Finger photoplethysmography during the Valsalva maneuver reflects left ventricular filling pressure

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Silber HA, Trost JC, Johnston PV, Maughan WL, Wang NY, Kasper EK, Aversano TR, Bush DE. Finger photoplethysmography during the Valsalva maneuver reflects left ventricular filling pressure. Am J Physiol Heart Circ Physiol 302: H2043–H2047, 2012. First published March 2, 2012; doi:10.1152/ajpheart.00609.2011.—It is often challenging to assess cardiac filling pressure clinically. An improved system for detecting or ruling out elevated cardiac filling pressure may help reduce hospitalizations for heart failure. The blood pressure response to the Valsalva maneuver reflects left heart filling pressure, but its underuse clinically may be due in part to lack of continuous blood pressure recording along with lack of standardization of expiratory effort. In this study, we tested whether Valsalva-induced changes in the pulse amplitude of finger photoplethysmography (PPG), a technology already widely available in medical settings, correlate with invasively measured left ventricular end-diastolic pressure (LVEDP). We tested 33 subjects before clinically scheduled cardiac catheterizations. A finger photoplethysmography waveform was recorded during a Valsalva effort of 20 mmHg expiratory pressure sustained for 10 s, an effort most patients can achieve. Pulse amplitude ratio (PAR) was calculated as the PPG waveform amplitude just before release of expiratory effort divided by the waveform amplitude at baseline. PAR was well correlated with LVEDP (r = 0.68; P < 0.0001). For identifying LVEDP > 15 mmHg, PAR > 0.4 was 85% sensitive [95% confidence interval (95CI): 54–97%] and 80% specific (95CI: 56–93%). In conclusion, finger PPG, a technology already ubiquitous in medical centers, may be useful for assessing clinically meaningful categories of left heart filling pressure, using simple analysis of the waveform after a Valsalva maneuver effort that most patients can achieve.

left ventricular end-diastolic pressure

HEART FAILURE IS THE MOST common hospitalization diagnosis, with over 1,000,000 admissions each year (5). The readmission rate for heart failure is high: 20% by 30 days after discharge and 30% at 60–90 days after discharge. Health care costs due to heart failure total over $35 billion each year (5, 7, 8). It is widely believed that improving the detection of elevated cardiac filling pressure could substantially reduce the number of hospitalizations and repeat hospitalizations for heart failure (7, 18, 35).

Unfortunately, physical examination has important limitations in detecting elevated cardiac filling pressure (2, 31). Various noninvasive diagnostic aids are available for detecting evidence of elevated cardiac filling pressures, including chest X-ray, serum brain natriuretic peptide and pro-brain natriuretic peptide, and echocardiography (4, 25). However, each has important limitations, such as sensitivity, specificity, convenience, or cost (14, 19, 22). A noninvasive diagnostic tool for assessing left heart filling pressure that is accurate, convenient, inexpensive, point-of-care, and immediate could contribute substantially toward reducing admissions and readmissions for heart failure. It would be of further advantage if the tool was already available in most hospitals.

The Valsalva maneuver has been described as an underused bedside biomarker of heart failure (6, 26, 36). The maneuver consists of an expiratory effort against a closed glottis. Normally, the increased intrathoracic pressure during the Valsalva strain reduces venous return and results in a transient drop in average blood pressure and in pulse pressure (20). In the setting of elevated left heart filling pressure, one may detect no change or even an increase in blood pressure during the maneuver. The method of measuring the blood pressure response to the maneuver using an ordinary sphygmomanometer (36) has not gained widespread clinical use, possibly due to several factors that may limit its accuracy, such as lack of standardization of expiratory effort and lack of continuous blood pressure measurement during the maneuver. Use of a continuous arterial waveform obtained invasively during the Valsalva maneuver has been shown to be useful in detecting elevated left heart filling pressure (26, 32, 37). A simple variable determined from the continuous signal is the pulse amplitude ratio, which is the ratio of pulse pressure during the Valsalva to the pulse pressure at rest. Noninvasive systems have been developed that continuously measure indexes of cardiac filling pressure. One recent study (28) suggests that using this technique to guide care may reduce rehospitalization for heart failure.

Unlike the volume-clamp and tonometric devices just described, photoplethysmography is already ubiquitous in medical settings. Finger photoplethysmography is currently used mainly to determine pulse oximetry and heart rate, but the photoplethysmography signal also reflects time-varying finger pulse volume, which reflects peripheral blood flow and peripheral blood pressure (1). Photoplethysmography waveform changes during a Valsalva maneuver closely resemble changes in an invasive arterial blood pressure waveform during the
maneuver (34). Furthermore, changes in the photoplethysmography waveform of the ear during Valsalva were shown to contain information indicating left ventricular filling pressure (3). Thus finger photoplethysmography, which is already widely available, may help assess the response to the Valsalva maneuver in evaluating left ventricular filling pressure.

The purpose of this study was to determine if pulse amplitude changes of a finger photoplethysmography waveform during a Valsalva maneuver correlate with left ventricular end-diastolic pressure (LVEDP) measured via cardiac catheterization. We also sought to determine the feasibility of using an expiratory effort that most patients can achieve: 20 mmHg for 10 s.

METHODS

Patients already scheduled to undergo nonemergent cardiac catheterizations were asked to participate in this study. All participants provided written informed consent before involvement. The Johns Hopkins University Institutional Review Board approved the protocol before study initiation. Patients were excluded if they had moderate or severe aortic stenosis, moderate or severe mitral stenosis, uncontrolled hypertension, atrial fibrillation, or hypertrophic obstructive cardiomyopathy. There was no order or pattern of selection for recruiting.

Participants were tested while in the semirecumbent position, within ~1 h before their catheterization. Participants were asked to sustain an exhalation effort of 20 mmHg for 10 s into a tube connected to a pressure transducer, while a photoplethysmography transducer was attached to a fingertip. The photoplethysmography probe was placed on the finger of an open, relaxed hand that was set down at rest. The subject was instructed to use the contralateral hand to hold the tube into which the expiratory effort was produced.

Both transduced signals were input into a digital acquisition system (Biopac Systems, Goleta, CA) and then into a computer. Filtering parameters of the photoplethysmography signal were 10-Hz low pass and 0.01-Hz high pass. The pressure signal was displayed to help guide the participant. At least three Valsalva efforts were recorded. Criteria considered acceptable for inclusion of an effort included maintaining an expiratory effort between 18 and 25 mmHg for ≥10 s. Also, the range must be achieved within ~3 s of initiating the effort. Waveforms were analyzed using software accompanying the digital acquisition system. For each Valsalva effort, the amplitudes of three typical cycles of the baseline photoplethysmography waveform were averaged. The amplitude of the cycle just before 10 s into the Valsalva maneuver was measured. We did not use multiple cycles when calculating pulse amplitude during the Valsalva maneuver because the amplitude changes continuously during the maneuver. Pulse amplitude ratio (PAR) was calculated as the ratio of the signal amplitude at end Valsalva to the average baseline signal amplitude. The average PAR over all the acceptable efforts was obtained for each subject.

LVEDP was measured via a catheter placed in the left ventricle during the cardiac catheterization procedure. The operators who performed the catheterization measurements were blinded to the photoplethysmography measurements. Standard least-squares linear regression analysis was used to examine the correlation between the PAR and LVEDP measurements. Receiver operating characteristic (ROC) analyses were also performed.

RESULTS

Of 36 participants enrolled, a total of 33 participants (92%) had at least one acceptable expiratory effort. Table 1 shows their baseline characteristics. The average age was 58 (11) years, and they consisted of 22 men and 11 women. Left ventricular ejection fraction was obtained clinically for all but one participant, a median of within 2 days of the catheterization. Ejection fraction was measured either by echocardiogram, left ventriculogram, or nuclear medicine scan.

Patients typically required about three attempts before they could generate an acceptable expiratory effort profile. The range of acceptable expiratory efforts used was 1 (only 2 subjects) to 8. The mean and median number of acceptable expiratory efforts used was 4. Figure 1 shows a photoplethysmography waveform response in a participant whose PAR was 0.4 and LVEDP was normal at 10 mmHg. Figure 2 shows a waveform response in a participant whose PAR was 0.9 and LVEDP was very elevated at 35 mmHg. PAR correlated well with LVEDP ($r = 0.68; P < 0.0001$; Fig. 3). Figure 4 shows a Bland-Altman plot. An ROC plot for identifying LVEDP $> 15$ mmHg is shown in Fig. 5. A PAR $> 0.4$ has an 85% sensitivity and 80% specificity in identifying LVEDP $> 15$ mmHg, under the area curve 0.83.

DISCUSSION

In this study, we investigated the utility of finger photoplethysmography to assess left heart filling pressure noninvasively during the Valsalva maneuver. We found a good correlation between PAR, a simple measure of waveform change during the maneuver, with invasively measured LVEDP. The main new physiological finding is that Valsalva-induced changes in finger perfusion via changes in pressure and flow amplitude as assessed by finger photoplethysmography reflect left ventricular filling pressure. In addition, ROC analysis suggests that PAR by finger photoplethysmography has good sensitivity and specificity for identifying clinical meaningful categories of LVEDP. A PAR cutoff of $>0.4$ may help identify patients with LVEDP $> 15$ mmHg, a cutoff value that has mortality implications in heart failure (30).

It has been known for over 50 yr that blood pressure responses to the Valsalva maneuver reflect cardiac volume
status (13, 15, 29). The major underlying physiology, as advanced in prior studies, is that the Valsalva maneuver increases intrathoracic pressure and limits systemic venous return, leading to a decrease in left heart filling pressure, thus a decrease in stroke volume, and thus a decrease in peripheral pulse amplitude. However, when there is thoracic fluid congestion and elevated LVEDP, then limiting systemic venous return into the thorax will not significantly limit the fluid available for the left heart to eject. In that situation, peripheral pulse amplitude will be less changed, or not changed at all, by the Valsalva maneuver (16, 20, 33, 38).

The blood pressure response to the Valsalva maneuver consists of four phases. These have been well described using continuous, invasive blood pressure measurement (37, 38). In individuals with normal filling pressure, the four phases consist of: phase 1: transient rise in blood pressure associated with the onset of strain; phase 2: decrease in average blood pressure and pulse amplitude with maintained strain, increased intrathoracic pressure and decreased venous return; phase 3: transient drop in blood pressure upon release of strain; and phase 4: overshoot of blood pressure with restored venous return (37). In individuals with elevated filling pressures, the maneuver may be associated with abnormal responses detectable with a sphygmomanometer: an increase in blood pressure with no subsequent decrease during phase 2 (“square wave response”) and no overshoot upon strain release.

For years, the Valsalva maneuver has been touted as an underused bedside test of heart failure (6, 26, 36). Two disadvantages of performing a bedside Valsalva maneuver with only a sphygmomanometer are that the expiratory effort is not measured and standardized and that a continuous blood pressure signal is not recorded. These drawbacks may limit accuracy because expiratory effort affects blood pressure response (21, 23) and because calculation of pulse amplitude ratio, a continuous variable, requires a continuous signal. These considerations may contribute to a lack of widespread clinical use of the technique. One implication of our study is that the bedside Valsalva test might be improved by employing equipment already available in most hospitals: a finger photoplethysmography transducer and medical tubing attached to a sphygmomanometer to measure a patient’s expiratory effort.

Photoplethysmography measures blood perfusion. Therefore, changes in amplitude most directly reflect changes in flow into the digit but as such are also dependent on pressure (1). A variety of noninvasive transducers have been used to measure continuously a physiological response to the Valsalva maneuver.
ver that reflects an invasive continuous blood pressure response. The first noninvasive, continuous signal shown to exhibit changes with Valsalva that correlated with LVEDP was photoplethysmography of the ear (3). However, the index used was derived retrospectively from multiple parameters of the photoplethysmography waveform. PAR, a much more simply derived index, was not tested. One study compared PAR of a finger photoplethysmography signal with changes in an impedance cardiographic signal but did not compare them with a direct measurement of cardiac filling pressure (21).

The VeriCor (CVP Diagnostics, Boston, MA) system’s sensor is a tonometer, a surface deformation sensor, applied to the finger or wrist (17). The Finapres device (Finapres Medical Systems) is a sophisticated system that employs an inflatable volume clamp with photoplethysmography used as a feedback signal. A reverse transfer function is applied to the detected waveform to provide essentially a calibrated, continuous blood pressure signal. A recent study (28) using the VeriCor suggests that guiding therapy in heart failure using the Valsalva technique may reduce repeat hospitalizations (28). The present study is the first to investigate the relationship between LVEDP and only the pulse amplitude response of ordinary photoplethysmography of the finger, which can be readily obtained in many medical settings.

We selected parameters of this study that would allow for the simplest and most convenient bedside examination with available hospital equipment, including the use of PAR only, expiratory effort of 20 mmHg, expiratory effort duration of 10 s, and semirecumbent body position. Some studies (27, 28) have employed indexes calculated from multiple descriptors of the recorded physiological waveform. For example, the most recent studies using the Vericor also incorporated the rate of decline of pulse pressure, rate of change of the slope of the systolic pressure, and rate of change of the pressure over time (dP/dt) of the upstroke of the arterial pressure. The ear photoplethysmography study (3) incorporated normalized slope of linear fit of pulse amplitude decay and also various time intervals. However, other studies PAR (9, 17, 23, 33) using the Finapres or the Vericor have shown close correlation between cardiac filling pressure and just PAR, which would be much easier to derive from a bedside photoplethysmography signal than combinations of multiple variables. Some studies (3, 9, 23, 38) have used a higher expiratory effort, as high as 40 mmHg, and one study (33) used a longer expiratory effort duration of 15 s. The expiratory effort needs to be consistent, because PAR is lower when expiratory effort is higher (10, 21, 32). We chose parameters that patients with heart and/or lung disease would be more likely to achieve (23). We chose to measure the response to Valsalva maneuver in a common examination position, semirecumbent, although PAR may be similar in different body positions (21). Therefore, the PAR measurements taken in a common examination position reflect the LVEDP measurements obtained in the supine position in the catheterization laboratory.

Factors such as skin pigment and thickness, nail polish, overall digit size, and shape affect the photoplethysmography waveform. However, those factors would be the same before and during the Valsalva maneuver. Thus the change in pulse amplitude with the maneuver is caused mainly by the flow and pressure changes from the maneuver.

There are several limitations to our study. One limitation was that this feasibility study was not powered to investigate the independent effects of specific baseline characteristics on PAR. This also means that we could not assess whether left ventricular ejection fraction affects the correlation between PAR and LVEDP, as was suggested by one study (11). Another limitation is that the sensitivity and specificity reported here are based on a threshold of PAR derived from the same set of data. A formal assessment of sensitivity and specificity needs to be done in a separate, prospective study on a larger population. Yet another limitation is that the study was not designed to compare photoplethysmography with other devices that measure PAR, such as the volume-clamp technique (i.e., Finapres). The correlations between LVEDP and PAR by volume-clamp technique and between pulmonary capillary wedge pressure and PAR by tonometry (VeriCor) were higher than in this study (9, 10, 17). However, those studies employed an expiratory effort of 40 mmHg, which may improve the correlation, but which fewer patients can achieve. Future larger studies using photoplethysmography may suggest improvements in the technique that could improve the correlation. It would also be useful in a future study to compare accuracy of the different techniques using similar expiratory pressures. Nevertheless, the main new finding of this study is that Valsalva-induced changes in finger photoplethysmography, a technology already widely used, reflect LVEDP.

Although pulse oximeters are ubiquitous in medical settings, many do not offer a printout of the photoplethysmography waveform, which limits the immediate clinical applicability of this study. However, if larger studies support the clinical utility of Valsalva photoplethysmography, more pulse oximeter models could be designed to include printout or screen-recall capability.

In conclusion, this study suggests that finger photoplethysmography, a technology already widely available in inpatient and outpatient settings and easily amenable to pulse amplitude

![Fig. 5. Receiver operating characteristic analysis for identifying LVEDP > 15 (mmHg). Area under the curve = 0.83. PAR > 0.4 has 85% sensitivity (95% confidence interval: 54–97%) and 80% specificity (95% confidence interval: 56–93%).](http://ajpheart.physiology.org/)

\[ \text{Sensitivity} \times \text{Specificity} = \text{Accuracy} \]

\[ \text{Accuracy} = \frac{\text{Sensitivity} \times \text{Specificity}}{\text{Sensitivity} + \text{Specificity} - \text{Sensitivity} \times \text{Specificity}} \]
estimation, may be used during a Valsalva maneuver effort that most patients can achieve to assess left heart filling pressure. The technique may help to detect or rule out elevated left heart filling pressure. Future studies should evaluate clinical utility further, including whether the technique predicts hospitalization or repeat hospitalization for decompensated heart failure.

GRANTS
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DISCLOSURES
H.A. Silber has filed a patent application based in part on work done in this study. His role in the study adheres to a protocol established by the Conflict of Interest Committee of the Johns Hopkins Office of Policy Management.

AUTHOR CONTRIBUTIONS

REFERENCES