

Radial-to-femoral pressure gradient quantification in cardiac surgery



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ABSTRACT

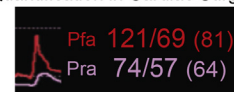
Background: A radial-to-femoral pressure gradient (RFPG) can occur in roughly one-third of cardiac surgical patients. Such a gradient has been associated with smaller stature and potentially smaller radial artery diameter. We hypothesized that preoperative radial artery diameter could be a predictor of RFPG. We also investigated the clinical impact of using a femoral versus a radial arterial catheter in terms of vasoactive support.

Methods: Using ultrasound, we measured the bilateral radial artery diameters of 160 cardiac surgical patients. All arterial pressure values were continuously recorded. Significant RFPG was defined as ≥ 25 mm Hg in systolic and/or ≥ 10 mm Hg in mean arterial pressure. One hundred and forty-nine additional patients were used to validate the impact of our observations.

Results: Using 78,013 pressure datapoints in 129 patients, 34.8% of patients had an RFPG with a mean duration of 54 ± 48 minutes. Patients with a radial artery diameter < 1.8 mm were more likely to have an RFPG ($n = 14$ [48.3%] vs 12 [22.2%]; $P = .042$). Patients with only a radial catheter received more phenylephrine ($P = .016$) despite undergoing shorter and less complex procedures. In the validation cohort, similar observations were made, and patients with a radial artery catheter received a longer duration of vasoactive support in the intensive care unit.

Conclusions: A significant RFPG occurs in one-third of cardiac surgical patients and in 48% of those with a radial artery diameter < 1.8 mm. The use of a single radial arterial catheter instead of dual radial and femoral catheters was associated with greater vasopressor requirements in the operating room and in the intensive care unit. We do not recommend the use of a single radial artery catheter in cardiac surgery. (JTCVS Open 2021;8:446-60)

Radial (Pra) to Femoral (Pfa) Pressure Gradient Quantification in Cardiac Surgery



Radial-to-femoral arterial pressure gradient in cardiac surgery.

CENTRAL MESSAGE

A significant radial-to-femoral pressure gradient was seen in 34.8% of all patients undergoing cardiac surgery and in 48% of those with a radial artery diameter < 1.8 mm. Exclusive radial artery monitoring increases vasoactive requirement.

PERSPECTIVE

A clinically significant radial-to-femoral pressure gradient occurred in 35% of 129 patients undergoing cardiac surgery with a mean duration of 54 ± 48 minutes, and in 48% of patients with a radial artery diameter < 18 mm. Patients with only a radial catheter received more phenylephrine and had a longer course of vasoactive medications in the intensive care unit despite undergoing shorter and less complex procedures.

See Commentaries on pages 461, 463, and 465.



Video clip is available online.

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A radial-to-femoral pressure gradient (RFPG), in which the radial pressure underestimates the actual blood pressure, is a frequent phenomenon occurring in approximately

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Abbreviations and Acronyms

BMI	=	body mass index
BSA	=	body surface area
CABG	=	coronary artery bypass grafting
CPB	=	cardiopulmonary bypass
ICU	=	intensive care unit
IQR	=	interquartile range
RFPG	=	radial-to-femoral pressure gradient

one-third of patients undergoing cardiac surgery.^{1,2} It can be observed in various types of cardiac surgical procedures,³ including minimally invasive cardiac surgery,⁴ and in the intensive care unit (ICU).^{5,6} Nonrecognition of an RFPG could lead to the inappropriate use of vasoactive medications when using radial artery pressure monitoring, with potential side effects for the patient. Although numerous studies have examined this phenomenon, there remains no consensus about the pathophysiology and elements causing an RFPG. Previous studies have identified potential risk factors, such as duration of cardiopulmonary bypass (CPB),^{1,2} reduced hematocrit,⁷ hypothermia,⁸ vasoactive medication,^{1,9} and plasma norepinephrine levels,^{9,10} and demographic characteristics, such as age, small height, and female sex^{1,8}; however, these factors were not consistently present across the various studies, and much uncertainty remains about the exact causes of an RFPG.

In a previous study, we retrospectively analyzed data from 435 patients undergoing CPB with simultaneous radial and femoral artery pressure monitoring and compared patients with and without an RFPG to identify potential risk factors.² We found that longer procedures and higher doses of vasoactive medications were associated with the appearance of a gradient. We also found that these patients were more likely to be women of older age and smaller stature. These results confirmed previous observations reported at our center.¹ Considering these risk factors, we hypothesized that a smaller radial artery diameter could predispose patients to developing an RFPG through its association with smaller stature and possibly because of vasoconstriction caused by vasoactive agents, further reducing the lumen diameter.¹⁰

In the present study, our primary objective was to determine whether preoperative radial artery diameter can predict the occurrence of an RFPG. Our second objective was to quantify the RFPG in terms of prevalence and duration, and a third objective was to compare the amount and duration of vasopressor support in radial artery versus femoral artery monitoring intraoperatively and postoperatively. These medications can have potential effects on patients, such as peripheral and mesenteric ischemia, arrhythmias, and coagulopathy.¹¹⁻¹³ For the second objective, we quantified the prevalence and

duration of the RFPG. For the third objective, we compared vasopressor use in patients who had only a radial catheter and those who had simultaneous radial and femoral catheters to monitor blood pressure in the operating room and, using an additional validation cohort, in the ICU.

METHODS

Following approval by the Montreal Heart Institute Research and Ethics Committee (2014-1568) and informed consent, all patients age >18 years undergoing heart surgery with CPB were eligible for inclusion. We excluded patients originating from the ICU who already had an arterial catheter in place before the procedure, patients whose radial artery showed thrombosis on the preoperative ultrasound assessment, patients with off-pump bypass surgery, and patients with data missing from the electronic database.

Recruitment was done on the day before surgery, because all patients are hospitalized at least 1 day before an elective case in our hospital. After informed consent was provided, we measured the radial artery diameter using a L12-5 (12 MHz) linear phased-array transducer (Sparq; Philips Healthcare, Amsterdam, The Netherlands). We did an intima-to-intima measurement using 2-dimensional ultrasound and used color Doppler when there was a doubt about the patency of the artery or if the edges of the intima were not clearly visible (Figure E1).¹⁴ After identifying the radial styloid articulation, radial diameter measurements were made on both wrists at 3, 6, and 9 cm above the styloid process. All images were recorded and stored in an electronic database. We then used an average of the 3 measurements on each side for the subsequent analysis and considered only the diameter of the radial artery used for the arterial catheter during surgery. Radial artery measurements were made by the same observer in 10 consecutive patients and repeated by a second observer to calculate the interobserver and intraobserver variability.

We collected data in the preoperative period on demographics (age, sex, weight, height, body mass index [BMI], and body surface area [BSA]), medications, and comorbidities, including recent myocardial infarction, coronary artery disease, hypertension, diabetes mellitus, and peripheral artery disease (see definitions in Table E1). Preoperative left ventricular ejection fraction was recorded. During surgery, blood pressure measurements from femoral and/or radial arterial catheters were recorded automatically every 15 seconds in an electronic database (CompuRecord; Philips Electronics). Data were then extracted in table format for further analysis. Using the electronic chart, we also collected data on the type of procedure (ie, coronary artery bypass grafting [CABG] only, 1 procedure other than CABG, and 2 or more procedures other than CABG), fluid balance, intraoperative vasoactive support (norepinephrine and phenylephrine), duration of CPB, clamping time, and whether CPB weaning was easy or difficult. We defined an easy CPB weaning as requiring no drugs or only vasopressors and a difficult weaning as requiring 2 classes of drugs (vasopressors plus inotropes or inhaled vasodilators), return on CPB, or a requirement for mechanical support to wean from CPB.¹⁵ These definitions were based on a previously described and validated algorithm for vasoactive management.¹⁶⁻¹⁸ The surgical procedure was performed according to established guidelines and reported previously CPB management.^{17,18}

The day of the procedure, the attending anesthesiologist decided whether to install a single radial artery catheter or both a radial catheter and a femoral catheter using ultrasound based on personal preference using standard technique.¹⁹ The arterial catheter routinely used at our institution is a 20G catheter (BD Angiocath; Beckton Dickinson, Franklin Lakes, NJ), and the femoral catheter is a 4F Avanti introducer (0.89 mm, 11 cm; Cordis, Bridgewater, NJ). Given the small size of the catheter, postoperative mobilization is the same in all patients regardless of the arterial insertion site. To avoid potential bias, the anesthesiology team was not aware of

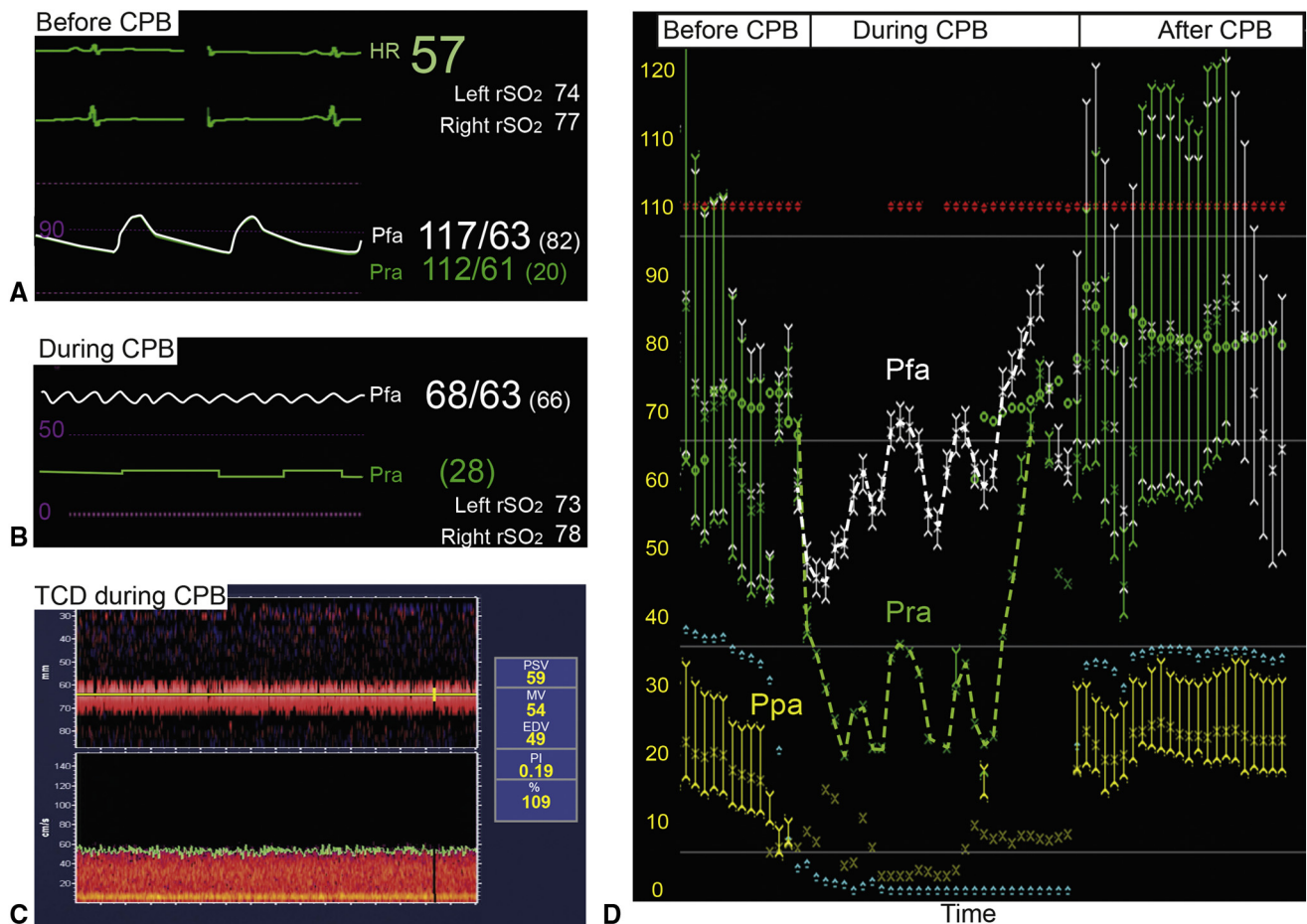


FIGURE 1. Radial (*Pra*) and femoral arterial pressures (*Pfa*) in a 60-year-old man undergoing coronary revascularization. A, No significant difference in the *Pra* and *Pfa* before cardiopulmonary bypass (*CPB*). B, Note the significant mean gradient of 38 mm Hg that appears during *CPB*. C, Despite a *Pra* of 28 mm Hg, brain saturation (*rSO₂*) and transcranial Doppler (109% from baseline) were normal. D, Intraoperative evolution of the *Pfa* (white) and *Pra* (green) during *CPB*. Note the significant gradient that appears only during *CPB*. *HR*, Heart rate; *TCD*, transcranial Doppler; *PSV*, peak systolic velocity; *MV*, mean velocity; *EDV*, end-diastolic velocity; *PI*, pulsatility index; *Ppa*, pulmonary artery pressure.

the preoperative radial artery diameter. Other standard intraoperative monitoring included a 5-lead electrocardiogram, heart rate, pulse oximetry,²⁰ and central venous pressure with or without pulmonary artery pressure. These values were recorded continuously during surgery. Perioperative transesophageal echocardiography was performed by American National Board of Echocardiography–certified cardiac anesthesiologists. The transesophageal echocardiography images were acquired in accordance with American Society of Echocardiography and European Association of Echocardiography recommendations and comprised the evaluation of systolic and diastolic function, chamber quantification, and the interrogation of all 4 valves by color Doppler.^{21,22}

Outcomes

The primary objective of the study was to evaluate the RFPG in relation to the radial artery diameter. Based on previous studies,^{1,2,23,24} we considered a clinically significant RFPG to be ≥ 25 mm Hg in systolic pressure and/or ≥ 10 mm Hg in mean arterial blood pressure for a minimum of 5 consecutive minutes. To more precisely describe the RFPG and to address our second objective, we also measured the area of gradient, which defines the area between the radial and femoral pressure curves. These values are reported in mm Hg·seconds. For each patient, the electronic blood pressure data were reviewed manually to remove any incorrect value, such as those

measured when the catheter is flushed for dynamic testing. Data were then entered into a preset Excel program that automatically indicated whether a significant RFPG was present and also calculated the area of the gradient, as defined by the area between the femoral and radial pressure curves, as an indirect index of the severity and duration of the gradient. Finally, to address our third objective, we compared patients with and without femoral artery pressure monitoring. The patients were divided into 2 groups and compared using the same variables as noted above. To validate our findings and explore the impact of the use of dual radial and femoral artery pressure catheters in the ICU as our third objective, we extracted data from 2 previously published prospective cohort studies.^{25,26}

Statistical Analysis

Continuous variables are summarized as mean \pm SD or median (interquartile range [IQR]), according to distribution. Categorical variables are summarized as number and percentage. The Kolmogorov–Smirnov test was used to determine the normality of data distribution. Clinical and anthropometric variables were compared between groups using the Student *t* test, one-way analysis of variance, the Mann–Whitney test, the Kruskal–Wallis test, the χ^2 test, or Fisher’s exact test, as appropriate. The patients were divided into tertile groups according to their radial artery diameter. This decision was based on pragmatic reasons and also on the

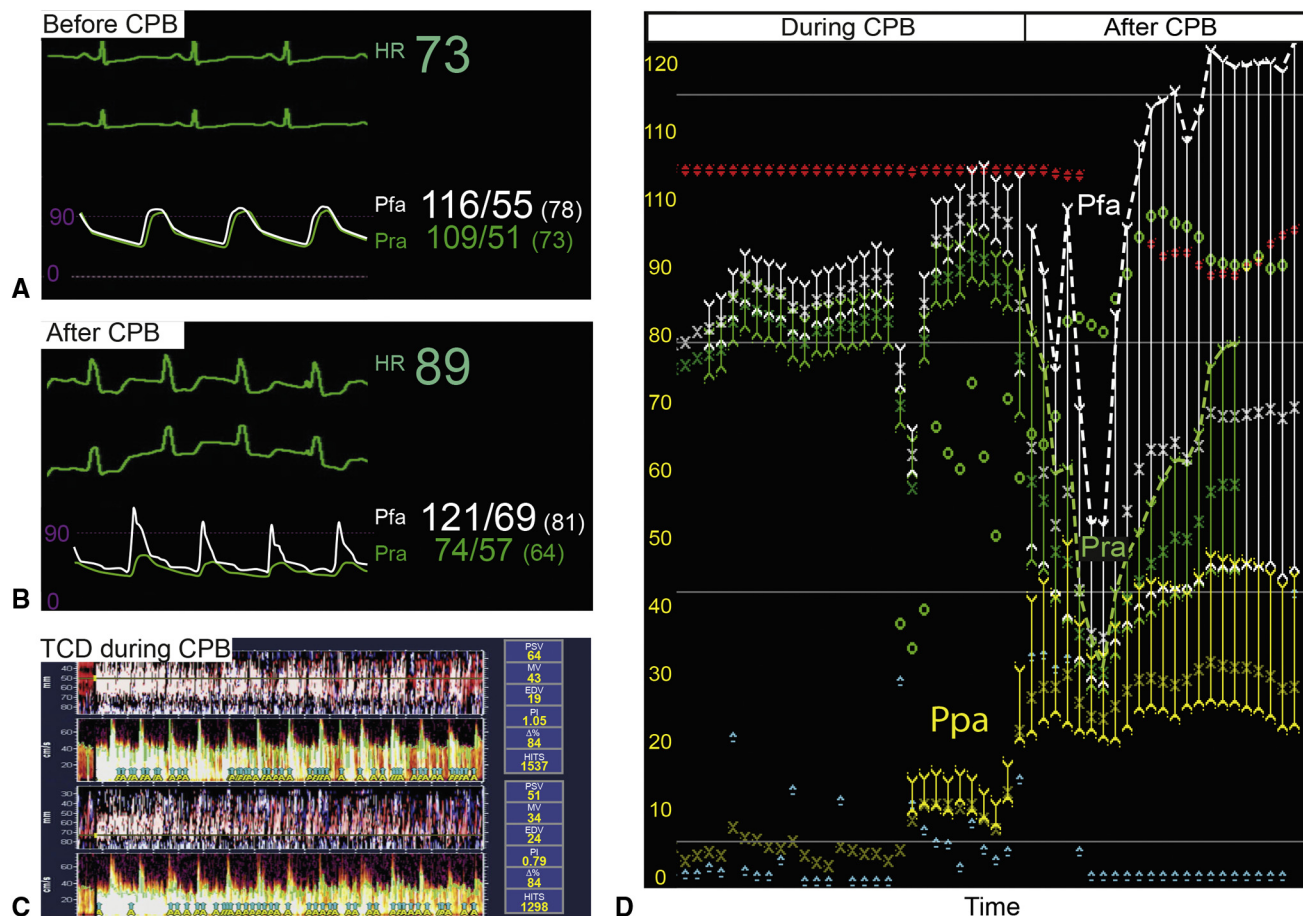


FIGURE 2. A and B, Radial (*Pra*) and femoral arterial pressure (*Pfa*) in a 75-year-old man before (A) and after (B) cardiopulmonary bypass (CPB) for aortic valve replacement. There was no difference in the *Pra* and *Pfa* before CPB; however, note the significant systolic (47 mm Hg) and mean (17 mm Hg) radial-to-femoral pressure gradient (RFPG) after CPB. C, This patient had significant high-intensity transient signals (*HITS*) after weaning from CPB, resulting in brain desaturation and associated with hemodynamic instability. D, Postoperative evolution of the *Pra* (green) and *Pfa* (white) in a 76-year-old man after revascularization. Note the RFPG that appeared during CPB but became highly significant after CPB. *HR*, Heart rate; *TCD*, transcranial Doppler; *PSV*, peak systolic velocity; *MV*, mean velocity; *EDV*, end-diastolic velocity; *PI*, pulsatility index; $\Delta\%$, change from baseline; *Ppa*, pulmonary artery pressure.

Youden index obtained by considering the presence or absence of an RFPG and the diameter of the radial artery. No adjustment for multiple testing was done. With a sample size of 110, the logistic regression test of $\beta = 0$ had 80.24% power to detect a β of 0.83 (odds ratio, 2.3). In doing so, it was assumed that this was a 2-sided test, with a significance level of 0.05, and that 1 normally distributed covariate was being added to the model after adjustment for prior covariates, that its multiple correlation with covariates already in the model was 0.3, and that the proportion of successes at the covariate means was 0.5. All tests were 2-sided, and a *P* value < .05 was considered significant. All analyses were performed using SAS version 9.3 or later (SAS Institute, Cary, NC).

Quality Assessment

We followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology: explanation and elaboration) checklist to evaluate and guarantee the quality of our study.²⁷

RESULTS

A total of 160 patients undergoing cardiac surgery with CPB at the Montreal Heart Institute between November

2016 and January 2017 were recruited (Figure E2). Radial artery diameter was obtained in 155 patients; 5 patients were excluded for technical acquisition problems, including radial artery thrombosis in 1 patient and incomplete data in 4 patients. Among these 155 patients, 26 were excluded, including 6 with a brachial artery catheter instead of a radial artery catheter, 5 with a significant pressure difference at baseline between the radial and femoral catheters because of peripheral arterial disease (radial artery not used), 8 with an off-pump procedure, 4 with an arterial catheter dysfunction during the procedure, 2 with cancelled procedures, and 1 with both a brachial artery catheter and an off-pump procedure. Among the remaining 129 patients included in the analysis, 92 (71%) had both a radial catheter and a femoral catheter inserted and 37 (29%) had only a radial catheter throughout the procedure. A total of 78,013 datapoints were recorded from the 129 patients. Thirty-two patients (34.8%) had a significant RFPG. The

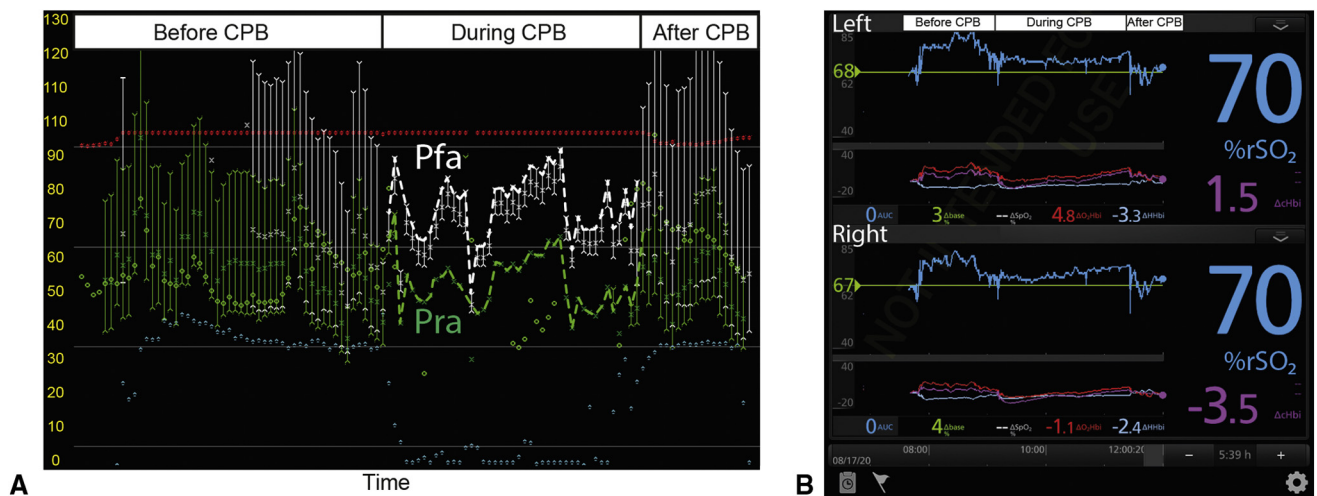


FIGURE 3. A, Radial (*Pra*) and femoral arterial pressure (*Pfa*) evolution in a 54-year-old man undergoing a Ross procedure. Note the significant systolic radial-to-femoral gradient from the beginning, during cardiopulmonary bypass (*CPB*), and until the end of the procedure. B, Brain saturation % change (*%rSO₂*) was normal during the procedure except after weaning from *CPB*, when it dropped transiently. *AUC*, Area under the curve; ΔSpO_2 , change in saturation measured with pulse oximetry; ΔO_2Hbi , change in oxyhemoglobin index; $\Delta HHbi$, change in deoxyhemoglobin index; $\Delta cHbi$, change in total hemoglobin index.

average duration of the gradient was 3237 ± 2899 seconds (54 ± 48 minutes).

Among these patients, an RFPG occurred before *CPB* in 5 (15.6%), during *CPB* in 27 (84.4%) (see example in Figure 1), and after *CPB* in 13 (40.6%) (see example in Figure 2). Ten patients had an RFPG during more than 1 stage of the procedure (see example in Figure 3).

To evaluate the impact of radial artery diameter, the patients were divided into 3 tertile groups (<1.8 mm, 1.8-2.2 mm, and >2.2 mm) according to the distribution of the radial artery diameter (Table 1). Patients in the first tertile group were more likely to be female ($P < .0001$)

and had lower weight ($P = .0027$), lower BMI ($P = .0049$), lower BSA ($P = .005$) and less hypertension ($P = .041$), but no differences were observed in other preoperative comorbidities or medication. In terms of procedures (Table 2), there was no differences between the groups regarding *CPB* and clamping times, procedure type, fluid balance, or vasoactive medications. In patients with both radial and femoral arterial catheters, the intraoperative blood pressure analysis showed more significant RFPGs in patients with a radial artery diameter <1.8 mm (48.3%; $n = 14$) compared with those with a diameter >2.2 mm (22.2%; $n = 6$) ($P = .042$) (Table 3).

TABLE 1. Patient characteristics for each tertile group of radial artery diameter

Variable	T1 (<1.8 mm) (N = 52)	T2 (1.8-2.2 mm) (N = 52)	T3 (>2.2 mm) (N = 51)	P value
Age, yr, median (IQR)	65.0 (59.0-72.0)	64.0 (57.0-72.0)	66.0 (59.0-73.0)	.7901
Male sex, n (%)	24 (47.1)	34 (65.4)	45 (88.2)	<.0001
Height, cm, mean \pm SD	165.9 \pm 10.5	166.3 \pm 10.3	168.8 \pm 9.3	.2961
Weight, kg, mean \pm SD	74.2 \pm 17.8	82.9 \pm 15.5	85.6 \pm 18.0	.0027
BMI, kg/m ² , median (IQR)	26.3 (22.9-30.1)	29.3 (26.6-32.4)	29.8 (26.8-33.3)	.0049
BSA, m ² , mean \pm SD	1.8 \pm 0.2	1.9 \pm 0.2	2.0 \pm 0.2	.0055
ACEI/ARB, n (%)	23 (45.1)	26 (51.0)	25 (51.0)	.7903
Beta-blockers, n (%)	30 (58.8)	26 (51.0)	26 (53.0)	.7127
Hypertension, n (%)	34 (66.7)	44 (86.3)	41 (82.0)	.0413
Dyslipidemia, n (%)	34 (66.7)	40 (78.4)	38 (76.0)	.3631
Diabetes, n (%)	14 (27.5)	16 (31.4)	14 (28.0)	.8944
Preoperative LVEF, median (IQR)	55.0 (45.0-60.0)	55.0 (50.0-60.0)	55.0 (50.0-60.0)	.7955
Peripheral vascular disease, n (%)	4 (7.8)	2 (3.9)	2 (4.0)	.7317

P values represent global differences among the 3 groups. *IQR*, Interquartile range; *SD*, standard deviation; *BMI*, body mass index; *BSA*, body surface area; *ACEI*, angiotensin-converting enzyme inhibitor; *ARB*, angiotensin receptor blocker; *LVEF*, left ventricular ejection fraction.

TABLE 2. Intraoperative data for each tertile group of radial artery diameter

Variable	T1 (<1.8 mm) (N = 52)	T2 (1.8-2.2 mm) (N = 52)	T3 (>2.2 mm) (N = 51)	P value
CPB time, min, median (IQR)	88.0 (63.0-120.5)	82.0 (62.0-111.0)	71.0 (51.0-96.5)	.1431
Clamping time, min, median (IQR)	62.0 (47.0; 88.0)	61.0 (44.0; 85.0)	55.5 (34.0-74.5)	.2007
Fluid balance, mL, mean ± SD	1066.9 ± 1034.0	927.0 ± 1013.8	792.6 ± 994.7	.4032
Norepinephrine, total µg, median (IQR)	738.2 (370.1-1375.0)	634.9 (352.4-1065.0)	1070.8 ± 894	.3603
Phenylephrine, total µg, median (IQR)	1950.0 (500.0-3433.5)	1273.3 (200.0-4900.0)	1541.0 (100.0-3390.0)	.7234
Ephedrine, n (%)				.4246
0	35 (68.6)	38 (74.5)	40 (80)	
≥1	16 (31.4)	13 (25.6)	10 (20)	
Epinephrine, n (%)				.9991
0	45 (88.2)	45 (88.2)	44 (88.0)	
≥1	6 (11.8)	6 (11.8)	6 (12.0)	
Vasopressin, n (%)				.5374
0	36 (70.6)	39 (76.5)	40 (80.0)	
≥1	15 (29.4)	12 (23.5)	10 (20.0)	
Milrinone post-CPB, n (%)				.3352
0	45 (88.2)	42 (82.3)	46 (92)	
≥1	6 (11.8)	9 (17.6)	4 (8)	
Type of procedure, n (%)				.6221
Isolated CABG	15 (29.4)	22 (43.1)	20 (41.7)	
Isolated valve	21 (41.2)	17 (33.3)	15 (31.3)	
Combined procedures	15 (29.4)	12 (23.5)	13 (27.1)	

CPB, Cardiopulmonary bypass; IQR, interquartile range; SD, standard deviation; CABG, coronary artery bypass grafting.

Moreover, patients in the first tertile group had a longer mean gradient duration and a larger mean area of gradient than those in the third tertile group ($P = .0206$). There also was no statistical significance in terms of systolic and mean blood pressure area gradients, although patients in

the first tertile group with the smallest radial artery diameter tended to have larger areas than those in the groups with larger radial diameters, as illustrated in [Figure 4](#).

To evaluate the impacts of using single radial arterial catheter or simultaneous radial and femoral catheter

TABLE 3. Gradient characteristics for each tertile group of radial artery diameter

Variable	T1 (<1.8 mm) (N = 29)	T2 (1.8-2.2 mm) (N = 36)	T3 (>2.2 mm) (N = 27)	P value
Incidence of gradient, n (%)	14 (48.3)	12 (33.3)	6 (22.2)	.1201 .2216 (T1 vs T2) .0420 (T1 vs T3) .3340 (T2 vs T3)
Duration of gradient, min, median (IQR)	0.0 (0.0-68.5)	0.0 (0.0-10.6)	0.0 (0.0-0.0)	.0543 .1153 (T1 vs T2) .0206 (T1 vs T3) .3508 (T2 vs T3)
Area of systolic gradient, mm Hg·s, median (IQR)				
Before CPB	24,075.0 (12,570.0-51,375.0)	20,640.0 (11,786.3-38,475.0)	20,062.5 (5257.5-38,610.0)	.3913
After CPB	24,180.0 (9757.5-38,055.0)	18,495.0 (3738.8-29,145.0)	18,825.0 (2040.0-25,755.0)	.4491
Total	52,357.5 (29,077.5-80,715.0)	39,446.3 (12,840.0-70,590.0)	43,972.5 (547.5-58,462.5)	.1787
Area of mean gradient, mm Hg·s, median (IQR)				
Before CPB	15,607.5 (7597.5-21,540.0)	9446.3 (5711.3-15,772.5)	9832.5 (5385.0-18,075.0)	.1442
During CPB	29,220.0 (15,255.0-91,837.5)	22,751.3 (12,588.8-45,600.0)	24,562.5 (9007.5-35,535.0)	.2821
After CPB	9210.0 (4087.5-13,455.0)	9300.0 (3446.3-10,908.8)	8272.5 (3907.5-10,950.0)	.5581
Total	55,237.5 (30,615.0-131,452.5)	46,571.3 (26,771.3-73,391.3)	36,937.5 (21,802.5-69,592.5)	.1738

IQR, Interquartile range; CPB, cardiopulmonary bypass.

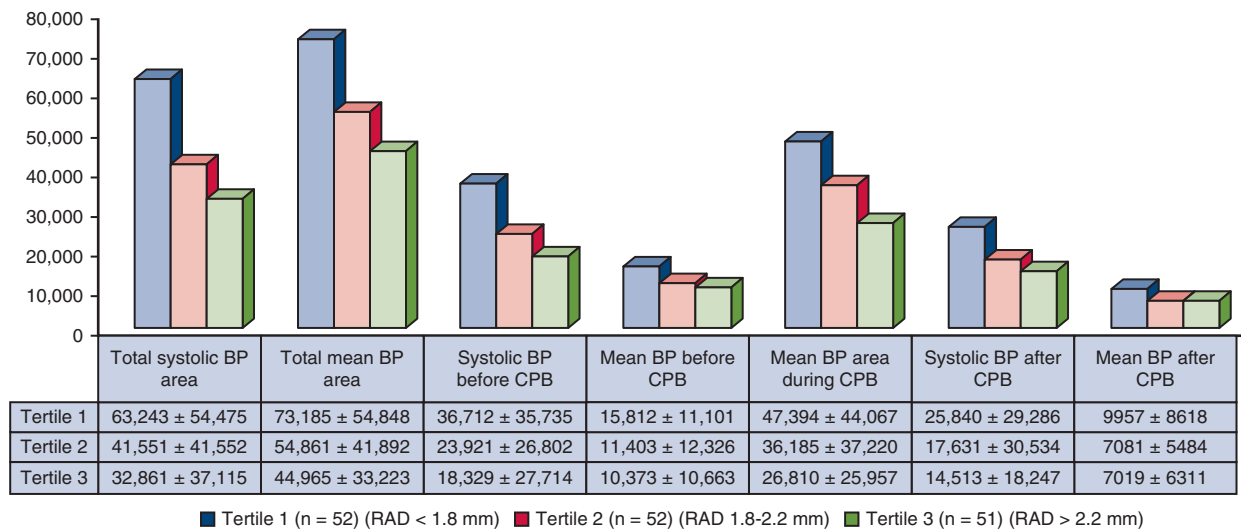


FIGURE 4. Radial-to-femoral pressure gradient and tertile groups of radial artery diameter (RAD). BP, Blood pressure; CPB, cardiopulmonary bypass.

monitoring, we compared patients with only a radial catheter (n = 37) and those with simultaneous radial and femoral catheters (n = 92) (Table 4). Although the patients with only a radial catheter had lower weight (P = .0470) and smaller BSA (P = .0429), there were no differences in terms of age (P = .1132), sex (P = .5204 for males), height (P = .2127), or BMI (P = .5881). There was also no difference between the 2 groups in terms of preoperative comorbidities. Radial artery diameter was also similar in the 2 groups (P = .5379). The intraoperative data differed between the groups, however. Patients with a radial catheter only had significantly shorter CPB (P = .0025) and clamping (P = .0004) times. They also were more likely to undergo a simple CABG procedure (P = .0293). Although there was no difference in terms of the total fluid balance (P = .2754) or total norepinephrine dose (P = .3001), patients with only a radial catheter received significantly more phenylephrine during the procedure (P = .0160) despite having less frequent difficult weaning from CPB (P = .0034).

The clinical impact of the use of the RFPG in the validation study is shown in Tables E2, E3, and E4. In the validation study, we analyzed a total of 149 patients requiring vasoactive drugs for <24 hours. Similar to the results of the current study, patients in the validation study in whom only a radial artery catheter was used (n = 40; 27%) had a lower mean EuroSCORE II (2.2 ± 3 vs 3.2 ± 4; P = .047), less frequent multiple surgeries (10% vs 32%; P = .007), shorter clamping time (median, 51 minutes [IQR, 39-51 minutes] vs 67 minutes [IQR, 45-90 minutes]; P = .006), higher intraoperative phenylephrine use (median, 3 mg [IQR, 1.2-5.2] vs 1.7 mg [IQR, 0.2-3.5]) but less inhaled prostacyclin and milrinone (18% vs 39%; P = .015). There was no

difference in terms of outcome in the ICU between the groups (Table E4), but the patients with only a radial artery catheter had a longer duration of vasoactive medication use (mean, 7.6 ± 6.2 hours vs 4.7 ± 5.1 hours; P = .026). Figure 5 and Video 1 summarizes our main findings.

DISCUSSION

This study suggests that RFPG is a frequent phenomenon that occurs in approximately one-third of patients undergoing cardiac surgery. The incidence that we observed (34.8%) is consistent with data from other prospective¹ and retrospective² studies; however, this is the first prospective study in which continuous radial and femoral blood pressure measurements were recorded every 15 seconds using a computerized system, which supports our current and past findings regarding the incidence of this phenomenon and in which the duration of the RFPG is reported.

We observed a significant RFPG in 48.3% of the patients with a radial artery diameter <1.8 mm, compared with 22.2% in those with a diameter >2.2 mm. Baba and colleagues²⁸ first studied the association between radial artery diameter and the occurrence of an RFPG in 75 CABG patients. Their methodology differed from ours; they measured the radial diameter not only after anesthesia induction, but also throughout the procedure, and reported their results as a ratio of the current radial diameter and the postinduction diameter. However, they used a mean pressure cutoff of 5 mm Hg to define patients with a high or low arterial pressure difference. They found that patients in the higher blood pressure difference group had significantly lower ratios during and after CPB, suggesting that radial artery constriction could be responsible for the RFPG. There also was a significant linear correlation

TABLE 4. Preoperative and intraoperative characteristics of patients with only a radial line versus those with simultaneous radial and femoral lines

Variable	Radial only (N = 37)	Radial + femoral (N = 92)	P value
Preoperative			
Age, y, median (IQR)	69.0 (63.0-74.0)	63.0 (58.0-71.5)	.1132
Male sex, n (%)	24 (64.9)	65 (70.7)	.5204
Height, cm, mean ± SD	165.8 ± 9.7	168.2 ± 10.2	.2127
Weight, kg, mean ± SD	76.4 ± 16.8	83.3 ± 18.3	.0470
BMI, kg/m ² , median (IQR)	28.2 (25.5-33.1)	28.7 (25.1-32.5)	.5881
BSA, m ² , mean ± SD	1.8 ± 0.2	1.9 ± 0.2	.0429
ACEI/ARB, n (%)	12 (32.4)	47 (51.1)	.0544
Beta-blockers, n (%)	17 (45.9)	53 (57.6)	.2291
Hypertension, n (%)	30 (81.1)	71 (77.2)	.6264
Dyslipidemia, n (%)	28 (75.7)	64 (69.6)	.4877
Diabetes, n (%)	11 (29.7)	27 (29.4)	.9657
Peripheral vascular disease, n (%)	1 (2.7)	4 (4.4)	1.0000
Preoperative LVEF, mean ± SD	55.3 ± 10.0	53.3 ± 10.1	.3222
Radial artery diameter, mm, mean ± SD	2.1 ± 0.5	2.0 ± 0.4	.5379
Intraoperative			
CPB time, min, median (IQR)	64.0 (52.0-91.0)	84.0 (64.5-129.0)	.0025
Clamping time, min, median (IQR)	45.0 (30.0-69.0)	64.5 (49.0-101.0)	.0004
Fluid balance, mL, mean ± SD	1072.5 ± 1037.7	865.2 ± 945.2	.2754
Type of procedure, n (%)			.0293
Isolated CABG	18 (48.7)	28 (30.4)	
Isolated valve	14 (37.8)	31 (33.7)	
Combined procedure	5 (13.5)	33 (35.9)	
Norepinephrine, total µg, median (IQR)	634.7 (455.5-935.8)	841.7 (362.6-1367.0)	.3001
Norepinephrine, µg/min, median (IQR)	10.8 (5.4-16.1)	9.3 (3.9-15.1)	.3149
Phenylephrine, total µg, median (IQR)	2650.0 (1273.3-6590.0)	1042.0 (150.0-3375.0)	.0160
Phenylephrine, µg/min, median (IQR)	37.7 (16.3-91.0)	10.8 (1.5-38.0)	.0020
Milrinone, n (%)	1 (3)	16 (17)	.0257
CPB weaning, n (%)			.0034
Easy	32 (86.5)	55 (59.8)	
Difficult	5 (13.5)	37 (40.2)	

IQR, Interquartile range; SD, standard deviation; BMI, body mass index; BSA, body surface area; ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; LVEF, left ventricular ejection fraction; CPB, cardiopulmonary bypass; CABG, coronary artery bypass grafting.

between the radial artery diameter ratio and the pressure difference. Although these results indicate that radial artery diameter could be associated with the pressure difference between radial and femoral measurements, the mean arterial pressure cutoff of 5 mm Hg seems less likely to be clinically significant, and the authors did not provide information about the precise radial artery diameter that can help predict the occurrence of an RFPG. Furthermore, anesthesiologists must use preoperative data to guide their decisions regarding blood pressure.

In the current study, we observed that patients with a smaller radial artery diameter were more frequently female and had lower weight, BMI, and BSA. Fuda and colleagues¹ also measured both radial and femoral artery diameters before insertion of a radial artery catheter at a single site in 73 patients. They observed a smaller radial artery diameter but no difference in the femoral artery diameter in patients who developed an RFPG. In that study, the

diagnosis of an RFPG was determined visually and not recorded continuously; in addition, radial artery diameter cutoff was not provided and, on multivariate analysis, the radial artery diameter was not identified as an independent predictor of the RFPG. It is possible that a smaller radial artery diameter will be altered by vasoactive agents and will increase the arterial resistance as the diameter decreases.²⁸

The pathophysiology of RFPG remains a subject of debate. Since its first description by Stern and colleagues in 1985,²³ numerous studies have suggested various explanations. Changes in distal arterial elasticity,²⁹ aging with a reduction in leg postjunctional alpha-adrenoceptor responsiveness to endogenous noradrenaline,³⁰ lower hematocrit level,⁷ lower minimal body temperature,⁸ CPB and clamping times,^{1,2} vasoactive medication,^{1,2,9,10,31,32} plasma catecholamine levels,^{9,10} vascular thrombosis,³³ vascular decoupling in vasoplegia,³⁴ and demographic data^{1,2} have all been described as potential risk factors.

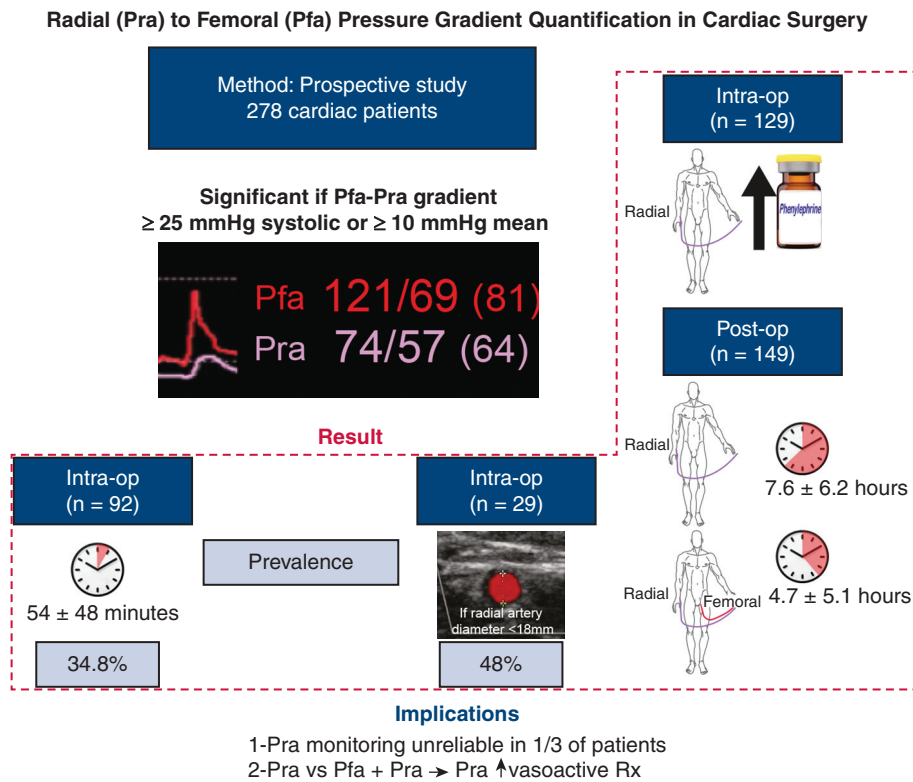


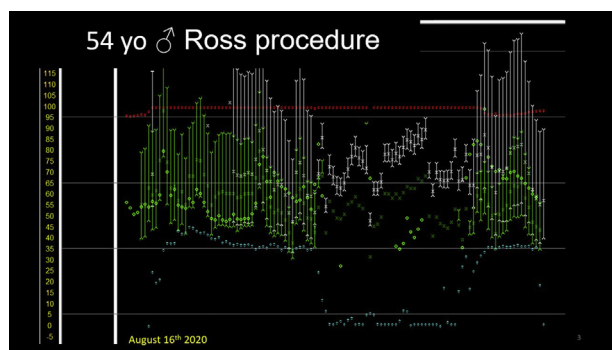
FIGURE 5. Study summary of the prospective study of 278 patients in which a significant radial-to-femoral arterial pressure gradient (RFPG) was observed in 34.8% of all patients and in 48% of those with a radial artery diameter <1.8 mm. In those patients with only a radial artery pressure, increased use of phenylephrine was observed, and in another cohort, the duration of postoperative vasoactive agent use was longer in the intensive care unit. *Intra-op*, Intra-operative period; *Post-op*, post-operative period; *Rx*, medication.

There is also a discrepancy in regard to vasoactive medication, since vasopressors and vasodilators have both been associated with the RFPG in different studies.^{9,28,31,32,35} Although none of these risk factors can explain the phenomenon by itself, most of them are related to vasoconstriction and thus to radial artery diameter. Our observations support the concept that a smaller preoperative radial artery diameter can affect pulse pressure and thereby generate an abnormally low reduction in radial arterial pressure compared with central or femoral arterial pressures.

The fact that the patients with only a radial catheter received more phenylephrine and as much norepinephrine as those with both radial and femoral catheters illustrates the potential adverse clinical impacts of underestimating the central blood pressure by not measuring the adequate arterial pressure with a femoral catheter. This result is even more significant when we consider the fact that patients in both cohorts with only a radial catheter underwent significantly shorter and less complex procedures. As supported by other investigators,^{4,6,36-38} this observation demonstrates that not measuring femoral arterial pressure could have potential clinical impacts

because vasoactive medications can have serious side effects, such as cardiac arrhythmias, peripheral ischemia, and metabolic disturbances.^{12,13} Moreover, several studies have demonstrated that vasoactive agents can generate a significant RFPG on their own.^{1,6,9,32} Therefore, we can postulate that underestimating the central arterial blood pressure, leading to the use of more vasoactive medication, could amplify the phenomenon even more. A suspected RFPG can be investigated using brain oximetry and transcranial Doppler as shown in Figure 1, as well as using mitral regurgitation to estimate systolic arterial pressure, as reported previously.³⁹

There are several limitations to this study. This was an observational study, and patients were not randomized to radial or simultaneous radial and femoral monitoring. The selection of single or simultaneous radial and femoral arterial pressure catheters was based on the opinion of the attending anesthesiologist, which is the case in approximately two-thirds of our cases. In our center, simultaneous monitoring is more common in complex cases. Some anesthesiologists prefer using only radial artery monitoring for simple cases or for minimally invasive cardiac surgery even if a significant RFPG has been reported in such



VIDEO 1. Presentation of the study results. Video available at: [https://www.jtcvs.org/article/S2666-2736\(21\)00218-7/fulltext](https://www.jtcvs.org/article/S2666-2736(21)00218-7/fulltext).

procedures.⁴ Therefore, there is a selection bias, but despite using radial pressure monitoring for simpler procedures, the use of vasoactive agents in these patients was similar as in patients undergoing more complex procedures, which may suggest overtreatment in the case of an unreliable radial artery pressure value. When we selected only patients undergoing coronary revascularization, patients with only a radial artery catheter still received more noradrenaline despite shorter clamping duration (Table E5). Because the number of patients is small and the population is different in the 2 groups, only a randomized controlled trial can definitively clarify this point and explore other potential impacts of such monitoring. The number of patients was insufficient for logistic regression to identify independent predictors of an RFPG to confirm the results of our retrospective study.² There are several factors associated with the RFPG⁴⁰; however, our main goals were to explore the role of radial artery diameter as a predictor of an RFPG, to electronically quantify the prevalence and duration of the gradient, and to evaluate the impact of dual radial and femoral monitoring. For this reason, the decision to use or not use femoral arterial pressure monitoring should be based not only on radial artery diameter, but also on other risk factors that may increase the risk of a significant RFPG, such as low BSA, complex procedures, and prolonged clamping time.² Femoral arterial pressure may be unreliable in some patients with vascular disease and may represent a higher-risk procedure. All our femoral artery catheters were inserted under ultrasound guidance, and the safety of this monitoring technique has been reported by other groups.^{36,37}

In conclusion, this study suggests that the RFPG is a frequent problem in patients undergoing cardiac surgery with CPB, occurring in roughly one-third of these patients. It occurs more frequently in patients with a smaller preoperative radial diameter, although this is not the sole factor explaining the phenomenon. Finally, ignoring the RFPG by not measuring femoral arterial pressure could lead to the inappropriate use of vasoactive medication in the operating room and the ICU, with potential side effects.

Based on our experience, we do not recommend the use of a single radial artery catheter in cardiac surgery.

Conflict of Interest Statement

Dr Denault serves on the speakers bureaus for CAE Healthcare, Masimo, and Edwards. The other authors report no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: cardiac surgery, femoral arterial pressure, radial arterial pressure, radial-to-femoral arterial pressure gradient, vasoactive support

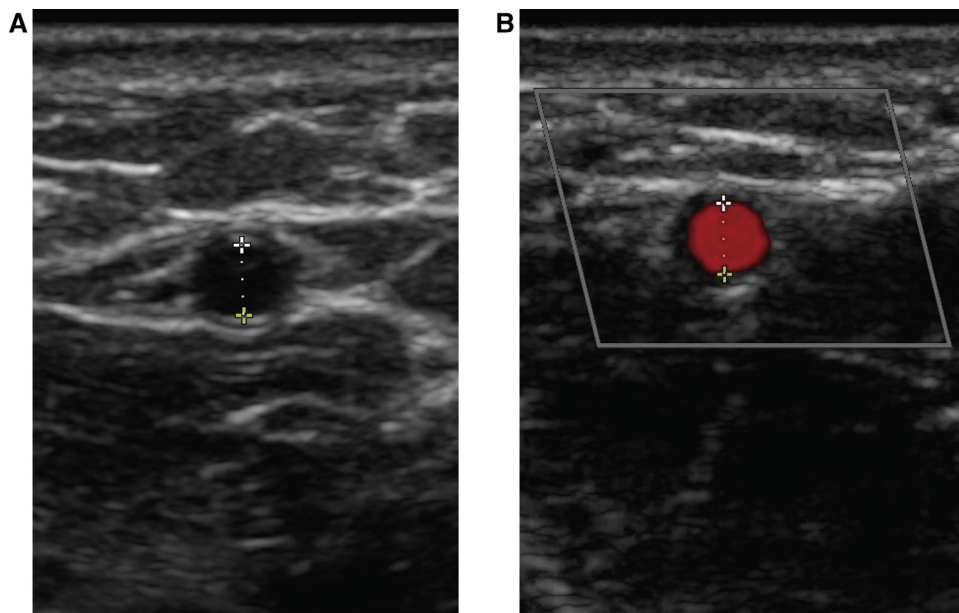


FIGURE E1. (A) Two-dimensional view of the radial artery (B) using color Doppler.

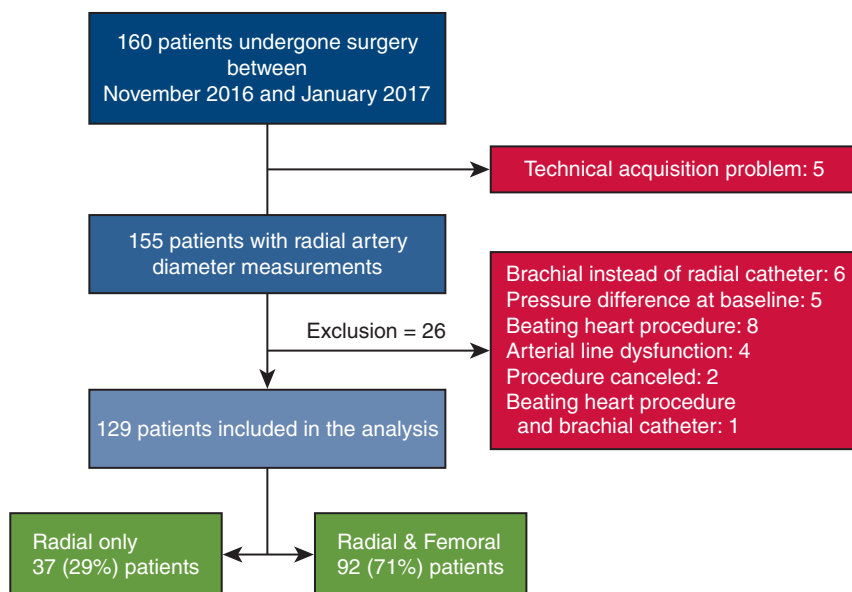


FIGURE E2. Flowchart of patient inclusion.

TABLE E1. Definitions of Variables

Comorbidities	
Recent myocardial infarction	History of documented myocardial infarction
Coronary artery disease	History of documented coronary artery disease by coronary angiography
Hypertension	Documented history of treated or untreated hypertension
Diabetes mellitus	Diabetes with drug or insulin requirement
Peripheral vascular disease	Documented history of vascular disease or previous vascular surgery
Pulmonary hypertension	Mean pulmonary artery pressure >25 mm Hg or systolic pulmonary artery pressure >30 mm Hg, measured by central venous catheterization
Renal failure, KDIGO criteria	Stage 1: $\geq 50\%$ or $27 \mu\text{mol/L}$ increase in serum creatinine Stage 2: $\geq 100\%$ increase in serum creatinine Stage 3: $\geq 200\%$ increase in serum creatinine or an increase to a level $\geq 254 \mu\text{mol/L}$ or dialysis initiation
Fluid balance	Cumulative fluid balances were collected using the input of fluids from the following types: crystalloids, colloids, red blood cells, or other blood products (eg, plasma, platelets) minus the output of fluids from urine, bleeding, nasogastric tube, and drains. Cumulative fluid balances were calculated between the beginning of surgery and the arrival in the intensive care unit.
Echocardiography	
Left ventricular ejection fraction (LVEF)	Normal LV function defined as LVEF >50%; severe LV dysfunction, as LVEF <35%
Right ventricular (RV) systolic function	Normal RV systolic function was defined as an RV fractional area change (FAC) >35% and tricuspid systolic annular plane excursion (TAPSE) >17 mm; moderate dysfunction, as RV FAC <24% and TAPSE <17 mm
RV dilatation	A diameter >41 mm at the base or 35 mm at mid-level
Hemodynamics	
RV pressure waveform analysis	Normal RV pressure waveform defined as a rapid systolic pressure upstroke and a horizontal (<4 mm) diastolic slope
Hemodynamic instability	Defined as difficult separation from cardiopulmonary bypass; requires at least 2 different types of pharmacologic agents (ie, inotropes \pm vasopressors \pm inhaled agents)
Simple surgery	Repair or replacement of a single valve or CABG surgery
Complex surgery	Redo surgery, combined vascular and valve, or double-valve procedures
Very complex surgery	Surgical treatment of aortic dissection or endocarditis
Intraoperative fluid balance	Calculated by subtracting urine output and blood loss (weight of the blood-soaked sponges during surgery) and the amount of suctioned blood from fluid replacement (including crystalloids and colloids) and transfusion products; insensible losses from surgery and preoperative fasting were excluded from the calculation
Vasopressors	Norepinephrine and vasopressin
Inotropes	Milrinone, dobutamine, and epinephrine
Inhaled agents	Inhaled prostacyclin, nitric oxide, and milrinone

KDIGO, Kidney Disease: Improving Global Outcomes; CABG, coronary artery bypass grafting.

TABLE E2. Preoperative characteristics of patients with only a radial line versus those with simultaneous radial and femoral lines in the validation group

Variable	Radial (N = 40)	Radial + femoral (N = 109)	P value
Age, y, mean \pm SD	64 \pm 10	63 \pm 13	.78
Male sex, n (%)	20 (50)	56 (51)	.88
BMI, kg/m ² , mean \pm SD	27 \pm 5	30 \pm 5	.006
ACEI/ARB, n (%)	22 (55)	55 (51)	.62
Calcium blockers, n (%)	7 (18)	30 (28)	.20
Beta-blockers, n (%)	23 (58)	60 (55)	.78
Hypertension, n (%)	28 (70)	89 (82)	.12
Dilated left ventricle, n (%)	5 (13)	14 (13)	.99
EuroSCORE II, mean \pm SD	2.2 \pm 3	3.2 \pm 4	.047
Diabetes, n (%)	13 (33)	35 (32)	.96

SD, Standard deviation; BMI, body mass index; ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker.

TABLE E3. Intraoperative data of patients with only a radial line versus those with radial + femoral lines in the validation group

Variable	Radial (N = 40; 27%)	Radial + femoral (N = 109; 73%)	P value
CPB time, min, median (IQR)	77 (56-99)	86 (67-114)	.38
Clamping time, min, median (IQR)	51 (39-51)	67 (45-90)	.004
Fluid balance, mL, mean \pm SD	1012 \pm 960	1094 \pm 899	.63
Norepinephrine, total μ g, median (IQR)	591 (337-1002)	799 (402-1461)	.05
Phenylephrine, total mg, median (IQR)	3 (1.2-5.2)	1.7 (0.2-3.5)	.006
Vasopressin, n (%)	10 (25)	32 (29)	.60
Epinephrine, n (%)	3 (8)	18 (17)	.16
Milrinone/Flolan, n (%)	7 (18)	42 (39)	.015
Isolated CABG, n (%)	25 (63)	54 (50)	.16
Combined procedure, n (%)	4 (10)	35 (32)	.007
Aortic surgery, n (%)	8 (20)	58 (53)	<.0001

CPB, Cardiopulmonary bypass; IQR, interquartile range; CABG, coronary artery bypass graft.

TABLE E4. Intensive care unit outcomes in the validation group

Variable	Radial (N = 40; 27%)	Radial + femoral (N = 109; 73%)	P value
Vasopressin, n (%)	3 (7)	11 (10)	.63
Epinephrine, n (%)	3 (7)	13 (12)	.44
Duration of stay in the ICU, h, mean \pm SD	35 \pm 34	37 \pm 28	.82
Duration of mechanical ventilation, h, mean \pm SD	5 \pm 2	4 \pm 2	.37
Cumulative fluid balance, mL, mean \pm SD	126 \pm 738	138 \pm 780	.83
Stage I renal failure*, n (%)	8 (20)	39 (36)	.06

ICU, Intensive care unit; SD, standard deviation. *Using KDIGO criteria: stage 1, 27 μ mol/L increase in serum creatinine.

TABLE E5. Preoperative characteristics of patients with only a radial line versus those with simultaneous radial and femoral lines undergoing coronary revascularization in the study group

Variable	Radial (N = 18)	Radial + femoral (N = 28)	P value
Age, y, mean ± SD	66 ± 8	65 ± 8	.71
Male sex, n (%)	16 (89%)	23 (82%)	.68
BMI, kg/m ² , median (IQR)	29.7 (27-33)	27.7 (25-32)	.21
Radial artery diameter, mm, mean ± SD	2.3 ± 0.4	1.9 ± 0.4	.03
ACEI/ARB, n (%)	7 (39)	16 (57)	.22
Beta-blockers, n (%)	12 (67)	19 (68)	.93
Hypertension, n (%)	18 (100)	26 (93)	.51
Vascular disease, n (%)	0	2 (7)	.51
LVEF, %, mean ± SD	51 ± 10	50 ± 11	.77
Diabetes, n (%)	8 (44)	10 (36)	.55
CPB duration, min, mean ± SD	64 ± 27	69 ± 22	.55
Clamping duration, min, median (IQR)	30 (23-45)	44 (35-60)	.03
Difficult separation from CPB, n (%)	3 (17)	9 (32)	.24
Fluid balance, mL, mean ± SD	682 ± 728	915 ± 827	.33
Total noradrenaline, µg, mean ± SD	965 ± 712	673 ± 572	.06
Total noradrenaline during CPB, µg/min, median (IQR)	11.4 (10-19)	7.3 (4-11)	.016
Total phenylephrine, µg, median (IQR)	2515 (0-6769)	1176 (300-3375)	.42
Total phenylephrine during CPB, µg/min, median (IQR)	36 (0-90)	20 (5-41)	.38

SD, Standard deviation; BMI, body mass index; IQR, interquartile range; ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; LVEF, left ventricular ejection fraction; CPB, cardiopulmonary bypass.