Cardiac Ultrasound TODAY

ISSN 1086-4237

Number 7/8
Volume 8
2002

Exercise Doppler Echocardiography

Utility in Obtaining Hemodynamic Evaluations

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Cardiac Ultrasound TODAY is published ten times per year by Chrestomathic Press, Inc., 3003 N. Central Ave., Suite 103–320, Phoenix, Arizona 85012. **Orders or literature:** 800–631–9238. **Customer service:** 601–582–3353. **Fax:** 601–582–3354. **Online:** www.chrestomathic.com

Cardiac Ultrasound TODAY

Number 7/8, Volume 8

Lesson Objectives

Upon completion of this lesson, the reader should be able to:

1. Identify the clinical indications for exercise Doppler.
2. Describe the technical elements and equipment required to perform exercise Doppler.
3. Discuss the circumstances where exercise Doppler is most valuable.
4. List the advantages of exercise Doppler over other modalities.
5. List the technical pitfalls to be avoided when performing exercise Doppler.

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Online Edition: www.chrestomathic.com 8(7/8):118–149, 2002

Exercise Doppler

Utility in Obtaining Hemodynamic Evaluations

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Since the early 1980s, Doppler recordings during exercise have been used by clinicians to assist in the functional assessment of patients with known or suspected cardiac or pulmonary disease. A variety of exercise methods have been employed over the years, from the basic Master two-step test or simple handgrip maneuvers to more elaborate arrangements, including sophisticated exercise equipment and measurement devices. Historically, pulmonary artery systolic pressure (PASP) has been the most common Doppler parameter acquired with exercise, since obtaining the tricuspid regurgitation (TR) peak velocity with continuous wave (CW) Doppler is a relatively simple task. It is probably still the most commonly performed exercise Doppler (ED) exam. In recent years, numerous applications have emerged allowing ED to play a more prominent role in the assessment and management of patients.

Exercise physiology or hemodynamics in man was extensively studied in cardiac catheterization laboratories between 1960 and 1985. As the patient profile shifted from valvular and congenital heart disease to diagnosis of coronary artery disease and to therapeutic coronary interventions, the typical cardiac catheterization laboratory is poorly equipped to study exercise hemodynamics. Furthermore, Doppler hemodynamics have replaced a need for invasive catheterization–obtained hemodynamics in nearly all types of valvular, congenital, and myocardial diseases. ED is therefore a natural extension of hemodynamic evaluation of a patient using physiologic stress. This information is invaluable in providing the hemodynamic effects of a disease during daily physical activities. The resting hemodynamics are often insufficient to assess the effects of valvular disease on pulmonary artery pressures or on effort-related symptoms. This information has in most instances a direct bearing on patient management.

Clinical Indications

A patient's reported symptoms are often out of proportion to the findings detected by a resting Doppler study. Provocation of exertional symptoms and acquisition of the Doppler data necessary to assess the level of the related disorder is the purpose of ED. This accurate, noninvasive method is recommended in the American College of Cardiology/American Heart Association (ACC/AHA) published practice guidelines for hemodynamic exercise response, when discordance exists between resting hemodynamics and symptoms. Severity of valvular disease, whether native or prosthetic, can be assessed in a serial manner with ED, while incurring minimal risk for the patient. The role of ED when timing an intervention or surgery for valve disease can be crucial, and it is gaining in popularity in current practice. Management of patients with chronic lung disease is enhanced when the pressure response, in the right ventricle, to exercise is determined. Information regarding functional reserve in these patients can also be garnered (Table 1).

Steady-State Circulatory Physiology

It has been well-recognized that an important component of exercise hemodynamics is to achieve a steady-state circulatory physiology. As workload is increased, the changes in heart rate, cardiac output, and intracardiac pressures achieve a steady state after 2 to 3 minutes at the given workload. This is a crucial component of exercise hemodynamics that

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Table 1
Exercise Doppler Indications

Discordance between resting hemodynamics and symptoms
Assessment of known valvular disease (MS/MR, AS/AR) to document effectiveness of current medical management
Assessment of valvular disease progression and timing of surgery/intervention
Prosthetic valve functional assessment
Assessment of pulmonary hypertension, latent or overt
PASP assessment in patients with CHF or cardiomyopathy
Hypertrophic obstructive cardiomyopathy

should be emphasized. It is for this reason that post treadmill exercise Doppler is quite unsatisfactory since in the post treadmill period the heart rate and cardiac output are rapidly changing and the intracardiac pressures are similarly undergoing a change. It is therefore difficult if not impossible to provide a meaningful interpretation of Doppler hemodynamics obtained during a non-steady state. Similar limitations apply to a common practice in "modern" cardiac catheterization laboratories: asking the patient to raise one or both arms with saline bags in hands. This is a sorry attempt at understanding effects of physical effort on intracardiac hemodynamics and pulmonary artery pressures. It is therefore incumbent upon all serious echocardiographic laboratories to develop expertise in bicycle exercise echo Doppler studies for hemodynamic evaluations. Figure 1 illustrates the supine bicycle method.

Technical Considerations

Every echocardiography lab currently providing conventional stress echocardiography (SE) for the assessment of coronary artery disease (CAD) has most of the necessary components to perform ED. Digital technology, available on recent generations of ultrasound systems, has provided the means for obtaining multiple cineloops during an exercise study. When performing SE, standard two-dimensional (2D) views are digitally obtained at

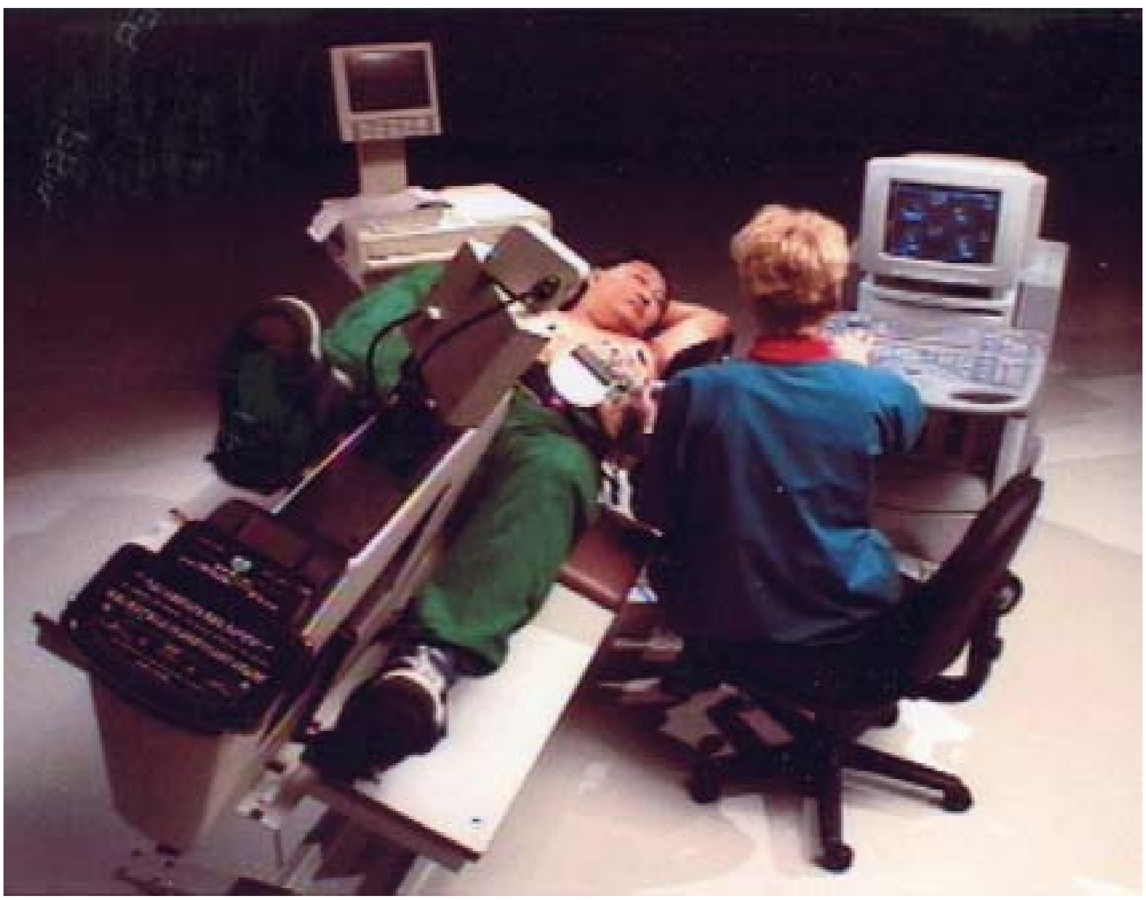

Figure 1. The supine bicycle method allows the sonographer to image at peak (or at each stage) while the patient continues to pedal. Exercise is performed in the supine posture, then the platform can be tilted laterally when ready to image.

rest, and again either during or immediately following cessation of exercise. The digital images can then be assessed for the presence or absence of new or worsening wall motion abnormalities and standard 2D measurements can also be performed. Likewise, digital technology plays an important role when performing ED. Doppler waveforms are obtained (and digitally stored) at rest and again at peak exercise. Because the waveforms are digitally stored, a variety of measurements and calculations can be performed after the exercise exam is completed, to assess changes in peak and/or mean gradients and valve areas.

The learning curve for the sonographer is not substantially different from that encountered when undertaking SE. The supine bicycle provides a stable platform for scanning the upper torso during peak exercise and is less "stressful" for the sonographer than the rapidly falling heart rate usually encountered with post exercise methods.

Frequently, contrast agents are employed to enhance the tricuspid regurgitant Doppler waveform. Timing the contrast injection while maintaining a high heart rate is crucial to the success of ED. Utilizing peak imaging stress methods, contrast can be injected as the patient continues to exercise, while Doppler images are simultaneously acquired.

In addition to equipment and supplies currently used for routine SE or pharmacologic studies, laboratories planning to implement ED should also use a pulse oximeter and an automatic blood pressure monitor. The pulse oximeter is used to monitor the saturated oxygen since a drop in oxygen saturation may indicate a marked increase in pulmonary hypertension. The automated blood pressure monitor allows ancillary personnel to perform other duties, such as contrast injection, as needed (Table 2).

A general ED protocol consists of obtaining the following parameters at rest and with exercise: cardiac output, inferior vena cava diameter (for assessing right atrial pressure), maximum TR velocity (pre and post saline injection when needed) and Doppler signals across valves. Valve areas and pressure gradients are calculated for stenotic valves, and color flow Doppler is used to assess regurgitant flow. Exercise endpoints include patient fatigue, decrease in arterial oxygen saturation < 85% (accompanies a marked increase in pulmonary hypertension), and a decrease in systolic blood pressure of > 20 mmHg.

Table 2
Exercise Doppler Equipment

Ultrasound system with digital capability
Supine bicycle ergometer
IV supplies (including 3-way stopcock with two 10-ml syringes), IV placed in right arm
Agitated normal saline or contrast agent; pharmacologic agent)
Automatic BP monitor (on left arm)
Pulse-oximeter (finger on right hand)
12-lead ECG

Evaluating Valvular Pathology

Mitral Stenosis

A standard utility of ED today is evaluating patients with mitral stenosis (MS) whose symptoms, such as exercise intolerance and exertional dyspnea, are disproportionate to the resting mean gradient and calculated valve area. In this subset of patients, the resting Doppler will generally show a mild to moderate transvalvular gradient and normal pulmonary artery pressure, depending on flow, since at rest the transmitral flow volume is the lowest and diastolic filling is longest. The mean pressure gradient across the mitral valve along with cardiac output are the major determinants of symptoms and development of pulmonary hypertension. The pressure gradient is related to volume of flow as well as heart rate. With exercise, the heart rate and cardiac output increase, thereby increasing left ventricular (LV) filling and transmitral flow but decreasing the diastolic filling period. Therefore, one sees more flow in less time, which substantially increases the mean and peak transmitral gradients with exercise (Figure 2).

Some patients with non-critical MS (i.e., MVA > 1.0 cm^2) may be symptomatic with effort as a result of a rapid heart rate response. This is especially true in the presence of atrial fibrillation. The appro-

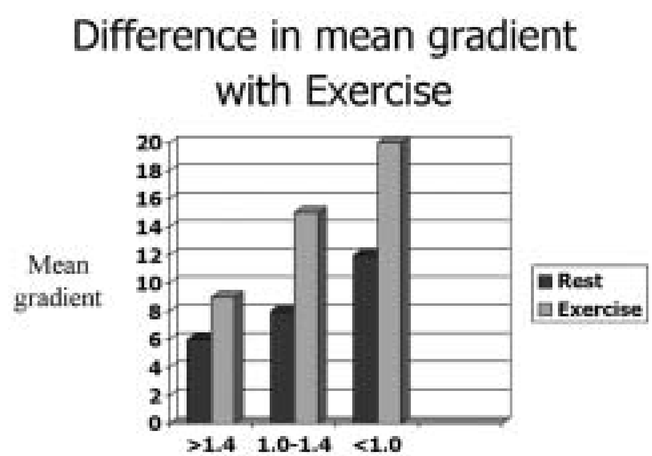

Figure 2. MVA and mean gradient at rest and with exercise. Data from References 3 and 9.

priate treatment may be directed to slowing heart rate response to activity with medications.

Editor's Comments: Reduced resting net atrioventricular compliance (which can be noninvasively estimated from the continuity-derived mitral valve area/E wave downslope) may also be responsible for exertional symptoms and PA pressure elevations in the presence of a relatively large mitral valve orifice area. —Brian D. Hoit, M.D.

Due to increased flow through the pulmonary system with increased resistance, a pronounced increase in PASP is also noted.

To document the changes that occur during exercise, transmitral gradients (peak and mean) and the TR velocity can be obtained, using CW Doppler from the apical window. Mitral valve area (MVA) is then calculated using the pressure half-time or continuity equation methods. Some investigators have found the flow-convergence-region method to be as reliable during exercise as at rest. The pressure half-time is useful in assessment of valve area with exercise at heart rates that do not abbreviate diastolic filling periods excessively. Thus, at heart rates up to 140 to 150 beats per minute, it should be feasible to measure pressure half-time accurately. MVA can also be reliably assessed in the presence of mixed disease, MS with mitral regurgitation (MR), using the pressure half-time method.

Exercise as a rule does not alter ventricular or atrial compliance acutely and should not result in less accurate assessment of valve area. However, mean pressure gradients and pulmonary artery pressures are of greater value in assessing symptoms and disease progression.

PASP is calculated by measuring the peak tricuspid regurgitant velocity to use in the modified Bernoulli equation, then adding the estimated right atrial pressure (RAP) to this value. In addition, if resting pulmonary hypertension is present, obtain the inferior vena cava diameter inspiratory to expiratory ratio. A ratio > 50% indicates a RAP of 10 mmHg, and <50% a RAP of 15 mmHg.

Editor's Comments: If the IVC is distended and nonpulsatile, the RAP is 20 to 25 mmHg. When the RAP is very high, an accurate assessment of RAP by echocardiography is often difficult. —P.A.N. Chandraratna, M.D.

ED is particularly suited to distinguishing patients who demonstrate no significant change or a minimal increase in transvalvular gradients and PASP, from the more dramatic rises seen in patients with abnormal pulmonary vascular resistance or significantly restricted valve orifices. The impact of ED on patient management when equivocal symptoms coexist with only mild to moderate obstructive data is evident, especially in cases where intervention would be the proper choice.

ED can identify patients who should experience some symptomatic improvement after percutaneous mitral balloon valvotomy. Patients who demonstrate mean gradients at peak exercise that are more than double the resting gradient or > 15 mmHg final gradient, are most likely limited by their obstructions and not another condition, such as diastolic dysfunction or pulmonary disease. Those factors would not influence the Doppler data in the same way as valvular dysfunction. ED lends itself to serial studies, and it can be an important adjunct to assist in timing of intervention or surgery, when valve replacement is inevitable.

Case Report: Mitral Stenosis. The patient is a 24-year-old woman with a history of mitral stenosis, who has had two prior uncomplicated pregnancies and desires to have more children. She currently has no symptoms of dyspnea and works out regularly on the treadmill, so she was referred for bicycle stress echocardiography for evaluation before becoming pregnant.

The resting transthoracic echocardiogram showed normal LV size and function. The left atrium was moderately enlarged. The MVA was 1.2 cm^2 with a mean gradient of 14 mmHg. The valvuloplasty score was 6: leaflet thickness 2, subvalvular thickness 2, leaflet mobility 1, and leaflet calcification 1. There was trace MR and normal estimated PASP.

The patient exercised on the supine bicycle to a maximum of 100 watts, stopping due to leg fatigue. The peak heart rate was 178 beats/minute (90% target heart rate). There were no LV wall motion abnormalities; however, there was marked ventricular septal shift and a D-shaped left ventricle. The mean mitral gradient increased to 40 mmHg with exercise. The TR velocity rose to 5.6 m/sec, the estimated PASP during exercise was 125 mmHg (Figures 3–6).

The patient was referred for percutaneous mitral balloon valvuloplasty. A prevalvuloplasty transesophageal echocardiogram confirmed the resting transthoracic mitral data and showed no evidence of left atrial or appendage thrombus.

The patient underwent successful balloon valvuloplasty. Post procedure the MVA was increased to 2.3 cm^2 and the mean gradient had decreased to 6 mmHg, with only trace MR.

Editor's Comments: Exercise Doppler echocardiography is particularly helpful in evaluating the patient with moderate mitral stenosis and mild symptoms or in the patient with mild mitral stenosis who is very symptomatic. The hemodynamic profile during exercise may reveal an excessive increase in heart rate or blood pressure which could be effec-

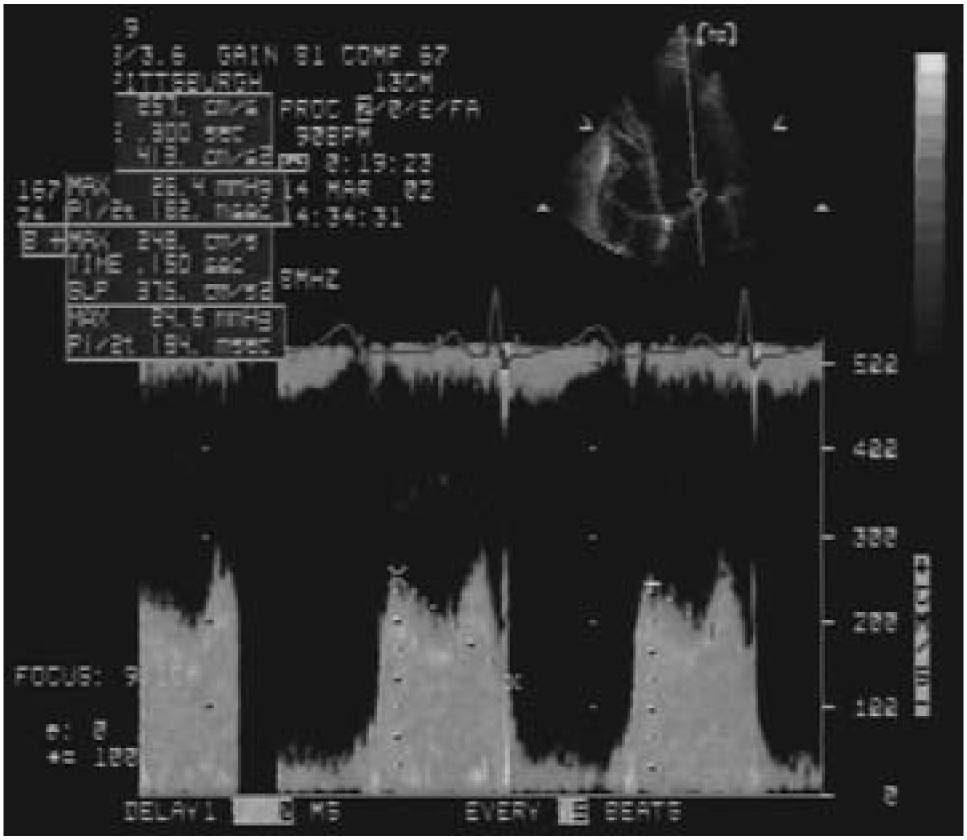

Figure 3. TTE CW Doppler signal of MV diastolic flow profile at rest, pressure half-time = 182 msec, MVA = 1.2 cm^2, mean gradient = 14 mmHg.

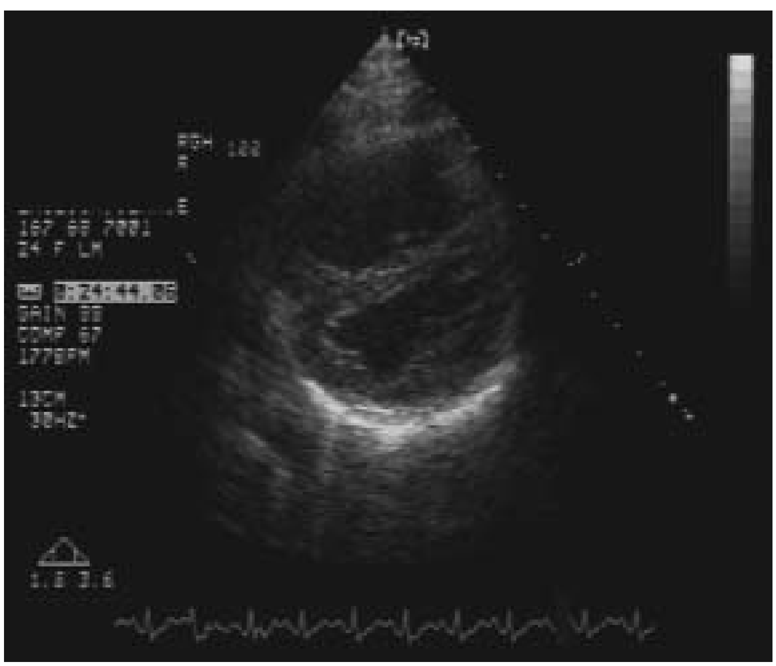

Figure 4. Parasternal short-axis view at peak exercise, showing a D*-shaped LV, indicative of the high pressure in the RV.*

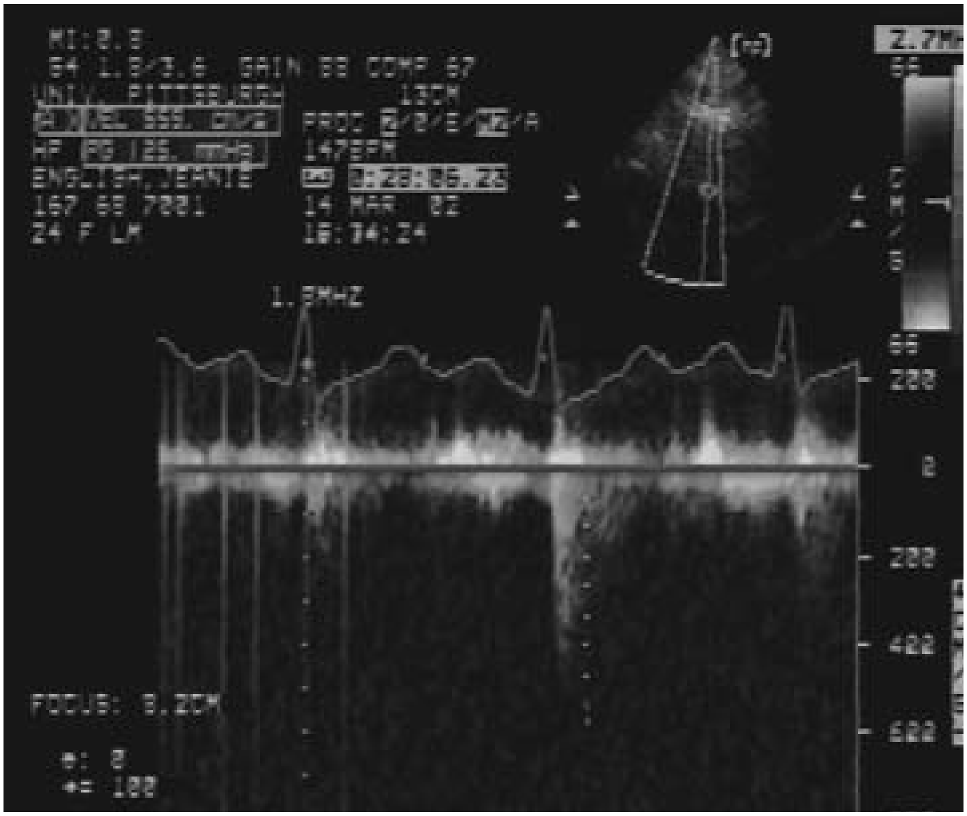

Figure 5. CW signal showing peak exercise TR velocity of 5.6 m/sec, estimated RVSP = 125 mmHg.

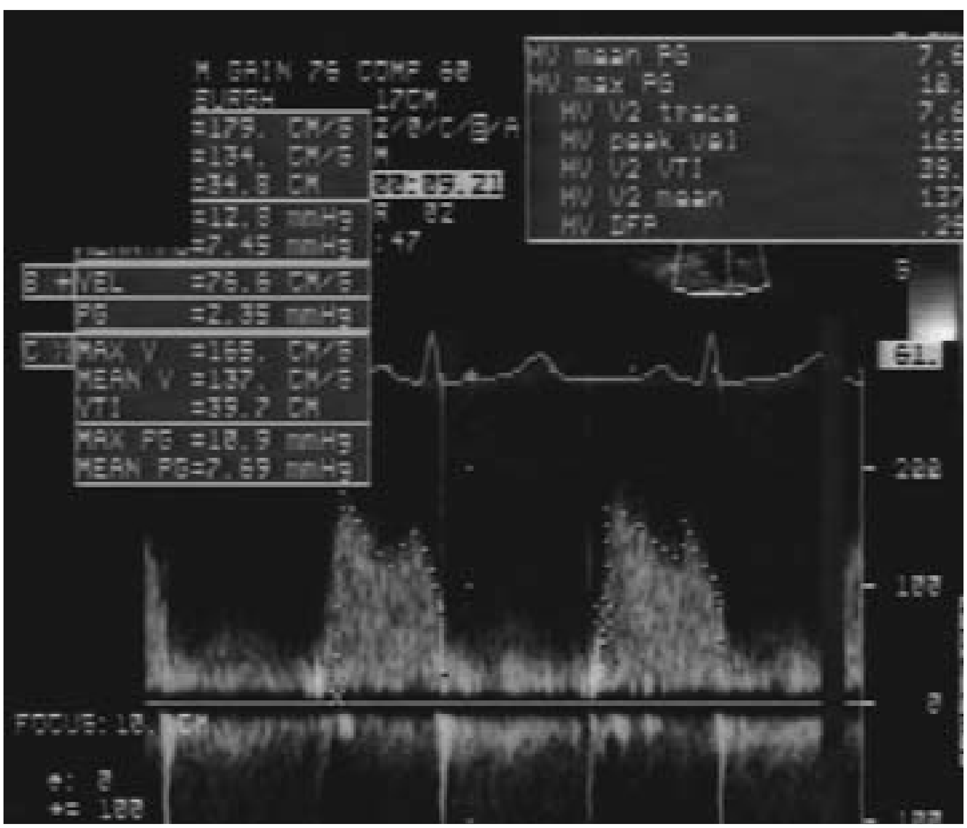

Figure 6. TTE CW Doppler signal of MV post balloon valvuloplasty, mean gradient = 7 mmHg.

tively treated with medical therapy. This may result in improvement of symptoms. —PANC

Mitral Regurgitation

The label of “moderate to severe” MR may place a patient in a state of clinical management uncertainty, particularly when the patient’s resting study is unremarkable. Mitral regurgitation results from varied disorders of the mitral valve apparatus, which includes ventricular geometry and function. The hemodynamic effects of exercise will, to some measure, be influenced by ventricular factors rather than valvular anatomy. Combined echo Doppler evaluation during supine bicycle exercise could provide information on ventricular function and may explain the basis for effort-related symptoms.

MR results in increased preload (i.e., LV end-diastolic volume) and decreased afterload (i.e., LV end-systolic volume) and thus ejection fraction is augmented under resting conditions. Exercise-induced hypertension may unmask myocardial dysfunction, and the ejection fraction may decrease in place of the normal expected increase. This is also true in the presence of unrecognized coronary artery disease. MR resulting from ischemic papillary dysfunction is often described as mild or moderate. Exercise-induced ischemia may result in acute worsening of MR and provide an explanation for effort-induced symptoms and guide appropriate management (Table 3).

Studies by investigators at the Cleveland Clinic suggest use of exercise-induced increase in LV end-systolic volume as an index of timing for surgery in asymptomatic patients with mitral regurgitation.

The exercise hemodynamic evaluation in mitral regurgitation should include pulmonary artery pressures, severity of regurgitation, and left ventricular function. An understanding of these parameters will permit a more appropriate therapeutic intervention. The effect of exercise on arterial blood pressure should be kept in mind. A markedly hypertensive response may be responsible for worsening mitral regurgitation, and hence appropriate treatment may be directed toward blunting such a response.

Table 3
Indications for Exercise Echo in MR

- Asymptomatic patients
  - Assess pulmonary artery pressure
  - Assess LV end-systolic volume
- Symptomatic patients
  - Correlate effort-induced symptoms with hemodynamics in the presence of normal baseline PASP
  - Evaluate role of ischemia on MR severity, segmental and global LV function

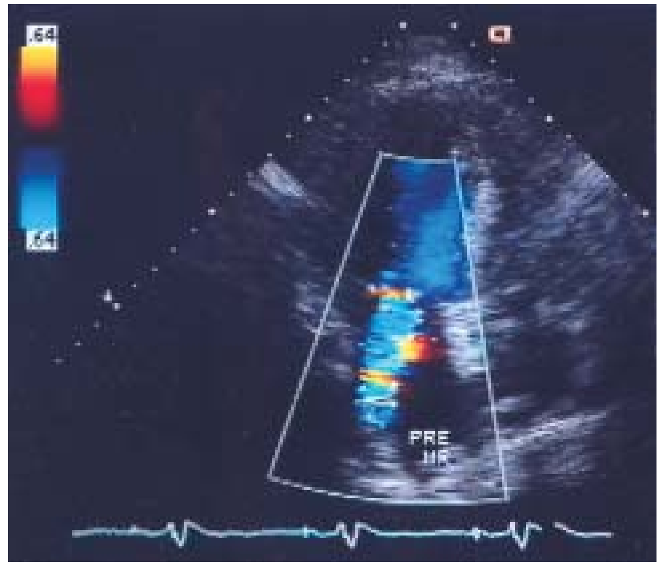

Figure 7. Color flow Doppler image of MR at rest.

Elevation of the PASP during dynamic exercise, and the onset or worsening of dyspnea, can be correlated to increasing mitral regurgitant volumes. Utilizing color flow (CF) Doppler, an exercise study is the ideal tool for assessing functional MR and its severity. Figures 7–10 show an example of exercise-induced increase in MR and resultant elevation of PASP. Reliable quantification of MR severity during exercise can be performed using any of several recommended methods.

Editor’s Comments: The severity of functional MR during bi-

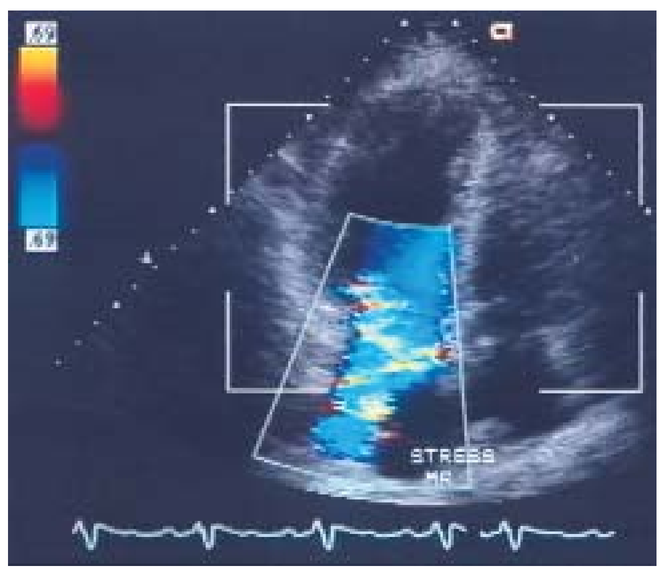

Figure 8. Color flow Doppler image of dramatic increase in MR with exercise.

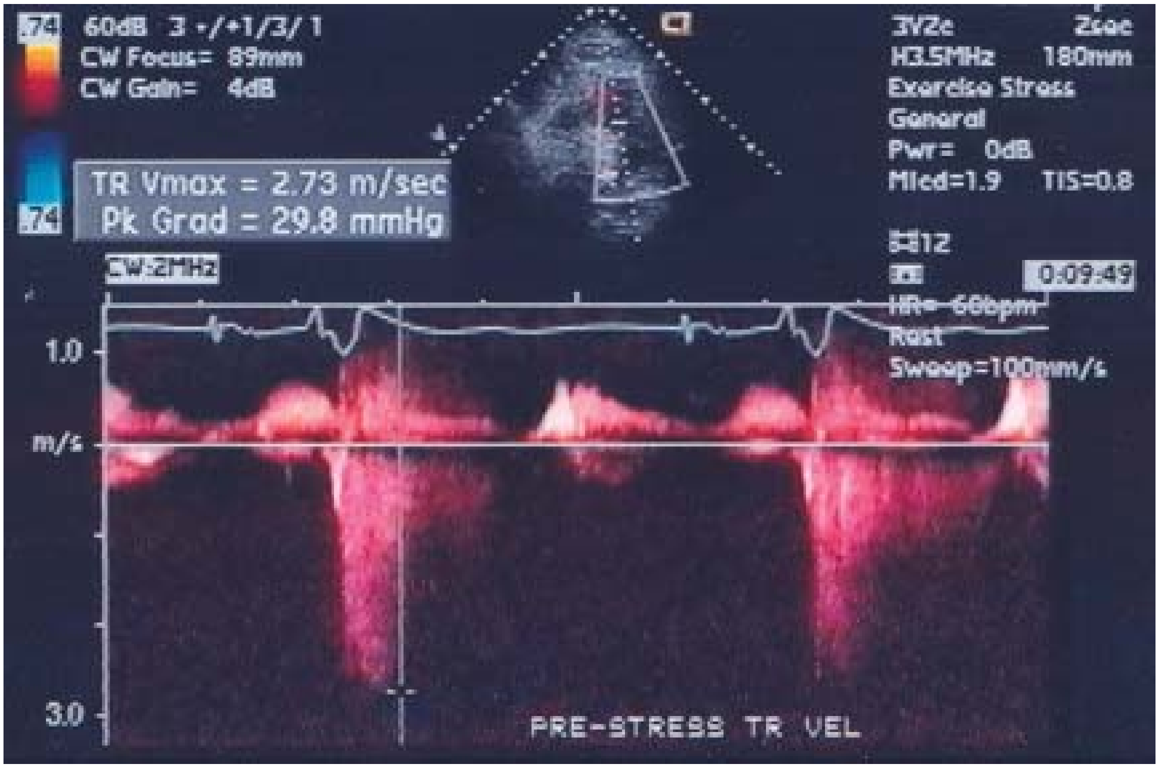

Figure 9. CW Doppler signal of TR velocity at rest, TR vel.= 2.7 m/sec, RVSP = 30 mmHg.

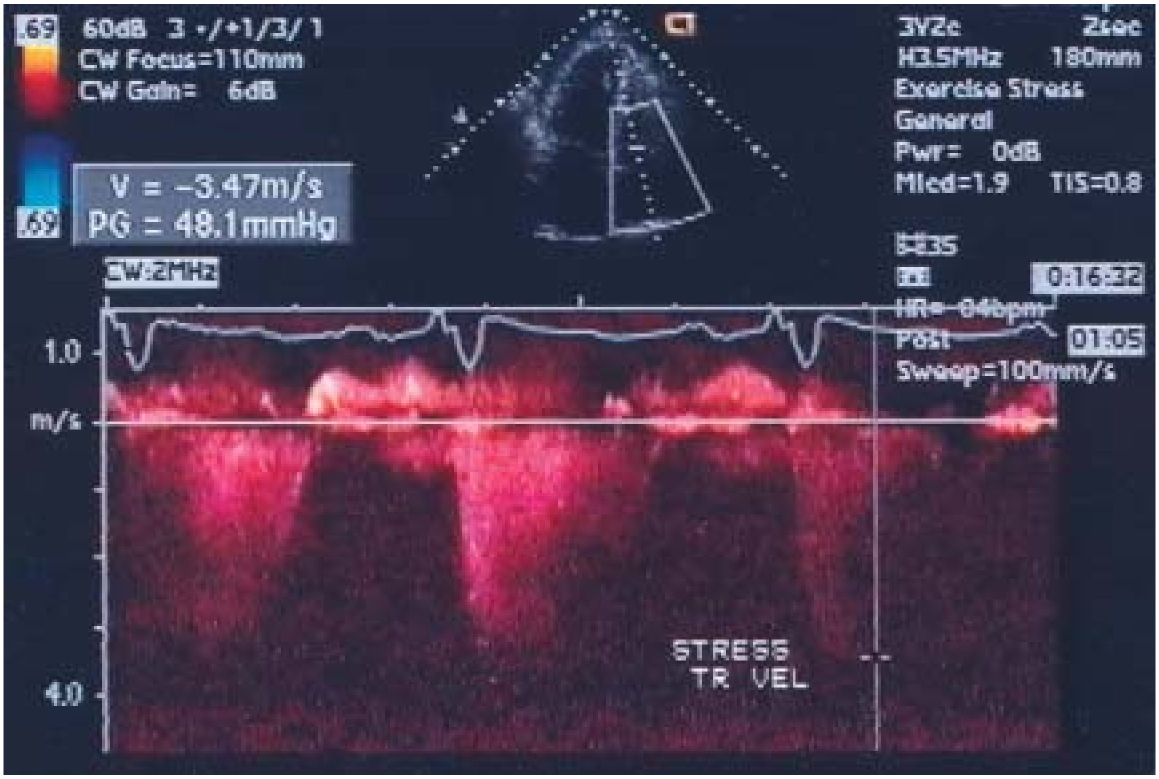

Figure 10. CW Doppler signal of TR velocity increasing to 3.5 m/sec with exercise, RVSP = 48 mmHg.

cycle exercise (quantified with either the PISA method or quantitative Doppler) correlates directly and very well with increases in pulmonary artery systolic pressure. —BDH

Editor's Comments: An increase in the severity of MR during exercise may result from an abnormal increase in systolic blood pressure or an increase in ischemic MR. Exercise Doppler echocardiography may help in making the distinction between these conditions. —PANC

Mitral Valve Prosthesis

Mitral valve prosthesis is nearly always somewhat stenotic (i.e., MVA 1.5 to 2.5 cm^2). Since most prostheses are mounted on a rigid frame, the valve orifice, unlike in normals, is not able to enlarge in order to accommodate increased flow. Hence, the exercise response in a patient with mitral prosthesis, whether mechanical or bioprosthesis, is one similar to mild or moderate MS. The mechanical bileaflet valves may exhibit higher velocities when the jet through the central narrower orifice is interrogated. The magnitude of this overestimation is small in the mitral bileaflet valves as compared to those in the aortic position.

Several studies have established the reliability of ED for the evaluation of transvalvular mitral prosthetic gradients and PASP. It is possible to diagnose early prosthetic valve obstruction. While an obstructed mitral valve and a normally functioning mitral prosthesis may display similar gradients at rest, the dramatic rise in mean gradient with exercise in the former is to be distinguished from the fairly level response of the normal prosthesis.

Patients who have undergone valve replacement surgery generally experience symptomatic relief, and significant improvement is found with follow-up Doppler studies. However, some patients fail to improve as expected, and an ED study may help differentiate between prosthetic valve dysfunction and persistent elevated PASP from structural changes in the pulmonary vascular bed or and from postoperative myocardial dysfunction with elevated LV end-diastolic pressures.

Aortic Stenosis

The safety of exercise in asymptomatic severe AS is well-demonstrated. It often provides an assessment of effort tolerance when a patient claims to be completely asymptomatic. It also provides analysis of left ventricular function and exercise-induced arrhythmias, which have impact on patient management. Data pertaining to jet velocity, maximal volume flow rate, changes in peak and mean gradients and valve area, as well as functional status and symptoms, may be obtained.

The location of the acoustic window which yields the optimal CW signal for peak flow velocity through the AV will influence the quality of the data. Generally, the apical window provides the easiest access at peak or post exercise for reproducibility.

There is no need to exercise symptomatic patients with severe aortic stenosis, i.e., with mean gradient > 45 mmHg and AVA < 0.9 cm^2. Indeed, exercise testing in such patients is generally contraindicated. The low-dose dobutamine is generally reserved for symptomatic patients with low cardiac output and reduced ventricular function in the presence of calcific aortic stenosis with low mean pressure gradients. If the low pressure gradient is a result of low cardiac output, dobutamine in doses of 5 to 15 µg/kg/min will result in marked increase in pressure gradient with modest increased in flow. On the other hand, if one is dealing with mild to moderate AS in the presence of depressed ventricular function, a dobutamine-induced increase in flow will not result in a significant increase in mean gradients.

Editor's Comments: In contrast to its presence, the absence of contractile reserve in patients with LV dysfunction and low aortic gradients is associated with a high operative mortality. —BDH

Aortic Regurgitation

When evaluating aortic regurgitation (AR) with ED, methodology and similar considerations to MR assessment should be employed. In addition, the rate of decline in regurgitant gradient, as measured by the slope of diastolic flow velocity profile is useful, when the AR is an isolated lesion. However, when there is coexistent AS, the pressure half-time may be short (< 250 msec), even in the presence of moderate AR, because of a markedly elevated LVEDP. As with MR, the LV loading conditions must be considered when performing serial ED studies for AR. A necessary component when intervention is being considered is the assessment of structural changes that occur over time. Exercise-induced reduction in ejection fraction is one of the parameters used in the determination of timing of surgery in asymptomatic patients with severe AR. Exercise may be well-tolerated as a result of a decrease in AR due to abbreviation of diastole.

Editor's Comments: A reduced resting annular velocity on DTI correlates with an exercise-induced reduction in ejection fraction and may be an index of subclinical LV dysfunction in asymptomatic patients. It should also be remembered that significant aortic insufficiency adversely influences the accuracy of exercise echocardiographic diagnosis of coronary artery disease. —BDH

Aortic Valve Prosthesis

Transvalvular gradients are normally increased through a prosthesis compared to native valves due to the inherent properties of construction (e.g., sewing ring, struts, rocker arm, cage). Individual sizes and flow rates can cause widely varying velocities and resultant derived gradients. Hence, the tables providing normal mean values for various sizes and types of valves are generally unhelpful. The importance of establishing a baseline hemodynamic profile following valve replacement must be underscored. A comprehensive Doppler examination, generally 1 to 3 months after surgery, will provide the means for serial follow-up.

Exercise-induced changes in peak and mean gradients and valve area in the patients with prosthetic valves provide helpful information. Generally, gradients through a prosthesis should increase modestly with exercise. Other indicators to follow include a later peaking velocity profile of the V_2 signal, producing a more rounded appearance compared to a sharp peak, and prolonged systolic ejection period. An effective orifice area (EOA) of < 0.8 cm^2 indicates a prosthetic AV obstruction.

Resting and immediate post exercise gradients compare well for the St. Jude and Medtronic Hall mechanical prostheses, but their peak gradients can increase by more than 50% with exercise. This can be an unsettling outcome, considering that the patient's daily activities may well evoke similar pressure gradients. Careful assessment by a controlled stress examination should guide recommendations for prescribed activity levels in patients with these types of valve replacements.

The aortic valve replacement with pulmonary autograft (also known as the Ross operation) is generally carried out in younger and middle-aged patients who are physically active. It has been demonstrated that the gradients across pulmonary autograft following severe exertion are no different than in age-matched normal subjects. ED is particularly suited to follow these generally active patients in a serial manner.

Editor's Comments: Hemodynamic evaluation of prosthetic valves in patients unable to exercise adequately is effectively assessed with dobutamine stress. —BDH

Patient/Valve Mismatch

When a normally functioning aortic prosthesis does not provide an adequate outflow area in relation to cardiac output based on patient size, it is known as valve prosthesis–patient mismatch. It produces a residual aortic stenosis following surgery. However, the intrinsic components of the individual prosthesis are the most important determinants of transvalvular gradients. Aortic valve prostheses demonstrate proportionally higher gradients, especially during exercise, than replacements in other positions, due to smaller diameter sizes and the influence of the sewing ring encroaching on the EOA.

Often defined as effective orifice area of the prosthesis being < 0.85 cm^2/m^2 mismatch may result from a small aortic root in older women with a small body surface area. The implantations of size 19 and at times size 21 prosthesis are associated with high gradients, especially with normal or increased cardiac output. Surgical procedures are often undertaken to enlarge the aortic annulus to accommodate a larger size prosthesis or alternative implantation of stentless tissue valves or a homograft.

Evaluation of Pulmonary Vascular Responses to Exercise

Pulmonary Hypertension

Pulmonary vascular problems that can be assessed with ED include latent pulmonary hypertension (PHTN), whether primary or secondary. As described previously, PASP is calculated on patients when "discordance exists between resting hemodynamics and symptoms." Frequently, the resting Doppler data falls within the mild-to-moderate range, but the patient's history reports debilitating symptoms of dyspnea. In these cases, ED is performed to assess for latent pulmonary hypertension, which develops with exertion.

Pulmonary arterial hypertension (PAH) is commonly associated with the CREST (calcinosis, Raynaud phenomenon, esophageal dysmotility, sclerodactyly, telangiectasia) syndrome, also known as limited cutaneous scleroderma. Figures 11 and 12 show an example of a patient with CREST syndrome. The true degree of the patient's PAH could not be demonstrated with a resting echo/Doppler. A moderate level of exercise revealed a precipitous rise in PASP.

Left heart pathology resulting in elevation of pulmonary venous pressure is the most common cause of PHTN, and an exercise study that yields information pertaining to both is desirable. A stress echo/Doppler study to assess myocardial and valvular function and estimated PASP can be accomplished in most patients when imaging and data acquisition are done at peak exercise.

A large percentage of patients with severe aortic or mitral disease develop PHTN. Along with data gathered pertaining to valve gradients and regurgitation, the PASP can be assessed with ED for corre-

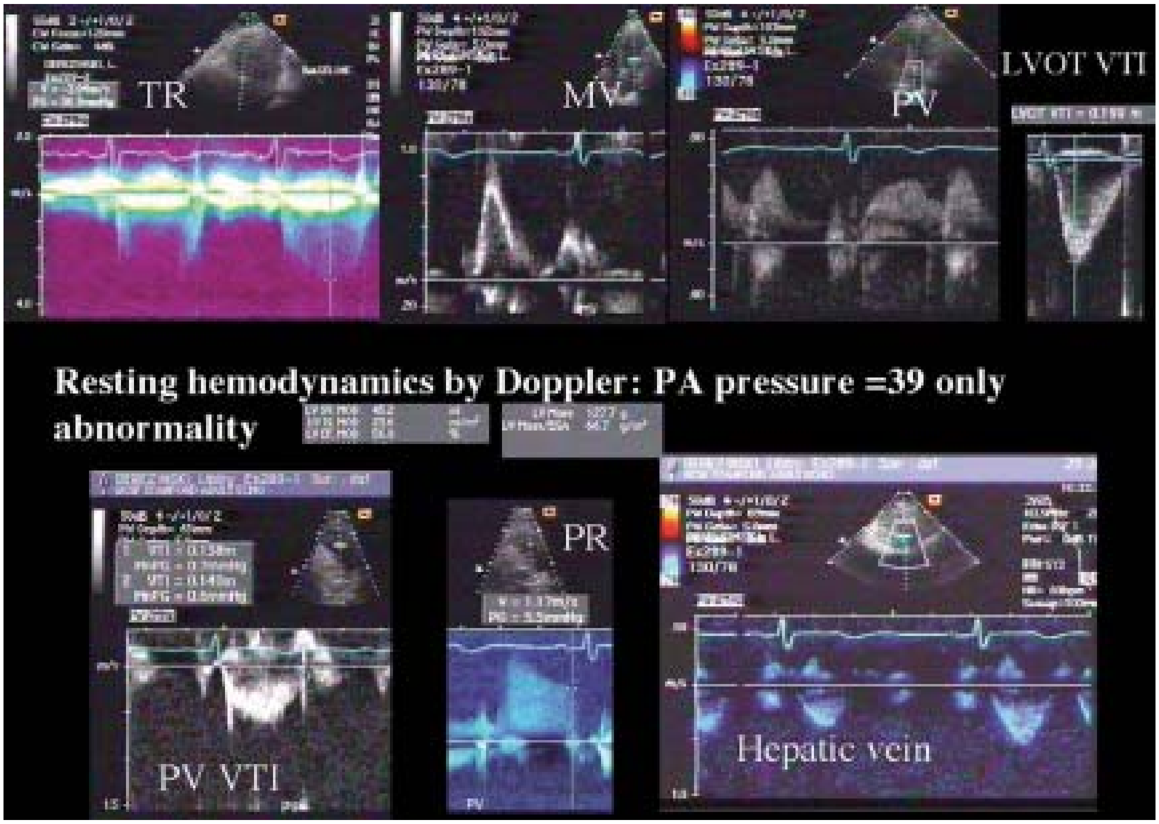

Figure 11. A 44-year-old woman with CREST syndrome reports increasing dyspnea. Her resting echo/Doppler study demonstrates a PASP of 39 mmHg, but was otherwise unremarkable.

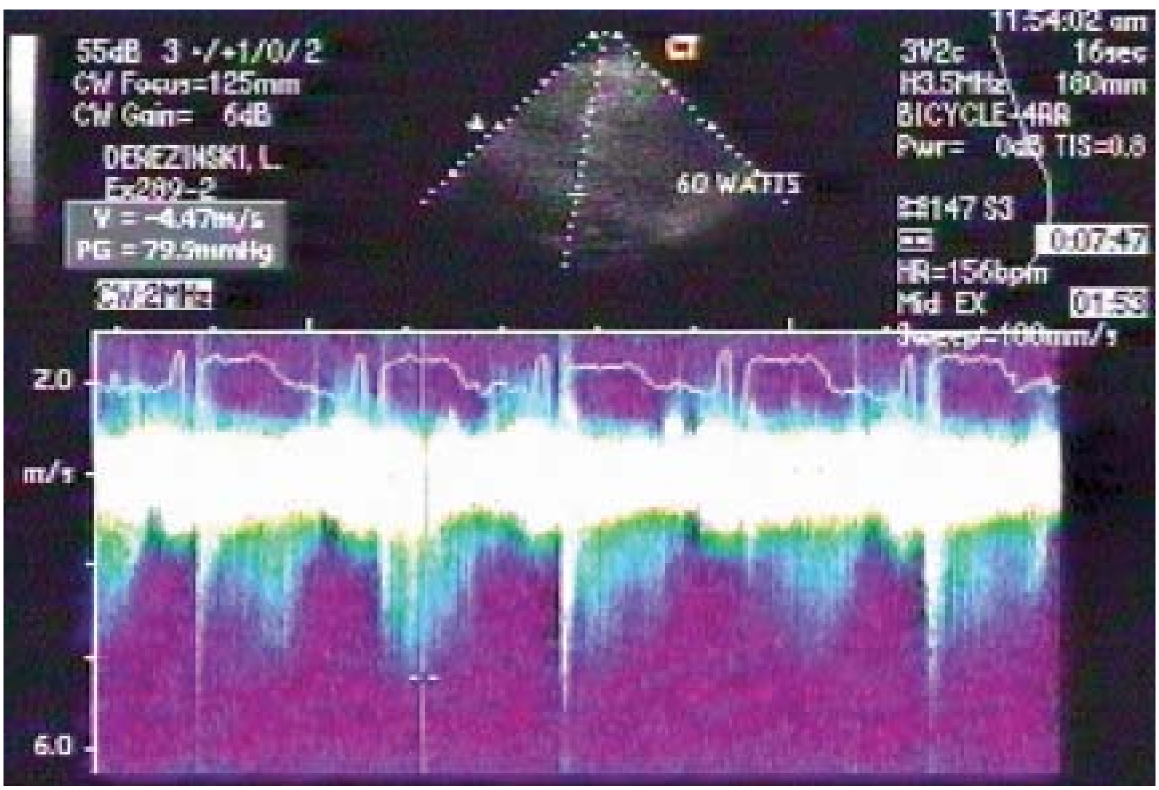

Figure 12. During Stage 3 of exercise, with only 60 watts of resistance on a supine bicycle, the patient's HR is 156 and her PASP has risen to 81 mmHg. The TR velocity is enhanced by contrast.

lation to symptoms and valvular function, as described previously.

Pulmonary hypertension without left heart disease (i.e., without elevation of pulmonary venous pressure), without pulmonary vascular occlusive disease (i.e., thromboembolism), and parenchymal pulmonary disease (i.e., chronic obstructive lung disease) is often termed *primary pulmonary hypertension* (PPH). The patient may only be diagnosed as having PPH when all underlying known causes are excluded. PPH is very rare and generally diagnosed in an advanced state. Early cases of mild PPH are often asymptomatic. Such cases may be diagnosed using exercise Doppler to assess the effect of bicycle exercise on PASP during different stages of exertion. When PASP exceeds an increase in cardiac output by an abnormal extent, PPH may be suspected.

For more than a decade, clinicians have employed contrast enhancement for Doppler studies with technically difficult patients, who have suboptimal spectral signals. Most commonly, when acquiring TR signals for PASP evaluation. Figure 12 demonstrates the use of contrast material to provide a measurable velocity. This method is especially helpful in patients with lung disease, who generally have limited acoustic windows, and in the more technically challenging circumstances of exercise studies. There have been differences seen in PASP elevation by age groups as well. Figures 13 and 14 contrast the two groups studied and compares the data to the findings in a study of COPD patients.

For contrast enhancement of TR signal, one may use agitated saline or new-generation contrast agent. Recent advances in technology have produced new-generation contrast agents that are not "washed out" in the lungs, thereby enhancing Doppler signals, as well as defining endocardial borders in the left heart. It is extremely important to obtain

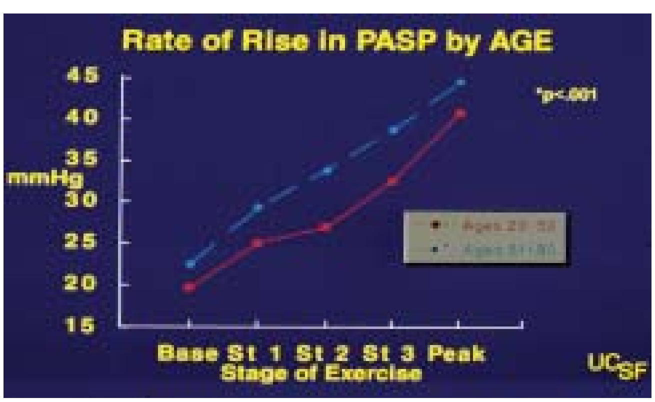

Figure 13. Demonstrates the differences in rate of rise of PASP with exercise in these two age groups.

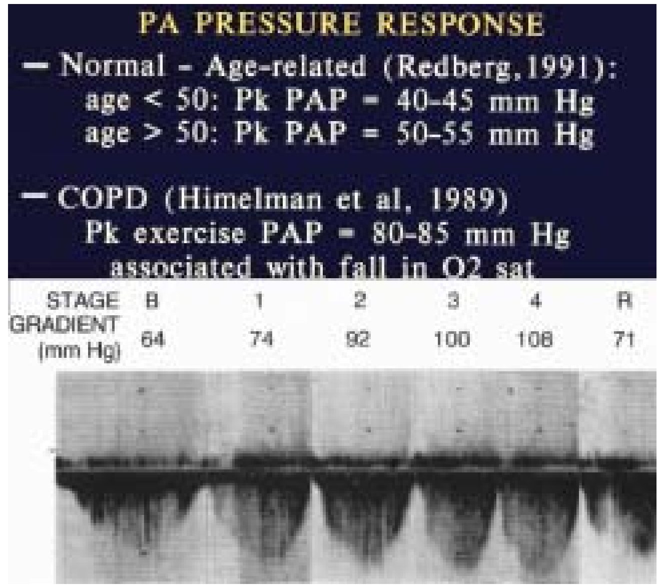

Figure 14. Data from two studies contrasting normal age-related rise in PASP and patients with COPD, who have high resting pressure, that rises even more dramatically with exercise.

velocity signals when the amount of contrast is markedly reduced so as to avoid high-frequency linear artifacts. Similarly, in patients in whom a proper AS signal is not obtainable, contrast agent with persistence to image the left heart may provide a more accurate assessment of peak and mean gradients as well as of left ventricular function. During supine bicycle exercise, the quantitation of left ventricular volumes from the apical window should precede attempting the continuous wave Doppler information of valvular lesions.

Editor's Comments: Invasive and noninvasive studies have demonstrated higher than expected pulmonary artery systolic pressure at rest and with exercise in normal highly conditioned athletes; the latter may approach 60 mmHg.

—BDH

Evaluation of Myocardial Disease

Left Ventricular Failure

ED has been used to examine a variety of patient populations, not limited to valvular disease alone. Diastolic heart failure provides a particular challenge in using exercise Doppler evaluation, since tachycardia not only alters rates of filling, but also may superimpose early and late diastolic filling, making it virtually uninterpretable in regard to diastolic function. There are no reliable parameters to assess filling characteristics from mitral valve flow velocity or pulmonary vein flow velocity once a heart rate of 100 beats per minute is exceeded. In addition, hypertensive response to exercise may influence the diastolic filling characteristics. One useful indicator of functional impairment and capacity is the PASP response of chronic CHF patients to exercise.

Hypertrophic Cardiomyopathy with Outflow Obstruction

Dynamic LV outflow obstruction (latent obstruction) is not uncommon with exercise, causing a high pressure gradient in the LV outflow.

Exercise Doppler is extremely useful in the follow-up of patients with hypertrophic obstructive cardiomyopathy in providing the hemodynamic effects of medical treatment, such as with beta-adrenergic or calcium channel blockers in improving exercise-induced gradients. It also provides prognostic information, since a response of increasing gradient and blunted or fall in blood pressure response are considered as risk factors for sudden death. Similarly, exercise-induced arrhythmias, especially monomorphic ventricular tachycardia, are also considered high risk for sudden death. These patients with varying symptomatology and variable dynamic obstructions should be more frequently and serially evaluated by supine bicycle exercise. Such an evaluation may help in decision-making as regards the timing of myectomy, be it surgical or with alcohol ablation.

Figures 15–18 show an example of a patient with a high resting gradient that rises further with exercise. Doppler signals were obtained at baseline and at every stage of exercise to correlate the patient's symptoms to the degree of obstruction, for management decisions. The baseline and peak LVOT and MR velocities and resulting gradients are shown.

Conclusion

ED is an important but often neglected part of echo Doppler evaluation of patients with heart disease. It can be a dynamic tool in a variety of clinical situations. All serious echo laboratories should establish supine bicycle exercise protocols depending on the clinical information desired in a given patient subset. For instance, clinically relevant information of exercise response in suspected coronary artery disease, dilated cardiomyopathy with mitral regurgitation, hypertrophic obstructive cardiomyopathy, or in valvular heart disease is quite diverse. Thus, appropriate clinical endpoints should be formulated prior to undertaking exercise Doppler protocol in a given patient. Although the basic exercise protocols of increasing workload, patient position, monitoring EKG and blood pressure, etc., are standardized, the data acquisition has to be individualized based on the clinical questions to be answered: Exercise Dop-

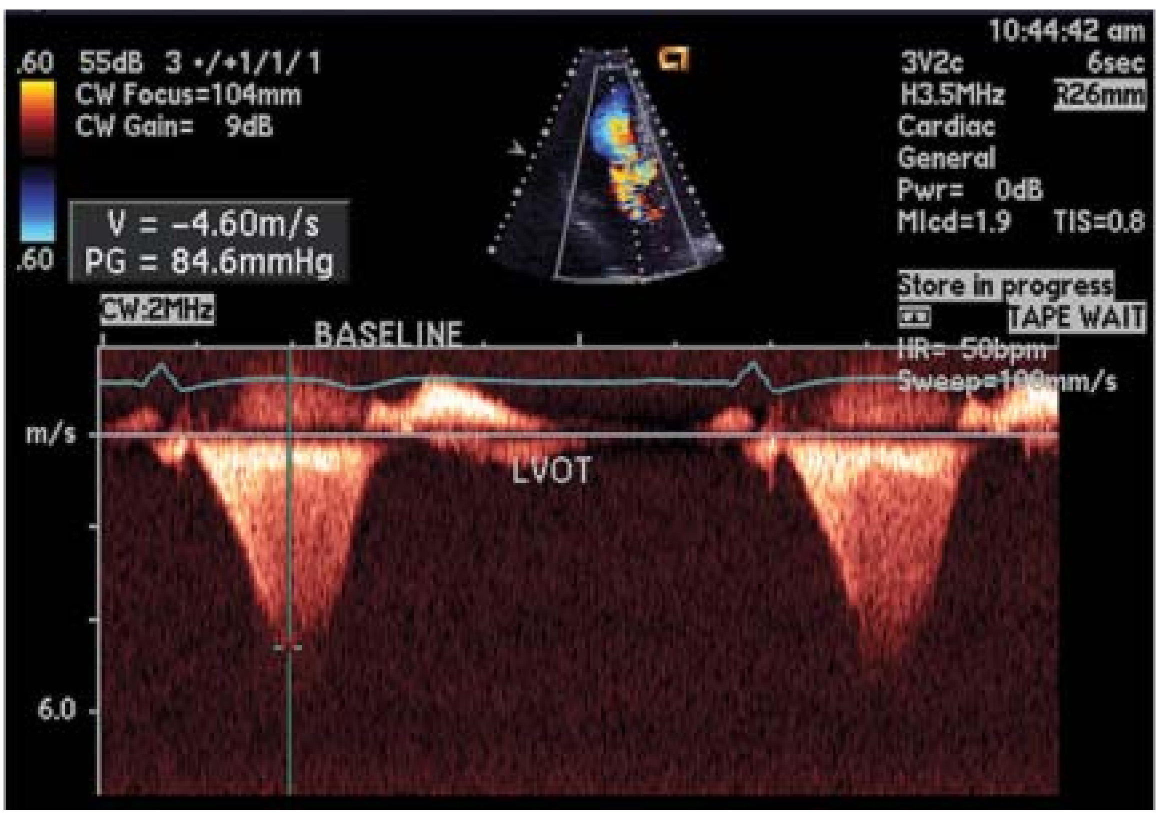

Figure 15. HOCM patient with a resting LVOT velocity of 4.6 m/s and peak gradient of 84 mmHg.

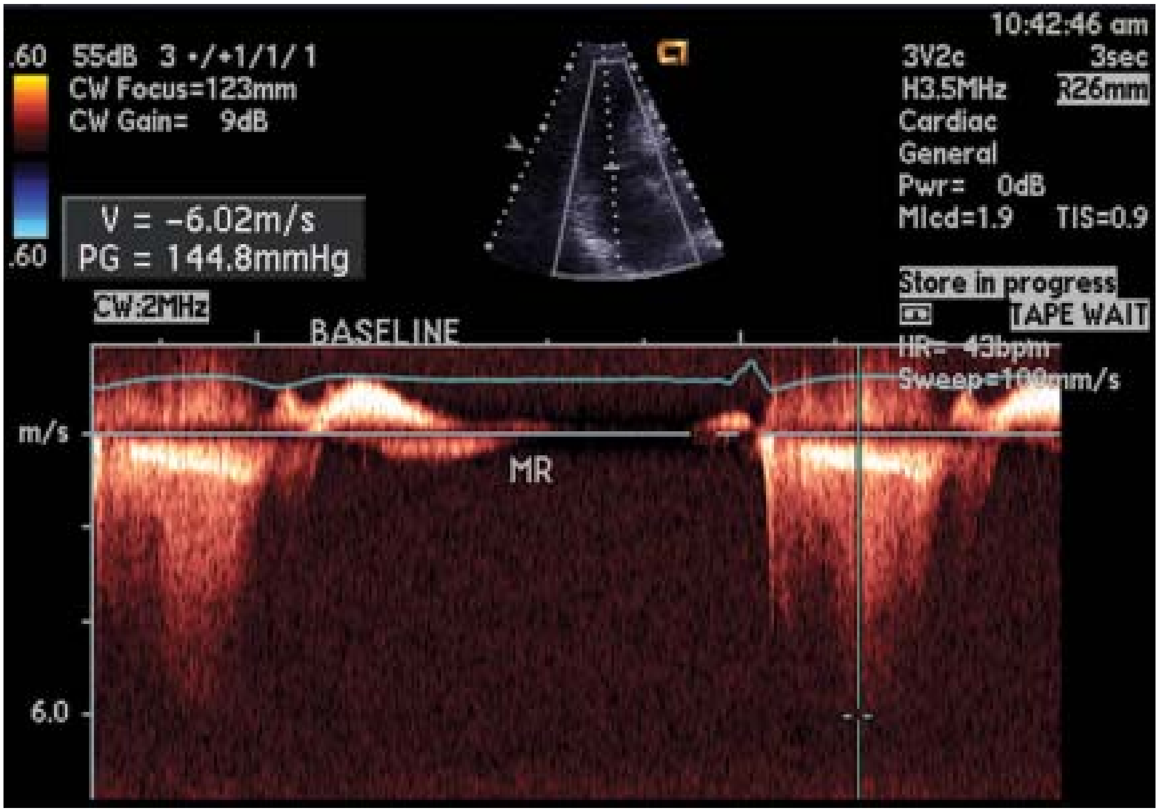

Figure 16. Same patient (Figure 6) with a resting MR velocity of 6.0 m/s and a peak gradient of 145 mmHg.

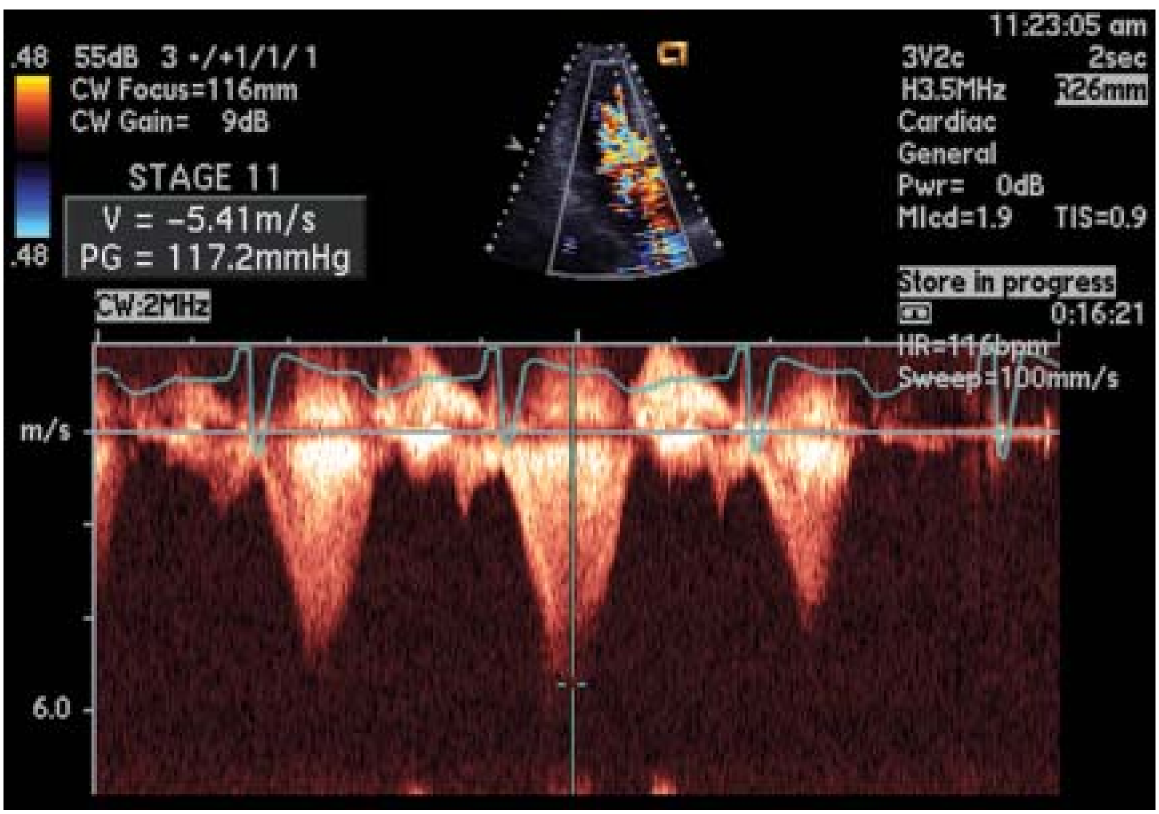

Figure 17. Patient at peak exercise, the LVOT velocity increased to 5.4 m/sec, peak gradient = 117 mmHg.

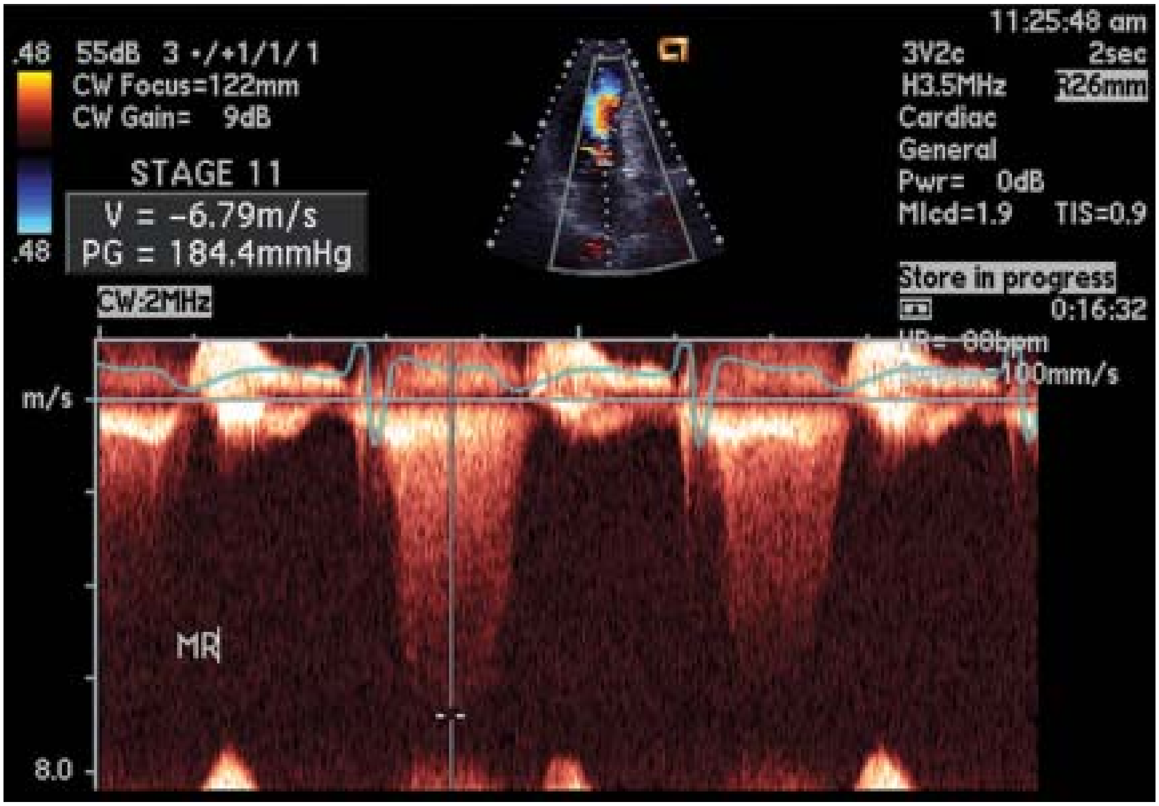

Figure 18. Patient at peak exercise, the MR velocity rose to 6.8 m/sec and the peak gradient was 184 mmHg.

pler is all the more important since most cardiac catheterization laboratories do not emphasize hemodynamics and even fewer utilize steady-state exercise protocol.

Awareness of the technical pitfalls that can occur will minimize errors in image acquisition and calculations, thus improving patient outcomes. Whether it is used for diagnostic purposes, correlation of symptoms, patient management, timing of intervention or the assessment of its outcome, evaluation of efficacy of therapy, or prognostic information, the adaptability of ED provides the diagnostician with valuable hemodynamic information in a versatile, inexpensive, and safe manner that promises additional benefits in the future (Table 4).

Editor's Comments: Fulps, Davis, and Shah summarize comprehensively and clearly the important role of exercise Doppler in the evaluation of the patient with heart (primarily non-coronary) disease. Stress laboratories can provide a clinically crucial service by functioning as a hemodynamic laboratory, measuring the response to exercise of valve gradients, orifice areas, regurgitant flows, and intracardiac pressure, in addition to right and left ventricular function. —BDH

Table 4
Advantages of Exercise Doppler

Provides correlation between symptoms and exercise-induced hemodynamics
Lends itself to serial studies
Less expensive/more informative than invasive studies in resting state

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Acknowledgements
Figures 3–6 and the mitral stenosis case report courtesy of William Katz, M.D., FACC, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania.
Figures 7–10 courtesy of Ramdas Pai, M.D., Diane Kotlarczyk, RDCS, RDMS, Charlene Rose, RDCS, and Marsi Owens, RDCS, Loma Linda University Medical Center, Loma Linda, California.
Figures 12–15 courtesy of Nelson B. Schiller, M.D., FACC, University of California at San Francisco, San Francisco, California.
Figures 15–18 courtesy of Lisa Meade Bowhay, RDCS, and Donald Waters, Hoag Memorial Hospital Presbyterian, Newport Beach, California.