Recent Advances in 2D Echocardiography and Live 3D Echo

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INTRODUCTION

Echocardiography is the most common diagnostic tool for patients with heart disease, providing detailed information about cardiovascular morphology and hemodynamics previously available only by angiography and catheterization. It is noninvasive, widely available and inexpensive. With its huge evidence base, echocardiography has a central position in modern cardiac diagnosis and management. Recent advances in computer technology, signal processing, and transducer design have allowed echocardiography to expand its capabilities beyond qualitative two-dimensional (2D) imaging and blood flow Doppler analysis. New modalities such as three-dimensional echocardiography (3DE), tissue Doppler imaging (TDI), and speckle tracking echocardiography (STE) to evaluate parameters such as ventricular volume, myocardial velocity, regional strain and strain rate, mechanical dyssynchrony, and ventricular twist have all provided new insights into cardiovascular morphology and ventricular function. Successful translation of these advances into clinical practice will show that these new techniques are complimentary and in some cases competitive with the new imaging methodologies. This review discusses the recent advances and their potential impact of cardiology.

ASSESSMENT OF LEFT VENTRICULAR FUNCTION

Echocardiography is the first choice for the assessment of left ventricular (LV) function. Heart failure patients undergoing echocardiography have a better outcome than those managed without the performance of this test, not because of any therapeutic effects of ultrasound, but rather reflecting the initiation of appropriate therapy in patients with systolic dysfunction.

1) LV systolic function assessment

LV systolic function can be characterized as either myocardial function or global pump function. Assessment of myocardial performance involves quantitative assessment of myocardial fiber contractility independent of loading conditions. Traditional parameters of LV myocardial contractility independent of loading conditions have been cumbersome and have not been measured routinely in most protocols. On the contrary, assessment of global LV systolic function is standard practice in most clinical centers and almost always involves measurement of shortening fraction and/or ejection fraction. Both parameters measure the change in LV size during a cardiac cycle relative to its diastolic size. Aside from their dependence on loading conditions, these parameters are also limited by geometric assumptions. In addition, shortening fraction evaluates only radial function, which is usually affected much later than longitudinal function in the setting of cardiac disease. All these limitations have been improved by the development of LV opacification (LVO) with echocardiographic contrast agents and three-dimensional echocardiography (3DE). 3DE measurements of LV volumes and ejection fraction do correlate well with magnetic resonance imaging measurements. The combination of LVO with 3DE overcomes many of the concerns related to lower spatial resolution, and comparative data have shown that the combination of LV opacification and 3DE (Fig. 1) is the closest ultrasound analogue to LV volume measurement with CMR. LV volume and mass are not routinely reported due to the complex measurements and calculations required. This process is much simpler with three dimensional...
echocardiography. Volume and mass are important markers of prognosis in heart failure and hypertensive heart disease and 3D echo should enable cardiovascular ultrasound to expand its role in risk assessment. It seems probable that there will always be some difference between 3DE and 2DE image quality, as the technique will finally be limited by not so much processing speed, but the speed of sound. A major barrier to be overcome in the incorporation of 3DE into standard practice is the ability to read these images without the use of proprietary software.

2) LV diastolic function assessment
Hemodynamically, ventricular diastole can be divided into three components: active relaxation (during the isovolumic phase and with rapid ventricular filling after the atrioventricular valve opens); passive ventricular expansion (determined by myocardial compliance); and atrial contraction. About one-half of the patients presenting with diagnosed heart failure have normal systolic function. Traditionally, ventricular diastolic function has been evaluated by characterizing the blood flow Doppler patterns across the atrioventricular valves and along the systemic and pulmonary veins. Indices of ventricular relaxation and compliance have included peak blood flow velocities during early diastole (E wave) and during atrial contraction (A wave) and isovolumic relaxation time (from semilunar valve closure to opening of the corresponding atrioventricular valve).

**Tissue Doppler Imaging (TDI):** Doppler assessment of regional myocardial velocities has evolved as a complement to conventional blood flow Doppler evaluation. Myocardial doppler profiles obtained from TDI have provided new parameters to assess ventricular function. TDI-derived indices of LV diastolic function have included the following:
- peak mitral valve annular velocity away from the apex during early diastole (E wave), which reflects the rate of active ventricular relaxation after the mitral valve opens;
- ratio of peak blood flow velocity across the mitral valve to myocardial mitral valve annular velocity during early diastole (E/E’ratio), which correlates well with LV filling pressures;
- and isovolumic relaxation time, which represents the time interval from the end of systolic annular motion towards the apex to the beginning of the E wave (Fig. 2). E/E’is predictive of outcome in both heart failure and following...
myocardial infarction. While the assessment of filling pressure should be a central component of transthoracic echocardiograms, like all individual measurements, it has some shortcomings and has been shown to be unreliable in the setting of patients with severe heart failure presenting with decompensation, particularly those undergoing cardiac resynchronisation therapy. Patients with restrictive cardiomyopathy and consequent problems with active relaxation exhibit lower $E'$ when compared with patients with constrictive pericarditis whose diastolic dysfunction results from problems with compliance during passive expansion. Early diastolic and systolic annular velocities are both affected in patients with dilated and hypertrophic cardiomyopathy, though the systolic parameters are less affected in the hypertrophic cardiomyopathy patients, consistent with their primary diastolic dysfunction.

3) Left ventricular twist

Active LV relaxation occurs during the isovolumic phase and rapid ventricular filling after the mitral valve opens, though the majority of LV relaxation occurs before the mitral valve opens. Consequently, parameters which are measured with changes in LV volume when the mitral valve opens (such as transmitral inflow and annular myocardial velocities) do not account for the significant diastolic events which occur during isovolumic relaxation. In the normal LV, there is opposing circumferential rotation of the basal and apical segments resulting from the variability of spiraling fiber orientation across the myocardial wall. The net difference in clockwise versus counter-clockwise rotation at the base and apex is known as LV twist or torsion. LV twist occurs during systole (Fig. 3), and this process results in storage of potential energy within the myocardium which, in turn, is released with the sudden untwisting or recoil which occurs during diastole. Diastolic recoil occurs primarily during isovolumic relaxation and generates the intraventricular pressure gradient (diastolic suction) which initiates LV diastolic filling when the mitral valve opens. Hence, assessment of the rate of untwisting (relaxation rate) provides insight into LV relaxation which includes the isovolumic phase and may be less dependent on preload than other indices of active relaxation.

Although TDI can assess rotation by measuring tangential velocities in LV short-axis views, STE uses a novel autocorrelation algorithm to follow small myocardial segments and to measure regional displacement and velocity, thereby providing another method to assess LV twisting and untwisting. Unlike TDI, STE is not dependent on the angle of interrogation. STE has been used in patients with hypertrophic and dilated cardiomyopathy, revealing decreased untwisting rates in both groups.

4) Myocardial tissue characterization

Tissue characterisation is an important issue in heart failure patients. At present, cardiac MRI is better established than echocardiography for this purpose. The recognition of infarct site and extent is a predictor of success of revascularisation, as well as a predictor of outcome. In nonischaemic cardiomyopathy, the presence and location of scar has also been shown to be prognostically important. Advanced echocardiographic techniques like myocardial backscatter, which is only function-independent marker, have some potential for this purpose. It corresponds to biopsy evidence of fibrosis. The other potential markers of fibrosis are function-dependent—including tissue velocity (especially in diastole) and strain. The dissociation of longitudinal from circumferential and radial strain, as well as gradations of the latter across the wall are potential echocardiographic techniques for evaluation of the transmural distribution of scar tissue.
5) Assessment of Cardiac morphology

2D echocardiography has been a perfect tool to implement the segmental approach for cardiac morphology, since sweeping an image plane from one end of the heart to the other end has allowed echocardiographers to mentally create a three-dimensional representation of the heart with all of its abnormal structures and connections. With its ability to display datasets in an infinite number of planes and render three-dimensional representations of cardiac anatomy, 3DE may supplant the need for mental reconstructions and facilitate better understanding of the segmental variations in heart diseases. Compared to information obtained from 2D echocardiography, 3DE has provided additional morphologic data which are clinically important in a number of patients. 3DE is especially useful in the visualization of the mitral valve apparatus with its elliptical and saddle-like shape and in the characterization and quantification of mitral regurgitation. Evaluation of the aortic outflow tract at the subvalvular and valvular levels has also been facilitated and augmented by 3DE from a transthoracic approach. Improved utility of 3DE has provided more reliable assessment of atrial size, and 3DE is now evaluating how transcatheter device closure of atrial septal defects may affect atrial systolic synchrony and function.

STRESS IMAGING

The sensitivity of standard stress echocardiography for assessing wall motion abnormality (approximately 80%) may reflect more the limitations of a wall motion analysis-based technique for recognition of ischaemia than the limitations of echocardiography. Ischaemia may not be induced in the setting of moderate stenoses, distal disease, collaterals, submaximal exercise or anti-ischaemic therapy. Sensitivity may be enhanced by the addition of perfusion or flow reserve data or the detection of subendocardial ischaemia. The use of 3DE may improve the accuracy of stress echo by ensuring that the same segment of myocardium is visualised at both rest and stress, a requirement which can be quite technically challenging for the sonographer.

The assessment of myocardial perfusion at rest and stress is the most sensitive approach to the non-invasive identification of coronary artery disease (CAD). Contrast echocardiography for assessment of myocardial perfusion has been shown to improve the sensitivity of stress echocardiography, quantitation remains difficult and absolute flow calculations even more so. The current US Food and Drug Administration (USFDA) approved contrast agents, perflutren protein-type microspheres for injection (Optison™, Amersham) and perflutren lipid microsphere injectable suspension (Definity, Bristol-Myers Squibb Medical Imaging) are available for contrast echocardiography studies.

Markers of contractile reserve (e.g. ejection fraction, stroke volume), can be measured with any imaging modality, but because exercise is the most physiologic stressor, this
has tended to be used with exercise. Contractile reserve responses have been used to stratify mild or preclinical dysfunction in heart failure and regurgitant valve lesions. The assessment of diastolic responses to exercise requires high temporal resolution attainable with Doppler echocardiography. Although imperfect, the assessment of filling pressure from the ratio of transmitral to annular velocity (E/e’, Fig. 2) has been repeatedly validated, and responses to stress (“diastolic stress test”) may be of value in reducing the heterogeneity of the population labelled as having heart failure with preserved ejection fraction, and is a worthwhile adjunct to stress testing in dyspneic patients that is probably best attainable with echocardiography.

NATIVE VALVE REGURGITATION
Assessment of regurgitant valves involves understanding the mechanism of regurgitation, its severity, the size and function of the left and right ventricles and to estimate the pulmonary pressure. Information about the coronary vasculature is required in the subset of patients requiring surgery. Echocardiography is likely to remain the primary investigation for the evaluation of valvular heart disease, based on the strengths of Doppler for evaluating pressures as well as the anatomic evaluation of the valve. For structural assessment, transoesophageal 3D echocardiography offers excellent spatial and temporal resolution. Evolution in the temporal and spatial resolution of 3DE has helped to quantify LV and regurgitant volumes.

Assessment of ischemic mitral regurgitation is always a challenge and it continues to carry significant risk. Its management requires consideration of both valvular and ventricular components. In addition to quantification of regurgitation (which may be difficult because it is nonuniform through the systolic period), 3DE detail of the valve and LV are important, as are the presence and location of ischaemic and viable myocardium and the coronary vasculature. The incorporation of echocardiography in clinical workflow helps in the recognition of this pathology.

STENOTIC VALVE LESIONS
The principal indications for management for stenotic valve lesions depends on the symptom status. Echocardiography remains the gold standard for assessing valve gradients, valve area, left ventricular hypertrophy, systolic and diastolic function, and detection of concomitant disease. Advances in myocardial tissue characterisation are likely to draw attention to the adverse consequences of surgical delay in the asymptomatic phase of aortic stenosis. The new echocardiographic measurements of LV systolic function, such as tissue velocity and strain are heavily influenced by disturbances of LV after load and are unlikely to contribute to decision-making in this setting.

In mitral stenosis, imaging should provide information on the valve morphology, gradient and area, left atrial size, pulmonary hypertension, right ventricular function, and concomitant disease. Valve area is readily evaluated using Doppler, but in the post-intervention patient, as well as some other settings, Doppler may be unreliable. Planimetry from 2D images is practically difficult due to the difficulty in aligning the optimal imaging plane with the available imaging windows, a problem which has been avoided with 3D imaging (Fig. 6). Also 3DE gives an insight to mitral valve morphology and the sub-valvular apparatus and provides an information which every surgeon will need before the surgery.
or strain within a myocardial region of interest, and strain rate is the change in deformation over time. Although TDI provides higher temporal and spatial resolution, STE is easier to perform and more reproducible than TDI. Reference values for the two modalities are different and should not be used interchangeably. STE-derived reference values for normal adults and children have been published recently (36), though age may not have a significant effect on longitudinal systolic strain in children (longitudinal systolic strain rate does decrease significantly over the first 10 years of life)37. It is interesting to note that strain and strain rate measured by TDI both decrease with age in older adults despite the fact that ejection fraction tends to increase with age38. The most significant value of myocardial deformation analysis rests in its ability to detect subclinical local myocardial dysfunction before the appearance of clinically significant global ventricular impairment, though the prognostic significance of these abnormal findings has not yet been studied. Among the population groups in whom early regional myocardial dysfunction has been described are patients with systemic hypertension, hypertrophic cardiomyopathy, hypothyroidism, and severe pulmonary regurgitation. In addition, peak systolic strain rate may provide a sensitive quantitative index of LV and RV systolic function immediately after open heart surgery.

3D ECHOCARDIOGRAPHY IN TRANSCATHETER CARDIAC INTERVENTION
Transcatheter cardiac interventions such as atrial septal defect closures, mitral valve repair, and aortic valve replacement depend on imaging by fluoroscopy or imaging with echocardiography30. 41. Although 2D transesophageal echocardiography (TEE) provides real-time imaging with no added ionizing radiation, imaging is required in multiple planes to reconstruct the desired anatomy. Recent advances in ultrasound and matrix-array technology have made the clinical application of real-time 3DE feasible in the dynamic arena of transcatheter cardiac interventions.

For Transcatheter Closure of Atrial Septal Defects, 3D TEE can often precisely image the occluder in its relation to the interatrial septal defect to prevent malocclusion and possible embolization caused by size mis-match relative to the ASD42-44. In addition, 3D TEE can image the interatrial septum precisely to enhance procedural success despite variations in anatomy. The utilization of 3D TEE in this setting can decrease reliance on fluoroscopy and intracardiac echocardiography.

The transcatheter revolution in mitral valve repair has recently been advocated. 3D TEE has shown utility in transcatheter mitral valve repair 42,45. Transcatheter aortic valve replacement is being increasingly applied as an alternative in high-risk surgical patients45. The role of 3D TEE in these complex aortic procedures is by expert consensus currently under evaluation. The additional imaging by 3D TEE may supplement the information provided by standard imaging techniques. Compared with 2D imaging, 3D TEE is superior for distinguishing between paravalvular and intravalvular regurgitation.

CONCLUSIONS - THE FUTURE OF ECHOCARDIOGRAPHY
All practitioners involved with cardiovascular imaging should be aware of growth in this field. A large part of this growth is related to the epidemic of coronary heart disease and heart failure.

The strength of echocardiography is its place at the bedside, and technique will continue to benefit from automation, miniaturisation and three-dimensional imaging. In parallel with increasing utility will be reducing cost, so the technique will be increasingly taken up by non-echocardiographers, who will need to be guided by imaging specialists regarding training, competency and indications.

There is need for an ongoing dialogue among imaging specialists to identify the single most appropriate test for many clinical diagnoses. In many situations, the new echocardiographic technologies - strain, 3D and contrast - will reduce the need for more expensive tests, which will be reserved to address complex questions in a limited number of patients.
REFERENCES


31. Zoghi WA, Enriquez-Sarano M, Foster E, Grayburn PA, Kraft CD,


