

AHA SCIENTIFIC STATEMENT

Standardization of Baseline and Provocative Invasive Hemodynamic Protocols for the Evaluation of Heart Failure and Pulmonary Hypertension: A Scientific Statement From the American Heart Association

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ABSTRACT: Contemporary hemodynamic testing intersects with many aspects of cardiovascular disease management. There is a growing understanding that accurate diagnosis, phenotyping, and management of cardiogenic shock, heart failure with preserved ejection fraction, and pulmonary hypertension, and left ventricular assist device support, require both baseline and provocative invasive hemodynamic testing, and often serial measurements. However, there is limited consensus regarding the standardization and interpretation of hemodynamic data. Provocative hemodynamic studies—whether related to volume, drugs, exercise, or device speed—are similarly nonuniform. A frequent limitation to their routine use relates to a lack of concise information regarding provocative study protocols. The aim of this scientific statement is to provide the evidence and rationale underlying best practices for static and provocative right heart catheterization, as well as actionable protocols to standardize their practice. In addition to outlining optimal resting right heart catheterization assessment, indications, and methods for vasodilator challenges to assess pulmonary hypertension reversibility in heart failure, this scientific statement includes discussion on volume challenges, invasive exercise hemodynamic testing, and vasodilator testing for acute pulmonary hypertension. Ramp, reverse-ramp, and exercise studies in patients with left ventricular assist devices are also detailed to help guide care and aid assessment for recovery. The utility and practical application of temporal changes in invasive hemodynamics are covered, from cardiogenic shock to remote patient monitoring. The standardization and advancement of invasive hemodynamic assessment in heart failure represent crucial steps toward optimizing patient outcomes. Continued collaboration across disciplines, enhanced focus on standardization, and investment in emerging technologies are crucial for bridging these gaps and driving innovation.

Key Words: AHA Scientific Statements ■ cardiac catheterization ■ dyspnea, paroxysmal ■ heart failure, diastolic ■ heart failure, systolic ■ hemodynamics ■ hypertension, pulmonary

Right heart catheterization (RHC) is a diagnostic test using invasive hemodynamics. After a period of declining use in the management of decompensated heart failure (HF) due to neutral trial results, pulmonary artery catheter (PAC) use has been increasing.^{1,2} This increased use has been in the context of advancements in understanding of cardiogenic shock, developments in diagnostic

algorithms and treatments for HF with preserved ejection fraction (HFpEF) and pulmonary hypertension (PH), as well as expansion of temporary and durable mechanical circulatory support options. In keeping with these clinical innovations, the utility of invasive hemodynamics has moved beyond a single set of standard parameters measured at rest. There is a growing understanding that

Supplemental Material is available at <https://www.ahajournals.org/doi/suppl/10.1161/HHF.0000000000000088>

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Circulation: Heart Failure is available at www.ahajournals.org/journal/circheartfailure

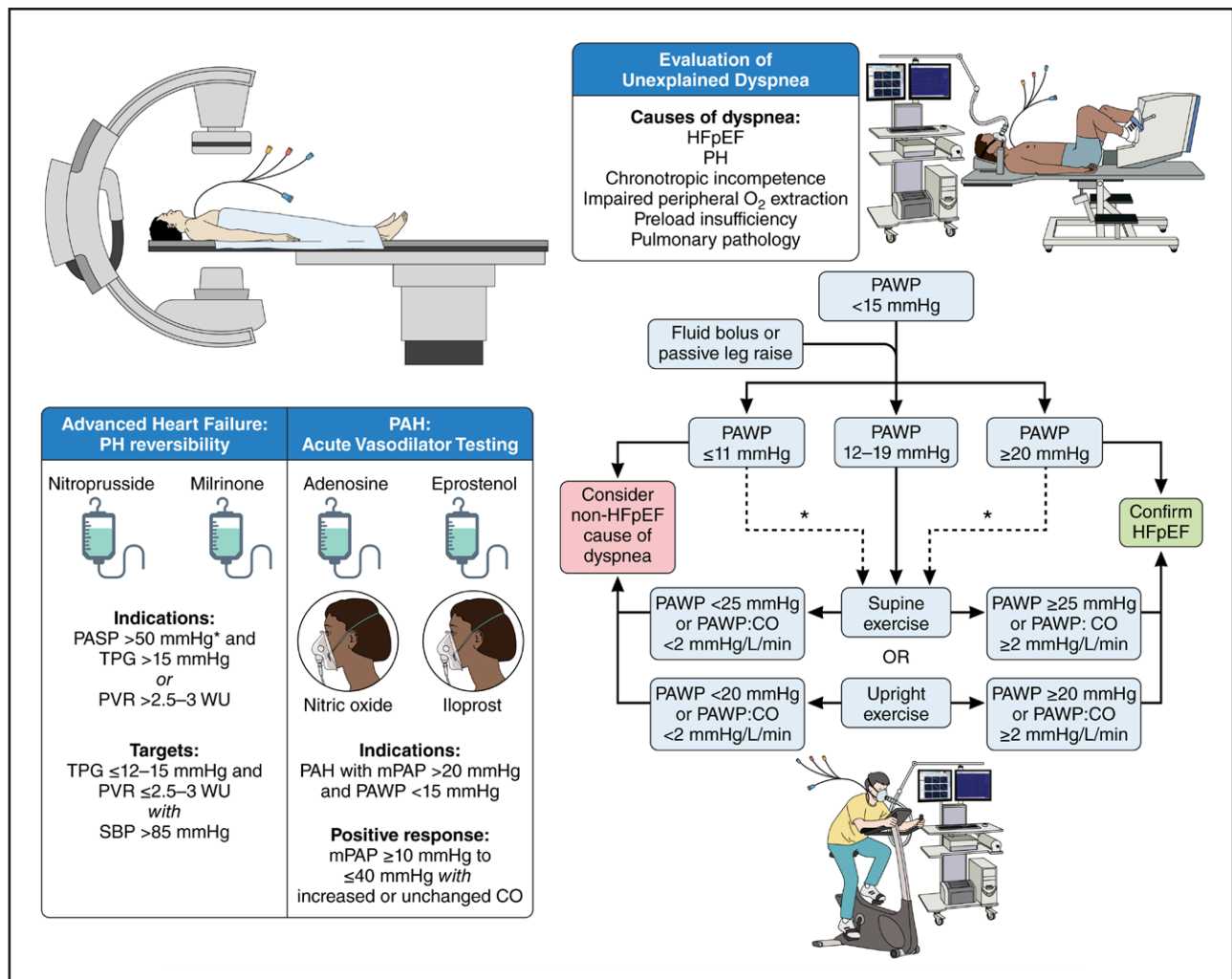


Figure. Combined invasive hemodynamic protocols used to assess pulmonary hypertension reversibility in advanced heart failure, perform acute vasodilator testing in pulmonary arterial hypertension, and evaluate unexplained dyspnea.

*Pulmonary artery systolic pressure (PASP) may not be increased with low cardiac output (CO). Consider testing if transpulmonary gradient (TPG) or pulmonary vascular resistance (PVR) is increased even if PASP is <50 mmHg. Dashed arrow indicates that hemodynamic exercise testing may be considered for further, complementary perturbational phenotyping to understand predominant mechanisms of exercise intolerance. HFpEF indicates heart failure with preserved ejection fraction; mPAP, mean pulmonary artery pressure; PAH, pulmonary arterial hypertension; PAWP, pulmonary artery wedge pressure; PH, pulmonary hypertension; and SBP, systolic blood pressure.

accurate diagnosis, phenotyping, and management of cardiogenic shock, HFpEF, PH, and left ventricular assist device (LVAD) support require both baseline and provocative invasive hemodynamic testing, and often serial measurements, ranging from minutes to months apart.

Despite this increased need, there is limited consensus regarding the standardization and interpretation of hemodynamic data.³ Furthermore, provocative studies—whether related to volume, drugs, exercise, or device speed—are similarly not uniform. A frequent limitation to their routine use relates to a lack of concise information regarding provocative study protocols. In addition, optimizing patients on LVAD support, and assessing for recovery and possible decommissioning or explant, requires nuanced hemodynamic assessment that should reflect current physiologic understanding.

The aim of this scientific statement is to provide the evidence and rationale behind best practices for static and provocative RHC, as well as actionable protocols to standardize their practice (Figure).

BEST PRACTICES AND STANDARDIZATION OF HEMODYNAMIC ASSESSMENT

Preparation for optimal hemodynamic assessment includes proper patient positioning, leveling, transducer zeroing, and confounder minimization to ensure accurate data collection. Fasting is generally not necessary and prescribed medications may be continued.⁴ Ultrasound guidance to identify venous anatomy is now standard of care, often allowing anticoagulation to be safely continued without interruption in most cases,

particularly with access from the internal jugular or brachial veins.^{5,6} Deferring intravenous sedation should be considered, as it may alter breathing patterns, vascular tone, and, possibly, the hemodynamic measures of interest.⁷ Topical or local anesthesia is favored. If premedication is required to manage anxiety, oral agents should be considered.

With the patient in the supine position, the transducer should be leveled with the mid-chest, approximating the level of the right atrium.⁸ For upright measurements, the transducer should be leveled with the phlebostatic axis, which is the intersection of the 4th intercostal space and the mid-chest. When the patient is supine, this location can be identified using fluoroscopy to mark the level of the right atrium on the chest wall to use for leveling after the patient moves to an upright position.⁹ A plane at this intersection can be used as a reference line in the semi-upright and upright position.^{8,10,11} The transducer is zeroed by opening the system to air to equilibrate with atmospheric pressure. Pressures measured are not absolute pressures, but rather pressure differences between hydrostatic pressures at the zero reference level (ie, where the transducer is placed). Pressure measurements should be taken during spontaneous breathing without breath-holding maneuvers, which can lead to inadvertent Valsalva with associated decreases in ventricular preload. Pressures should generally be measured at end-expiration, when the intrathoracic pressure most closely approximates atmospheric pressure.¹⁰ Use of average pressure values automatically displayed on clinical monitors should be discouraged as the algorithms incorporated into these values do not account for the effects of respiration or ectopy.¹² In some circumstances (eg, mechanical ventilation, obesity, severe lung disease, hyperventilation, exercise), there may be wide respiratory variations and augmented intrathoracic pressures that lead to an end-expiratory pressure that is higher than at atmospheric pressure. In these circumstances, the average pressure across the respiratory cycle may be taken, or both end-expiratory and average may be reported.^{10,13–17}

Filling Pressures

Right atrial pressure (RAP) and pulmonary artery wedge pressure (PAWP) measurements should be taken at end-diastole, when the atrioventricular valves are open, to best approximate ventricular end-diastolic pressure, corresponding with the mean of the a-wave for those in sinus rhythm. Avoid measurement during or just after an ectopic beat. For patients in atrial fibrillation, the PAWP should be measured 130 to 160 ms after the onset of the QRS and before the V-wave.¹⁸

Measurement of the PAWP requires particular attention; PAWP serves as a surrogate for the left ventricular (LV) end-diastolic pressure (in the absence of clinically

significant mitral stenosis) and is obtained by balloon occlusion of the distal pulmonary artery (PA) creating a static column of blood between the PA and the left atrium. Incomplete occlusion will incorporate contributions from the PA, leading to falsely elevated pressure measurements, although there is some evidence that partial balloon inflation may represent more accurate PAWP measurements in patients with pulmonary arterial hypertension (PAH).¹⁹ Overinflation of the balloon may also lead to overestimation of the pressure with loss of typical waveform morphology. Obtaining a saturation (after first discarding 5–10 mL of blood in the wedged position) within 3% to 5% of the measured arterial saturation on the pulse oximeter when in the wedged position will verify appropriate positioning.²⁰ Confirmation is of particular importance when the PAWP is elevated, because inappropriate values could misclassify patients with PAH.^{17,20,21}

In the setting of atrioventricular valvular regurgitation or noncompliant atria, prominent V-waves may be present. Excluding the V-waves would best estimate the ventricular end-diastolic pressure. However, the “mean” PAWP, which incorporates contributions of the V-wave, better quantifies the total contribution of left atrial/pulmonary venous pressure to PH, and should be used in calculations of pulmonary vascular resistance (PVR). Examples of waveforms and interpretation have been recently published in hemodynamic reviews.^{18,22,23}

Estimates of Cardiac Output

Cardiac output (CO) and cardiac index assessment are integral to many aspects of cardiovascular care, including management of cardiogenic shock; evaluation of patients with advanced HF for heart transplantation (including listing priority) or LVAD candidacy; calculation of PVR and systemic vascular resistance (SVR); determination of valvular disease or PH severity; and diagnosis of high-output HF. CO is commonly assessed using thermodilution or Fick methods.

In thermodilution, 10 mL of saline at a known temperature is injected into the proximal port of the catheter, mixes in the right ventricle, and the resultant change in blood temperature is detected in the PA. CO is inversely proportional to the change in temperature.²⁴ The thermodilution process should be repeated with outlying data censored until 3 consistent values within 10% of each other are obtained and averaged. Performing injections at the same point of the respiratory cycle may improve precision.²⁵

The Fick method ($\text{CO} = \text{oxygen consumption} [\text{VO}_2] / \text{systemic arterio-venous oxygen difference}$) is the gold standard for determination of CO if oxygen consumption is measured directly (ie, direct Fick).²⁶ However, direct measurement of VO_2 requires additional equipment and training, and is not available in most cardiac

Table 1. Vasoactive Medication Titration Protocols for Assessment of Reversibility of Pulmonary Hypertension in Advanced Heart Failure

Medication	Formulation	Administration	Contraindications
Nitroprusside	IV: 50 mg/2 mL vials Diluting 50 mg vial in 250 mL dextrose 5% in water yields a concentration of 0.2 mg/mL or 200 µg/mL Infuse with an infusion pump only Light sensitive: cover infusion bag	Initial: 0.25–0.5 µg·kg·min Titration: ↑ 0.50 µg·kg·min q 3–5 min Reassess hemodynamics at each dose or at conclusion of study Max dose: 10 µg·kg·min	SBP <85 mmHg Consider milrinone if SBP <85 mmHg, low SVR, or low CO Consider iNO if PAWP <12 mmHg Consider stopping infusion if PAWP <12 mmHg
Milrinone	IV: 1 mg/mL; 10 mL/20 mL/50 mL vials available Can be diluted in dextrose 5% in water or normal saline 0.9%; diluting 20 mg in 100 mL yields a concentration of 0.2 mg/mL or 200 µg/mL Infuse with an infusion pump only	Bolus: 25–50 µg/kg over 5–10 min Titration: not required Reassess hemodynamics 5 min after bolus	Unstable tachyarrhythmias eGFR <30 mL/min: use with caution; t1/2 is prolonged

Hemodynamic indications: pulmonary arterial systolic pressure >50 mmHg and transpulmonary gradient >15 mmHg or pulmonary vascular resistance > 2.5–3 WU; hemodynamic targets: transpulmonary gradient ≤12–15 mmHg and pulmonary vascular resistance ≤2.5–3 WU, with systolic blood pressure (SBP) >85 mmHg. CO indicates cardiac output; eGFR, estimated glomerular filtration rate; iNO, inhaled nitric oxide; IV, intravenous; PAWP, pulmonary artery wedge pressure; and SVR, systemic vascular resistance.

catheterization laboratories. The indirect Fick method estimates VO₂ using nomograms and formulae derived from infants and children or highly selected homogenous adults without the cardiac disease processes requiring hemodynamic assessment in contemporary practice.^{27–30} Indirect Fick estimation has been demonstrated to be inaccurate in numerous studies. On the other hand, thermodilution has been shown to retain its accuracy, even in the presence of tricuspid regurgitation, although not in the presence of intracardiac shunts or for patients supported by extracorporeal membrane oxygenation.^{31–35}

Advanced Hemodynamic Metrics

Advanced hemodynamic metrics are emerging as valuable diagnostic and prognostic tools in the management of advanced cardiac disease (Supplemental Table 1).¹⁸ Cardiac power output can be used to assess both LV and right ventricular (RV) function. A low LV cardiac power output predicts poor outcomes in acute myocardial infarction followed by cardiogenic shock, and identifies stable patients with advanced HF, but has not proved to be prognostic in patients with HF-associated cardiogenic shock (HF-CS).^{36–38} The original cardiac power output calculation incorporated RAP, which is omitted from the current commonly used formula.³⁹ More recent data show that when RAP is reincorporated into the calculation, the prognostic value improves in acute decompensated HF and HF-CS.^{40–42} LV stroke work index has been used as a surrogate for cardiac reserve.⁴³ Aortic pulsatility index (API) represents the efficiency of ventricular ejection and may be a better marker for prognosis in advanced HF.^{42,44,45} API has been shown to be a predictor of myocardial recovery and ability to wean off temporary mechanical circulatory support.⁴⁶ The RV equivalent, pulmonary arterial pulsatility index, identifies severe RV dysfunction in AMI and predicts RV failure after LVAD.^{47,48} Analogous to the LV stroke work index, the RV stroke work index

accounts for beat-to-beat work of the RV and is prognostic in HF-CS and in postoperative RV failure after LVAD implantation.⁴⁹ The myocardial performance score, which combines API and cardiac power output to reflect the power efficiency of the ventricle, strongly correlates with ventricular coupling and mechanical efficiency of the heart and informs the overall energetic state of the heart.⁵⁰ Whereas most studies have identified dichotomous cut points to define high versus low risk, these metrics all exist on a continuous spectrum of risk and severity, and should be interpreted as such. Further study into the role of routine assessment of advanced hemodynamic data and changes in therapy based on these metrics is needed.

DYNAMIC TESTING FOR PATIENTS WITH HF

Vasodilator Challenges for Assessment of PH Reversibility in HF

There are long-standing, Class I recommendations to perform RHC for patients with HF to evaluate PH and its reversibility during the evaluation of candidacy for heart transplantation, as well as periodically after initial listing.⁵¹ PH remains an important predictor of increased 30-day mortality risk after heart transplant.⁵² The 2024 International Society of Heart and Lung Transplantation (ISHLT) guidelines state that for adult heart transplant candidates with PA systolic pressure >50 mmHg and either a transpulmonary gradient ≥15 or PVR ≥3 Wood Units, the first step is to administer a vasodilator to assess for reversibility of PH.⁵¹ This is commonly done with either intravenous sodium nitroprusside (SNP) or milrinone (Table 1 and Supplemental Table 2). Patients with low CO may not be able to mount an elevated PA systolic pressure, and acute vasoreactivity testing should still be considered in the presence of a high transpulmonary gradient or PVR. Inhaled nitric oxide can also be used for this indication,

Table 2. Vasoactive Medication Titration Protocols for Pulmonary Arterial Hypertension

Medication	Formulation	Dosing/titrations	Stopping criteria/adverse effects	Contraindications
iNO*	Gas mixture, often combined with nitrogen, administered with a face mask, nasal cannula, endotracheal tube, or ventilator	Initial: 10–20 ppm Titrations: every 5 min Max dose: 40–80 ppm PAC measurements: taken after 10–15 min of administration; if positive response, titrate dose down before ceasing administration	Peripheral edema, hypoxemia, systemic hypotension, headache	No contraindications for short-term vasoactive testing in adults with PAH If used to assess for PH reversibility in patients with HF, avoid if PAWP is elevated If patient is hypoxic, consider administering 100% oxygen for 3–5 min and monitoring hemodynamics before initiating iNO
IV epoprostenol*	Vial reconstituted with sterile water for injection or sodium chloride 0.9% Infusion concentration determined on the basis of patient weight and institutional product availability per consultation with pharmacist Administration through central or peripheral venous catheter Infusion sets with an in-line 0.22- μ m filter should be used	Initial: 2 ng·kg ⁻¹ ·min ⁻¹ Titration: 2 ng·kg ⁻¹ ·min ⁻¹ every 10 min Max dose: 12 ng·kg ⁻¹ ·min ⁻¹ PAC measurements: after 10 min at a given dose	Nausea, vomiting, headache, hypotension, flushing, chest pain, anxiety, dizziness, bradycardia, dyspnea, abdominal pain, musculoskeletal pain, tachycardia, pulmonary edema	Pulmonary edema
Inhaled iloprost*	50 μ g in 5 mL of isotonic saline solution and nebulized over 15 min, aerosolized particles at diameter of 2.2 μ m	Initial: 5–17 μ g Titration: none PAC measurements: taken after 10–15 min of administration	Peripheral edema, hypoxemia, systemic hypotension, facial flushing, jaw pain, headache	None for short-term vasoactive testing in adults
Adenosine†	3 mg/mL injection for infusion	Initial: 50 μ g·kg ⁻¹ ·min ⁻¹ Titration: increased by 50 μ g·kg ⁻¹ ·min ⁻¹ at 2–5 min intervals Max dose: $\approx$ 350–500 μ g·kg ⁻¹ ·min ⁻¹ PAC measurements: taken during administration	Reduction in systemic blood pressure to a mean of 70 mm Hg, >50 beats/min increase or decrease in heart rate, chest pressure or heaviness, flushing, dyspnea, headache, tingling, jaw discomfort, abdominal discomfort, numbness of the extremities, nausea	Second- or third-degree AV block Sick sinus syndrome Symptomatic bradycardia (except in patients with a functioning artificial pacemaker) Known or suspected bronchoconstrictive or bronchospastic lung disease, asthma Preexcited atrial fibrillation/flutter Recent administration or consumption of caffeine, aminophylline, theophylline

Indications: patients with pulmonary arterial hypertension (PAH; most commonly idiopathic, heritable, or drug-induced) with mean pulmonary artery pressure >20 mm Hg and pulmonary artery wedge pressure (PAWP) <15 mm Hg. Positive response: decrease in mean pulmonary artery pressure of ≥ 10 to ≤ 40 mm Hg, with an increased or unchanged cardiac output. AV indicates atrioventricular; HF, heart failure; iNO, inhaled nitric oxide; IV, intravenous; PAC, pulmonary artery catheter; and PH, pulmonary hypertension.

*Class I recommendation for vasoreactivity testing in 2022 European Society of Cardiology/European Respiratory Society guidelines for the diagnosis and treatment of pulmonary hypertension.¹²⁵

†No longer recommended in the 2022 European Society of Cardiology/European Respiratory Society guidelines for the diagnosis and treatment of pulmonary hypertension¹²⁵ for vasoreactivity testing due to frequent side effects.

provided the PAWP is not elevated, to avoid pulmonary edema (Table 2).

Sodium Nitroprusside

SNP is a water-soluble salt acting as a prodrug that releases nitric oxide (NO) in reaction with erythrocytes. As a systemic vasodilator, it has both a rapid onset of action and a short half-life of <2 minutes. The failing LV chamber is highly afterload sensitive, and SNP-mediated reduction in SVR enhances ejection and lowers LV filling pressure. Therefore, the immediate hemodynamic effects of SNP initially described for patients with severe refractory HF with reduced ejection fraction included decreases in mean arterial blood pressure and increases in CO.⁵³ In addition, SNP may exert direct effects to improve LV compliance, which may contribute to the marked decreases in PAWP. The effect of SNP to lower PAWP and increase CO is the primary

driver of reductions in PA pressure and PVR. Clinicians should take caution when using SNP in patients with PAH and RV dysfunction, because immediate drops in blood pressure may precipitate decompensation.

Whereas SNP has been deployed as a therapeutic agent for severe refractory HF or as an experimental probe to manipulate vascular tone and ventricular afterload, we have focused on the experience with SNP for immediate vasodilator testing in patients undergoing evaluation for advanced HF therapies (Supplemental Table 2). In the cardiac catheterization laboratory, SNP should only be infused with a volumetric infusion pump for accurate titration. The suggested titration protocol for SNP can be found in Table 1.

Milrinone

Milrinone is a PDE3 (phosphodiesterase-3) inhibitor that decreases the degradation of cyclic adenosine monophosphate, thereby increasing phosphorylation

of multiple proteins to enhance myocardial contractility and systemic vasodilation. The immediate hemodynamic effects of intravenous milrinone in patients with HF include decreases in PAWP, RAP, and SVR, and increases in CO and LV contractility.⁵⁴ Despite similar reductive effects as SNP on systemic blood pressure, SVR, and PAWP, milrinone resulted in higher LV peak positive dP/dt and LV stroke work index, demonstrating more potent inotropic effects.⁵⁵ As such, the effect of milrinone to lower PAWP and increase CO drives the decrease in PA pressure and PVR, respectively, with less dependency on lowering of arterial pressure.

Milrinone has been deployed as a therapeutic agent for severe, refractory HF in both acute hospital-based and ambulatory care. However, there is less experience with milrinone for evaluating PH reversibility in candidates for heart transplantation. There is little information on the specific utility of milrinone-associated hemodynamic thresholds to predict clinical outcomes after heart transplantation (Supplemental Table 2).

Within the cardiac catheterization laboratory setting for patients with advanced HF, intravenous administration of milrinone with a bolus has been reported most frequently. Dosages are calculated as micrograms per kilogram, and typically between 25 and 75 $\mu\text{g}/\text{kg}$ is administered over as little as 1 minute, up to 10 minutes. The bolus infusion has the further advantage of a more rapid challenge, without the requirement for incremental uptitration. A suggested titration protocol for milrinone can be found in Table 1. Based on its more potent inotropic effect, milrinone may be preferable to SNP for patients with HF meeting the ISHLT thresholds for vasodilator testing, but who have hypotension or a reduced SVR, or for whom an elevated PVR is based on a low CO state.

Volume Challenge

There is increasing recognition that nonpharmacologic maneuvers or interventions performed during RHC can unmask pathophysiologic cardiac responses. These interventions are indicated in patients for whom standard cardiac testing at rest does not explain disabling symptoms, such as dyspnea. Maneuvers recommended to unmask occult postcapillary PH include the fluid bolus challenge and the passive leg raise (PLR). However, the current data should be considered in the context of the diagnostic uncertainty regarding specific cutoffs for defining postcapillary PH. In addition to obtaining an accurate hemodynamic assessment, it is imperative to interpret the results in the context of the degree of associated left heart disease, including integration of clinical phenotype, comorbidities, and imaging beyond hemodynamics alone.^{14,56}

The fluid bolus challenge and PLR maneuvers increase cardiac preload. Both tests may result in similar increase in intracardiac pressures: healthy, compliant

hearts are expected to meet modest elevation in biatrial filling pressures with $\approx 10 \text{ mL}/\text{kg}$ at an infusion rate of 100 to 200 mL/min (on average, +5 mmHg in RAP, +6 mmHg in PAWP, and +7 to 8 mmHg in mean PA pressure [mPAP]).^{57,58} This is accompanied by a 1.5- to 2-L CO augmentation, for predominant stroke volume (+12–13 mL) rather than heart rate (+6 bpm) increase (Supplemental Table 3).^{57–63} The extent of filling pressure and CO elevation may be independent from baseline hemodynamics. A steeper increase in pressure has been suggested in elderly patients, particularly older women.^{57,63}

In symptomatic patients, both the fluid bolus challenge and PLR may be considered during RHC in patients with risk factors for postcapillary PH (eg, elevated natriuretic peptide levels, structural changes on cardiac imaging, associated conditions such as systemic sclerosis).^{4,11,56,64,65} PAWP $\geq 19 \text{ mmHg}$ has been proposed as the diagnostic threshold for occult postcapillary PH after both fluid bolus challenge and PLR tests, with excellent positive predictive value, and PLR has been suggested to rule out postcapillary PH when PAWP is $\leq 11 \text{ mmHg}$.⁴ These admittedly robust findings are from a single-center study, and more data are needed for confirmation. Nevertheless, the high proportion of intermediate results (ie, PAWP 12–18 mmHg) may limit its diagnostic utility. Positive fluid bolus challenge results may influence management and therapeutic decisions, provide insight on the CO reserve, and predict prognosis, although more data are needed in this field.^{64,66} For instance, the fluid bolus challenge could provide insights on RV reserve in HF with reduced ejection fraction and predict long-term outcomes after advanced therapies.⁶⁷

The standard fluid bolus challenge consists of infusing 7 to 10 mL/kg ($\approx 500 \text{ mL}$) of 0.9% saline at a minimum of 100 mL/min .⁶⁸ PLR has long been used in the intensive care unit using a simple bed tilt, but in patients undergoing elective RHC in the cardiac catheterization laboratory, PLR is often obtained with “feet on pedals,” precluding exercise in case of nondiagnostic results, or with a wedge underneath the patient’s legs to target an angle of $\approx 45^\circ$. Complete hemodynamic measurements should be obtained from 20 seconds to 3 minutes after completion of the fluid bolus challenge or PLR. Both tests are simple, easily available, and safe. More robust data on optimal diagnostic thresholds, treatment implications, and outcomes of individuals undergoing the fluid bolus challenge/PLR are needed.

Invasive Exercise Stress Testing

Invasive hemodynamic exercise stress testing helps evaluate the hemodynamic causes of exertional symptoms, with assessment of cardiac reserve, preload insufficiency, exercise-induced changes in hemodynamics consistent with HFpEF or PH, muscular deconditioning, chronotropic incompetence, and other limitations.^{69–72} Coupling

Table 3. Comparison of Supine and Upright Exercise

Supine	Upright
Higher venous return to evaluate exaggerated PCWP responses during low-level exercise	Closer representation of daily activities and accounting for gravitational pooling
Validation with an established HFpEF treatment	Improved rate-responsiveness in pacemaker-dependent patients
Greater ease for practitioners and staff with lower barrier of access for cardiac catheterization laboratories	Greater ability to achieve peak exercise and ascertain the extent of other physiologic limitations
Majority of data definition and prognostication in HFpEF based on peak PAWP or PAWP indexed to workload and body mass, and in PH on PAP/CO slope	Majority of data definition and prognostication in HFpEF based on PAWP/CO slope, and in PH on PAP/CO slope

CO indicates cardiac output; HFpEF, heart failure with preserved ejection fraction; PAP, pulmonary arterial pressure; PAWP, pulmonary arterial wedge pressure; PCWP, pulmonary capillary wedge pressure; and PH, pulmonary hypertension.

exercise RHC with arterial blood sampling and breath-by-breath respiratory gas exchange measurements (ie, VO_2 , VCO_2 , minute ventilation using a metabolic cart) permits comprehensive cardiopulmonary exercise testing to broadly understand exercise limitations.

In healthy individuals, exercise is associated with increased preload, contractility, chronotropy, and lusitropy. As CO increases to cope with increasing metabolic demands, full recruitment of the distensible pulmonary circulation occurs, reducing PVR. Because PVR falls, mPAP increases only mildly. Similarly, enhanced cardiac chamber compliance during exercise results in only mild increases in intracardiac filling pressures despite higher flow.^{73,74} In patients with obesity (body mass index ≥ 30 kg/m²), there are conflicting data regarding the presence and importance of elevated resting filling pressures; measures of CO are consistently higher, although unchanged when indexed to body size.^{75,76} With exercise, peak PAWP is higher, and peak VO_2 lower, in patients with obesity.

Supine Versus Upright

Exercise hemodynamic studies can be completed in both the supine and upright positions.^{9,77–79} There are advantages and disadvantages to both approaches, and certain technical considerations should be noted (Table 3). Equipment and protocols for supine exercise testing are more easily added to standard cardiac catheterization laboratories, and the PAC may experience greater ringing artifact and catheter whip during upright exercise, along with increased variability in PAWP when measured across different pulmonary West zones.^{80,81} Supine exercise with elevated legs, with minimal gravitational impact, generally yields higher venous return and more stable hemodynamic measurements, but offers a more compact window than upright exercise due to $\approx 50\%$ lower achievable exercise workload and therefore fewer opportunities to perform repeated hemodynamic measures than

during upright exercise. Absolute supine hemodynamic pressures and PAWP response have been associated with dynamic pulmonary congestion in HFpEF, and validation of the known benefit of dapagliflozin in HFpEF was recently reported with improvement in supine exercise hemodynamics.⁸²

The optimal way to report supine exercise PAWP remains uncertain. A large multicenter study assessing the diagnostic implication of absolute supine PAWP ≥ 25 mmHg versus PAWP/CO slope ≥ 2 mmHg·L·min noted $\approx 20\%$ discordance. Patients with pulmonary capillary wedge pressure (PCWP)/CO slope < 2 mmHg·L·min but PCWP ≥ 25 mmHg had higher body mass index and more atrial fibrillation, along with higher resting filling pressures, but also had higher exercise CO (12.3 L/min), whereas patients with PCWP/CO slope > 2 with PCWP < 25 had similar exercise excursions in PCWP but lower peak CO (7.7 L/min), along with nearly identical prevalence of diabetes or hypertension, as well as the same average left atrial volume index and creatinine levels. Prognostic data were not available to determine whether reclassification was associated with outcomes or future HF events in that study.⁸³

In a meta-analysis of 2180 patients with HFpEF and 682 controls from 27 studies, Baratto et al⁸⁴ concluded that PAWP/CO slope consistently differentiated patients with HFpEF from controls in both upright and supine positions, whereas there was more overlap in absolute exercise PAWP. More recently, Kovacs et al⁸⁵ conducted a multicenter study in 764 patients with a combination of supine and upright exercise, in which PAWP/CO slope, but not absolute PAWP, predicted outcomes. Studies by Dorfs et al⁸⁶ and Ahlgrim et al⁸⁷ reported that supine exercise PAWP values indexed to workload predicted mortality, and Omote et al⁸⁸ found that supine PAWP indexed to workload and CO, as well as absolute PAWP, predicted outcomes in HFpEF. Further studies are needed to refine optimal utilization of these cut points, but the aforementioned studies have advanced our understanding of the utility of exercise hemodynamics for diagnosis and prognostication in HFpEF. For exercise hemodynamic evaluation of PH, regardless of body position, studies have established mPAP/CO > 3 mmHg·L·min to be appropriate for diagnosis and prognostication.⁸⁵ Additional information on exercise-induced PH is presented later in this review.

Upright exercise better replicates daily activities and symptom-provoking conditions, in which gravitational pooling is relevant. For upright exercise testing, lower PAWP cutoffs and a focus on PAWP/CO slopes and mPAP/CO slopes are appropriate, particularly for diagnosis and prognostication of HFpEF and PH.^{85,89,90} Upright comprehensive cardiopulmonary exercise testing also permits maximum exercise to ascertain peak VO_2 and its component variables to assess chronotropic incompetence, peripheral oxygen extraction impairment, and stroke volume augmentation.^{91,92}

Submaximal supine measures limit the ability to draw conclusions about the level of impairment in measures beyond PAWP, such as peak achievable heart rate and peripheral oxygen extraction. In pacemaker-dependent patients, upright testing also better allows for rate responsiveness.⁹³ However, further studies are needed to ascertain whether quantification of abnormalities at peak exercise will translate into effective targeted interventions that translate to improvement in overall exercise capacity. For example, in recent randomized trials, β -blocker withdrawal in chronotropic incompetent HFpEF was associated with improvement in peak $\text{VO}_{2\text{t}}$, but atrial pacing to augment exercise heart rate was not, and results with ivabradine have been mixed.^{94–97} These studies highlight the need to further understand how targeting precise exercise phenotypes will translate to efficacious interventions in HFpEF.

Beyond ascertainment of relative predominance of physiologic impairments limiting peak exercise, it is important to recognize that clinically relevant submaximal exercise variables, such as ventilatory responses, are similarly ascertainable with either supine or upright exercise.⁹⁸ Recent data note improvement in ventilatory abnormalities with submaximal supine exercise after treatment with dapagliflozin,⁹⁸ and submaximal upright exercise is the most appropriate period to assess ventilatory efficiency as a prognostic variable in HFpEF.⁹⁹

Setting Up for Success

In preparation for exercise studies, the patient should be told to wear exercise-appropriate clothing and footwear. Before exercise RHC, the patient should be told that sedation will not be used because they will need to exercise. After standard supine hemodynamic data have been obtained, if upright exercise is to be performed, the patient should be safely transitioned to an upright ergometer while ensuring sterility of vascular access. Before initiating exercise, patients should have their feet put in the pedals and repeat hemodynamic data measured in the resting position. Exercise should begin at 0-W (unloaded) resistance on the cycle ergometer, and the patient coached to pedal at 60 to 80 rpm. Repeat hemodynamic measurements are taken at each stage, including simultaneous RAP and PA pressure with subsequent PAWP, systemic blood pressure, arterial saturation, and CO (either by thermodilution or by direct Fick, if using a metabolic cart). An indirect Fick cannot be estimated accurately during exercise; the PA saturation will be low from increased oxygen uptake during exercise and not accounted for by the fixed formulae. Exercise is continued with increased resistance (by 10–20 W per stage, every 1–3 minutes depending on estimated degree of patient limitation) until maximal effort is achieved. Maximal effort can depend on either patient-reported maximum exercise tolerance or a respiratory exchange ratio >1.05 if breath-by-breath analysis is being concurrently

Table 4. Invasive Hemodynamic Criteria for Diagnosing Causes of Dyspnea on Exertion

HFpEF
At least 1 of the following: 1. Resting PAWP ≥ 15 mm Hg 2. PAWP ≥ 20 mm Hg with fluid bolus or passive leg raise 3. Peak exercise PAWP ≥ 25 mm Hg during supine exercise ergometry ≥ 20 mm Hg during upright exercise ergometry 4. PAWP/CO slope >2 mm Hg·L·min regardless of body positioning
Chronotropic incompetence
HRR <0.80 or <0.62 if on β -blockers HRR=[observed peak HR–observed rest HR]/[predicted peak HR–observed rest HR] Predicted peak HR calculated using the following formula: $(220-\text{age})$
Impaired peripheral O_2 extraction
1. Peak $\text{VO}_2 <80\%$ predicted, peak CO $\geq 80\%$ predicted 2. Peak $\text{C(a-v)}\text{O}_2 <14$ mg/dL or peak $\text{C(a-v)}\text{O}_2$ corrected by Hgb concentration <0.80
Preload insufficiency
Both of the following criteria must be met: 1. Peak $\text{VO}_2 <80\%$ predicted and peak CO $<80\%$ predicted 2. Hemodynamics during exercise stress test: adynamic to minimal (ie, change in PAWP <7 mm Hg) increment in cardiac filling pressures during exercise with associated reduced exercise stroke volume and CO consistent with inadequate preload

$\text{C(a-v)}\text{O}_2 = \text{CaO}_2 - \text{CvO}_2$; $\text{CaO}_2 = (\text{Hgb} \times 1.39 \times \text{SaO}_2) + (0.003 \times \text{PaO}_2)$; $\text{CvO}_2 = (\text{Hgb} \times 1.39 \times \text{SvO}_2) + (0.003 \times \text{PvO}_2)$. CaO_2 indicates arterial oxygen content; CO, cardiac output; CvO_2 , venous oxygen content; HFpEF, heart failure with preserved ejection fraction; Hgb, hemoglobin; HR, heart rate; HRR, heart rate reserve; PaO_2 , partial pressure arterial oxygen; PvO_2 , partial pressure venous oxygen; PAWP, pulmonary arterial wedge pressure; SaO_2 , arterial oxygen saturation; SvO_2 , venous oxygen saturation; and VO_2 , oxygen consumption.

measured. Greater increases in resistance can be used in patients with higher exercise tolerance, with the goal for the patient to achieve peak exercise within ≈ 10 minutes. Sophisticated analysis of advanced hemodynamic and metabolic measures is then performed to assess the cause of symptoms with exercise (Table 4 and Supplemental Table 4). Exercise RHC ideally will permit multiple matched, repeated measures of RHC pressures and CO to derive mPAP/CO and transpulmonary gradient/CO slopes, identifying exercise-induced PH, as well as PAWP/CO slope, with a PAWP/CO slope >2 mm Hg·L·min consistently differentiating patients with HF from controls.^{84,90} In the absence of reliable CO assessments, peak exercise PAWP normalized to workload normalized to body weight (PCWL; mm Hg·W·kg) can also be considered to aid in risk stratification of patients with HF. PCWL accounts for discordant rises in PAWP during exercise proportional to the degree of patient exertion. Greater values (>25.5 – 34.7 mm Hg·W·kg) have been associated with higher mortality risk in patients with HF with reduced ejection fraction or HFpEF.^{86,87,100,101}

Exercise-Induced PH

Exercise-induced PH is defined by steeper flow-normalized mPAP increase (mPAP/CO slope > 3 mm Hg·L·min) and predicts outcomes independently from resting pulmonary

hemodynamic measures.^{85,102} Both precapillary and postcapillary components can contribute to exercise PH.⁸⁹

Exercise may reveal a postcapillary component to otherwise presumed precapillary PH, unmasking postcapillary PH and therefore influencing the prescription of PAH-specific therapy.^{14,56,103} However, whereas combined use of hemodynamic slopes (eg, mPAP/CO and PAWP/CO) may help the clinician better infer precapillary versus postcapillary physiology, it cannot be used alone for diagnosis of PAH or prescription of PAH-specific therapy. Exercise-induced precapillary PH, including high transpulmonary gradient/CO slope and limited PVR reduction, may highlight an early stage of pulmonary vasculopathy and a higher-risk patient.^{104,105} This finding might be relevant in populations at risk for pulmonary vascular disease (eg, systemic sclerosis, *BMPR2* sequence variation carriers) or to determine pulmonary vascular reserve after specific treatment.^{106–108} However, blunted PVR decrease may also be observed occasionally in patients with postcapillary PH.¹⁰⁹ Overall, exercise-induced PH is largely a physiologic finding, and not a distinct therapeutic entity.

RV Adaptation

Describing RV adaptation to exercise ideally requires RV pressure–volume conductance catheters or a combination of RHC with volumetric imaging. This challenging approach allows identification of RV dynamic dilation, further contributing to prognostic stratification.¹¹⁰ Alternatively, when relying on RHC alone, inability to increase CO (and stroke volume) together with right atrial hypertension and LV underfilling (blunted PAWP rise) points to dynamic RV maladaptation.¹¹¹

Application With LVADs

Invasive hemodynamic exercise use in patients supported with durable LVADs is more nascent, and largely used to augment the understanding of the dynamic physiology in this unique patient population to improve functional status and quality of life. Exercise protocols for these patients are similar to those for patients without LVADs. Exercise studies with metabolic assessment have been done successfully with both standard PACs and conductance catheters in the right ventricle in both the supine and upright positions.^{112–114} Patients on LVAD often have poor RV reserve, marked elevation in biventricular and pulmonary filling pressures, and severe ventilatory inefficiency with exercise.^{112,113,115} In one study, invasive hemodynamic response to exercise did not change before or after LVAD implant, regardless of fixed or adjusted speeds in follow-up.¹¹⁴ However, active increases in pump speed during exercise improved peak VO_2 .¹¹⁶

Hemodynamic Evaluation of Arteriovenous Fistulae

Patients with arteriovenous fistulae (AVF) are at risk for developing high-output HF or PH. The flow through the

AVF should be considered during invasive hemodynamic evaluation.^{117,118} High-output flow through the AVF has been defined as flows >1 to 1.5 L/min or 20% of CO.¹¹⁹ Temporary AVF compression has been associated with modest reductions in RAP, CO, and PVR along with increases in SVR. Decrease in CO of up to 4 L/min can be achieved with permanent ligation or reduction. Clinically significant changes in filling or PA pressures are not typically seen with temporary occlusion, but may be noted after permanent ligation or reduction.^{117,120}

If planning to assess hemodynamics after AVF occlusion, consultation with a vascular imaging expert and nephrology before or during the procedure to discuss safety of temporary AVF occlusion is recommended. Alternatively, in the setting of upper extremity AVF, the direct or indirect Fick principle can be used to estimate CO using the inferior vena cava saturation and PA saturation, separately, and attributing the differences in calculated CO to flow through the AVF.

DYNAMIC EVALUATION OF PH

Acute Vasoreactive Testing



Acute vasoreactive testing (AVT) in PAH is an essential piece of the comprehensive hemodynamic evaluation. Although initially defined by a 20% reduction in PVR, a positive AVT response is now defined by a reduction of mPAP by at least 10 mmHg to an absolute value of <40 mmHg without a decrease in CO.^{121,122} The definition change was based on the ability of a positive AVT response to predict long-term clinical response to calcium channel blocker monotherapy and its associated positive prognosis. Assessing PA compliance (estimated as stroke volume/pulmonary pulse pressure) during AVT may further aid in prediction.⁹⁸

Responders to AVT are relatively rare ($\approx 10\%$), and a positive AVT response has only been shown to yield predictive and prognostic value in patients with idiopathic, heritable, or drug-induced PAH.^{122–124} Therefore, AVT is not recommended in other forms of PH, which, if suspected, should be interrogated before proceeding to AVT.¹²⁵ Because of their unique physiology and outcomes, long-term calcium channel blocker responders have recently been assigned their own World Symposium on Pulmonary Hypertension PH subclassification.¹⁰² Lack of AVT response does not predict response to other PAH therapy.

Several agents have been used to perform AVT (Table 2). Inhaled prostacyclin analogs and inhaled nitric oxide, which have similar response rates, are preferred over intravenous formulations of epoprostenol and adenosine due to risks of systemic hypotension and other adverse events with the latter two.^{122,123,126,127} Evaluation of PH is best done in stable, nonacute settings to appropriately differentiate PH pathogenesis.

In addition to AVT, hemodynamic evaluation of PH-associated comorbidities during RHC—specifically porto-PH and interatrial shunts—should be considered. An experienced operator may obtain a hepatic wedge pressure in patients with liver disease and PH. A gradient >6 to 10 mmHg between the wedged hepatic venous pressure (representing portal pressure) and the hepatic venous pressure, along with hemodynamics consistent with PH, can secure the diagnosis.¹²⁸ A stepwise “shunt run,” in which oxygen saturations are analyzed at multiple levels of the proximal vasculature and cardiac chambers, whenever an interatrial shunt is suspected, including a PA saturation $>75\%$ or unexplained hypoxemia, may prove useful.¹²⁵

DYNAMIC EVALUATION OF PATIENTS WITH AN LVAD

Ramp Study

Ramp studies are designed to optimize LVAD pump performance to match patient-specific needs and identify pump malfunction. During a ramp study, pump speed is incrementally increased, and cardiac and pump measures are examined at each stage and used to inform next steps in the protocol. Echocardiography alone was used in the original ramp test protocol; however, the addition of invasive hemodynamics has further refined speed optimization, and is necessary with current-era centrifugal flow pumps due to different unloading characteristics and less predictable change in LV echocardiographic measures.^{129–131} Hemodynamic optimization during an invasive ramp study (central venous pressure <12 mmHg, PAWP <18 mmHg, and cardiac index >2.2 L·min⁻¹·m⁻²) was associated with reduced hospital readmissions as well as a reduction in hemocompatibility-related adverse events in patients who received the HeartMate 3 LVAD.^{132–134} In the RAMP-IT-UP study (Impact of Hemodynamic Ramp Test-Guided HVAD RPM and Medication Adjustments on Exercise Tolerance and Quality of Life), a prospective, randomized pilot study of hemodynamic ramp optimization in patients supported with HVAD, there was a trend toward higher event-free survival with hemodynamic optimization.¹³⁵ As in patients without an LVAD, when compared with the gold standard (direct Fick), CO is more accurate when measured by thermodilution than estimated Fick.¹³⁶ In addition to speed optimization, invasive hemodynamic ramp studies can be used for PVR assessment, diagnosis of suspected LVAD complications, volume assessment, and evaluation of exercise intolerance.¹³⁷

Reverse Ramp Study

Ventricular unloading enhances myocardial efficiency and cardiac energetics, potentially promoting partial or

complete recovery in suitable patients.¹³⁸ Patients on LVAD who meet functional and echocardiographic criteria for recovery should undergo a comprehensive hemodynamic assessment at both full and nominal LVAD support to better understand the underlying ventricular energetic reserve. To perform a reverse ramp, hemodynamics are first obtained at the patient's baseline speed. After ensuring full anticoagulation, the LVAD speed is incrementally lowered until nominal LVAD flow (defined as net zero flow through the LVAD) is achieved, with repeat hemodynamics obtained at each stage of the recovery ramp (Supplemental Figure 1).¹³⁹

Recovery ramp protocols traditionally have incorporated minimally acceptable thresholds (PAWP ≤ 12 – 15 mmHg, cardiac index ≥ 2.4 – 2.6 L·min⁻¹·m⁻², and mean arterial blood pressure ≥ 65 mmHg) while on nominal LVAD support as indicative of hemodynamic recovery.^{140–144} (Supplemental Table 4). Emerging evidence suggests that a more nuanced assessment using advanced hemodynamic measures, which better reflect the energetic state of the heart, may be more prognostic. The API reflects LV efficiency and strongly correlates with ventriculo-arterial coupling.^{45,50} Although data are limited on the role of API in durable LVAD recovery, augmentation of API with LV unloading has been shown to strongly predict successful weaning off temporary mechanical circulatory support. A stable or rising pulse pressure or a persistently low PAWP while on nominal flow, the principal components of API, have been shown to predict sustained recovery.^{141,145} Prospective studies are needed to better define the appropriate advanced hemodynamic thresholds most predictive of sustained LV recovery.

ASSESSMENT OF TEMPORAL CHANGES IN HEMODYNAMICS

Indications for PAC Use in the Intensive Care Unit

PAC use is dependent on the clinical scenario and whether the information provided would change management. These evolving indications are worthy of further study. Continuous monitoring may help better elucidate the degree of pulmonary vascular remodeling in patients with HF. Changes in PVR after 3 hours of infusion with nesiritide or nitroglycerin were shown to be more predictive of outcomes than baseline or early measurements.¹⁴⁶ The ISHLT recommends PAC use for perioperative monitoring of selected patients undergoing procedures associated with clinically significant hemodynamic changes, including patients with advanced PH or RV dysfunction undergoing intermediate-risk to high-risk procedures.¹⁴⁷ The American College of Cardiology/American Heart Association guidelines¹⁴⁸ state that it is reasonable to use invasive hemodynamic monitoring to guide intraoperative and postoperative care in patients with severe

PH undergoing elevated-risk noncardiac surgery. PAC use should also be considered perioperatively in patients undergoing durable LVAD implantation, patients undergoing pulmonary endarterectomy for chronic thromboembolic PH, or liver transplant recipients with porto-PH. PAC is recommended postoperatively in these patients to allow early detection of hemodynamic instability.¹⁴⁸

There growing evidence supporting the routine use of PAC in cardiogenic shock.^{149,150} PAC is reasonable for hemodynamic-guided therapy in pre-heart transplant patients with cardiogenic shock requiring intravenous inotropes or temporary mechanical circulatory support.⁵¹ Nonrandomized studies have shown lower mortality rates with PAC compared with non-PAC use in patients with cardiogenic shock, and can be particularly helpful in HF-CS.^{151–155} PACCS (Pulmonary Artery Catheter in Cardiogenic Shock Trial; URL: <https://www.clinicaltrials.gov>; Unique identifier: NCT05485376), in which patients with HF-CS are randomized to early PAC use compared with no or delayed PAC use to evaluate for differences in in-hospital mortality, is currently enrolling.

Indications for Repeat Invasive Hemodynamic Testing During Index Hospitalization

For patients with PH, when continuous PAC monitoring is not feasible, it is advisable to perform an initial RHC, commence therapy, and conduct repeat RHCs as necessary.¹⁴⁷ Repeat RHC should be considered in patients with HF-CS shock who are stabilized but unable to tolerate addition or titration of medical therapy to reassess disease severity and prognostication.

Indications for Repeat Outpatient Testing

RHC repetition tracks disease evolution and guides therapy escalation in pulmonary vascular diseases either when clinical worsening occurs or 3 to 6 months after diagnosis to assess for treatment changes.^{125,156,157} This latter indication is particularly relevant in intermediate-risk PAH, which can be further risk-stratified on the basis of RAP and SV index/cardiac index/SvO₂^{156,158–160}; PAH with positive vasoreactivity testing, to evaluate long-term calcium channel blocker response^{102,123,125}; borderline PH with *BMPR2* sequence variation (or systemic sclerosis), to detect PH development^{107,161}; and PAH and risk factors for HFpEF, because postcapillary PH may be unmasked by improved pulmonary blood flow.^{65,162} The role of repeating RHC in HFpEF is less clear,⁷⁵ unless HFpEF complications that may merit hemodynamic reevaluation to guide treatment appear over time, including secondary tricuspid regurgitation.^{163,164} The ISHLT assigns a Class I indication for RHC to be repeated every 3 to 6 months in patients listed for heart transplantation, especially in the setting of reversible PH or worsening HF.¹⁶⁵ For patients with LVADs, repeat RHC can be performed every 3 to 6

months after implantation to assess changes in PVR (if considering bridge to transplant) or to assess for myocardial recovery.¹³⁷

Indications for Remote PA Monitoring

Remote PA pressure monitoring is recommended for high-risk patients with HF, particularly those with New York Heart Association Class II or III symptoms, recent HF hospitalization, or elevated natriuretic peptide levels.¹⁶⁶ There are limited data regarding their use in patients with PAH.¹⁶⁷ Landmark randomized trials, such as CHAMPION (CardioMEMS Heart Sensor Allows Monitoring of Pressure to Improve Outcomes in NYHA Class III Heart Failure Patients), GUIDE-HF (Hemodynamic-Guided Management of Heart Failure), and MONITOR-HF (Hemodynamic Monitoring With a Wireless PA Pressure Monitoring System in Heart Failure), which used the CardioMEMS HF System (Abbott), demonstrated that timely detection of rising PA pressures—often occurring days to weeks before clinical congestion—enables proactive outpatient therapy adjustments, such as tailored diuretic dosing, and titration of HF guideline-directed medical therapies, to avert emergency care.^{168–170} PA-guided remote patient management consistently reduces HF-related hospitalizations and urgent visits across varying ejection fractions, complementing guideline-recommended therapies. Recent findings from PROACTIVE-HF (A Prospective, Multi-Center, Open Label, Single Arm Clinical Trial Evaluating the Safety and Efficacy of the Cordella Pulmonary Artery Sensor System in NYHA Class III Heart Failure Patients), which evaluated the Cordella PA Sensor System (Edwards Lifesciences), further support the benefits of PA pressure-guided management.¹⁷¹ This study showed significant reductions in HF-related hospitalizations and confirmed the safety of seated PA pressure monitoring in high-risk patients with HF, adding to the growing evidence for remote hemodynamic monitoring. The primary goal of PA pressure monitoring is the prevention of cardiac decompensation with ensuing hospitalizations as well as a reduction in mortality risk.^{172,173} Ideal candidates are those who can engage in structured remote patient management within multidisciplinary teams, ensuring responsive treatment modifications. In addition, with the growing physician shortage and reduced access to medical care in rural regions, remote patient management provides an opportunity to improve care delivery to a wider population.¹⁷⁴

CONCLUSION

The standardization and advancement of invasive hemodynamic assessment in HF represent key steps toward optimizing patient outcomes. However, several knowledge gaps remain that must be addressed. One key challenge lies in tailoring clinical care to the results of

dynamic testing. Dynamic evaluations offer valuable insights into cardiovascular physiology, but translating these findings into individualized treatment strategies remains a vital unmet need. Knowledge gaps persist, particularly regarding the integration of dynamic testing into routine practice and addressing essential research questions related to patient identification, phenotyping, treatment optimization, and long-term outcomes.¹⁷⁵ Looking ahead, the integration of artificial intelligence into hemodynamic analysis holds transformative potential through the interpretation of waveforms that could enhance diagnostic precision, streamline data analysis, and identify subtle patterns that might otherwise go unnoticed. Future efforts must focus on simplifying the methodology and democratizing the assessment of cardiovascular physiology. To assist in this endeavor, we have provided a poster template that can be printed and hung for reference in cardiac catheterization laboratories (Supplemental Figures 2 and 3). Some of these studies require considerable resources that may not be widely available due to variable levels of infrastructure and personnel expertise. Novel methods to increase successful uptake of provocative maneuvers, especially exercise, are needed.

Continued collaboration across disciplines, enhanced focus on standardization, and investments in emerging technologies are imperative for bridging these gaps and driving innovation. These efforts will ultimately advance the role of invasive hemodynamic testing in improving

outcomes for patients with HF or other cardiovascular conditions.

ARTICLE INFORMATION

The American Heart Association makes every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

This statement was approved by the American Heart Association Science Advisory and Coordinating Committee on September 16, 2025, and the American Heart Association Executive Committee on October 22, 2025. A copy of the document is available at <https://professional.heart.org/statements> by using either "Search for Guidelines & Statements" or the "Browse by Topic" area. To purchase additional reprints, call 215-356-2721 or email Meredith.Edelman@wolterskluwer.com

The American Heart Association requests that this document be cited as follows: Belkin MN, Fudim M, Baratto C, Grinstein J, Hollis I, Ijioma N, Kataria R, Lewis G, Mak S, Tedford RJ, Thibodeau JT, Yaku H; on behalf of the American Heart Association Fellow-In-Training and Early Career Committee of the Council on Clinical Cardiology. Standardization of baseline and provocative invasive hemodynamic protocols for the evaluation of heart failure and pulmonary hypertension: a scientific statement from the American Heart Association. *Circ Heart Fail*. 2026;19:e000088. doi: 10.1161/HHF.0000000000000088

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Disclosures

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(Continued)

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*Modest.

†Significant.

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This table represents the relationships of reviewers that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all reviewers are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives ≥\$5000 during any 12-month period, or ≥5% of the person's gross income; or (b) the person owns ≥5% of the voting stock or share of the entity, or owns ≥\$5000 of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

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