



Number of attempts and interventions to obtain a valid pulmonary artery wedge pressure

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Background: A valid pulmonary artery wedge pressure (PAWP) is essential for the hemodynamic characterization of pulmonary hypertension (PH). We prospectively investigated the methodology for obtaining a valid PAWP measurement, while assessing the impact of prespecified factors on its determination.

Methods: In this prospective observational cohort study, we included consecutive patients who underwent right heart catheterization (RHC) using fluoroscopy at the Pulmonary Vascular Disease program at Cleveland Clinic, between February and May 2023. Once a valid PAWP was obtained, we recorded the number of attempts, reason for repeating the determination, pulmonary artery location, depth of the pulmonary artery catheter (PAC) from the introducer hub, and inflation volume of the PAC balloon.

Results: We included 195 patients, age: 57.5 ± 15.7 years, 111 (57%) women, 156 (80%) with PH. The PAWP was 16.4 ± 5.9 mmHg, requiring 1, 2 and ≥ 3 attempts for a valid measurement in 139 (71%), 39 (20%) and 17 (9%) patients, respectively. PAWP was repeated due to abnormal waveform, incomplete wedge and over wedge. A valid PAWP was obtained in the right pulmonary circulation in 168 (86%) patients, and in the lower third in 134 (69%), middle third in 58 (30%), and upper third of the lung in 3 (2%) patients. The pulmonary artery catheter balloon inflation at valid PAWP was 1.0 ± 0.3 mL, at a distance from the introducer hub of 52.6 ± 5.2 cm. Aspiration of blood in PAW position was obtained in 141 (72%) patients with an arterial oxygenation of 97% (95–99%). The number of measurements for a valid PAWP was directly associated with mean pulmonary artery pressure (mPAP) ($r=0.18$, $P=0.01$), PAWP ($r=0.22$, $P=0.002$), and pulmonary artery diameter on computed tomography ($r=0.16$, $P=0.04$).

Conclusions: A valid PAWP was obtained during the first or second attempt in about 90% of patients that undergo RHC. Advanced interventions such as relocating the PAC to a different place of the same lung or contralateral pulmonary circulation are needed in about 10% of patients.

Keywords: Pulmonary hypertension (PH); pulmonary artery wedge pressure (PAWP); errors in measurement; right heart catheterization (RHC); hemodynamics

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Introduction

Right heart catheterization (RHC) with flow-guided balloon-tipped pulmonary artery catheter (PAC) was introduced by Swan and Ganz in 1970 (1). Currently, over 2 million RHC are performed annually in the US alone. RHC is essential for the diagnosis and hemodynamic classification of pulmonary hypertension (PH). Key hemodynamic determinations include cardiac output (CO), mean pulmonary artery pressure (mPAP) and pulmonary artery wedge pressure (PAWP). A PAWP >15 mmHg in the presence of PH (mPAP >20 mmHg) indicates either isolated post-capillary PH [when pulmonary vascular resistance (PVR) is <2 Wood units (WU)] or combined pre- and post-capillary PH (when PVR is \geq 2 WU) (2).

The most challenging hemodynamic determination during RHC is the PAWP, given potential errors in the measurement that lead to hemodynamic misclassification and inadequate management (3,4). Five criteria are used to define an adequate PAWP measurement: (I) PAWP is less than the diastolic pulmonary artery pressure (PAP); (II) tracing is compatible with the atrial pressure waveform; (III)

fluoroscopic image demonstrates a stationary PAC; (IV) free flow is present within the PAC (flush test) and (V) highly oxygenated blood is obtained from the distal port of the PAC (5).

Although the acquisition of valid PAWP is of utmost importance, there is limited information regarding the methodology for measuring this pressure (5). Therefore, the main objective of the present study is to carefully evaluate the process of acquiring a valid PAWP, describing the methodology, including number of attempts required and interventions performed to obtain a valid PAWP. In addition, we recorded prespecified clinical, hemodynamic, and radiographic factors to assess their role with difficulties in obtaining a valid PAWP in the first attempt. We present this article in accordance with STROBE reporting checklist (available at <https://cdt.amegroups.com/article/view/10.21037/cdt-24-189/rc>).

Methods

Study participants and design

In this prospective observational cohort study, we included consecutive patients who underwent PAC at the Cleveland Clinic Pulmonary Vascular Disease program, between February 2023 and May 2023. Hemodynamic data during RHC was prospectively collected as part of a quality improvement project, with the goal of identifying factors affecting a valid PAWP acquisition. All patients during the study period were included as we were able to obtain a valid PAWP in all of them. Standard of care was followed in all patients, and no specific interventions were performed as part of the present study. Additional clinical, echocardiographic, and radiographic data were retrospectively collected as part of a Cleveland Clinic Institutional Review Board (IRB) approved project (IRB No. 23-517). Informed consent was waived. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013).

The RHC was ordered by the patient's treating physician for a variety of reasons including suspected PH, re-evaluation of previously known PH, or as a component of an invasive cardiopulmonary test performed for dyspnea of unknown origin, exercise intolerance and/or chronic thromboembolic disease.

RHC including PAWP measurement:

RHC was performed in the outpatient setting by three

Highlight box

Key findings

- We found that a valid pulmonary artery wedge pressure (PAWP) was obtained in the first or second attempt in 71% and 91% of the patients, respectively. A valid PAWP was obtained in the right pulmonary circulation in 86% of the patients with a pulmonary artery catheter balloon inflation of around 1 mL and at a distance from the introducer hub of about 53 cm. The main reason for repeating the PAWP was incomplete wedge, and the main intervention was to advance the pulmonary artery catheter.

What is known and what is new?

- Errors in the determination of the PAWP are common and may lead to hemodynamic misclassification and inadequate management. There is limited information regarding the methodology used for measuring the PAWP.
- The present manuscript carefully evaluates the process of acquiring a valid PAWP, describing the methodology, including number of attempts required and interventions performed to obtain a valid PAWP.

What is the implication, and what should change now?

- This is the first study that systematically evaluated the process of obtaining a valid PAWP in a relatively large cohort of patients who underwent right heart catheterization predominantly for pulmonary hypertension. The data presented provide guidance on what to expect and do when obtaining a valid PAWP determination.



Figure 1 Pulmonary artery wedge pressure determination. The figure shows three attempts to obtain a valid PAWP determination. The initial attempt corresponded to over wedge (A), with a rapid and linear increase in vascular pressure without the characteristic PAWP waveform. Therefore, the PAC was withdrawn. In the second determination, we observe an incomplete PAWP (B), with vascular pressures higher than the diastolic PAP and lacking the characteristic PAWP waveform. Hence the PAC was slightly advanced. In the third determination we observe a valid PAWP (C) with a vascular pressure that is lower than the diastolic PAP, while depicting characteristic waveform and the expected respiratory oscillation in vascular pressures. The white arrows pointing upwards mark the moment of PAC balloon inflation. The red arrows pointing upwards mark the time of PAC balloon deflation. The green arrow points the place for a valid PAWP determination (mid “a” wave at end-expiration). Y axis shows electrocardiographic leads in DII and V5, Resp, SPO₂ and PA vascular pressure determinations with pressure scale lines every 9 mmHg starting from 0 mmHg. PAWP, pulmonary artery wedge pressure; PAC, pulmonary artery catheter; PAP, pulmonary artery pressure; Resp, respiratory impedance; SPO₂, pulse oximetry; PA, pulmonary artery.

experienced operators using local anesthesia (6,7). In all cases we accessed the right internal jugular vein with ultrasound guidance. An 8.5 Arrow (Arrow International LLC, Morrisville, NC, USA) introducer was placed. We used 3 types of C-tip, thermodilution PAC manufactured by Edwards (Edwards Lifesciences LLC, Irvine, CA, USA), including (I) a standard 4 lumen 7 Fr (131F7) for regular RHC, (II) a Paceport 5 lumen 7.5 Fr (931F75) for patients also undergoing exercise in whom we additionally measure the right ventricular pressure, and (III) a synthetic ControlCath 4 Lumen 7 Fr (C146F7) for subjects with latex allergy.

After advancing the PAC to the mid-right atrium, the mean right atrial pressure (RAP) was recorded. Subsequently, the PAC with the balloon inflated was advanced using fluoroscopy until the PAC achieve a stationary position in one of the pulmonary artery (PA) branches. During PAC insertion, no specific interventions were performed to select the right or left pulmonary arteries or a particular third (upper, middle or lower) of the lung for initial hemodynamic measurements.

After the PAC achieved a stationary position by fluoroscopy, the balloon was deflated, and PAP determined. After recording the PAP, the balloon of the PAC was progressively inflated until obtaining an adequate PAWP

waveform or reaching the maximum balloon inflation of 1.5 mL. The minimal volume of air required to obtain an adequate PAWP waveform was recorded. We recorded whether the PAC wedged in the right or left pulmonary circulation and in upper, middle, or lower third of the lung. If the PAWP waveform was considered adequate, then other criteria for a valid PAWP determination were checked (5). In the event of over wedge in the waveform tracing, the PAC was withdrawn (about 1 cm) and if incomplete PAWP was suspected, the PAC was advanced (about 1 cm) (Figure 1).

After the PAC was repositioned, the PAWP was remeasured. If the PAWP waveform was considered adequate, then the other criteria for a valid PAWP determination were checked (5). Similarly, in the presence of over wedge or incomplete PAWP by waveform analysis, the catheter was again withdrawn or advanced, respectively, and PAWP remeasured. If the PAWP waveform was still inadequate, the PAC was relocated in the contralateral pulmonary circulation using fluoroscopy and a J tip 0.025” wire. The PAC was then advanced until stationary on fluoroscopy, following the steps previously described. Both the mPAP and the valid PAWP were measured at end-expiration, using electronic calipers and waveform tracings including three respiratory cycles. CO was measured by thermodilution and PVR was calculated as $(mPAP - PAWP)/CO$.

Once a valid PAWP was obtained, we recorded the PA location, number of attempts, the reason for repeating the determination, interventions performed, the depth of the PAC from the introducer hub, and the need to access the contralateral pulmonary circulation. In all patients we tried to obtain PAW blood for gasometry using co-oximetry and recorded if this was successful. If PAW blood could not be obtained or wedge blood oxygen saturation (SwO_2) was $<88\%$, we still consider a PAWP valid if all other criteria for a valid PAWP were met (8). The depth of the PAC from the introducer hub to wedge position was added later in the protocol and therefore only recorded in 1/3 of patients.

Additional data collected

We retrospectively collected data on demographics, type of PH based on the 2022 ERS/ESC guidelines, need for oxygen supplementation, World Health Organization (WHO) functional class, risk assessment based on the Registry to Evaluate Early and Long-Term PAH Disease Management (REVEAL) light 2 and 3-strata Noninvasive French criteria, and right heart function by echocardiography (2,8,9). In addition, we measured the PA diameter and the PA/aorta (Ao) diameter ratio in patients with available contrast and non-contrast computed tomography of the chest.

Statistical analysis

Continuous data are presented as mean \pm standard deviation (SD) or median [interquartile range (IQR)], as appropriate. Normal distribution of the data was assessed with Q-Q plots and Shapiro-Wilk test. Categorical data are summarized as discrete values and percentages [n (%)]. We chose a convenience sample size that included all patients that underwent RHC during the 4-month period of our quality improvement project. We specifically chose to use a 4-month window based on the prior year number of cases and the goal of including a representative sample size of >150 patients in our project. Comparison of continuous variables among three subgroups (1, 2 or ≥ 3 PAWP measuring attempts) was performed with analysis of variance (ANOVA) or Kruskal-Wallis based on normality. Categorical data among three groups was compared with Chi-square test. Groups of independent continuous variables were contrasted with *t*-test. We tested the association between number of PAWP measuring attempts and a series of continuous prespecified variables using Pearson or Spearman rank correlation. A P value of <0.05

was considered significant. The statistical analyses were performed using the statistical package IBM SPSS, version 22 (IBM; Armonk, NY, USA).

Results

Patient characteristics

We included 195 patients, age: 57.5 ± 15.7 years, 111 (57%) women. A total of 39 (20%) patients had no PH, while the rest had PH due to a variety of conditions (Table 1). Only 41 (21%) patients were on PAH-specific medications at the time of RHC, including 12 who were treated with parenteral prostacyclin therapy. The PA diameter on computed tomography (n=163) was 32.0 ± 7.1 mm with a PA/Ao ratio of 1.03 ± 0.22 (Table 1).

Hemodynamic determinations

The PAWP was 16.4 ± 5.9 mmHg and the PVR was 2.7 (1.5–4.6) WU. Pre-capillary, isolated post-capillary and combined pre- and post-capillary PH were observed in 55 (28%), 24 (12%) and 64 (33%) patients, respectively (Table 2).

Number of attempts to obtain a valid PAWP

The number of attempts to get a valid PAWP was 1, 2 and ≥ 3 in 139 (71%), 39 (20%) and 17 (9%) patients, respectively (Tables 1,2). In the group with ≥ 3 PAWP attempts, 10 patients required 3, 5 patients required 5, while the remaining 2 patients required 5 and 9 attempts, respectively.

Methodology to obtain a valid PAWP

In 124 (64%) patients we used a conventional triple lumen Edwards 7F PAC. The distance from the introducer hub to the tip of the PAC, at first PAWP attempt was 52.3 ± 4.6 cm (n=64) with a PAC balloon inflation of 1.1 ± 0.3 mL. The PAC preferentially went to the right pulmonary circulation in 184 (94%) patients, predominantly to the lower and middle third of the lung in 188 (96%) patients (Table 2).

Factors associated with valid PAWP at first attempt

A valid PAWP at first, versus more than one attempt,

Table 1 Baseline characteristics

Variables	Overall (N=195)	1 PAWP attempt (N=139)	2 PAWP attempts (N=39)	≥3 PAWP attempts (N=17)	P (ANOVA, Kruskal-Wallis, Chi-square test)
Age (years)	57.5±15.7	57.3±15.7	56.7±17.0	61.3±12.8	0.58
Female	111 [57]	78 [56]	23 [59]	10 [59]	0.94
BMI (kg/m ²)	32.5±9.8	31.7±8.7	34.3±12.6	34.9±10.6	0.19
BSA (m ²)	2.00±0.28	1.98±0.27	2.04±0.34	2.04±0.28	0.31
O ₂ supplementation (yes)	54 [28]	36 [26]	12 [31]	6 [35]	0.64
FiO ₂ (%)	27.4±15.6	27.6±16.6	27.6±14.9	25.8±7.5	0.91
COPD (yes)	46 [24]	37 [27]	8 [21]	1 [6]	0.14
Asthma (yes)	55 [28]	39 [28]	13 [33]	3 [18]	0.49
Obstructive sleep apnea (yes)	98 [50]	74 [53]	17 [44]	7 [41]	0.42
Hx of pulmonary embolism (yes)	36 [19]	22 [16]	9 [23]	5 [29]	0.28
Diabetes mellitus (yes)	59 [30]	39 [28]	11 [28]	9 [53]	0.10
Coronary artery disease (yes)	65 [33]	42 [30]	16 [41]	7 [41]	0.15
Connective tissue disease (yes)	34 [17]	22 [16]	7 [18]	5 [29]	0.38
PH groups [^]					0.25
No PH	39 [20]	34 [24]	4 [10]	1 [6]	
Group 1	39 [20]	25 [18]	10 [26]	4 [24]	
Group 2	51 [26]	34 [24]	13 [33]	4 [24]	
Group 3	35 [18]	26 [19]	7 [18]	2 [12]	
Group 4	27 [14]	17 [12]	5 [13]	5 [29]	
Group 5	4 [2]	3 [2]	0 [0]	0 [0]	
Severity of PAH (N=34)					
REVEAL lite 2*	7.2±3.0	7.1±3.0	8.2±5.3	5.3±2.5	0.34
French risk score*	2.2±0.8	2.2±0.9	2.3±0.9	2±0.0	0.84
Echocardiogram					
RVSP (N=131)*	52±25	52±24	53±25	52±28	0.98
TAPSE (N=139)*	2.0±0.5	2.0±0.5	2.1±0.6	1.9±0.5	0.72
RV function (N=177)*					0.93
Normal	112 [63]	80 [64]	22 [61]	10 [67]	
Reduced	65 [37]	46 [37]	14 [39]	5 [33]	
NT-pro BNP (N=154)*	250 [68–1,638]	212 [63–1,332]	266 [106–1,835]	299 [125–1,478]	0.59
PAH-specific medications at RHC (yes)	41 [21]	28 [20]	7 [18]	6 [35]	0.31
Number of PAH medications					0.45
1	17 [42]	12 [43]	1 [14]	4 [67]	
2	12 [29]	8 [29]	3 [43]	1 [17]	
3	12 [29]	8 [29]	3 [43]	1 [17]	
Parenteral prostacyclin at RHC (yes)	12 [6]	8 [6]	3 [8]	1 [6]	0.91
PA diameter (mm) (N=163)	32.0±7.1	31.4±6.5	32.1±7.3	35.7±9.5	0.08
PA/Ao diameter (N=163)	1.03±0.22	1.02±0.23	1.02±0.21	1.09±0.25	0.53

Data are presented as mean ± SD, median [IQR] or n [%]. *, only variables with n<195; ^, PH groups based on the 2022 ESC/ERS Guidelines for the diagnosis and treatment of pulmonary hypertension. BMI, body mass index; BSA, body surface area; FiO₂, fraction of inspired oxygen; COPD, chronic obstructive pulmonary disease; Hx, history; PH, pulmonary hypertension; PAH, pulmonary arterial hypertension; RVSP, right ventricular systolic pressure; TAPSE, tricuspid annular plane systolic excursion; RV, right ventricle; NT-pro BNP, N-terminal pro-brain natriuretic peptide; RHC, right heart catheterization; PA, pulmonary artery; Ao, aorta; PAWP, pulmonary artery wedge pressure; SD, standard deviation; IQR, interquartile range; ESC, European Society of Cardiology; ERS, European Respiratory Society.

Table 2 Hemodynamic determinations

Variables	Overall (N=195)	1 PAWP attempt (N=139)	2 PAWP attempts (N=39)	≥3 PAWP attempts (N=17)	P (ANOVA, Kruskal- Wallis, Chi-square test)
Physician performing the procedure					0.53
#1	143 [73]	105 [73]	28 [20]	10 [7]	
#2	30 [15]	19 [63]	6 [20]	5 [17]	
#3	22 [11]	15 [68]	5 [23]	2 [9]	
PAC used					0.10
Edwards 7F	124 [64]	84 [60]	27 [69]	13 [76]	
Edwards Paceport 7.5F	59 [30]	49 [35]	8 [21]	2 [12]	
Edwards synthetic ControlCath 7F	12 [6]	6 [4]	4 [10]	2 [12]	
Initial PAC distance from hub (cm) (N=65*)	52.3±4.6	51.9±4.4	54.8±4.8	52.5±6.4	0.27
Final PAC distance from hub (cm) (N=65*)	52.6±5.2	51.9±4.4	56.9±4.9	52.8±10.0	0.04
Initial location of the PAC					0.82
Right PA	184 [94]	132 [95]	36 [92]	16 [94]	
Left PA	11 [6]	7 [5]	3 [8]	1 [6]	
Final location of the PAC					<0.001
Right PA	168 [86]	132 [95]	31 [80]	5 [29]	
Left PA	27 [14]	7 [5]	8 [21]	12 [71]	
Initial location of the PAC					<0.001
Lower third of the lung	136 [70]	93 [67]	27 [69]	16 [94]	
Middle third of the lung	52 [27]	45 [32]	7 [18]	0 [0]	
Upper third of the lung	7 [4]	1 [1]	5 [13]	1 [6]	
Final location of the PAC					0.30
Lower third of the lung	134 [69]	93 [57]	30 [77]	11 [65]	
Middle third of the lung	58 [30]	45 [32]	8 [21]	5 [29]	
Upper third of the lung	3 [2]	1 [1]	1 [3]	1 [6]	
Initial PAC balloon volume (mL)	1.1±0.3	1.0±0.3	1.1±0.4	1.2±0.3	0.02
Final PAC balloon volume (mL)	1.0±0.3	1.0±0.3	1.0±0.3	1.2±0.4	0.14
Atrial fibrillation at RHC (yes)	8 [4]	6 [4]	2 [5]	0 [0]	0.66
RAP (mmHg)	11.2±5.5	10.6±4.8	12.6±7.5	12.7±4.9	0.07
mPAP (mmHg)	34.4±15.9	32.9±15.2	36.2±17.1	43.0±16.9	0.03
PAWP (mmHg)	16.4±5.9	15.7±5.2	17.1±7.1	20.4±6.2	0.005
CI (L/min/m ²)	3.1±0.8	3.0±0.8	3.2±1.0	3.0±1.1	0.68
PVR (WU)	2.7 [1.5–4.6]	2.6 [1.4–4.4]	2.7 [1.7–6.1]	3.6 [2.3–6.0]	0.33

Table 2 (continued)

Table 2 (continued)

Variables	Overall (N=195)	1 PAWP attempt (N=139)	2 PAWP attempts (N=39)	≥3 PAWP attempts (N=17)	P (ANOVA, Kruskal-Wallis, Chi-square test)
Pulmonary hemodynamic classification					0.08
No PH	39 [20]	34 [25]	4 [10]	1 [6]	
Pre-capillary PH	55 [28]	39 [28]	13 [33]	3 [18]	
Isolated post-capillary PH	24 [12]	16 [12]	6 [15]	2 [12]	
Combined pre- and post-capillary PH	64 [33]	41 [30]	12 [31]	11 [65]	
Unclassified PH	13 [7]	9 [7]	4 [10]	0 [0]	
Wedge blood obtained (yes)	141 [72]	100 [72]	29 [74]	12 [71]	0.94
SwO ₂ (N=141)*	97 [95–99]	97 [95–98]	98 [96–99]	97 [93–99]	0.40

Data are presented as mean ± SD, median [IQR] or n [%]. *, only variables with n <195. PAC, pulmonary artery catheter; PA, pulmonary artery; RAP, right atrial pressure; mPAP, mean pulmonary artery pressure; PAWP, pulmonary artery wedge pressure; CI, cardiac index; PVR, pulmonary vascular resistance; WU, Wood units; PH, pulmonary hypertension, SwO₂, oxygen saturation in wedge blood; SD, standard deviation; IQR, interquartile range.

required a lower air volume of the PAC balloon (1.0 ± 0.3 vs. 1.2 ± 0.4 mL, $P=0.006$) and a shorter distance from the hub [51.9 ± 4.4 (n=52) vs. 54.0 ± 5.2 cm (n=12), $P=0.16$]. PAWP was valid in the first attempt in 132/184 (72%) of the patients in whom the PAC initially went to the right pulmonary circulation and in 7/11 (64%) patients in whom the PAC initially went to the left side ($P=0.56$). Interestingly, the PAWP was valid in 93/136 (68%) patients in whom the initial PAWP was attempted in the lower, 45/52 (87%), in the middle and 1/7 (14%) in the upper third of the lung ($P<0.001$).

PAWP remeasurement

Reasons for repeating the initial PAWP measurement (n=56) were unusual waveform: 7 (13%), incomplete wedge: 38 (68%) and over wedge: 11 (20%). Initial PAC manipulation consisted in advancing and withdrawing the PAC in 36 (64%) and 12 (21%) patients, respectively; or due to the vascular anatomy directing the PAC to the contralateral PA in 8 (14%) patients (Table 3). Pertinent data on subsequent PAWP remeasurements are provided in Table 3.

In 2 patients after the third unsuccessful attempt to obtain a valid PAWP, including PAC repositioning to the contralateral circulation, the standard Edwards PAC was changed to a polymer blend Control Catheter (C144F7). In both cases, the PAC was wedged in the lower third of the left pulmonary circulation with balloon inflation of

0.7 and 1.1 mL, at 60 and 61 cm from the introducer hub, respectively.

Characteristics of a valid PAWP

Overall, a valid PAWP was obtained in the right pulmonary circulation in 168 (86%) patients. In the rest [n=27 (14%)], the PAWP was obtained in the left pulmonary circulation (spontaneously in 11 patients and as a result of PAC repositioning in 16 patients) (Table 2). The PAC balloon inflation at valid PAWP was 1.0 ± 0.3 mL (range, 0.3–1.5 mL), at a distance from the hub of 52.6 ± 5.2 cm (range, 41–70 cm, n=65). The final lung location of the valid PAWP was the lower in 134 (69%), middle in 58 (30%), and upper third in 3 (2%) patients (Table 2). The PAC distance from the hub to a valid PAWP was similar in the right and left lung [52.4 ± 4.6 (n=56) vs. 53.8 ± 8.2 cm (n=9), $P=0.47$], as it was the degree of balloon inflation (1.0 ± 0.3 vs. 1.1 ± 0.3 mL, respectively, $P=0.66$).

PAW blood gasometry

Blood from the PAW position was obtained in 141 (72%) patients, with SwO₂ of 97% (95–99%). Of the patients in whom PAW blood was obtained, only 5 had a SwO₂ <88%. Even though wedge blood showed a lower saturation than expected, all other criteria for a valid PAWP were met and no further attempts to remeasure the PAWP were made in

Table 3 Reasons for PAWP remeasurement and required PAC manipulations

Variables	First PAWP remeasurement (N=56)	Second PAWP remeasurement (N=17)	Third PAWP remeasurement (N=8)	Forth PAWP remeasurement (N=2)
Reason for a non-valid PAWP				
Incomplete	38 [68]	10 [59]	4 [50]	1 [50]
Over wedge	11 [20]	3 [18]	3 [38]	1 [50]
Unusual waveform	7 [13]	4 [24]	1 [13]	0 [0]
PAC manipulation				
Advance	36 [64]	10 [59]	4 [50]	1 [50]
Pullback	12 [21]	2 [12]	1 [13]	1 [50]
Reposition to the contralateral pulmonary circulation	8 [14]	5 [29]	3 [38]	0 [0]

Data are presented as n [%]. PAWP, pulmonary artery wedge pressure; PAC, pulmonary artery catheter.

these subjects.

Factors associated with the number of measuring attempts to get a valid PAWP

The number of PAWP measurements to obtain a valid PAWP was directly associated with RAP ($r=0.16$, $P=0.03$), mPAP ($r=0.18$, $P=0.01$), PAWP ($r=0.22$, $P=0.002$), PA diameter ($r=0.16$, $P=0.04$) and initial PAC balloon inflation ($r=0.18$, $P=0.007$); but not PVR or severity of PH by REVEAL light 2 or French noninvasive criteria risk scores.

Discussion

In the present study we found that a valid PAWP was obtained in the first or second measuring attempt in 71% and 91% of the patients, respectively. A valid PAWP was obtained in the right pulmonary circulation in 86% of the patients with a PAC balloon inflation of around 1 mL and at a distance from the introducer hub of about 53 cm. PAW blood could only be obtained in 72% of the patients, even when all other criteria for a valid PAWP were met. The main reason for repeating the PAWP was incomplete wedge, and the main intervention was to advance the PAC catheter. In 8% of the patients the PAC had to be repositioned to the contralateral pulmonary circulation using wire support, and in two patients the standard PAC had to be replaced for a more rigid PAC. Factors weakly associated with the number of attempts to obtain a valid PAWP included a higher RAP, mPAP, PAWP, PA diameter and initial wedging of the PAC in the upper third of the lung.

The PAWP is an essential determination for the hemodynamic classification of the patients with PH; however, errors in the measurement are common (3,4). We have previously demonstrated that in order to obtain a valid PAWP, both repositioning of the PAC and a lower PAC balloon inflation may be needed to facilitate the complete occlusion of the PA branch that is wedged (5,10). For the first time, we have prospectively recorded the number of measuring attempts needed to obtain a valid PAWP, the reasons for repeating it and corrective maneuvers applied. It is critical to mention that the PAWP determination was done under fluoroscopy, in a large volume academic center, by three experienced operators, and following a strict protocol (11). Therefore, it is likely that the number of measuring attempts to obtain a valid PAWP will increase when performing this procedure without fluoroscopy guidance and/or by less experienced operators.

A valid PAWP was obtained at a PAC distance from the introducer hub of slightly more than 50 cm and at a PAC balloon inflation of 1 mL, values that can serve as guide in the absence of fluoroscopy (5,12). Advancing or withdrawing the PAC based on the PAWP waveform analysis is certainly possible at bedside. However, more complicated interventions (noted in 9% of our cohort) such as repositioning the PAC in the contralateral PA and/or a different portion of the lung and switching the PAC for a more rigid one are best performed under fluoroscopy guidance (12).

We were not able to identify factors strongly associated with the difficulty in obtaining a valid PAWP. In fact, neither the PH clinical groups or the PH hemodynamic

groups were associated with the number of attempts to obtain a valid PAWP. Similarly, in our cohort, the operator, type of PAC, and the initial location of the PAC in the right *vs.* left PA had not significant impact in the process of acquiring valid PAWP. However, the initial PAC position in the upper third of the lung frequently led to an inadequate PAWP measurement and hence the need to reposition the PAC. Importantly, both mid and lower lung zones yield similar percentages of a valid PAWP. Ideally, PAWP is obtained in zone 3 of the lung, which is in the lung bases in the upright position (13). However, since all hemodynamic measurements obtained in our study are in supine position, traditional lung zones differ, since the dominant effect of gravity is in the anterior to posterior axis instead of apical to basal. In fact, in supine position zone 3 is the most posterior. The methodology of advancing the PAC with balloon inflated until stationary tends to guide the balloon to a vessel with adequate flow, likely in zone 3 (14). No patients had conditions in which the zone 3 was reduced in supine position such as the use of positive end-expiratory pressure, mechanical ventilation or hypovolemia.

Factors that were weakly associated with the number of measuring attempts before a valid PAWP determination were a higher RAP, mPAP and PAWP. The explanation for these associations, could be that a more tortuous pulmonary circulation due to vascular remodeling secondary to higher pulmonary pressures, interfere with an adequate pulmonary vascular seal (15). The need to confirm a higher PAWP may trigger a remeasurement; although this factor did not impact our numbers as we followed a strict protocol to determine a valid PAWP. In the rare event an operator wanted to confirm a valid PAWP determination with a second measurement (even when all criteria for a valid PAWP were present), this was not considered a remeasurement. Importantly, when all criteria were met for a valid PAWP, the rare remeasurement (<10 occasions) always confirmed the initial determination (11).

A larger PA was weakly associated ($r=0.16$) with a higher number of measuring attempts for a valid PAWP. This was noted when the PAWP attempts were incorporated as continuous variable. We noted a trend towards a significant association between a larger PA and measuring attempts when we clustered them into three groups (1, 2 and ≥ 3). It is plausible that larger proximal PA vessels with rapid tapering may complicate the seal of the PAC balloon, likely causing an incomplete wedge and requiring the advancement of the PAC to a more distal vascular area.

Our study has limitations such as the use of fluoroscopy

and a strict protocol that limits the extrapolation of our findings to less experienced centers, bedside PAC placement, or RHC for conditions other than PH. Our findings are only applicable when performing the RHC through the right internal jugular vein, using 7 or 7.5 F PAC. The variables reported were available in all patients, except for the PAC distance from the vascular introducer hub to wedge position that was not part of our initial data collection protocol, and a number of missing echocardiograms, NT-pro BNP, and PA diameter determinations. Despite these limitations, this is the first study that systematically evaluated the process of obtaining a valid PAWP in a relatively large cohort of patients who underwent RHC predominantly for PH.

Conclusions

A valid PAWP was obtained at the first or second attempt in about 90% of the patients that undergo a RHC, with a PAC balloon inflation volume of about 1 mL. Incomplete PAWP or over wedge are relatively common and can generally be corrected by advancing or withdrawing the PAC, respectively. PAC that wedge in the upper third of the lung usually provide inadequate PAWP determinations and need repositioning. In about 10% of patients more advanced interventions requiring fluoroscopy for reposition or switching to a stiffer PAC are needed.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was Cleveland Clinic IRB approved project (IRB No. 23-517) and informed consent was waived.

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