Noninvasive Evaluation of Pulmonary Capillary Wedge Pressure by BP Response to the Valsalva Maneuver*

Daniel Weilenmann, MD; Hans Rickli, MD; Ferenc Follath, MD; Wolfgang Kiowski, MD; and Hans Peter Brunner-La Rocca, MD

Study objectives: To determine the BP response to the Valsalva maneuver (VM) at baseline and after changes in therapy and to compare this response to the invasively measured pulmonary capillary wedge pressure (PCWP).

Design: Comparison of the BP response to the VM with invasively measured PCWP. In a subset of patients, direct PCWP and pulse amplitude ratio (PAR) measurements were repeated (mean ± SD) 3.2 ± 4.5 months later after adjusting the therapy.

Setting: Tertiary-care center.

Patients: Forty-two stable patients (8 women; mean age, 58 ± 13 years) undergoing right heart catheterization who were in sinus rhythm.

Measurements: PAR calculated between the end and the beginning of the VM using the last two beats and the first three beats of the straining phase and simultaneous measurement of PCWP.

Results: There was a highly significant correlation between the invasively measured PCWP (range, 2 to 32 mm Hg) and the PAR (range, 0.28 to 1.15; $R^2 = 0.75$; $p < 0.001$). In addition, changes of PCWP during follow-up (−16 to 13 mm Hg) were well-correlated ($R^2 = 0.93$; $p < 0.001$; $n = 11$) with changes in PAR (−0.44 to 0.47). The administration of medication (eg, β-blockers, amiodarone, angiotensin-converting enzyme inhibitor, and digoxin) did not influence the results.

Conclusions: PCWP and changes during therapy can be estimated noninvasively by measuring the PAR during the VM with acceptable accuracy in stable patients with cardiac conditions. Thus, this method may be a useful tool in detecting an elevated PCWP and hemodynamic response to therapy.

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Key words: congestive heart failure; pulmonary capillary wedge pressure; therapy; Valsalva maneuver

Abbreviations: ACE = angiotensin-converting enzyme; CHF = congestive heart failure; PAR = pulse amplitude ratio; PCWP = pulmonary capillary wedge pressure; ROC = receiver operating curve; VM = Valsalva maneuver

Pulmonary capillary wedge pressure (PCWP) is an important indicator of the hemodynamic severity of congestive heart failure (CHF) and is related to prognosis in these patients.1 In addition, PCWP is a useful tool for the guidance of therapy in patients with CHF.2,3 Its measurement, however, requires right heart catheterization,4 a method that is inconvenient for patients and is associated with some morbidity and even mortality.5,6 Thus, this method has its limitations for the routine screening of CHF or for repeated measurements as a guide to ambulatory therapy. Attempts at noninvasive approaches to estimate the PCWP are scarce, and clinical and radiographic signs are quite insensitive methods for the detection of an elevated PCWP in patients with CHF.7,8

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The arterial pressure during the Valsalva maneuver (VM) is abnormal in patients with CHF, with the contour of the strain phase of the arterial pressure response to the VM having a square-wave response.9,10 Anecdotal experience presumed a semiquantitative estimation of the left ventricular systolic function by the arterial pressure response to the VM.11 Furthermore, the BP response to the VM may have a direct correlation to the PCWP in patients with CHF.12 However, confirmation of this finding is
still lacking, and no data are yet available on the correlation between changes in the BP response to the VM and changes in the PCWP after modification of long-term drug therapy. Thus, the aim of this study was to compare the BP response to the VM with the invasively measured PCWP in a prospective, blinded study in patients undergoing right heart catheterization. Additionally, assessment was repeated in those patients undergoing right heart catheterization after modification of therapy.

**MATERIALS AND METHODS**

**Patient Characteristics**

Forty-two patients (8 women) with a mean (± SD) age of 58 ± 13 years (range, 25 to 78 years) were included in the study. All were in stable clinical condition and had undergone elective cardiac catheterization as part of a pretransplant assessment or before other potential cardiac surgery. The diagnoses given were ischemic heart disease (17 patients; 41%), idiopathic dilated cardiomyopathy (14 patients; 33%), aortic stenosis (9 patients; 21%), and no cardiac disease (2 patients; 5%). All patients gave informed consent to participate in the study.

**VM and Pressure Recordings**

The VM was performed with the patient in the supine position in the catheter laboratory with a Swan-Ganz catheter inserted under fluoroscopic control to the pulmonary artery after careful instruction of the patient. Heart rate and arterial pressure were continuously monitored by means of noninvasive equipment (Finapress; Ohmeda; Liberty Corner, NY). The principle of this instrument is based on the volume clamp method of Pen˜a`z and the physical criteria of Wesseling.13 This method accurately reflects intra-arterial BP changes.14,15 Data were transferred and recorded online on an IBM-compatible computer and were analyzed offline by a person blinded to the results of the invasively assessed PCWP. In patients undergoing both left and right heart catheterization, all measurements were performed before any contrast dye was administered.

Patients were asked to exhale after a normal inspiration into a tube that was connected to a sphygmomanometer. A tiny air leak was placed in the tube to ensure that airway pressure was produced from the thoracic cavity and not the pharynx. The straining phase was maintained for 15 s with an airway pressure of 30 mm Hg. The pulse amplitude ratio (PAR) was defined as the ratio of the final pulse amplitude (phase 2) to the initial pulse amplitude (phase 1) during the straining phase of the VM using the last two and the first three beats of the strain.

Two measurements were performed within 3 to 5 min, and mean values for both PCWP and PAR were used for analysis. Immediately before each of the two VMs, the mean PCWP was invasively measured by a 7F balloon-tipped pulmonary catheter and was recorded on paper with a speed of 100 mm/s and a pressure range of 40 mm Hg.

In 11 patients, measurements were repeated after changes in medical therapy by the same procedure as described >3.2 ± 4.5 months later. In these patients, changes in PCWP were compared with changes in the BP response to the VM.

**Statistical Analysis**

Values were expressed as frequency and mean ± SD, as indicated. A standard least-squares linear regression analysis was used to analyze the capacity of the PAR to predict the PCWP. The same method was used for the differences in 11 patients with serial measurements. A Bland-Altman plot was used to depict individual variance from an estimated value of PCWP. A receiver operating curve (ROC) was used to assess diagnostic accuracy to detect an elevated PCWP (ie, > 15 mm Hg). All statistical analysis was performed using a commercially available statistical program (SPSS, version 9.0; SPSS; Chicago, IL).

**RESULTS**

The characteristics of our study population are shown in Table 1. Twenty-seven patients (64%) were receiving angiotensin-converting enzyme (ACE)-inhibitors, 8 patients (19%) were receiving β-blockers, 11 patients (26%) were receiving amiodarone, and 24 patients (57%) were receiving digoxin. The mean ejection fraction was moderately reduced, and PCWP was elevated (ie, > 15 mm Hg) in 22 patients (52%). In 11 patients (26%), the PCWP

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*Values given as mean ± SD or No. (%). EF = ejection fraction; CVP = central venous pressure; MPAP = mean pulmonary arterial pressure.
was < 10 mm Hg, and in 15 patients (36%) it was > 20 mm Hg. The PAR ranged from 0.28 to 1.15 (mean, 0.71 ± 0.23). In seven patients (17%), the pulse amplitude did not decrease during the VM (ie, PAR, ≥ 1.0). As shown in Figure 1, the PAR predicted the invasively measured PCWP with an acceptable accuracy over a range of 2 to 32 mm Hg ($R^2 = 0.75$; root mean square error = 4.1 mm Hg; $p < 0.001$). The Bland-Altman plot (Fig 2) gives the difference between the true and calculated PCWPs, demonstrating that 31 of the noninvasively assessed PCWPs (74%) did not differ by > 4 mm Hg from the invasively measured PCWPs. Although the accuracy of this correlation has its limitations, a PAR of ≥ 0.7 predicted the presence of an elevated PCWP (ie, > 15 mm Hg) with a sensitivity of 91% and a specificity of 95% (Table 2). The positive predictive value was 95%, the negative predictive value was 91%, and the diagnostic accuracy was 93%. Despite some inaccuracy of the linear correlation, the area under the curve of the ROC was very high ($0.985 ± 0.013; p < 0.001$). Accordingly, cutoff values of PAR for 100% sensitivity and 100% specificity were separated by only 0.06 (ie, 0.66 and 0.72, respectively). Thus, all patients with PARs ≤ 0.66 had a PCWP of < 15 mm Hg, while all patients with PARs ≥ 0.72 had PCWPs > 15 mm Hg.

Table 2—Relationship of PAR During the VM and the Invasively Assessed PCWP*

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*Values given as No. of patients (%).

Medication with an antiadrenergic agent (ie, a β-blocker or amiodarone) did not influence the correlation between the PAR and the PCWP (Fig 3, 4). No patient was treated simultaneously with a β-blocker and amiodarone. Patients receiving ACE inhibitors had a slightly, but statistically not significant, better correlation ($R^2 = 0.81; p < 0.001$) compared to patients not receiving ACE inhibitors ($R^2 = 0.63; p = 0.001$). The area under the curve of the ROC was identical in patients receiving ACE inhibitors ($0.99 ± 0.01; p < 0.001$) as in patients not receiving ACE inhibitors ($0.98 ± 0.03; p = 0.003$).

In 11 patients (mean age, 51 ± 13 years), repeat measurements of the PCWP were performed 3.2 ± 4.5 months after the first examination. In these 11 patients, changes in the PAR predicted changes in the invasively assessed PCWP with an acceptable accuracy over a range of 2 to 32 mm Hg ($R^2 = 0.75$; root mean square error = 4.1 mm Hg; $p < 0.001$). The Bland-Altman plot (Fig 2) gives the difference between the true and calculated PCWPs, demonstrating that 31 of the noninvasively assessed PCWPs (74%) did not differ by > 4 mm Hg from the invasively measured PCWPs. Although the accuracy of this correlation has its limitations, a PAR of ≥ 0.7 predicted the presence of an elevated PCWP (ie, > 15 mm Hg) with a sensitivity of 91% and a specificity of 95% (Table 2). The positive predictive value was 95%, the negative predictive value was 91%, and the diagnostic accuracy was 93%. Despite some inaccuracy of the linear correlation, the area under the curve of the ROC was very high ($0.985 ± 0.013; p < 0.001$). Accordingly, cutoff values of PAR for 100% sensitivity and 100% specificity were separated by only 0.06 (ie, 0.66 and 0.72, respectively). Thus, all patients with PARs ≤ 0.66 had a PCWP of < 15 mm Hg, while all patients with PARs ≥ 0.72 had PCWPs > 15 mm Hg.

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measured PCWP with very good accuracy \((R^2 = 0.93;\) root mean square error = 2.6 mm Hg; \(p < 0.001\)) [Fig 5]. It is important to note that the slope of the regression line \((32.7 \pm 2.9)\) was nearly identical to that of the first measurement in the whole study population \((32.0 \pm 2.9)\) and that the constant of this regression line was close to \(0\) \((0.6 \pm 0.8)\).

11 patients showed a square-wave response to the VM. Eight of these patients had a left ventricular ejection fraction of \(< 40\%\). Taking into account these 11 patients did not influence the overall results.

### Discussion

In the present study, the ratio of the pulse pressure amplitude changes during the VM correlated with the invasively measured PCWP. In particular, our data show that an elevated PCWP \((\text{i.e.,} > 15 \text{ mm Hg})\) can be detected with clinically meaningful accuracy. This is in concordance with previous observations by McIntyre et al.\(^{12}\) In addition, changes in PCWP may be assessed noninvasively not only in the short term\(^{12}\) but also, as shown in this study, in the long term. Thus, changes in pulse amplitude during the VM may be helpful in the routine screening of patients with suspected elevations of PCWP and in the assessment of success of therapy in patients with CHF. Furthermore, this noninvasive method is independent of heart failure therapy (e.g., \(\beta\)-blockers, amiodarone, ACE inhibitors, digoxin, and diuretics).

During the straining phase of the VM, the arterial pressure rises with maintained pulse amplitude as a result of the transmission of the increased intrathoracic pressure to the periphery (phase 1). Due to a decrease in venous return, decreased stroke volume then leads to an acute drop in BP and a narrowing of the pulse amplitude with a compensatory rise in heart rate (HR) and peripheral vascular resistance (phase 2). With the release of the strain, a further sudden drop occurs in arterial pressure (phase 3). Thereafter, as a result of an increased venous return, the arterial pressure overshoots to levels above control with a widened pulse amplitude (phase 4).
pressure overshoots to levels above control with a widened pulse amplitude and a rise of stroke volume, while peripheral resistance remains transiently elevated (phase 4). Figure 6 shows a normal hemodynamic response to the VM in one patient.

It has long been suggested that the BP response to the VM may be useful in evaluating left ventricular dysfunction. The normal drop of the systolic BP and the pulse amplitude during the VM are absent in heart failure patients with elevated cardiac filling pressures. In these patients, the increase in BP during phase 1 of the VM is followed by a plateau during phase 2 (see Fig. 7). Gorlin et al showed that this abnormal response of the BP was consistently associated with an increased PCWP. In the presence of decreased venous return, the maintenance of left ventricular filling throughout the strain of the VM seems to be a prerequisite for this square-wave response. This assumption is supported by the finding that left ventricular end-diastolic volume and left atrial dimension, as assessed by echocardiography, did not change during the VM in patients with CHF compared to healthy subjects. Accordingly, the BP response to the VM may be a clinically useful tool in detecting elevated left side filling pressure due to left ventricular dysfunction. Although the correlation between the PAR and the PCWP in this study explained only 75% of the variance of PCWP and, therefore, would not allow an exact prediction of PCWP in all cases, the sensitivity and specificity were high enough to predict the presence of an elevated PCWP in most patients. Importantly, serial examinations in 11 patients showed that the measurement of the BP response to the VM also is useful for the assessment of changes in left heart filling pressure after a change of therapy. The identical slopes of the regression lines of single and repeat measurements further support the accuracy in assessing PCWP by this method.

Zema and coworkers have proposed this noninvasive assessment since the early 1980s. But, despite the easy applicability and various studies showing the clinical usefulness of the VM, this clinical tool is continually neglected. We have shown that an abnormal response of BP during the VM is associated with a considerable elevation of natriuretic peptides and is inversely related to indexes of functional capacity, such as peak oxygen uptake and respiratory response to exercise. All these indexes are associated with morbidity and mortality, and the BP response to the VM might, therefore, serve to be a predictor of bad outcomes in patients with CHF. Since the serial assessment of PCWP appears to be particularly useful for risk assessment in these patients, it also may be speculated that serial measurement of the BP response to the VM might be of help in this regard. In an editorial, it has been stated that the physiology has been elucidated, the technology is available and reasonably inexpensive, the preliminary data are encouraging, and the expectation, therefore, is justifiably high. This study further expands on previous findings and underscores this statement.

**Conclusion**

The pulse pressure response to the VM is an easily applicable and inexpensive clinical tool for the detection of elevated filling pressure in patients with suspected or known CHF. In addition, changes of the PCWP in response to therapeutic interventions during follow-up are reliably detected by this method. Thus, this test should be added to the routine assessment in clinical practice of patients in whom the measurement of left heart filling pressure is of clinical importance.

**References**


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