Echocardiographic Evaluation of Hemodynamics in Patients With Decompensated Systolic Heart Failure

Sherif F. Nagueh, MD; Rajat Bhatt, MD; Rey P. Vivo, MD; Selim R. Krim, MD; Sebastian Imre Sarvari, MD; Kristoffer Russell, MD; Thor Edvardsen, MD, PhD; Otto A. Smiseth, MD, PhD; Jerry D. Estep, MD

Background—Doppler echocardiography is currently applied for the assessment of left ventricular and right ventricular hemodynamics in patients with cardiovascular disease. However, there are conflicting reports about its accuracy in patients with unstable decompensated heart failure. The objective of this study was to evaluate the accuracy of the technique in patients with unstable heart failure.

Methods and Results—Consecutive patients with decompensated heart failure had simultaneous assessment of left ventricular and right ventricular hemodynamics invasively and by Doppler echocardiography. In 79 patients, the noninvasive measurements of stroke volume (r=0.83, P<0.001), pulmonary artery systolic (r=0.83, P<0.001) and diastolic pressure (r=0.51, P=0.009), and mean right atrial pressure (r=0.85, P<0.001) all had significant correlations with invasively acquired measurements. Several Doppler indices had good accuracy in identifying patients with pulmonary capillary wedge pressure >15 mm Hg (area under the curve, 0.86 to 0.92). The recent American Society of Echocardiography/European Association of Echocardiography guidelines were highly accurate (sensitivity, 98%; specificity, 91%) in identifying patients with increased wedge pressure. In 12 repeat studies, Doppler echocardiography readily detected the changes in mean wedge pressure (r=0.75, P=0.005) as well as changes in pulmonary artery systolic pressure and mean right atrial pressure.


Key Words: diastole ■ Doppler ■ echocardiography ■ heart failure

Patients with acute decompensated heart failure (ADHF) have increased morbidity and mortality. Furthermore, these patients are prone to readmission, with rates ≥50% within the first 6 months after discharge. The hemodynamic assessment of ADHF offers the potential of tailored therapy. However, the invasive gold standard is not without risks. Accordingly, the noninvasive assessment by Doppler echocardiography can play an important role in this population. A recent study has reported that Doppler measurements, including tissue Doppler, do not provide an accurate assessment of left ventricular (LV) filling pressures in ADHF. However, there were limitations to that study. Pulmonary capillary wedge (PCWP) pressure was measured in a supine position, but imaging was acquired in a left lateral decubitus position, which weakens the relationship between Doppler and hemodynamic variables because pulmonary venous return varies with position, and patients were rolled onto their left side after pressure measurement. In addition, the measured pressure is altered by a similar magnitude to the change in the level of the catheter in the vascular system, which shifts with body position. Furthermore, PCWP in pulmonary hypertension requires confirmation by oxygen saturation, which was not done, and many patients in the latter study had pulmonary hypertension. Finally, some of the Doppler examples presented showed poor alignment of the Doppler beam for the lateral tissue Doppler velocities along with a broad and poorly defined spectral envelop. Aside from these issues, the clinical utility of a comprehensive echocardiographic approach for the assessment of hemodynamics in this population is unknown. Given the importance of the question, we conducted this prospective, 2-center study to examine the application of Doppler echocardiography for the hemodynamic assessment of patients with ADHF.

Clinical Perspective on p 227

Methods

Patient Population

ADHF was defined as new-onset decompensated heart failure or decompensation of chronic heart failure with severe symptoms that warranted hospitalization. Seventy-nine consecutive patients (not included in previous studies, 66 at Houston and 13 at Oslo) with a clinical indication for right heart catheterization were prospectively enrolled and underwent simultaneous imaging and cardiac catheterization. Right heart catheterization was performed for clinical reasons and not for the sole purpose of the study. Some patients were evaluated while on their oral regimen on admission before the initiation of additional heart failure treatment. Other patients were
enrolled after initiation of intravenous vasodilators, diuretics, and/or pressors. This enabled us to include patients with a wide range of hemodynamic measurements. Mitral stenosis was an exclusion criterion but none of the patients had this condition. Patients with aortic valve disease and those with mitral regurgitation were not excluded. No patients were excluded because of suboptimal images because satisfactory Doppler recordings were obtained in all patients.

**Echocardiographic Imaging**

The patients were imaged with an ultrasound system equipped with a multifrequency transducer. A complete echocardiographic study was performed per standard views and guidelines. From the apical window, pulsed-wave Doppler was used to record mitral inflow for 3 to 5 cardiac cycles at the level of the mitral valve annulus and at the tips level. Pulmonary venous flow was recorded from the right pulmonary vein, guided by color Doppler. Tissue Doppler (TD) was applied to record mitral annular velocities at the septal and lateral sides of the annulus. The resulting annular velocities by pulsed-wave Doppler were recorded for 3 to 5 cardiac cycles at a sweep speed of 100 mm/s. Using color Doppler, the M-mode cursor was positioned within the mitral inflow stream, and the early diastolic flow propagation velocity (Vp) was recorded. Baseline shift was performed as needed to obtain a distinct color border of the propagation velocity that extended well into the distal third of the LV cavity. Tricuspid and pulmonary regurgitation signals were recorded by continuous-wave Doppler from multiple windows. Saline contrast was used as needed and increased the feasibility of acquiring tricuspid regurgitation jets to 80%. Inferior vena cava diameter and its collapse and hepatic venous flow were recorded in the subcostal view.

**Echocardiographic Analysis**

Measurements were performed on a computerized off-line analysis stations (Digisonics EC, and EchoPAC, GE Healthcare) without knowledge of invasively derived hemodynamic data. Mitral inflow from the tips level was analyzed for peak early (E) and late (A) diastolic velocities, E/A ratio, and deceleration time (DT) of mitral E velocity. Mitral A duration was measured at the level of the mitral annulus. Pulmonary venous flow was analyzed for the peak velocity of the systolic (S), diastolic (D), and atrial reversal (A) signals. The systolic filling fraction and the difference in duration between pulmonary vein Ar velocity and mitral A velocity were derived. Mitral annulus early (‘e’) and late (‘a’) diastolic velocities were measured at septal and lateral mitral annulus, and E/e’ ratios were computed. Interobserver error (mean±SD) for mitral E velocity was 4±3% and for annulus e’ velocity was 5±2%. Intraobserver error (mean±SD) for mitral E velocity was 3±2% and for annulus e’ velocity was 3±2%. Measurements were averaged over 3 cardiac cycles.

The algorithm of the American Society of Echocardiography/European Association of Echocardiography (ASE/EAE) guidelines for the estimation of LV filling pressures in patients with depressed ejection fraction (EF) was applied. Briefly, when the E/A ratio is <1 and with an E velocity ≤50 cm/s, a normal left atrial (LA) pressure is assumed. When the E/A ratio is ≥2, or with DT <150 ms, an increased LA pressure is assumed. When the E/A ratio is ≥1 but <2, or when it is <1 but with an E velocity >50 cm/s, the presence of abnormally elevated values in 2 of the following Doppler measurements was needed to support the conclusion that LV filling pressures are elevated: average E/e’ ratio >15, E/VT ratio ≥2.5, pulmonary veins systolic to diastolic ratio ≤1, or Ar-A duration ≥30 ms and PA systolic pressure ≥35 mm Hg.

LV stroke volume was derived as the cross-sectional area of the LV outflow tract×time-velocity integral of LV outflow tract flow by pulsed-wave Doppler. This method was used to avoid overestimation of systemic output that occurs when 2D-derived stroke volume (difference between LV end-diastolic and end-systolic volumes) is computed in patients with significant mitral regurgitation. Cardiac output was calculated as the product of LV stroke volume and heart rate. Pulmonary artery (PA) systolic pressure was derived using the modified Bernoulli equation as PA systolic pressure in mm Hg =4 (v^2) of peak tricuspid regurgitation velocity in m/s+RAP in mm Hg, and PA diastolic pressure was calculated as 4 (v^2) of end-diastolic pulmonary regurgitation velocity in m/s+RAP in mm Hg. Right atrial pressure (RAP) was estimated using the inferior vena cava diameter and its change with respiration and hepatic venous flow. Valvar regurgitation was assessed using ASE guidelines.

**Cardiac Catheterization**

Mean right atrial pressure, pulmonary artery systolic and diastolic pressures, and PCWP were measured with a pulmonary artery catheter during right heart catheterization in 73 patients. The wedge position was verified by fluoroscopy, changes in the waveform, and, when needed, with O2 saturation (O2 saturation >95%). Invasive measurements were acquired without knowledge of echocardiographic data. All were derived as an average of 5 cycles. Fluid-filled transducers were balanced before the study with the zero level at the midaxillary line. Cardiac output (average of 3 cycles with <10% variation) was derived by thermodilution in the majority of patients, though in some it was calculated by Fick method also. Because most patients with ADHF have pulmonary hypertension, the transpulmonary gradient was derived and was computed as mean PA pressure—mean PCWP. In 6 patients, left heart catheterization only was performed and LV diastolic pressures were obtained. None of them had more than mild mitral regurgitation. In these 6 patients, LV pre-A pressure was determined and used in lieu of wedge pressure, based on the very close correlation between the 2 pressures.

**Repeat Studies**

Hemodynamic and echocardiographic measurements were repeated as described above in patients who had a clinical indication for an indwelling PA catheter for ongoing hemodynamic assessment. In addition, patients who had a repeat hospitalization for ADHF and who had a clinical indication for another cardiac catheterization were included.

**Statistical Analysis**

Continuous data are presented as mean±SD. Linear and polynomial regression analysis was performed to determine the correlation between noninvasive and invasive measurements of LV and right ventricular hemodynamics showing correlation coefficient and standard error of estimate (SEE). Receiver operating characteristic curves were used to determine the threshold Doppler values that separated patients with PCWP >15 mm Hg from those with PCWP ≤15 mm Hg. Changes in LV volumes and hemodynamics on repeat studies were evaluated by paired t tests because the data had a normal distribution. The differences between noninvasive and invasive measurements of hemodynamics were evaluated by Bland-Altman plots. P<0.05 was considered significant.

**Results**

The mean age of the study sample was 57±11 years (range, 24 to 80), and 15 patients were female (19%). In 37 patients,

| Table 1: Summary of Invasive Hemodynamics and LA/LV Volumes and EF |
|-----------------------|-----------------------|
| 1. Heart rate, beats/min | 80±15 |
| 2. Systolic blood pressure, mm Hg | 117±18 |
| 3. Diastolic blood pressure, mm Hg | 75±15 |
| 4. PA systolic pressure, mm Hg | 50±17 |
| 5. PA diastolic pressure, mm Hg | 23±9 |
| 6. PA mean pressure, mm Hg | 32±11 |
| 7. PCWP, mm Hg | 21±9 |
| 8. Transpulmonary gradient, mm Hg | 11±6 |
| 9. Mean RAP, mm Hg | 14±7 |
| 10. Cardiac index, L/min per m² | 2.1±0.6 |
| 11. LV end-diastolic volume, mL | 255±78 |
| 12. LV end-systolic volume, mL | 200±73 |
| 13. LV EF, % | 23±9 |
| 14. LA maximum volume, mL/m² | 48±15 |
ADHF was due to dilated cardiomyopathy and in 42 patients due to coronary artery disease. Table 1 presents a summary of their invasive hemodynamics. There were 53 patients with pulmonary hypertension diagnosed by invasively measured mean PA pressure >25 mm Hg and 35 patients with a transpulmonary gradient >10 mm Hg. The group had severe LV dilation and a mean EF of 23 ± 9%. Mitral regurgitation of moderate severity was present in 11 patients and was moderately severe in 3. The remaining patients had trace to mild lesions. All patients were on diuretics in various combinations, 66 patients were receiving oral/intravenous inotropic/vasodilator drugs, and 3 had an intra-aortic balloon pump. Forty-three percent had received biventricular pacing (not single site pacing).

Feasibility of Doppler Measurements

Mitral inflow velocities were feasible in all patients. A single early diastolic mitral inflow velocity was present in 18 patients (due to atrial fibrillation in 12 patients and sinus tachycardia in 6 patients). TD velocities also had a high feasibility for septal (96%) and lateral (92%) mitral annulus velocities. Vp was feasible in 77%, but satisfactory pulmonary vein signals were obtained in only 32 patients (41%). Adequate tricuspid regurgitation signals were acquired in 63 patients (80%), and RAP could be estimated in 60 patients (76%). On the other hand, the pulmonary regurgitation jet had the lowest feasibility at 32%.

Figure 1. Mitral inflow from a patient admitted with ADHF. Data were acquired on admission before initiation of intravenous therapy but while the patient was still on oral medications. Her mean wedge pressure was 36 mm Hg. Mitral inflow (upper left panel) shows restrictive filling, with a peak mitral early diastolic velocity (E) of 113 cm/s, an A (late diastolic) velocity of 35 cm/s, an E/A ratio of 3.2, and a deceleration time of 84 ms. The peak tricuspid regurgitation (TR) velocity (upper right panel) corresponds to a systolic gradient across the tricuspid valve of 38 mm Hg. Both septal (lower left) and lateral (lower right) TD early (e') and late (a') diastolic velocities are reduced, and the average E/e' ratio is 24.5. CW indicates continuous-wave.

Figure 2. Mitral inflow from a patient admitted with ADHF. Data were acquired on admission before initiation of intravenous therapy but while the patient was still on oral medications. His mean wedge pressure was 30 mm Hg. Mitral inflow (upper left panel) shows restrictive filling, with a peak mitral early diastolic velocity (E) of 94 cm/s, an A (late diastolic) velocity of 27 cm/s, an E/A ratio of 3.5, and a deceleration time of 78 ms (vertical scale at steps of 20 cm/s). Pulmonary venous flow (upper right panel) shows reduced systolic (S) velocity and a higher diastolic (D) velocity, with an S/D ratio <1. Pulmonary vein atrial velocity (A') had a duration that exceeded mitral A duration by 101 ms. Both septal (lower left) and lateral (lower right; vertical scale at 4 cm/s) TD early (e') and late (a') diastolic velocities are reduced, and the average E/e' ratio is 18.25.
Adequate quality signals obtained in only 25 patients. Figures 1, 2, and 3 show examples from 3 patients.

**Estimation of LV Stroke Volume**
A good correlation was present between stroke volume obtained by cardiac catheterization and that obtained by echocardiography in the whole group ($r=0.83$, $P<0.001$, SEE=11 mL). Likewise, the correlation was good in patients with greater than mild tricuspid regurgitation and/or greater than mild mitral regurgitation ($r=0.89$, $P<0.01$, SEE=9 mL).

**Estimation of PA Systolic and Diastolic Pressures**
Significant correlations were present between invasively obtained and Doppler derived PA systolic pressure ($r=0.83$, $P<0.001$; Figure 4). The mean difference was 3±8.6 mm Hg (range, −27 to 22 mm Hg). There were 49 patients with PA systolic pressure >35 mm Hg; of these, 46 were correctly identified by Doppler (sensitivity, 94%). The 3 cases that were not correctly identified had invasive measurements of 38, 36, and 39 mm Hg, with Doppler estimates of 34, 33, and 31 mm Hg, respectively. Specificity was 90%.

A significant correlation was present between PA diastolic pressure by cardiac catheterization and Doppler ($r=0.51$, $P=0.009$, Figure 5). The mean difference was 2.6±6.7 mm Hg (range, −9 to 16 mm Hg). All 24 patients with PA diastolic pressure >12 mm Hg by right heart catheterization were correctly identified by Doppler. There was 1 patient with an invasive measurement of 10 mm Hg and a Doppler estimation of 13 mm Hg.

**Estimation of Mean PCWP**

**Accuracy of Individual Doppler Measurements**
Several Doppler measurements related significantly with mean PCWP with good accuracy (Table 2 and Table 3). However, LA maximum volume index >34 mL/m² had lower accuracy because of a low specificity of 33%. The relation between mean PCWP and average E/e’ ratio was better in patients without left bundle-branch block/biventricular pacing than in patients with bundle-branch block or biventricular pacing (Figure 6).

**ASE/EAE Guidelines**
Mitral inflow alone was sufficient for predicting mean PCWP (whether increased or not) in 65 patients, based on the ASE/EAE cutoff values for E/A ratio and DT and summarized in the Methods section above. In 14 patients with an E/A ratio >1 but <2, additional Doppler measurements were needed to predict mean PCWP. In 13 cases, all additional variables (E/e’ ratio, E/Vp ratio, and PA systolic pressure by Doppler) were

Figure 3. Mitral inflow from a patient admitted with ADHF. Data were obtained after initiation of intravenous therapy with milrinone and furosemide. Mean wedge pressure after therapy was 8 mm Hg. Mitral inflow (upper left panel, vertical scale of 20 cm/s) shows an impaired relaxation pattern with an E/A ratio <1 and a deceleration time of 232 ms. The peak tricuspid regurgitation (TR) velocity (upper right panel) corresponds to a systolic gradient across the tricuspid valve of 25 mm Hg. Septal (lower left) and lateral (lower right) tissue Doppler (TD) early (e’) and late (a’) diastolic velocities are reduced, and the average E/e’ ratio is 8.6. CW indicates continuous-wave.

Figure 4. The relation between pulmonary artery systolic pressure (PAS) by Doppler versus pressure obtained by right heart catheterization is shown in the left panel ($n=63$; $y=1.1x–0.8$). The graph shows the line of equality and the relation of the data points to this line. The Bland-Altman plot is shown in the right panel. The middle line corresponds to the mean difference. The upper line corresponds to the mean difference +2 SD, whereas the lower line corresponds to the mean difference −2 SD.
available and concordant, whereas in 1 patient only E/e’ and E/Vp ratios could be obtained without an adequate tricuspid regurgitation signal by continuous-wave Doppler.

The ASE/EAE algorithm had the highest accuracy, with a sensitivity of 98% and a specificity of 91%. There were only 3 of 79 patients in whom mean PCWP was incorrectly predicted by the algorithm. An invasively measured mean wedge pressure of 10 mm Hg was incorrectly predicted by mitral inflow, E/e’, and E/Vp ratios, and there was no adequate tricuspid regurgitation signal by continuous-wave Doppler. The second patient had a mean PCWP of 8 mm Hg but an E/A ratio of 2.3 and an E/e’ of 4.1. This patient had an average E/e’ ratio of 15.96, E/Vp ratio of 2.38, and a PA systolic pressure by Doppler of 28 mm Hg. The third patient missed by the algorithm had a mean PCWP of 20 mm Hg but an E/A ratio of 1.4, E/e’ ratio of 9.4, E/Vp of 1.4, and the PA systolic pressure by Doppler was 36 mm Hg.

**Estimation of Mean RAP**

A strong correlation was present between the invasive and noninvasive estimates of mean RAP (r = 0.85, P < 0.001, Figure 7 and Table 4). The mean difference was 1 ± 3.6 mm Hg (range, −5 to 10 mm Hg). There were 15 patients with RAP < 8 mm Hg. RAP could be estimated noninvasively in 12 of these 15 patients (there was no adequate subcostal view in 3 of 15) and correctly identified 11 of 12 as having RAP < 8 mm Hg (specificity of 92%). The exception was a patient who had a RAP of 7 mm Hg, but the noninvasive estimate was 12 mm Hg. All patients with RAP ≥ 8 mm Hg were correctly identified by echocardiography except for 2 patients (sensitivity of 96%). The exceptions were 2 patients with RAP of 8 and 10 mm Hg, but the noninvasive estimate was 5 mm Hg in both cases.

**Detection of Changes in Hemodynamics on Repeat Studies**

Eleven patients underwent a total of 12 repeat studies (11 patients with a single repeat study and 1 patient with 2 repeat studies). In 8 instances, the repeat measurements were obtained during the same hospitalization but after different treatments. This included intravenous furosemide in 2 patients, sodium nitroprusside in 2 patients, intravenous milrinone in 1 patient, and intravenous pressors (dopamine, dobutamine, and vasopressin) in another patient. Repeat assessment was performed after aggressive hemodialysis in 1 patient and after DC cardioversion in another patient. In the remaining 3 patients, repeat studies were acquired during a repeat hospitalization for ADHF.

This subgroup of patients had an average age of 56 ± 9 years (4 women). Six patients had already received biventricular pacing before both studies. There were 4 patients in this group who had postinfarction cardiomyopathy, and the rest had heart failure caused by dilated cardiomyopathy. Three patients had moderate mitral regurgitation; the rest had mild lesions. Two patients had severe tricuspid regurgitation, 2 had mild to moderate tricuspid regurgitation, and the rest had mild or trace lesions. There was no change in severity of mitral regurgitation or the severity of tricuspid regurgitation between the 2 studies. A summary of LV volumes and hemodynamics for this group with repeat studies is shown in Table 3.

**Table 2. Correlation of Doppler Measurements With Mean PCWP**

<table>
<thead>
<tr>
<th>No. of Patients</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>AUC (95% Confidence Intervals)</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanol</td>
<td>82</td>
<td>82</td>
<td>0.87 (0.79–0.96)</td>
</tr>
<tr>
<td>alcohol</td>
<td>89</td>
<td>81</td>
<td>0.86 (0.73–0.99)</td>
</tr>
<tr>
<td>water</td>
<td>89</td>
<td>83</td>
<td>0.91 (0.81–0.99)</td>
</tr>
</tbody>
</table>

**Table 3. Accuracy of Individual Variables in Identifying Patients With PCWP > 15 mm Hg**

<table>
<thead>
<tr>
<th>PV indicates pulmonary vein. Mitral A velocity was measured in only 61 patients because 18 patients had a single mitral inflow velocity. In the patients without lateral or septal e’ velocity, the available e’ velocity was used to compute E/e’ ratio and used in the regression analysis.</th>
<th>79</th>
<th>0.6</th>
<th>&lt; 0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mitral E velocity</td>
<td>79</td>
<td>0.6</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>2. Mitral A velocity</td>
<td>61</td>
<td>0.47</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>3. Mitral E/A ratio</td>
<td>61</td>
<td>0.64</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>4. Deceleration time of mitral E</td>
<td>79</td>
<td>0.46</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>5. Isovolumetric relaxation time</td>
<td>79</td>
<td>0.56</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>6. PV systolic filling fraction</td>
<td>32</td>
<td>0.61</td>
<td>0.002</td>
</tr>
<tr>
<td>7. E/Vp</td>
<td>61</td>
<td>0.53</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>8. Average E/e’</td>
<td>79</td>
<td>0.61</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>9. PA systolic pressure by Doppler</td>
<td>63</td>
<td>0.57</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>10. PA diastolic pressure by Doppler</td>
<td>25</td>
<td>0.41</td>
<td>0.04</td>
</tr>
<tr>
<td>11. LA maximum volume index</td>
<td>79</td>
<td>0.25</td>
<td>0.029</td>
</tr>
</tbody>
</table>

**Figure 5.** The relation between pulmonary artery diastolic pressure (PAD) by Doppler versus pressure obtained by right heart catheterization is shown in the left panel (n = 25; y = 0.62x + 12.2). The Bland-Altman plot is shown in the right panel. The middle line corresponds to the mean difference. The upper line corresponds to the mean difference + 2 SD, whereas the lower line corresponds to the mean difference − 2 SD.
Of note, most patients had large increments or large decrements in their mean wedge pressure on repeat studies. Significant correlations were observed between the changes in echo Doppler measurements and the actual hemodynamic changes measured by right heart catheterization. This included changes in PA systolic pressure ($r=0.9$, $P<0.005$), mean wedge pressure ($r=0.75$, $P=0.005$; Figure 8), mean right atrial pressure ($r=0.87$, $P=0.01$), and LV stroke volume ($r=0.63$, $P=0.05$). The results were unchanged after excluding 1 data set from the patient who had 2 repeat studies.

**Discussion**

This study shows that Doppler echocardiography can be readily applied to assess LV hemodynamics in patients with ADHF, including PA pressures, mean wedge pressure, and mean right atrial pressure. The study also validates the approach recommended in the recent ASE/EAE guidelines for the assessment of LV filling pressures in patients with depressed EF.6

**Assessment of LV Hemodynamics in ADHF**

ADHF patients are usually treated on the basis of clinical assessment, though PA catheters are not infrequently used to guide treatment in this population. However, the invasive approach is not without risks and did not translate to a better clinical outcome.10 A noninvasive approach is appealing, provided its measurements are accurate. In that regard, a comprehensive assessment of LV hemodynamics is feasible by Doppler echocardiography. The techniques were validated over the past 20 to 30 years by several laboratories. Furthermore, the measurements of LV stroke volume, PA pressures, and LV filling pressures are currently an integral component of echocardiographic reports in many laboratories. Although the previous validation studies included patients with depressed EF, the critical question about the accuracy of Doppler measurements in ADHF was not directly addressed, except for the recently published report by Mullens et al.3

**Doppler Estimation of Mean PCWP**

The results of our study in ADHF are consistent with several previous reports showing the accuracy of mitral inflow velocities and time intervals in predicting LV filling pressures in patients with depressed EF and stable heart failure.11–21 However, we specifically included patients who were acutely decompensated and some were receiving a number of intravenous drips, including diuretics, vasodilators, positive inotropic drugs, and intraaortic balloon pump. Similar to previous studies, pulmonary vein velocities and the systolic filling fraction exhibited significant correlations with mean PCWP, albeit with a lower feasibility than mitral and TD velocities. We and others have noted the lower feasibility of adequate pulmonary vein velocity signals in patients imaged in the cardiac catheterization laboratory or in the intensive care unit settings.17,18

Both E/e' ratio and E/Vp ratio had good accuracy in predicting mean PCWP in our study. However, the correlation of E/e'

**Figure 6.** The relation between average E/e' ratio and mean PCWP in patients without left bundle-branch block (LBBB) and without cardiac resynchronization therapy (CRT) is shown in the left panel ($n=45$; $y=2.1x-0.03x^2-5.5$; $R^2=0.56$). The right panel shows the relation in patients with LBBB or CRT ($n=34$; $y=9.4x+0.76x$).

**Figure 7.** The relation between mean RAP by Doppler echocardiography versus pressure obtained by right heart catheterization is shown in the left panel ($n=60$; $y=0.96x+1.69$). The Bland-Altman plot is shown in the right panel. The middle line corresponds to the mean difference. The upper line corresponds to the mean difference $+2$ SD, whereas the lower line corresponds to the mean difference $-2$ SD (there are 21 overlapping data points).
ratio with mean PCWP was lower in patients with left bundle-branch block or biventricular pacing. This is probably because of the abnormal septal motion and longitudinal rotation in left bundle-branch block, which can affect annular diastolic velocities.\textsuperscript{22} Of note, the weaker relation in patients with left bundle-branch block was previously reported in patients with normal E/F\textsuperscript{23} and depressed EF\textsuperscript{3}. The current study and that by Mullens et al\textsuperscript{5} emphasize the limitations of TD in patients with biventricular pacing, the need for satisfactory signals, and the impact of technically challenging recordings on the accuracy and the clinical application of the methodology.

Interestingly, a Doppler-derived PA systolic pressure >35 mm Hg was a good predictor of an increased mean PCWP by cardiac catheterization in patients with ADHF. In that regard, our study using invasively measured mean PCWP extends the findings of a previous report, which showed a significant correlation between PA systolic pressure and the noninvasive estimation of mean PCWP in patients with normal LV EF\textsuperscript{24} to patients with ADHF.

### Application of ASE/EAE Guidelines for the Estimation of LV Filling Pressures in ADHF

Although most of the individual Doppler parameters had good accuracy, the comprehensive approach recommended in the recent ASE/EAE guidelines had the highest accuracy\textsuperscript{6} and only 3 patients were incorrectly classified when these guidelines were applied. Accordingly, we recommend the guidelines approach in lieu of isolated Doppler measurements in patients with ADHF. Of note, a different algorithm is applied in patients with normal EF.

### Detection of Changes in Mean PCWP

A clinically useful noninvasive measurement of mean PCWP should be able to detect meaningful changes in PCWP with therapy. Previous studies have shown that Doppler can detect changes in filling pressures in heart failure patients who are clinically stable\textsuperscript{21}. The current study shows that Doppler echocardiography can also be applied for that objective in patients with ADHF, including patients with an increase or a decrease in mean PCWP >5 mm Hg.

### Limitations

There are a number of limitations to this study. Some are related to the lower feasibility of acquiring satisfactory pulmonary regurgitation and pulmonary venous flow signals. Fortunately, the feasibility of their acquisition can be increased with intravenous contrast agents that may be needed for LV cavity opacification. LA pressure was not measured directly because it was difficult to justify transseptal puncture for the sole purpose of the study. However, mean wedge pressure and LV pre-A pressure are good surrogates of LA pressure. We included few patients with repeat hemodynamic measurements, and additional observations in this population are needed to confirm our findings.

### Conclusions

We have demonstrated that Doppler echocardiography can be used to reliably assess LV and RV hemodynamics in patients with acute decompensated heart failure\textsuperscript{25}. This includes the demonstration that estimation of LV filling pressure is feasible by combining measurements of blood flow velocities and myocardial velocities.

### Disclosures

None.
References


5. Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, Picard MH, Roman MJ, Seward JB, Solomon SD, Spencer KT, Sutton MS, Stewart WJ; Chamber Quantification Writing Group; American Society of Echocardiography’s Guidelines and Standards Committee European Association of Echocardiography. Recommendations for chamber quantification: a report from the American Society of Echocardiography’s Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. J Am Soc Echocardiogr. 2005;18:1440–1463.


Clinical Perspective

The assessment of hemodynamics in patients with acute decompensated heart failure can be of value in their treatment. We evaluated the accuracy of Doppler echocardiography in estimation of left and right ventricular hemodynamics in 79 patients with unstable heart failure. The technique had a good accuracy in the estimation of stroke volume, pulmonary artery systolic and diastolic pressure, and mean right atrial pressure. Several Doppler indices, including tissue Doppler, had good accuracy in identifying patients with pulmonary capillary wedge pressure >15 mm Hg. In addition, the recent American Society of Echocardiography/European Association of Echocardiography guidelines were highly accurate in identifying patients with increased wedge pressure. In 12 repeat studies, Doppler echocardiography readily detected the changes in mean wedge pressure as well as other hemodynamic changes.
Echocardiographic Evaluation of Hemodynamics in Patients With Decompensated Systolic Heart Failure
Sherif F. Nagueh, Rajat Bhatt, Rey P. Vivo, Selim R. Krim, Sebastian Imre Sarvari, Kristoffer Russell, Thor Edvardsen, Otto A. Smiseth and Jerry D. Estep

Circ Cardiovasc Imaging. 2011;4:220-227; originally published online March 11, 2011;
doi: 10.1161/CIRCIMAGING.111.963496
Circulation: Cardiovascular Imaging is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2011 American Heart Association, Inc. All rights reserved.
Print ISSN: 1941-9651. Online ISSN: 1942-0080

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circimaging.ahajournals.org/content/4/3/220

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation: Cardiovascular Imaging can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation: Cardiovascular Imaging is online at:
http://circimaging.ahajournals.org//subscriptions/