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REVIEW

The Clinical Utility and Enduring Versatility of Stress Echocardiography

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Stress echocardiography is an established cardiac imaging modality for the detection and quantification of severity of coronary artery disease. In recent years, there has also been an increasing use of stress echocardiography in the assessment of non-ischaemic cardiac disease given its ability to assess functional capacity and haemodynamic changes with exercise which can help guide therapy and inform prognosis. The emerging use of strain, myocardial contrast and three-dimensional (3D) echocardiography further assists in improving diagnostic accuracy particularly in patients with coronary artery disease. This paper summarises the protocols, indications and clinical applications of stress echocardiography in both ischaemic and non-ischaemic cardiac disease.

Keywords Stress • Echocardiography • Imaging • Ischaemia • Stress echocardiography

Introduction

Stress echocardiography (SE) is a reliable and well-established cardiac imaging modality. According to the Australian Medicare Medicare Benefits Schedule (MBS) 2017 Report from the Cardiac Clinical Services Committee (www.health.gov.au), this test accounts for over $56 million in billing annually and has grown each year at a rate of 12% for the past 5 years. This popularity is due to the availability, feasibility, clinical utility and broad spectrum of diagnostic and prognostic information which this test provides. Whilst newer, more expensive, and less accessible cardiac imaging modalities are available, the versatility and extensive evidence for SE underscore its value in cardiology. Given its continued prevalence, SE should continue to be an important part of cardiology training programs with appropriate time and emphasis assigned to it.

Stress echocardiography plays a pivotal role in the risk stratification of patients with suspected ischaemic heart disease (IHD), risk assessment after myocardial infarction (MI), and also in determining myocardial viability to guide decisions for revascularisation [1].

Stress echo has also been increasingly used to assess patients with non-ischaemic heart disease (non-IHD). It provides haemodynamic assessment in patients with valvular heart disease (VHD), in addition to evaluation of suspected diastolic dysfunction, pulmonary hypertension (PH) and hypertrophic cardiomyopathy (HCM).

This paper summarises the protocols, indications and clinical applications of SE in contemporary cardiological practice.

Myocardial Ischaemia Assessment

Indications

Indications for SE in IHD include [1]:

1 Assessment of undifferentiated chest pain.
2 Assessment of exertional dyspnoea.

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3 Ischaemia localisation and assessment of functional significance of coronary artery stenosis.
4 Risk stratification and prognosis in patients with established diagnosis of CAD.
5 Evaluation of symptoms after revascularisation.
6 Myocardial viability assessment.
7 Preoperative risk assessment.

Stress Modalities

Baseline echocardiographic views should include an apical four-, three- and two-chamber view and a parasternal long and short axis. Baseline echocardiographic assessment should also include: 1) valve function and morphology; 2) aortic root and ascending aorta; 3) left atrial volume; 4) right ventricular (RV) systolic pressures; 5) mitral inflow velocity profile; and 6) medial and lateral mitral annular velocity.

Exercise Echocardiography

Exercise SE can be performed either using treadmill or bicycle. Bicycle SE is performed in upright, semi-recumbent or recumbent position. Exercise SE has the advantage of providing information regarding a patient's functional capacity and haemodynamic response during exertion. It is recommended that images are acquired within 60 seconds after cessation of exertion to minimise the chance of a false negative result given regional wall motion abnormalities (RWMAs) may recover rapidly after termination of exercise. The most widely utilised treadmill protocol is the Bruce protocol while the Modified Bruce protocol and Naughton protocol can be used in patients with limited exercise capacity or in the elderly. In bicycle SE, workload starts at 25 W, with 25 W incremental every 2 to 3 minutes [2]. Image acquisition should be performed at baseline, 25 W, peak exercise and in recovery.

Pharmacologic Stress Testing

Pharmacologic stress testing via dobutamine or vasodilators (adenosine or dipyridamole) should be considered when the patient is unable to exercise or when exercise electrocardiography (ECG) is contraindicated or non-diagnostic.

The standard protocol used for dobutamine stress echocardiography (DSE) includes a starting dose of 5 μg/kg/min incrementing every 3 minutes to 10, 20, 30, to a maximum dose of 40 μg/kg/min. If target heart rate is not achieved, isometric hand grips and/or atropine may be used [2]. DSE should be terminated if the test achieves 85% of maximal predicted heart rate (MPHR), emergence of significant arrhythmias, significant decrease in blood pressure (BP) (>20 mmHg drop from baseline), severe hypertension (>240 mmHg systolic or >120 mmHg diastolic), new or worsening RWMAs, or if intolerable side effects occur.

The standard dipyridamole protocol consists of intravenous infusion of 0.84 mg/kg over 10 minutes while standard adenosine protocol consists of infusion of adenosine at a maximum dose of 140 μg/kg/min over 6 minutes [2].

Pacing

In patients with a permanent pacemaker, pacing SE can be conducted by gradually increasing the pacing rate by 10 beats every 2 minutes from a baseline pacing rate of 100 bpm to 85% of MPHR with or without the use of dobutamine [2].

Interpretation and Prognosis

Qualitative Analysis

Both qualitative and quantitative measures can be used in the analysis of SE. By qualitative analysis, a normal result is defined as the visual augmentation of all left ventricular (LV) segments during exertion. However, accurate qualitative interpretation of SE is highly dependent on the experience of the reader [3]. A normal exercise SE confers a good prognosis with a cardiac event rate of 0.9% per person year of follow-up [4]. Patients with a normal DSE have also been shown to ''warranty period'' of approximately 7 years compared to those with an abnormal DSE [5].

The presence of resting RWMAs unchanged with stress suggests the presence of an area of previous infarction while new or worsening RWMAs indicates the presence of ischaemia. The site, extent (number of segments with new RWMAs), severity (magnitude of new RWMAs) and ischaemic threshold of LV myocardium have been shown to predict major adverse cardiac events (MACE) [6]. In addition, global dilatation of the LV cavity may indicate triple vessel disease, and has also been associated with a high rate of MACE of up to 19.7%/year [7]. The patient's haemodynamic response to exercise, the level of stress achieved, the emergence of symptoms, the reason for termination of the test and ECG changes should also be considered in the interpretation of the SE.

Other negative prognostic echocardiographic markers in SE include the following: -

1) Low resting ejection fraction (EF) [8]
2) Absence of LV contractile reserve (typically defined as <5% increase in left ventricular ejection fraction (LVEF) or <2% improvement in LV global longitudinal strain) [9]
3) Increasing peak wall motion score index [8]
4) Time taken for RWMAs to normalise [10]
5) Achieving submaximal MPHR, even with an otherwise normal SE [11]

Quantitative Analysis

Strain is a measure of myocardial deformation and is measured via two dimensional (2D) speckle tracking echocardiography (2DS) or tissue Doppler imaging (TDI). TDI has the advantage of superior temporal resolution [12]. Strain derived measures including strain rate (SR) and post-systolic shortening (PSS) are echocardiographic indices used for the detection of ischaemia. PSS is highly sensitive to ischaemia [13], but can occur in other conditions (LV hypertrophy, left bundle branch block and in a proportion of normal hearts). To improve the specificity for detection of myocardial ischaemia, the ratio of PSS to peak strain can be used [13]. A potential drawback to the use of strain imaging is that TDI is extremely dependent on the angle of measurement while speckle tracking relies on good 2D image quality and adequate frame rate.

Supplementary Techniques

Contrast Enhanced Stress Echocardiography

Left ventricular contrast SE is indicated when two or more contiguous myocardial segments cannot be adequately visualised at rest. Recent guidelines also provided a Class 1A indication for the use of myocardial contrast echocardiography for improved diagnosis of coronary artery disease (CAD) and also to assess myocardial viability, particularly in dobutamine non-responsive myocardial segments [14].

For assessment of myocardial perfusion and wall motion, a low mechanical index (MI) is preferential (MI 0.1) while a low to intermediate MI (MI 0.2 – 0.3) should be used for optimal assessment of LV structure. Contrast SE is based on the concept of rate of replenishment of myocardial contrast and plateau contrast intensity in the myocardium after destruction of the microbubbles by a high MI. A functionally significant stenosis is most likely present when an area of myocardium does not replenish within approximately two seconds after a high MI impulse post exertion.

Three-Dimensional (3D) Stress Echocardiography

Three-dimensional stress echocardiography (3DSE) allows the theoretical advantage of rapid image acquisition at peak exercise, improved LV apex visualisation, more accurate evaluation of LV volumes and EF and the assessment of multiple LV segments from different planes from a single data set with a similar diagnostic accuracy for CAD compared to 2DSE [15]. Limitations include stitching artefacts secondary to respiration or irregular R-R intervals and, importantly, lower spatial resolution and frame rates. Another strategy is the use of bi- or triplane echocardiography to capture multiple ''2D'' cardiac planes in the same beat. This has the advantage of superior frame rates as compared to 3D whilst still visualising the important coronary territories.

Comparison with Other Techniques for Detection of Myocardial Ischaemia

The sensitivity and specificity of different modalities for the assessment of myocardial ischaemia are shown in Figure 1.

Exercise ECG

Exercise ECG remains one of the most readily available and utilised modalities for detection of myocardial ischaemia. The sensitivity and specificity of exercise ECG is quoted to be 67% and 72%, respectively [16]. In patients who achieve 10 metabolic equivalents (METs), the risk of MACE is extremely low [17] but conversely, lack of physical fitness can result in inconclusive test results.

Both methods (Exercise ECG and Exercise SE) offer the ability to monitor patient's exercise capacity, and haemodynamic response during exertion. Exercise SE offers the advantage of being able to localise and quantify areas and extent of ischaemia, allows assessment of the functional significance of intermediate coronary lesions found on computed tomography coronary angiography (CTCA) or coronary angiography (CA), and overcomes the other limitations of exercise ECG such as the presence of abnormal resting ECG. Normal wall motion at peak stress confers a benign prognosis even with ischaemic ECG changes during stress testing [18].

Nuclear Stress Imaging

Single photon emission computed tomography (SPECT) is a widely used nuclear stress test for the diagnosis of myocardial ischaemia. Major limitations of SPECT include false negative tests in setting of balanced ischaemia, the use of radiation and test results which can be affected by the presence of left bundle branch block [19]. A meta-analysis comparing stress SPECT with SE revealed stress SPECT had a higher sensitivity (88% vs 70%) but a lower specificity (67% vs 90%) when compared to dipyridamole SE [20]. Compared to SPECT, PET scanning offers the advantage of a higher spatial resolution enabling detection of smaller perfusion defects with less attenuation artefacts and also allows myocardial blood flow quantification.

Cardiac Magnetic Resonance (CMR)

CMR can detect myocardial ischaemia through the assessment of myocardial perfusion using vasodilators or assessment of regional RWMAs using dobutamine. Gadolinium is

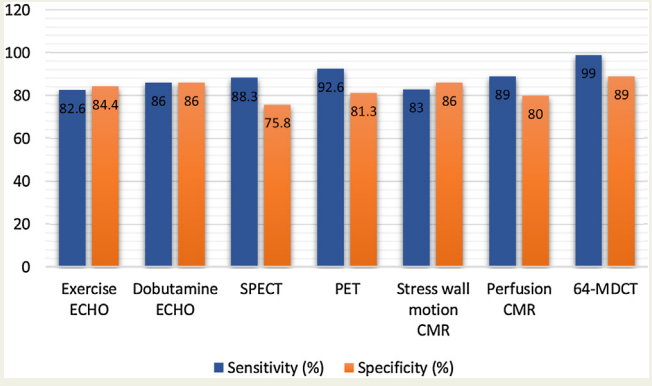

Figure 1 Diagnostic accuracy of different non-invasive cardiac imaging modalities for diagnosis of CAD. Adapted from Hamoudi et al. [54].
Abbreviations: CAD, coronary artery disease; SPECT, single-photon emission computed tomography; PET, positron emission tomography; CMR, cardiac magnetic resonance; 64-MDCT, 64-slice multi detector computed tomography.

used during stress perfusion CMR. Major limitations include limited clinical access, the time-consuming nature of the test, expense, patient intolerance due to claustrophobia and the risk of nephrogenic systemic fibrosis in patients with kidney disease. A meta-analysis comparing CMR, contrast-enhanced SE and SPECT for the diagnosis of coronary artery disease (CAD) showed a higher sensitivity and specificity with CMR (sensitivity - 91% vs 87% vs 83%; specificity - 80% vs 72% vs 77% respectively) for the diagnosis of obstructive CAD [21].

CT Coronary Angiography (CTCA)

CTCA is a non-invasive imaging technique which provides an anatomical assessment of the coronary arteries. It also allows identification of high risk coronary plaque which have been associated with MACE [22]. CTCA is highly sensitive (99%) for the detection of CAD with a high negative predictive value (NPV) approaching 100% (86%–100%) compared to invasive CA as the reference standard [23]. A comparison between CTCA and functional testing in symptomatic patients with suspected CAD showed more patients in the CTCA group undergoing invasive coronary angiography and revascularisation with no significant difference in cardiovascular outcomes in both groups [24]. Blooming artefacts secondary to heavily calcified coronary arteries and its (current) inability to assess haemodynamic significance of coronary lesion, exposure to a small radiation dose (1-2 mSv) and the use of iodinated contrast are potential drawbacks of CTCA.

Stress Echocardiography Prior to Non-Cardiac Surgery

Patients undergoing non-cardiac surgery should be risk stratified based on the patient's clinical risk factors and the risk of the surgery using established perioperative cardiac risk indices [25]. It is recommended that patients with elevated risk and a poor functional capacity of less than 4 METS undergo cardiac stress testing (with DSE) if it will change management [25]. The finding of moderate to large areas of inducible ischaemia on SE translates to an increased risk of perioperative MI or death [26].

Myocardial Viability

The assessment of myocardial viability is important in evaluating patients with chronic ischaemic LV dysfunction. Myocardial viability refers to reversible LV systolic dysfunction which could be secondary to myocardial stunning, myocardial hibernation or a combination of both. Low dose DSE is a commonly used method for assessing myocardial viability.

Baseline transthoracic echocardiogram (TTE) should be evaluated for thinned LV segments (≤0.5 cm) or bright segments which rarely recovers post revascularisation. Standard protocol for DSE for myocardial viability testing includes an initial infusion of dobutamine at 2.5 μg/kg/min with gradual increase to 5, 7.5, 10 and 20 μg/kg/min every 3–5 minutes. Echocardiographic images are obtained at rest, each stage of stress and in recovery period.

The possible findings include: -

1 Monophasic or sustained response: Improvement in function at low dose which persists or improves at higher doses. (Viable myocardium with no stenosis of coronary artery supplying the dysfunctional region);
2 Biphasic response: Improvement in function at low dose followed by deterioration at higher doses. (Viable myocardium with flow-limiting stenosis of coronary artery supplying the dysfunctional segment);
3 Ischaemic response: Deterioration in function without contractile reserve (CR). (Presence of ischaemic myocardium secondary to flow limiting stenosis);
4 Non-phasic response: No change in function is observed (non-viable scarred myocardium).

Dobutamine stress echocardiography has a good sensitivity (81%) and specificity (80%) with a positive predictive value (PPV) of 77% and negative predictive value (NPV) of 85% for predicting global and regional LV function improvement following revascularisation [27]. Patients with a greater amount of dysfunctional but viable myocardium (≥6 segments) have a lower cardiac event rate and a higher likelihood of improvement in EF compared to those with minimal or no viable myocardium after revascularisation of the appropriate territories [28]. In addition, the presence of a biphasic response has also been shown to have the highest predictive value for functional recovery post revascularisation [29].

Dobutamine stress echocardiography has a comparable sensitivity with good specificity for detection of viable myocardium in comparison to other imaging modalities (Figure 2) [27]. Late-gadolinium enhancement CMR (LGE-CMR) is another imaging technique that can be used for the assessment of myocardial viability with a higher sensitivity (84%) but lower specificity (63%) compared to DSE [30].

Valvular Heart Disease

Stress echocardiography can provide an objective assessment of exercise capacity in patients with VHD and reveal the dynamic nature of valvular disease [31]. It can also guide decisions for intervention, broadly in three situations 1) asymptomatic severe valve disease; 2) when there is discordance between symptoms and severity of valve disease; and 3) in presence of severe valve disease with LV systolic dysfunction.

Stenotic Valve Disease

Aortic Stenosis

The emergence of symptoms in patients with severe aortic stenosis (AS) confers a poor prognosis [32]. These symptoms can be masked in sedentary patients or in those who avoid exercise to avoid precipitation of symptoms. Hence, in patients with "asymptomatic" severe AS, SE can be used

	Sensitivity	Specificity	PPV	NPV
Thallium SPECT	86	59	69	80
Thallium Reinjection	88	50	57	83
Tc SPECT	81	66	71	77
FDG-PET	93	58	71	86
DSE	81	80	77	85

Figure 2 Sensitivity, specificity, PPV and NPV of different imaging techniques in predicting functional recovery post revascularisation. Source data from Bax et al. [27].
Abbreviations: PPV, positive predictive value; NPV, negative predictive value; SPECT, single-photon emission computed tomography; Tc SPECT, technetium single-photon emission computed tomography; FDG-PET, fluorodeoxyglucose positron emission tomography; DSE, dobutamine stress echocardiography.

to unmask symptoms which would help guide the timing of the decision for valve intervention. In addition, an exercise-induced increase in mean gradient (MG) ≥18 mmHg, absence of LV contractile reserve and dynamic PH during exertion (systolic pulmonary artery pressure (SPAP) ≥60 mmHg) are markers of poor prognosis and help to guide subsequent clinical decisions [33,34].

In patients with low-flow low-gradient aortic stenosis (LFLG AS) with reduced systolic function (stroke volume (SV) index <35 ml/m^2, Aortic Valve Area (AVA) <1 cm^2, Aortic Velocity <4 m/s, MG < 40 mmHg, and LVEF < 50%), DSE can be used to differentiate patients with true (valvular) severe AS from pseudo-severe AS due to LV dysfunction. This is important as patients with true severe AS are more likely to benefit from intervention [35]. The low output state may be secondary to: 1) depressed LV systolic function secondary to the severe AS with LV afterload mismatch, or 2) an underlying cardiomyopathy, or 3) a combination of both. In the presence of CR (>20% increase in SV), patients with true severe AS would demonstrate increased gradients (peak stress MG ≥ 40 mmHg) with minimal or no change to the AVA (peak stress AVA < 1 cm^2). On the contrary, patients with pseudo-severe AS would demonstrate minimal or no changes to the transaortic valve gradients (peak stress MG < 40 mmHg) while the AVA (peak stress AVA >1 cm^2) would increase significantly during dobutamine infusion.

To assess LFLG AS, a low dose dobutamine infusion protocol is used starting from 5 mcg/kg/minute with 5-minute stages and incremental dose increases of 5, 10, 15, 20 mcg/kg/min. The aim is to maximise inotropic effect and increase transvalvular gradient without causing an exaggerated increase in heart rate (HR). The test is stopped when this protocol is complete, there is an increase in HR of 10–20 beats/minute or a target increase in SV (left ventricular outflow tract (LVOT)-derived SV > 20%) is achieved [31].

The absence of CR is a powerful prognostic marker which is associated with higher operative mortality with surgical AVR [36]. If discordance between peak stress MG and AVA persist after DSE, projected AVA is one further way to help distinguish between true AS and pseudo-severe AS [37].

Mitral Stenosis

Stress echocardiography can be used to evaluate the emergence of exercise-induced symptoms in patients who are asymptomatic at rest but have echocardiographically severe mitral stenosis (MS). In those with moderate MS and symptoms, it can be used to assess the haemodynamic significance of the stenosis. The presence of symptoms with severe MS is an indication for valve intervention [35]. In those with non-severe MS but symptoms, the presence of a mean transmitral gradient ≥18 mmHg during exercise and an increase in systolic pulmonary artery pressure (sPAP) >60 mmHg are markers of haemodynamically significant MS and can be used to guide decision making [38].

Regurgitant Valve Disease

Aortic Regurgitation

In patients with asymptomatic severe aortic regurgitation (AR), exercise testing can again unmask symptoms which will help dictate timing for valve intervention. Absence of LV CR (<5% increase in LVEF) has been previously associated with postoperative LV systolic dysfunction [39]. For the assessment of symptoms, exercise SE is recommended choice of stress testing while for the assessment of CR (<5% increase in EF), the use of supine bicycle SE allows image acquisition at low and high workloads.

Mitral Regurgitation

In patients with primary mitral regurgitation (MR), SE can be used to assess the presence of exercise-induced PH (sPAP ≥60 mmHg) or verify the absence of symptoms in those with severe MR. The finding of symptoms on SE in patients with asymptomatic severe MR is an indication for surgery [35] while the presence of exercise-induced PH has been associated with a reduced symptom-free survival [40].

In addition, the absence of LV CR (<5% increase in EF or <2% increment in global longitudinal strain) and the presence of exercise-induced RV dysfunction (tricuspid annular plane systolic excursion [TAPSE] <19 mm during exertion) have also been shown to be associated with poor prognosis and could guide decision making for earlier MV surgery [41,42].

In patients with secondary MR, SE can be used to identify the cause of recurrent, unexplained pulmonary oedema and dyspnoea disproportionate to MR severity or LV dysfunction and also to identify markers of poor prognosis (exercise-induced PH [sPAP ≥60 mmHg] and increase in Effective

Regurgitant Orifice Area [ERO] ≥13 mm^2) which may guide decisions for MV surgery during coronary artery bypass grafting in those with moderate MR [43,44].

Prosthetic Valves

Stress echocardiography can be used to evaluate the cause of dyspnoea in patients with prosthetic heart valves (PHV) with a normal resting transthoracic echocardiogram (TTE). Patients with prosthesis-patient mismatch (PPM) or with significant PHV stenosis can exhibit marked increases in transprosthetic gradients. An increase in transvalvular gradient (>20 mmHg with aortic prosthesis or >12 mmHg for mitral prosthesis) indicates either PHV stenosis or PPM [34]. Low dose DSE can be used to differentiate true stenosis from pseudo-stenosis or PPM in patients with PHV with low cardiac output. Resting trans-prosthetic flow could be reduced in a low output state leading to a underestimation of PPM or PHV stenosis [34]. During DSE, patients with pseudo-severe PHV stenosis often have a substantial increase in valvular effective orifice area (EOA) with little or no increase in transprosthetic valvular gradients. In contrast, patients with true PHV stenosis or PPM will have no or only a small increase in valvular EOA with a significant increase in trans-prosthetic valvular gradients. Patients with PPM (with no PHV stenosis) will demonstrate a stress EOA close to the normal reference value while patients with isolated PHV stenosis will have a stress EOA significantly smaller than the normal reference valve of the same valve [34].

Diastolic Stress Echocardiography

In patients with dyspnoea of unclear aetiology and risk factors for diastolic dysfunction (e.g. obesity, hypertension), diastolic SE can be considered. Echocardiographic indices requiring to be assessed are mitral inflow by pulsed Doppler, mitral annular velocities, and tricuspid regurgitation (TR) jet by continuous wave (CW) Doppler measured at baseline, during low level exercise and after the termination of exercise. The use of intravenous agitated saline can help to accentuate the Doppler TR signal. There is often fusion of the mitral E and A waves at higher heart rates. It is suggested then that TR velocity is measured first, allowing the heart rate to fall prior to assessment of mitral annular velocities or inflow pattern as elevated filling pressures usually persist for a few minutes post exercise [34].

In healthy patients, there will be a proportional increase in mitral inflow and mitral annular velocities during exercise, leading to a roughly constant E/ e′ ratio during rest and at peak exertion [34]. However, in patients with significant diastolic dysfunction, E/e′ ratio should increase after exercise with a corresponding increase in TR velocity and SPAP. Previous studies have shown a correlation between raised E/e′ with exercise and an incremental rise in LV end-diastolic pressure measured invasively [45]. Diastolic SE would be considered abnormal when the following criteria are met: 1) post exercise average E/e′ > 14 or septal E/e′ > 15, 2) resting septal e′ velocity < 7 cm/sec, and 3) post exercise peak TR velocity> 2.8 m/sec. The test is considered negative for significant diastolic dysfunction when post exercise average or septal E/e′ ratio is < 10 and post exercise peak TR velocity is <2.8 m/sec [46].

Elevated LV filling pressures after exertion have been previously associated with MACE. An exercise E/e′ > 2SD above normal is a marker for raised LV filling pressures and has been associated with increased cardiovascular morbidity independent of presence of ischaemia [47]. There is however, a lack of data regarding medical intervention and clinical benefit in those with an abnormal diastolic SE.

Hypertrophic Cardiomyopathy

In patients with HCM, SE is useful to evaluate: 1) exercise capacity, 2) the presence of dynamic LV outflow tract obstruction (LVOTO), and 3) the presence of a dynamic increase in mitral regurgitation, often due to systolic anterior motion (SAM) of the mitral valve.

Stress echocardiography in HCM can be performed standing (via treadmill), sitting or semi-supine. Pharmacological stress testing (dobutamine) is not recommended as it is often poorly tolerated and has the potential to induce LVOT gradients even in healthy patients. Resting TTE should focus on the degree of LV hypertrophy, presence of SAM of mitral valve, the severity of MR, the presence of an LVOT gradient at rest and after Valsalva, diastolic parameters and sPAP. Changes in blood pressure (BP), HR and symptoms should be evaluated closely throughout the test. LVOT gradients, LV systolic/diastolic function and sPAP should also be measured during the test and immediately in recovery period [34].

Exercise SE to evaluate for LVOTO is indicated when patients are symptomatic with the resting TTE or the Valsalva manoeuvre fails to induce a LVOTO ≥ 50 mmHg [48]. This is important as the consideration of invasive treatment options is recommended when patients have a maximum exercise-induced LVOTO gradient of ≥50 mmHg [48]. The presence of LVOTO has been shown to improve risk stratification for SCD when considering a primary prevention implantable cardioverter-defibrillator [49].

Pulmonary Hypertension

Pulmonary hypertension (PH) is defined as a mean pulmonary artery pressure (mPAP) ≥25 mmHg at rest with pulmonary capillary wedge pressure ≤15 mmHg, measured by right heart catheterisation (RHC). However, there is no standardised definition of exercise-induced PH in the current guidelines, given the differences in mPAP with age and types of activity [50]. This increase in mPAP during exertion reflects either an excessive increase in left atrial pressure or increase in pulmonary vascular resistance secondary to pulmonary vascular disease and could be a cause of dyspnoea in patients referred for SE.

An elevation of mPAP during exercise has been associated with worse outcome [51]. Stress echocardiography is a reliable method for the evaluation of haemodynamic changes in the pulmonary circulation and RV during exertion, having previously been compared to measurements obtained from CMR [52]. SE should be considered in patients who have dyspnoea of unclear cause with normal pulmonary artery pressure at rest or in patients at high risk of PH (e.g. patients with connective tissue disease) to aid identification of patients early in the disease course [34]. In patients with established PH, the clinical value of this test is less clear but a lack of RV contractile reserve in these patients has been previously associated with poor long-term survival [53].

For assessment of exercise-induced PH, graded semi-supine exercise SE is optimal as it allows CW Doppler assessment of TR jet at baseline, low workload and peak exercise. To enhance Doppler signals of TR and improve RV views, contrast may be used. Oxygen saturation should also be recorded throughout any stress assessment for PH.

Conclusion

Stress echocardiography is a well-established cardiac imaging technique in the assessment of patients with suspected or known ischaemic and non-ischaemic HD. Despite the advent of newer cardiac imaging modalities, SE retains good diagnostic accuracy while having the additional advantages of lower cost, greater availability and a lack of radiation exposure. In these patients, the use of contrast agents and the novel techniques of strain imaging and 3D SE can be additionally utilised to potentially further improve diagnostic and prognostic accuracy. The evolving role of SE in patients with suspected diastolic dysfunction and pulmonary hypertension, in addition to its established role in valvular heart disease, confirms its place as a valuable and versatile test.

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