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Clinical assessment of cannula performance during adult minimally invasive valve surgery using predictive mathematical models

Korneel Vandewiele [a,*], Filip De Somer [a], Michael Vandenheuvel [b], Pascal Verdonck [c] and Thierry Bové [d]

[a]Department of Perfusion, Ghent University Hospital, Ghent, Belgium
[b]Department of Cardiac Anaesthesia, Ghent University Hospital, Ghent, Belgium
[c]Department of Biomedical Engineering, Ghent University, Ghent, Belgium
[d]Department of Cardiac Surgery, Ghent University Hospital, Ghent, Belgium

*Corresponding author. Tel: +329 3320877; fax: +3 9 332 4999; e-mail: korneel.vandewiele@ugent.be (K. Vandewiele).

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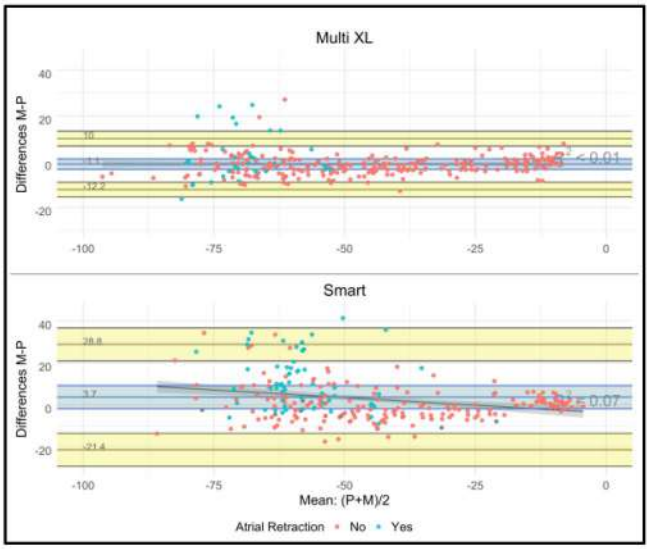
Clinical Evaluation of Peripheral Venous Cannula Performance in Adult Minimally Invasive Valve Surgery Using Predictive Models

Summary

This observational study assessed the efficiency of 3 venous cannulas in 75 adults undergoing MICS using DS predictions. In 856 measurements, Lin's concordance was >0.95 for MultiXL and Nextgen but only 0.80 for Smart cannulas, confirmed by Bland-Altman analyses. In-vivo performance evaluation might improve venous cannula choice and venous drainage management during MICS.



Legend: MICS: Minimally Invasive Cardiac Surgery; DS: Dynamic Similarity.

Abstract

OBJECTIVES: Peripheral cannula selection in minimally invasive cardiac surgery (MICS) is crucial, as venous drainage limitations during cardiopulmonary bypass (CPB) can impair end-organ perfusion and overall outcomes. This study evaluates the *in vivo* venous drainage efficiency of different peripheral venous cannulas for adult MICS by applying dynamic similarity (DS) prediction formulas.

METHODS: This observational study included 75 adult MICS patients with use of single peripheral venous cannulation from January 2017 to June 2023. The analysis included cannulas Bio-Medicus Multi XL Life Support, Nextgen Bicaval and Smart cannulas. Cannula performance was assessed by comparing predicted pressures with *in vivo* measurements.

RESULTS: A total of 278, 314 and 264 measurements were recorded for the Multi, Next and Smart cannulas, respectively. No significant demographic differences were found between groups. Lin's concordance correlation coefficients for agreement between predicted and

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measured pressures were >0.95 for the Multi and Next cannulas but substantially lower for the Smart cannula (0.80). Bland-Altman analysis showed a mean bias of −1.09 mmHg for the Multi, −0.15 mmHg for the Next and 3.68 mmHg for the Smart cannula, with the latter exceeding the ±12.5 mmHg limits of agreement.

CONCLUSIONS: DS-based predictions revealed significant performance variability among peripheral venous cannula types. The *in vivo* performance was adequately predicted for the Multi and Next cannulas but not for the Smart cannula, underscoring the need for real-life evaluations and performance monitoring during CPB. Incorporating dynamic performance assessments into clinical decision-making might optimize venous drainage and patient outcomes.

Keywords: cardiopulmonary bypass • minimally invasive cardiac surgery • venous drainage • cannula performance • dynamic similarity • ECMO

ABBREVIATIONS

AV	Aortic valve
BA	Bland-Altman
BSA	Body surface area
CCC	Concordance correlation coefficient
CP	Centrifugal pump
CPB	Cardiopulmonary bypass
CVP	Central venous pressure
DO_2	Oxygen delivery
DS	Dynamic similarity
ECMO	Extracorporeal membrane oxygenation
MICS	Minimally invasive cardiac surgery
MV	Mitral valve
PFI	Pump flow index
R	Resistance
TEE	Transesophageal echocardiography

INTRODUCTION

Peripheral vessel cannulation for cardiopulmonary bypass (CPB) during minimally invasive cardiac surgery (MICS) has generated significant interest in recent decades. However, debate persists over the most appropriate cannula type and size considering vessel and patient size, predicted blood flow and surgical type. Nevertheless, maintaining optimal blood flow during CPB in MICS poses substantial challenges [1]. Particularly, limitations of venous drainage leading to inadequate cardiac emptying complicate the surgical procedure, resulting in venous congestion, impairment of end-organ perfusion and overall outcome despite the use of enhanced venous drainage techniques.

The lack of clinically relevant performance data on most cannulas, typically tested with water at 20°C, creates uncertainty in selecting the safest and most effective option. Smaller cannulas increase circuit pressure drop and shear stress, while larger ones risk vessel damage and obstruct venous return from the distal limb. Moreover, all cannula types have a unique design, varying in length, diameter and number and position of side holes. To adjust water-based performance data for blood viscosity and density, several mathematical methods have been validated [2, 3]. An *in vitro* study comparing three methods—M-number, parabolic equation and dynamic similarity (DS)—found that M-number and DS significantly outperformed the parabolic equation. Therefore, these methods were recommended for optimizing cannula in CPB or extracorporeal membrane oxygenation (ECMO) [3].

However, the *in vitro* studies all fail to account for common conditions like hypovolaemia, turbulence and caval vein wall collapse during drainage. This collapse generates "suction events", which limits venous drainage during CPB and ECMO, causing excessive negative pressures in the extracorporeal system [4]. Given the prior *in vitro* validation of the DS prediction model, comparing real-time clinical *in vivo* data with this model could enhance the detection of inadequate cannula performance under dynamic conditions in MICS. This may urge clinicians to adjust venous drainage management or cannula positioning to optimize CPB blood flow and address hypovolaemia.

From this perspective, this study aims to evaluate the *in vivo* performance of different commercially available peripheral venous cannulas for adult MICS based on DS prediction formulas.

MATERIALS AND METHODS

Population sample

This single-centre study at Ghent University Hospital, Belgium, included adult patients undergoing minimally invasive mitral (MV) or aortic valve (AV) surgery with peripheral CPB using a single venous cannula between January 2017 and June 2023. The cannula type and size were selected in consultation between the surgeon and the perfusionist. The cannulas used in this analysis were the Bio-Medicus Multi XL Life Support cannula (23 to 29 Fr, tip length 55–61 cm), the Bio-Medicus Nextgen Femoral Bicaval venous cannula (23 to 27 Fr, tip length 60 cm; Medtronic) and the 24 Fr Smart Cannula (lengths 630, 680, and 730 mm; SmartCannula LLC). Ethical approval for the establishment and monitoring of the databases was obtained, and informed consent was waived because of the observational nature of routinely collected data (ONZ 2022–0159/dmponline.be—ID: 153061).

Surgical techniques

The MICS technique for mitral valve surgery has been previously described [1]. In MV surgery, femoral vessel access was obtained using the open surgical cut-down technique, while in AV surgery, the venous cannula was placed percutaneously. Via Seldinger technique, the venous cannula tip was positioned 2–3cm inside the superior vena cava, as confirmed by transoesophageal echocardiography (TEE). The MV was accessed through left atriotomy with a tissue retractor, while a J-sternotomy was preferred for AV surgery. Cold St Thomas cardioplegia was used in all cases.

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Anesthetic techniques

Standardized anaesthesia induction involved fentanyl (2–3 $\mu g \cdot kg^{-1}$), propofol (1–2 $mg \cdot kg^{-1}$), and rocuronium (1 $mg \cdot kg^{-1}$). Maintenance of anaesthesia included fentanyl boluses (up to a total dose of 10–15 $\mu g \cdot kg^{-1}$) and sevoflurane (minimum end-tidal concentration: 1%). For MV surgery, single-lung ventilation was achieved using a double-lumen endotracheal tube during right mini-thoracotomy until CPB initiation.

CPB equipment and techniques

Before cannulation, 300 $IU \cdot kg^{-1}$ (total body weight) of porcine heparin was administered. The CPB system included an arterial roller pump, a closed collapsible venous reservoir and a membrane oxygenator (Inspire 6F, LivaNova). A mixture of gelatin solution, mannitol and 2500 IU of heparin was used as priming solution. Moderate to tepid hypothermia was employed at the surgeon's discretion. CPB targeted a pump flow index (PFI) of 2.4 $l \cdot min^{-1} \cdot m^{-2}$, maintaining the indexed oxygen delivery (DO_{2i}) >270 $ml \cdot min^{-1} \cdot m^{-2}$, mixed venous saturation (SvO2) >70% and the CPB-haematocrit >22%. Adjustments included increasing CPB blood flow or administering packed red blood cells if targets were unmet. Kinetically augmented venous drainage (KAVD) with standard 3/8″ venous drainage kits was employed using a centrifugal pump (CP) with venous line pressure measured 10 cm before the CP inlet (Fig. 1). The venous line length was 1.5–1.7m. A mean negative pressure of −75 mmHg, with the transducer leveled to the midaxillary line, was the most negative pressure tolerated to achieve sufficient venous drainage. Mean arterial pressure during CPB was maintained above 50 mmHg.

Data collection

Patient demographics and CPB parameters were collected from the surgical and perfusion records. CPB was initiated using gravity drainage, followed by incrementally increasing the venous CP speed by incremental steps (0, 300, 600, 800, 900, 1000, 1100, 1200 revolutions per minute [RPM], or higher when deemed necessary) to reach the desired PFI (PFI; 2.4 $l \cdot min^{-1} \cdot m^{-2}$) and empty the heart. Venous CP speed, venous blood flow, CVP, haematocrit, venous line temperature and CP inlet pressure were recorded during each step, waiting 20 seconds between steps for parameter stabilization. Once a stable CPB was established, these parameters were collected at a 15-minute interval for the entire duration of CPB. During the weaning phase of CPB, data collection was repeated with decreasing pump speed according to the stepwise recordings during CPB initiation.

Prediction formulae

Based on these data, additional established calculations for whole blood viscosity and density, velocity, Reynolds numbers and friction, the expected pressure drop through the venous line for each data point was calculated [5]. Any height differences between the pressure transducer and the patient's midaxillary line (CPB transducer height−Patient's midaxillary line-height) were corrected for the corresponding hydrostatic pressure.

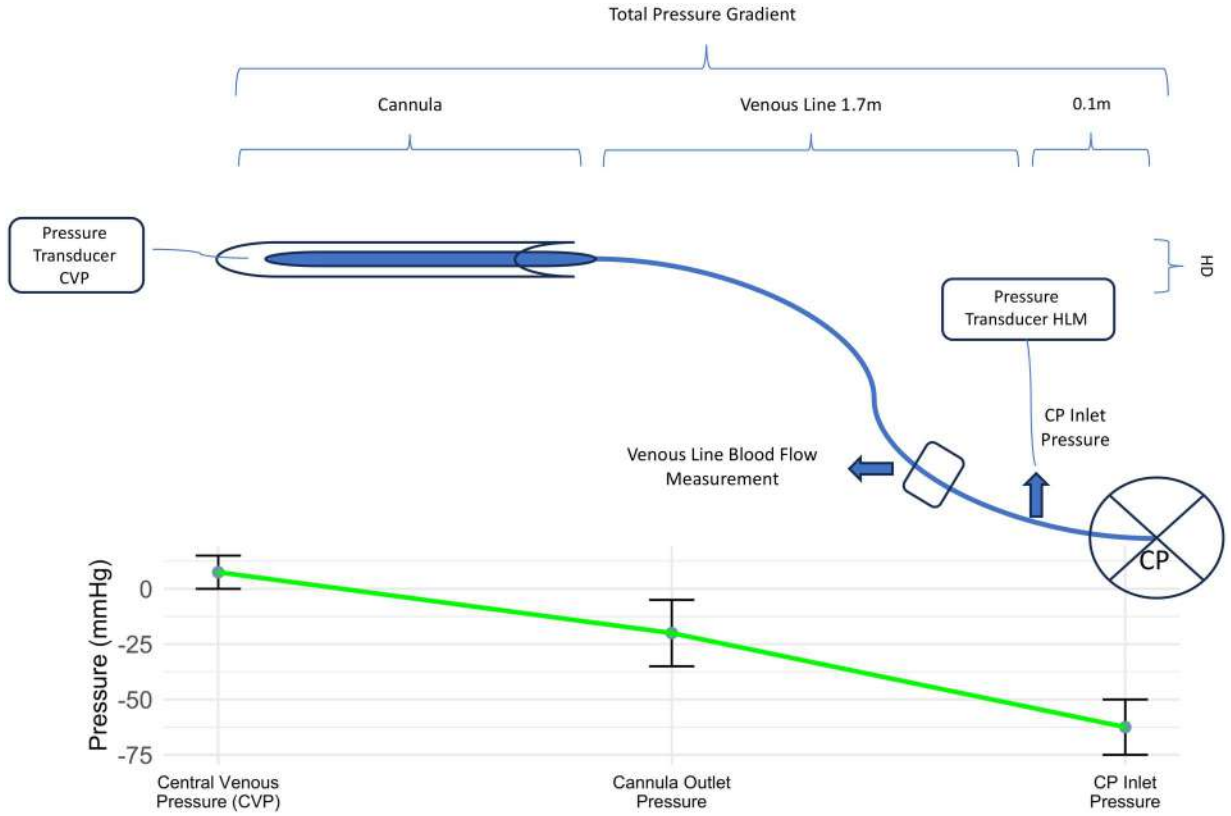

Figure 1: The venous drainage system with associated pressure levels. CP: centrifugal pump; HD: height difference between CPB pressure transducer and patient's mid-axillary line; HLM: heart lung machine; CVP: central venous pressure

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The regression coefficients of the pressure/flow curve for water at 20°C for each cannula were derived from the manufacturer's datasheets. For the Smart group, the factors of Broman *et al.* [6] were used and adjusted for viscosity and density. The venous cannula pressure predictions for each data point employed the DS technique, which states that flows become identical if the Reynolds numbers are equal in the bench test with water and the clinical situation with blood [3]. The regression coefficients of the manufacturer's water flow/pressure curve were then adjusted for blood in the specific conditions during CPB. Finally, the predicted pressure decline across the entire venous drainage system was calculated by adding up all separate calculated components that determine the CP inlet pressure (Equation 1):

$$\text{Predicted CP Inlet Pressure} = -\Delta P_{can} - \Delta P_{VenLine} - \Delta P_{HD} + CVP \quad (1)$$

with CP = centrifugal pump, ΔP = pressure drop (mmHg), can = cannula, VenLine = venous line, HD = correction for the height difference between CPB transducer and patient's mid-axillary line perpendicular to the floor (mmHg) and CVP = central venous pressure (mmHg).

Cannula performance was evaluated by calculating the measured and expected cannula resistances according to Equations 2 and 3:

$$\Delta P_{can} = \text{Measured CP Inlet Pressure} + \Delta P_{VenLine} + \Delta P_{HD} - CVP \quad (2,\ \text{rearranged from } 1)$$

$$R = \frac{\Delta P_{can}}{Q_{VenLine}} \quad (3)$$

with R = cannula resistance ($mmHg \cdot L^{-1} \cdot min^{-2}$), and $Q_{venline}$ = venous line bloodflow ($L \cdot min^{-1}$).

Statistics

Patients were grouped per cannula type. Continuous variables are presented as means ± standard deviations, and categorical variables are presented as numbers and percentages. Between-group comparisons were conducted using a one-way ANOVA if variances were equal (confirmed by Levene's test), or Welch's ANOVA if variances were unequal. When the (Welch's) ANOVA *P*-value was below 0.1, *post hoc* analyses were performed using the Games-Howell test. Categorical variables were compared using the Fisher's exact tests.

The agreement between the predicted and measured CP inlet pressure for each cannula type was assessed using Bland-Altman (BA) plots, adjusted for repeated measurements [7]. The 95% confidence interval around the mean difference was calculated, and a regression line of the differences was plotted to detect proportional differences. A maximum spread of ±12.5 mmHg was considered clinically acceptable, and the percentage of data points outside these limits was calculated. Lin's concordance correlation coefficients (CCC) were computed. Statistics were performed using RStudio version 2022.02.3.

RESULTS

Demographics

The study cohort included 79 patients: 24 underwent MICS for AV surgery and 55 for MV surgery. The Bio-Medicus Life Support Multi XL cannula was used in 25 patients (Multi-group), the Nextgen Bicaval cannula in 33 patients (Next-group) and the Smart cannula in 21 patients (Smart group). Due to invalid CVP measurements, four patients (1 in Multi, 3 in Next) were excluded from the analysis. Additionally, three datapoints in the Next-group and two in the Smart group were excluded due to missing variables, impeding calculations. This resulted in a sample size of 75 patients, yielding 278, 314 and 264 datapoints in the Multi, Next and Smart groups.

Table 1 shows demographic data. No significant differences were found in age, sex distribution, body surface area (BSA) or targeted PFI between groups. Procedural times were similar. The Smart group had fewer AV procedures ($P = 0.028$).

Concordance correlation coefficients

The CCCs for each group can be found in Supplementary Table S1. Lin's coefficient was very good (>0.95) for the Multi (0.967; 95% CI: 0.958 to 0.974) and the Next-group (0.973; 95% CI: 0.967 to 0.978) but substantially lower for the Smart group (good agreement: 0.803; 95% CI: 0.758 to 0.840). Closer analysis revealed a restriction in cannula flow dynamics, particularly during the atrial retraction period in MV surgery. Therefore, a secondary analysis, using the atrial retraction period as a dichotomous variable, was performed on the CCCs and BA plots.

The results of this secondary analysis are shown in Table 2; CCCs were lower during atrial retraction for all groups, with the largest difference observed in the Smart group (poor agreement: 0.085; 95% CI: −0.053 to 0.220). In the Multi-group, CCC indicated fair agreement (0.384; 95% CI: 0.078 to 0.624), while the Next-group showed a good agreement (0.637; 95% CI: 0.349 to 0.815).

BA plots

The results of the BA analysis are demonstrated in Fig. 2A–C and given in Table 3. The mean bias was −1.1 mmHg for the Multi-group, −0.1 mmHg for the Next-group and 3.7 mmHg for the Smart group. The limits of agreement (LOA) were within the predetermined ±12.5 mmHg range for all groups except for the Smart group (−21.4/28.8 mmHg). The percentage of data points outside the acceptable range of ±12.5 mmHg was 4.0%, 3.8% and 17.9% for the Multi, Next and Smart groups, respectively. As in the CCC analyses, BA statistics were repeated after excluding the atrial retraction data points. The mean bias showed no significant differences across groups (−1.5, −0.6 and 0.2 mmHg for Multi, Next and Smart). Although the LOAs improved for all groups during the non-retraction period, the LOAs for the Smart group were still higher than the predetermined ±12.5 mmHg threshold (lower LOA: −16.4/upper LOA: 16.8 mmHg). In addition, the percentage of data points outside the acceptable predetermined limits was >5% in the Smart group (Multi = 1.2%, Next = 2.8% and Smart = 9.2%).

Cannula resistance

Figure 3 presents the expected versus measured resistances (R) per cannula type and diameter. The *in vivo* measured R was the lowest in the 29F Multi, the 27F Next and all Smart cannulas (mean R: 4.3 ± 1.8 $mmHg \cdot L^{-1}$ for 29F MULTI, 5.5 ± 2.0 $mmHg \cdot L^{-1}$ for 27F Next and 5.5 ± 3.5 $mmHg \cdot L^{-1}$ for Smart). However,

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Table 1: Demographical and periprocedural data

Variable	Multi, $N = 24$	Next, $N = 30$	Smart, $N = 21$	P-value
Male sex	15 (63%)	22 (73%)	13 (62%)	0.67
Age (years)	64.5 ± 13.5	64.6 ± 12.6	64.5 ± 11.8	
Height (cm)	172.2 ± 9.4	171.7 ± 9.8	172.6 ± 6.2	0.96
Weight (kg)	81.6 ± 16.2	76.3 ± 15.0	78.6 ± 11.9	0.62
BSA (m^2)	2.0 ± 0.2	1.9 ± 0.2	1.9 ± 0.2	0.49
Target pump flow ($L \cdot min^{-1}$)	4.7 ± 0.5	4.6 ± 0.5	4.6 ± 0.4	0.49
ECC time (Min)	116.7 ± 38.3	130.0 ± 48.2	130.4 ± 53.6	0.51
Aortic crossclamp time (min)	71.0 ± 27.6	84.2 ± 34.4	80.3 ± 42.9	0.38
Mean temperature (°C)	34.8 ± 1.3	34.8 ± 0.8	34.7 ± 0.7	0.90
Procedure (N-patients)				0.03
Aortic valve	10 (42%)	12 (40%)	2 (10%)	
Mitral valve	14 (58%)	18 (60%)	19 (90%)	

n/N (%); mean ± SD; Fisher's exact test; one-way ANOVA.

Table 2: Concordance correlation statistics stratified by atrial retraction period

Cannula type	Atrial retraction	N datapoints	Pearson correlation	Bias correction factor	Lin's coefficient (estimate)	Lin's coefficient (lower CI)	Lin's coefficient (upper CI)
Multi	R	37	0.389	0.987	0.384	0.078	0.624
Multi	NR	240	0.978	0.998	0.976	0.969	0.981
Next	R	24	0.689	0.924	0.637	0.349	0.815
Next	NR	288	0.981	0.998	0.979	0.973	0.983
Smart	R	68	0.149	0.572	0.085	−0.053	0.220
Smart	NR	184	0.920	0.999	0.919	0.893	0.939

R: retraction; NR: no retraction.

corresponding to the BA analysis, the number of outliers was more prominent in the Smart group showing a higher incidence of unexpectedly high R.

CPB haemodynamics

Venous cannula performance changed significantly during the atrial retraction in MV surgery, prompting an analysis of the differential effects of cannula types on arterial PFI and CVP. Based on the apparent difference in the distribution of AV surgery (only two AV patients in the Smart group), in which no atrial retraction was used, only MV procedures were selected for this analysis. The average arterial PFI was $2.36 \pm 0.17\ l \cdot min^{-1} \cdot m^{-2}$ across all groups. *Post hoc* analysis revealed a significant difference in PFI between the MultiXL and the Smart versus the Next-group ($P < 0.001$ for both comparisons). Furthermore, the CVP was higher in the Smart group versus the MULTI and Next-groups ($P = 0.01$ and 0.13). A higher haemoglobin concentration in the Smart group resulted in a higher DO_{2i} than in Multi and Next-groups ($P < 0.001$ for both comparisons). There were no differences in intraoperative lactic acid concentration between groups. Detailed results are presented in Table 4.

DISCUSSION

This study reveals that Multi XL and Nextgen venous cannulas perform as predicted by DS during CPB, whereas the Smart cannula does not. Lin's coefficients and BA analyses indicated reduced but acceptable agreement for all cannulas during atrial retraction in MV surgery, except for the Smart cannula, where the limits of agreement exceeded the predetermined 12.5 mmHg threshold. Furthermore, even without atrial retraction, BA analysis revealed unpredictable performance in the Smart group, while other cannulas remained more consistent. These findings suggest that cannula performance varies under different conditions, with certain designs being more prone to underperformance in specific intraoperative scenarios. This highlights the value of *in vivo* performance evaluations for optimizing cannula selection and venous drainage management in MICS.

These findings challenge the previously reported superior performance of the Smart cannula [8, 9]. Despite having a low mean resistance to flow (R), the Smart group exhibited the highest frequency and proportion of unexpectedly higher resistances. Notably, while the venous bloodflow was restricted multiple times during surgery, this did not result in decreased arterial blood flow during CPB, regardless of the cannula used. Nevertheless, the suction pressures in the Smart group had to be increased to the same level as that required for smaller rigid cannulas to maintain sufficient venous return.

Several factors may explain this discrepancy with prior studies. While the Smart cannula has been shown to improve blood drainage compared to the traditional rigid cannulas [8, 9], many studies lacked dynamic, real-life conditions [10]. For example, most *in vitro* studies did not account for caval vein collapse, which can obstruct the cannula's side holes during CPB. Additionally, comparisons were often made against relatively small and less effective cannulas with less performant lighthouse

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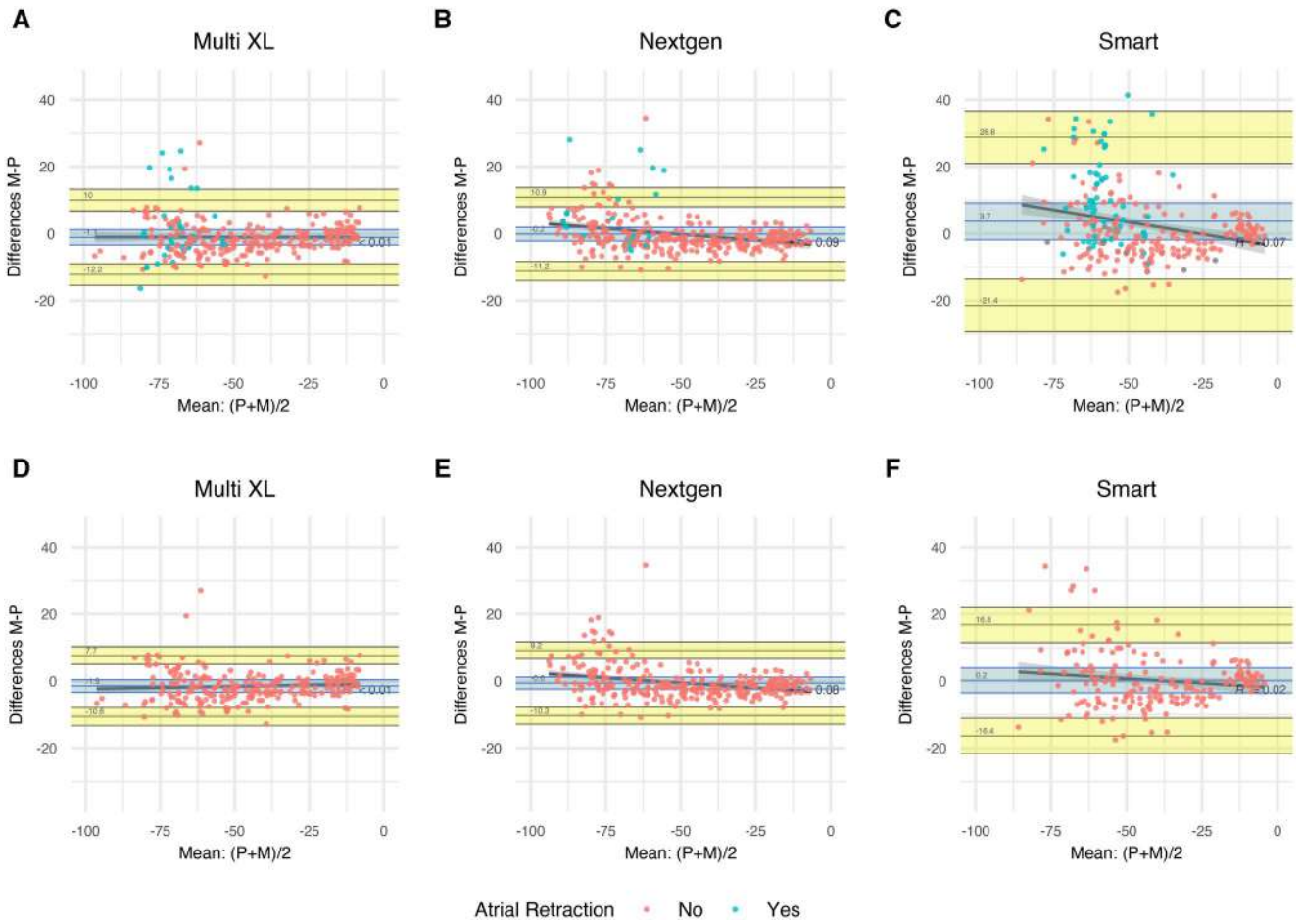

Figure 2: Bland-Altman plots for the groups stratified with (A–C) and without (D–F) atrial retraction. M: measured; P: predicted

Table 3: Bland-Altman Statistics without and without atrial retraction

Group	Atrial retraction incl/excl	Mean bias	Mean bias (lower CI)	Mean bias (upper CI)	Lower LOA	Upper LOA	% of Datapoints outside accepted ±12.5 mmHg range
Multi	*incl.*	−1.1	−3.4	1.2	−12.2	10.0	4.0
Multi	*excl.*	−1.5	−3.3	0.4	−10.6	7.7	1.2
Next	*incl.*	−0.1	−2.2	1.9	−11.2	10.9	3.8
Next	*excl.*	−0.6	−2.3	1.2	−10.3	9.2	2.8
Smart	*incl.*	3.7	−1.8	9.2	−21.4	28.8	17.9
Smart	*excl.*	0.2	−3.5	3.9	−16.4	16.8	9.2

tips [10], or lacked appropriate control groups [11, 12]. Other studies failed to specify critical parameters such as venous drainage flow, the method of drainage pressure measurement [13] or the height difference between the patient and the CPB system, which influences gravity-driven drainage. The internal resistance caused by venous line length and diameter is another key factor affecting drainage pressure [14, 15], yet this remains often unreported. Importantly, no previous study has examined the performance of peripheral venous cannulas under conditions of partial orifice obstruction or heart manipulation, limiting the applicability of prior findings to real-world scenarios.

Venous drainage techniques, such as vacuum and kinetically assisted drainage, are now standard perfusion practice. These methods enhance blood flow using smaller venous cannulas while minimizing circuit size to reduce haemodilution. The required suction pressure depends on the cannula type, venous line fluid dynamics and fluid properties. While no universal safety threshold exists for negative pressure applied to blood, clinicians commonly consider −50 to −80 mmHg to be acceptable. Exceeding this range has been associated with venous chattering, impaired drainage, blood trauma and the introduction of gaseous micro-emboli (GME) into the circuit [15–24]. Therefore, it has been recommended to measure the venous line pressure when using assisted venous drainage [25].

The cannula's fluid dynamics play a crucial role in ascertaining the patient's blood flow within acceptable limits during CPB.

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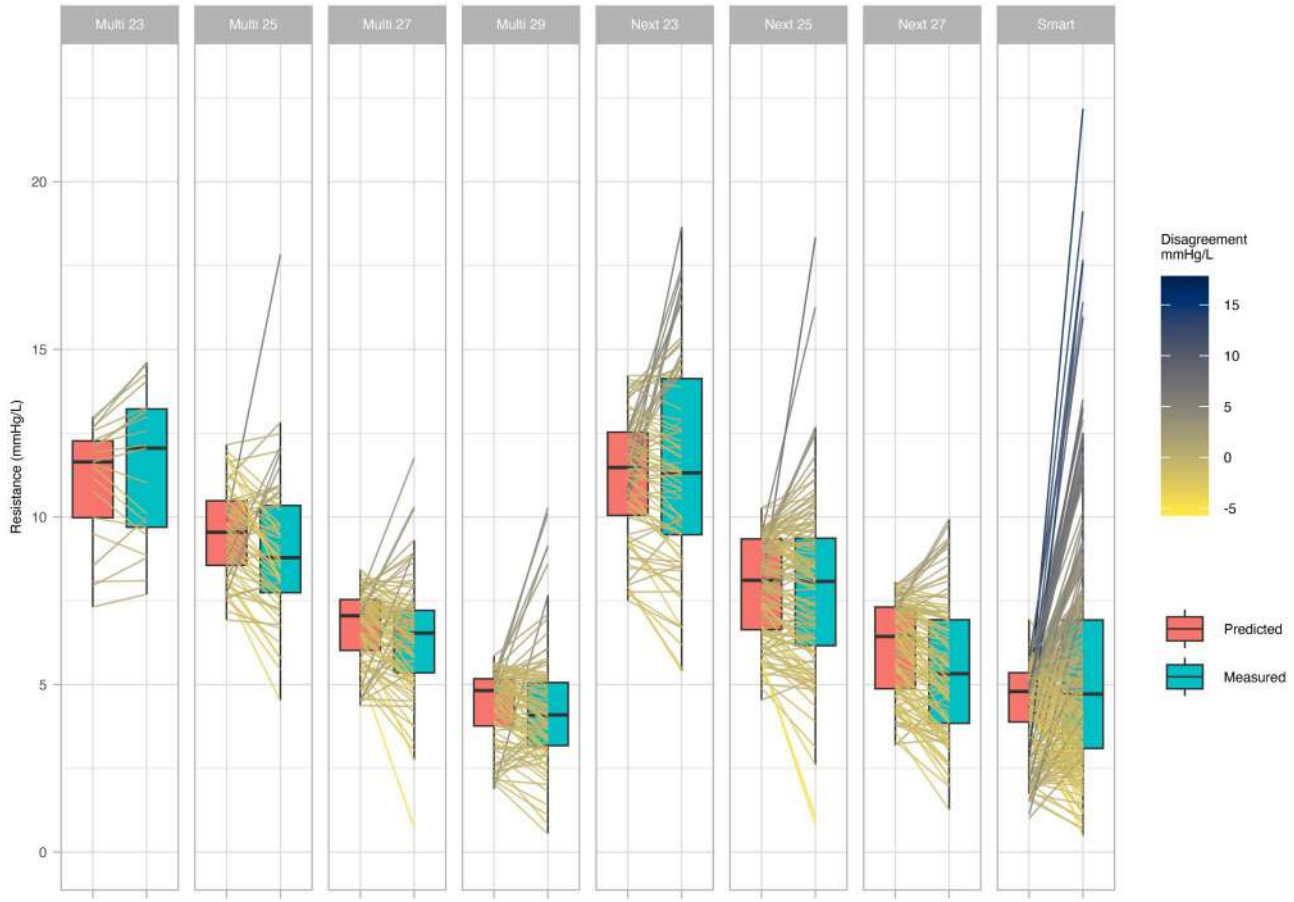

Figure 3: Predicted versus measured cannula resistances stratified for type and diameter

Table 4: CPB-data in mitral valve patients

		ANOVA				Post hoc comparisons: Games-Howell test *P*-values		
Variable	Overall	Multi	Next	Smart	ANOVA *P*-value	Multi vs Next	Multi vs Smart	Next vs Smart
PFI	2.36 (0.17)	2.4 (0.2)	2.3 (0.12)	2.39 (0.18)	≤0.001	≤0.001	0.96	≤0.001
CVP	6.51 (4)	5.6 (3.94)	6.32 (3.39)	7.28 (4.44)	0.01	0.35	≤0.01	0.13
Hb	10.16 (1.29)	9.79 (1.41)	9.92 (1.35)	10.62 (1)	≤0.001	0.79	≤0.001	≤0.001
DO_{2i}	327.69 (47.95)	320.48 (57.58)	313.31 (44.9)	346.05 (36.96)	≤0.001	0.59	≤0.001	≤0.001
LA	1.84 (0.6)	1.86 (0.67)	1.88 (0.47)	1.8 (0.67)	0.61	–	–	–

Mean ± SD; Welch's ANOVA. PFI: pump flow index ($ml \cdot min^{-1} \cdot m^{-2}$); CVP: central venous pressure (mmHg); Hb: haemoglobin concentration ($g \cdot dl^{-1}$); DO_{2i}: indexed oxygen delivery ($ml \cdot min^{-1} \cdot m^{-2}$); LA: intraoperative lactic acid concentration ($mmol \cdot L^{-1}$).

The cannula's design, the tip design, the position, size and angle of the side holes, which are different amongst cannula types, influence the performance of the cannula. These characteristics create both high shear or stagnant zones of blood flow depending on the location of the blood inflow and influences blood handling [26–29]. While various prediction methods have been investigated and validated to estimate the unique cannula performance, the DS method emerged being the one of the most accurate [3, 5].

The clinical application of mathematical conversion tools is particularly interesting for venous cannulas due to the caval vein collapsibility. First, these methods could provide a reliable prediction of expected drainage pressure, aiding in the selection of the appropriate cannula diameter and enabling the CP to operate closer to its best efficiency point [24]. Second, if the *in vivo* measurements exceed the predictions, it may indicate early vein collapse and partial obstruction of the cannula's side holes as venous collapse often develops gradually [30]. When venous preload is sufficient, inlet obstruction can be avoided, and the drainage pressure is highly predictable. However, when the inlet of the cannula gets obstructed, the performance is less predictable. During CPB, the deviation of measured pressures can alert the perfusionist of early or periodic inlet obstruction before the complete collapse of the vessel and cessation of drainage flow. In the recent guidelines for CPB in adult cardiac surgery, it is recommended to avoid excessive suction pressures, which have

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been reported to be below −400 mmHg during caval collapse [4, 25, 31, 32]. However, *in vitro* studies have demonstrated degassing phenomena in pressures above −100 mmHg in rich gas content solutions [24]. Optimizing venous drainage by allowing timely adjustments to CP pump speed, venous preload, or the position of the heart or cannula could help mitigate these risks and improve patient safety.

Limitations

The cannula performance data were collected in real-time and might induce potential bias related to the continuously changing conditions. Minor height differences between the pressure heads of CPB and the patient are not entirely excluded, although the table position rarely changes during the course of MICS. Additionally, there was no continuous evaluation of the cannula's position with TEE during the procedure, while inter-operator variability in cannula placement may have influenced the results. While it seems a logical assumption that the less rigid cannula wall of the Smart cannula might be more sensitive to external compression, it remains speculative and warrants further investigation. Despite the absence of differences in arterial PFI between groups, the blood flow of venting catheters was not recorded. Higher venting flow could indicate inadequate venous drainage and flooding of the surgical field. Moreover, insufficient venous drainage can lead to an increased CVP, cerebral venous pooling and decreased brain oxygenation. Unfortunately, we did not collect data concerning brain near-infrared spectroscopy. Although this was not intended in this study, patient outcome data were not registered, attenuating the clinical relevance of these findings.

CONCLUSION

This study revealed significant performance variability among different peripheral venous cannula types based on DS measurements to predict the *in vivo* performance of peripheral venous cannulas. In particular, the Smart Cannula exhibited less predictable resistances than the classical rigid cannulas, requiring more negative venous drainage pressure than anticipated preoperatively. This discrepancy highlights the limitations of *in vitro* data and the necessity for real-life evaluations. Our findings also suggest that the intraoperative manipulation of the heart, like during MV exposure via MICS, affects venous cannula performance. Using DS-based predictions alongside continuous measurements of the venous line pressures might aid to optimize venous drainage and patient outcomes. Future research should examine the incorporation of dynamic real-time cannula performance assessments into clinical decision-making.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *ICVTS* online.

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CONFLICT OF INTEREST

None declared.

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DATA AVAILABILITY

The corresponding author will share the article's data at reasonable request.

INSTITUTIONAL REVIEW BOARD

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Author contributions

Korneel Vandewiele: Conceptualization; Data curation; Formal analysis; Methodology; Writing—original draft; Writing—review & editing. **Filip De Somer:** Methodology; Supervision; Writing—review & editing. **Michael Vandenheuvel:** Formal analysis; Methodology; Visualization; Writing—review & editing. **Pascal Verdonck:** Conceptualization; Methodology; Writing—review & editing. **Thierry Bové:** Conceptualization; Methodology; Supervision; Writing—original draft; Writing—review & editing

Reviewer information

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