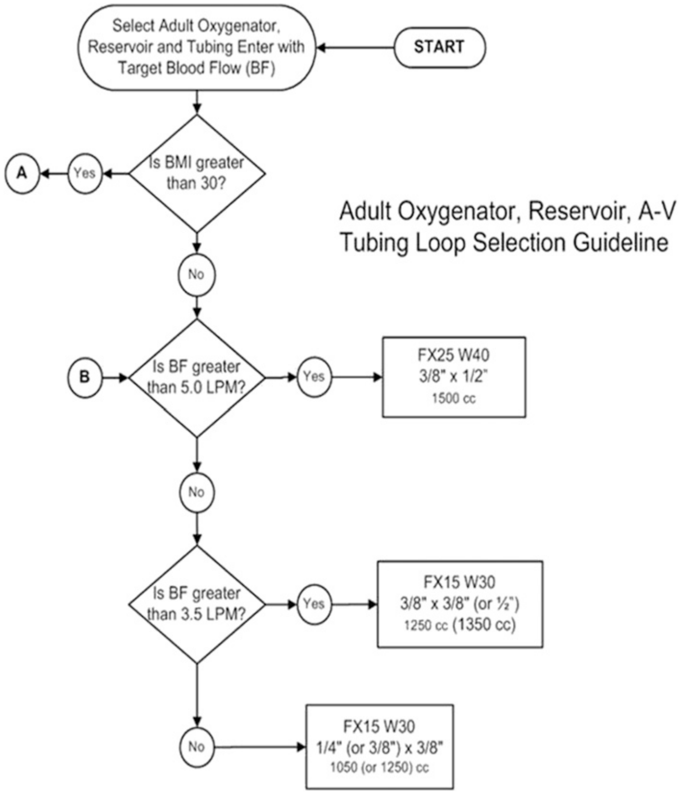

Figure 2. FX15, FX25, W40, and W30 are trademarks of Terumo Cardiovascular Systems Inc. The volumes are the crystalloid dynamic prime requirements for the perfusion circuits prior to autologous priming. Target BF is based on BSA and CI = 2.4 L/min/m^2 and may be adjusted for BMI or LBM. Values in parentheses are optional setups based on patient parameters. "A" connects to the algorithm in Figure 2.

native-BMI patients were placed on the FX25W40 oxygenator reservoir combination with a 3/8″ × 1/2″ AV loop. In addition, the effects of lean flow on women were explored, as gender differences make up a key division in the new algorithm. A comparison of BMI-adjusted and native-BMI BSA women was conducted.

This retrospective chart review project qualified for exemption as a quality improvement project by the Mayo Clinic Institutional Review Board. Patient records from the Connect Manager® electronic perfusion record (LivaNova) and the hospital blood management database were exported into a Structured Query Language (SQL) database on a secure server. The information from the SQL server was exported into Excel® for analysis.

Statistical Analysis

Statistical analysis was performed using JMP® 10.0.0 software (SAS Institute Inc., Cary, NC, www.jmp.com). Patients were divided into gender, target BF, BSA, BMI, and circuit component groups for compliance scoring, trending, and analysis. When data were missing, the patient record was not included in the analysis. Demographic and percent result contingency tables were created and analyzed using χ^2 comparison. Group means were compared with Tukey statistic to analyze HB nadir, blood product usage, hospital length of stay (LOS), and percent change in serum creatinine by patient groups. Statistical significance was set at $p < .05$.

RESULTS

All adult, non-congenital CPB patients over 18 years (n = 2,816) operated between March 2014 and January 2016 were included in the chart review. The distribution of patients by procedure and BMI (greater and less than 30 kg/m^2) is presented in Table 2. In Table 3, overall perfusionist compliance with the algorithms in Figures 1 and 2 is evaluated by the three major CPB circuit components; oxygenators, reservoirs, and AV tubing loops. In each component analysis, the hemoglobin (HB) nadir observed in the operating room is significantly higher in the on protocol, perfusionist compliant groups. Furthermore, compliance with the algorithm in the reservoir and oxygenator selection led to significant ($p < .05$) decreases in operating room (OR) donor exposures and percent of the patients who were transfused.

Analysis of lean flow patients, who were downsized from FX25 oxygenators with 3/8″ × 1/2″ AV loops to FX15 oxygenators with 3/8″ × 3/8″ loops, is shown in Table 4. "Aggressive sizing" is used to denote the use of a smaller CPB circuit than the native-BSA would call for. An increase in nadir HB and decrease in the number of RBCs transfused and donor exposures in the OR was shown to be significant ($p < .05$).

Table 1. Steps to estimate lean BF.

Action	Comment
1. Calculate BSA, BMI, and LBM	1. Use body weight and height
2. If BMI >30 calculate body weight at BMI = 25	2. Use algorithm in Figure 1
3. Use BMI = 25 body weight to calculate lean BSA	3. Use lean body weight
4. Use lean BSA to estimate lean flow	4. Calculate lean flow at CI = 2.4
5. Select right-sized ECC for lean flow	5. Use algorithm in Figure 2

BSA (m^2), BMI (kg/m^2), LBM (kg), CI (L/min/m^2). Lean BF is the target BF (L/min) based on the BSA at LBM.

Table 2. Distribution of high and low BMI by procedure category.

Procedure	BMI <30 kg/m^2 (%)	BMI >30 kg/m^2 (%)	Total
Valve	672 (65)	365 (35)	1,037
CABG	310 (49)	323 (51)	633
Aorta	210 (62)	129 (38)	339
Valve CABG	163 (56)	126 (44)	289
Myectomy	117 (43)	152 (57)	265
Other	68 (64)	39 (36)	107
LVAD	62 (60)	41 (40)	103
Transplant	27 (69)	12 (31)	39

CABG, coronary artery bypass grafting; LVAD, left ventricular assist device. The frequency distribution of high and low BMI patients by procedure categories for 2,861 adult, non-congenital procedures between April 2014 and January 2016. The distribution of high and low BMI is significantly different between procedure categories ($p < .001$), the CABG and myectomy groups having the higher percentage high BMI patients.

Table 5 shows acute kidney injury (AKI) Akin stage scores post-operatively by right-sizing group; there is no significant difference between groups. Positive trends can be seen in Table 6 where a comparison of adjusted and native BSA females is shown. HB nadir was significantly ($p < .05$) higher in this group; however, no other statistical significance could be found due to the low power of the comparison.

DISCUSSION

National care guidelines indicate that perfusionists make efforts to minimize hemodilution to avoid unnecessary blood transfusions. We have shown in this study that one modality for accomplishing this is the use of smaller CPB circuits on both small, lean patients as well as short obese patients. In using this new technique, it is imperative that the safety and adequacy of perfusion for the patient are not compromised.

DO_2, mixed venous percent saturation of HB with oxygen (SvO_2), VO_2, and carbon dioxide production should be monitored throughout the bypass period to insure adequate perfusion of the patient. The use of electronic CPB monitoring and data collection can further aid the perfusionist in meeting the patient's perfusion requirements (Goal-Directed Perfusion [GDP™]) (8–10). The DO_2 at the lower BSA CI BF rate and post-dilutional HB must be adequate to preserve cerebral and renal function, and can be ameliorated with attention to S_VO_2 and maintaining arterial blood pressure (11–15).

Smaller CPB circuits can reduce prime volume and hemodilution of patients; in addition, the low-prime circuits allow for a greater percentage of prime to be displaced with the same amount of blood during the traditional retrograde autologous prime (RAP). To achieve a higher post-dilution HB, we displace the extracorporeal circuit (ECC) crystalloid prime with the patient's own blood through both traditional RAP and rapid autologous prime displacement (16–23). Lower static volumes in these circuits, paired with lower minimum operating levels also allow for hemoconcentration during the bypass period. Post-operatively, the decrease in static volume can make reinfusion of circuit blood less obtrusive and can reduce the amount of blood sent for cell salvage from the CPB circuit. In addition, patients supported by lean flow can also be sustained on smaller cannulas, which in turn can reduce gaseous micro-embolic activity and load (16,24,25).

Women have long been treated identically to men, despite differing physiological needs. In the wake of our initial right-sizing project, we proposed that the use of smaller CPB circuits on female patients could further improve outcomes while meeting their perfusion needs (26). In a recent publication, women with high BMIs were at higher, statistically significant, risk of RBC transfusion than

Table 3. Perfusionist compliance to right-sizing algorithms.

Dimension	Parameter	On Protocol	Off Protocol	p Value
Right oxygenator	HB nadir OR	9.3	8.5	<.0001
92% compliant	No. of OR donor exposures	2.8	4.6	<.0001
2,593/2,816	% transfuse in OR	47	59	.0007
	% transfuse in ICU	28	29	.6590
Right reservoir	HB nadir OR	9.4	8.7	<.0001
87% compliant	No. of OR donor exposures	2.8	3.7	.0107
2,440/2,816	% transfuse in OR	47	58	.0040
	% transfuse in ICU	27	32	.0013
Right tubing loop	HB Nadir OR	9.4	9.0	<.0001
64% compliant	No. of OR donor exposures	2.8	3.2	.0529
1,800/2,816	% transfuse in OR	47	49	.5136
	% transfuse in ICU	27	30	.1004

ICU, intensive care unit.
On protocol is perfusionist compliance with right-sizing algorithm, off protocol is not complying. HB nadir is lowest recorded HB concentration (g/dL) in the OR. Compliance to right size the oxygenator and the reservoir appears to have more affect than right sizing the tubing for these non-congenital adult patients.

Table 4. Aggressive oxygenator right sizing for patients with BMI >30 kg/m^2.

Dimension	Parameter	Adjusted for high BMI (*n* = 224)	Native BMI (*n* = 964)	*p* Value
Aggressive	HB nadir in OR	9.7	9.4	.0415
Oxygenator	No. of RBCU in OR	.6	1.1	.0334
Right sizing	No. of RBCU in ICU	.8	.9	.7674
	% transfuse in OR	46	54	.2198
	% transfuse in ICU	25	24	.8077
	No. of OR donor exposures	1.9	2.9	.0229
	No. of ICU donor exposures	1.1	1.3	.5794
	Hospital LOS (days)	10.2	11.1	.4478
	% change in sCr	35	30	.4589

RBCU, red blood cell units.
The HB nadir, number of units of RBCs, and number of total donor exposures administered in the operating room were significantly lower for the high BMI group with circuit size and target BF adjusted down to a more normal BMI BSA. There was a tendency toward a lower percent transfusion rate in the OR for the BSA-adjusted group. There were no significant differences in LOS, percent change in pre- and post-serum creatinine levels (sCr), and in ICU homologous blood usage measures.

Table 5. Distribution of Akin AKI scores by right-sizing groups.

		Akin AKI Stage (%)				
Adjusted BSA	High BMI	0	1	2	3	Patients
No	No	1,457 (96.8)	21 (1.4)	18 (1.2)	9 (.6)	1,505
	Yes	929 (96.5)	14 (1.5)	9 (.9)	11 (1.1)	963
Yes	No	119 (96.8)	2 1.6)	1 (.8)	1 (.8)	123
	Yes	215 (96.0)	3 (1.3)	0 (.0)	6 (2.7)	224

Non-congenital adult patients distribution of AKI stages experienced after CPB when BSA is adjusted high BMI to down-size circuits; Akin AKI stage 0 is <150% increase in sCr, 1 = 150–200% increase, 2 = 200–300% increase, 3 = more than 300% increase.

Table 6. Two hundred and seventy-eight females with BMI = 32 kg/m^2: 44 treated with adjusted BSA and down-sized circuit.

Dimension	BMI >32	Parameter	BSA Adjusted (*n* = 44)	Native BSA (*n* = 234)	*p* Value
Female	Yes	HB nadir in OR	9.2	8.6	.0341
		% transfusion in OR	48	52	.5914
		RBC units in OR	.8	1.4	.2227
		No. of donor exposures in OR	2.1	3.4	.2615
		% transfusion in ICU	30	34	.5453
		No. of RBC units in ICU	.6	1.7	.3223
		No. of donor exposures in ICU	.5	1.2	.3239
		% change in sCr	10	23	.1068
		% akin stage AKI = 0	98	97	.5939
		Total LOS (days)	9.1	12.1	.2035

Females with BMI >32 kg/m^2 with down-sized circuits were compared to non-adjusted patients. There were tendencies to fewer donor exposures in the OR and ICU, and significantly higher HB nadirs in the OR.

their male counterparts, creating a paradox in the use of BSA as a guide for flow requirements (24). We believe women are getting more transfusions than men, because we are using the wrong size circuits. The use of lean flow for females can allow smaller circuits to be used for CPB, further meeting the individualized needs of this unique patient population.

This study is not without limitations; the use of cardiotomy suction, our current one-to-one protamine dosage, and patient cooling could all contribute to the need for additional blood products. Surgeon preferences and perfusionist autonomy have kept us from achieving full compliance with the circuit selection algorithms.

With this retrospective study, we have provided data to support the efficacy of using lean flow to meet patient perfusion needs, while pairing the lean flow with the use of smaller CPB circuits to meet patient metabolic needs. The BMI-adjusted algorithm, in conjunction with the Excel® spreadsheet, can aid in identifying minimum safe BF requirements for obese patients to allow for the use of smaller CPB circuits. As we continue the use of this practice, we hope to improve the compliance within our group through the use of statistical analysis and feedback, in turn increasing the percent use of smaller circuits within our patient population to reduce exposure to homologous blood products.

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