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IMPORTANT ADVANCES IN TECHNOLOGY: ECHOCARDIOGRAPHY

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Abstract

Echocardiography has evolved over the past 45 years from a simple M-mode tracing to an array of technologies that include two-dimensional imaging, pulsed and continuous wave spectral Doppler, color flow and tissue Doppler, and transesophageal echocardiography. Together, these modalities provide a comprehensive anatomic and functional evaluation of cardiac chambers and valves, pericardium, and ascending and descending aorta. The switch from analog to digital signal processing revolutionized the field of ultrasound, resulting in improved image resolution, smaller instrumentation that allows bedside evaluation and diagnosis of patients, and digital image storage for more accurate quantification and comparison with previous studies. It also opened the door for new advances such as harmonic imaging, automated border detection and quantification, 3-dimensional imaging, and speckle tracking. This article offers an overview of some newer developments in echocardiography and their promising applications.

Introduction

Echocardiography is a well-established imaging modality that plays a pivotal role in the evaluation of patients with known or suspected heart disease. Over the past 45 years, the technique has evolved from a simple M-mode tracing to a family of technologies that include two-dimensional (2D) imaging, pulsed and continuous wave spectral Doppler, color flow Doppler, tissue Doppler, and transesophageal echocardiography (TEE) (Figure 1). The combined use of these modalities allows a comprehensive anatomic and functional evaluation of cardiac chambers, the

pericardium, ascending and descending aorta, and native or prosthetic valves. The conversion more than 10 years ago of analog to digital signal processing revolutionized the field of ultrasound. Instruments became smaller, image resolution progressively improved, and digital image storage allowed for more accurate quantification and comparison with previous studies. It also opened the door for exciting new developments in transducer technology and digital image processing, giving birth to newer advances such as harmonic imaging, automated border detection and quantification, 3-dimensional (3D) imaging, and speckle

Figure 1. Images of the common echocardiography and Doppler modalities used in cardiac ultrasound.

Figure 2. Contrast echocardiography using pulse sequencing technology performed in a patient with a dilated cardiomyopathy in whom there was suspicion of a thrombus at the apex (Panel A; arrows). Note in Panel B the excellent contrast effect that fills the entire LV cavity excluding the presence of a mass. Also note the contrast effect within the myocardium resulting from micro bubbles within the capillary circulation.

tracking. In addition, miniaturization of instruments now allows physicians to examine patients at the bedside and render a more accurate diagnosis than that provided by physical examination. In this article, we will provide a brief discussion of some of these newer developments and their promising applications.

Advances in Image Quality and Border Detection

The quality of echocardiographic images is dependent on the expertise of the sonographer and also on the body size and habitus of the patient. Improvements in transducer technology, digital image acquisition, and computer processing are providing better image quality in the difficult patient. However, there is still a sizeable subgroup of patients with suboptimal images that do not allow accurate cavity measurements to be made. Certain ultrasound contrast agents consist of stable microbubbles that reflect ultrasound waves and are small enough to cross the pulmonary capillaries when injected intravenously. These agents, when administered intravenously, opacify the left ventricle (LV) and provide a clear delineation of the cavity-endocardial border, thus improving the accuracy of LV volumes and ejection fraction (EF) determination.¹ Because microbubbles are easily destroyed by ultrasound energy, performance of contrast imaging requires optimization of several settings in the ultrasound machine and the use of a low mechanical index (the setting that controls ultrasound power). Newer pulse sequencing technology has been developed that recognizes and processes the unique nonlinear fundamental and high-order harmonic signals generated by the reflected microbubbles. This results in improved sensitivity and a stronger contrast signal that provides excellent recognition of the cavity-endocardial border (Figure 2).

Automated gain control simplifies the process of acquiring images while optimizing gain settings for a particular window of examination. These improvements have facilitated detection of endocardial borders that, when combined with new pattern recognition technology, allow the system to automatically perform measurements of dimensions, area, and spectral Doppler velocities (Figure 3). When properly used, this improves the accuracy and reproducibility of measurements as well as patient flow in a busy clinical laboratory.

Advances in 3-Dimensional Echocardiography

Commercial ultrasound systems with 3D capability have been available for the past 8 to 10 years and have included both transthoracic and TEE transducers. Despite this, the modality has been slow to get incorporated into routine clinical use, with the

possible exception of 3D TEE, which has gained popularity in the evaluation of mitral valve pathology and in guiding complex interventional catheter procedures (Figure 4). The promise of 3D was that it could shorten the time of an examination by taking one or two volumetric acquisitions from which multiple 2D and 3D views could be reconstructed. However, limitations in processing time reduce the size of the volumetric acquisition. Consequently, several acquisitions over multiple cardiac cycles have to be stitched together to construct a 3D image of the entire LV. This often results in image artifacts.² Furthermore, transducer technology has lagged behind image processing technology, thus limiting the quality of the images, particularly in patients with less than perfect image quality. This has also limited the quality of 3D color flow and has kept the technique from being routinely used to evaluate structural abnormalities and valve function. Despite these limitations, 3D provides automated quantification of LV volumes and EF. The results obtained can be quite accurate if the examination is properly performed and the patient has good image quality. However, in the absence of either of these, the results can be highly inaccurate and, if accepted by the interpreting physician, can lead to the wrong clinical decision.

More recent advances in transducer technology combined with fast processors allow for a single 3D cardiac cycle acquisition with superior time resolution that should provide more reproducible and accurate quantification of LV volumes and EF (Figure 5). It should also improve the overall assessment of valvular structures.

In addition to quantification of LV volumes, there are two other 3D applications that deserve mentioning. The first is quantifying the severity of mitral regurgitation (MR) by measuring the area of the vena contracta with 3D color flow, more often done with TEE (Figure 6). Studies from this institution suggest that this could provide a more accurate assessment of MR severity than current echocardiographic Doppler methods.³ With the technical improvements mentioned above, we may expect a greater application of this measurement with transthoracic 3D. The second application is to derive simultaneous and selected biplane orthogonal 2D images to facilitate and shorten the time of a TEE examination, especially during TEE-guided catheter interventions (Figure 7).

Advances in Strain Imaging

Strain (S) and strain rate (SR) imaging is one of the new promising technologies for the evaluation of cardiac function. Strain is the fractional shortening of two points within the myocardium (i.e., myocardial deformation) that could be aligned with a vector within the subendocardium, midwall, or subepicardium along a circumferential, radial, or longitudinal plane. In the past strain measurements were possible with tissue Doppler, but speckle tracking is now the preferred method due to less noisy signals and higher reproducibility. Speckle tracking is a recent development within the digital matrix of the reflected ultrasound. The system tracks minute speckles of reflected ultrasound throughout the cardiac cycle, measures the change in distance between them throughout systole and diastole, and creates strain and strain rate curves (Figure 8). Speckle tracking echocardiography (STE) is currently available on most ultrasound systems, and the accuracy of strain measurements has been validated in animal and clinical models. The analysis can be performed online as well as offline. Based on image quality and the experience of the analyst, reasonable levels of reproducibility can be attained. A more recent advancement combines 3D with strain imaging, allowing a 3D rendering of the strain vectors.

Figure 3. Panels A and B show end-diastolic and end-systolic frames, respectively, of a 2-dimensional echo parasternal view of the left ventricle, illustrating automatic measurements of left ventricular dimensions using a new pattern recognition technology. Panel C shows the same technology applied to pulsed-wave spectral Doppler.

Figure 4. Three-dimensional echocardiography images obtained by TEE during an intervention to close a large paravalvular defect in a mechanical mitral prosthesis (yellow arrow). A reconstruction of the defect using 3D color Doppler is shown on panel B (arrows). Panel C illustrates placement of the guide wire (white arrow) across the defect (yellow arrow), which required making a loop in the left atrium and was guided by 3D. Panel D shows an image taken at the conclusion of the procedure demonstrating the two occluders in place. TEE: *transthoracic* echocardiogram; 3D: 3-dimensional.

Figure 5. Left ventricular volume curve derived from a single-beat 3-dimensional acquisition and with automated border detection software.

Over the past decade, strain measurements have moved from validation studies to clinical applications that include assessment of myocardial function in patients with coronary artery disease (CAD), hypertension, heart failure, valvular heart disease, and cardiomyopathy.⁴⁻⁸ Many of these studies have shown a decline in myocardial contractile function with these disorders despite

Figure 6. Effective regurgitant orifice area (EROA) in a patient with mitral regurgitation derived with 3D color Doppler (Panel C). EROA is reconstructed from multiple orthogonal tomographic planes derived from the 3D acquisition (Panels A, B and D). 3D: 3-dimensional.

Figure 7. Biplane real-time images acquired simultaneously during a 3-dimensional transthoracic echocardiographic examination of the left atrial appendage. The image in Panel B is orthogonal to the plane outlined by the line in Panel A. A thrombus is seen in the left atrial appendage (Panel B).

normal EF and absence of symptoms (Figure 9). Furthermore, several studies are showing incremental prognostic value of strain measurements in these diseases. Measurements of strain and strain rate have also been applied to the right ventricle (RV) and left atrium (LA), as preliminary studies suggest they may provide a more accurate assessment of RV and LA function than that available by conventional measurements. Finally, integration of strain curves throughout the cardiac cycle from base to apex is providing insight into the mechanics of LV contraction, the importance of torsion, and the contribution of circumferential and longitudinal strain to LV function.

Several studies in animals and humans have shown abnormal systolic and diastolic deformation in the setting of acute ischemia. More recently, regional changes in diastolic strain were able to identify ischemia several minutes after the acute event.⁴ The detection of persistent abnormalities after relief of chest pain is

Figure 8. Longitudinal strain imaging derived with speckle tracking in an apical long-axis view. Strain is derived along six segments from base to apex. The individual regional strain curves are depicted in the right upper panel with the dotted white line indicating global strain in that view. The regional values for peak systolic strain are shown on the left lower panel. The right lower quadrant represents a color histogram that plots the time course of one cardiac cycle on the x axis and the circumference of the left ventricle on the y axis. The colors represent strain values, with the higher values highlighted with darker colors. The homogeneity of colors indicates synchronous contraction and relaxation along the six segments.

Figure 9. Longitudinal strain imaging obtained in a 45-year-old man with severe hypertension, concentric left ventricular hypertrophy, and normal ejection fraction (EF) (> 65%). Panel A shows strain imaging in the apical 2-chamber view. Regional strain curves from the apical 4-chamber, 2-chamber, and long-axis views are illustrated in panel B together with a "bull's-eye" depiction of peak systolic strain in all segments. Note that despite a normal EF, peak systolic strain is diminished in basal and mid septal, anteroseptal and inferior segments as well as in the apical inferior segment.

particularly appealing in patients who present after pain resolution with abnormally elevated diastolic transverse strain in the risk area. This initial investigation opens the door for multicenter studies to evaluate which of the available S and SR parameters are the most accurate and reproducible. Notwithstanding the need for such studies, it is conceivable that measurements of S and SR will lead to greater objectivity and reproducibility in assessing regional function than what is currently available with subjective evaluation. Measurements of global longitudinal strain (as well as circumferential strain in some studies) have been shown to provide incremental prognostic information over clinical data, EF, and diastolic indices in patients with a variety of myocardial and valvular diseases.^{9,10} In addition, diastolic strain and strain rate measurements have been applied to assess LV relaxation and estimate filling pressures in patients with normal and depressed EF.¹¹⁻¹³ LA strain has also been used to estimate LA pressures.¹⁴

Several studies have shown that myocardial imaging can detect abnormal cardiac function in patients with hypertrophic cardiomyopathy (HCM). In these studies, regional and global LV function were evaluated by myocardial S and SR. Reduced diastolic strain is often observed in these patients¹⁵ as well as profound abnormalities in septal and global LV longitudinal strain in the presence of preserved circumferential strain. Thus, it appears that LVEF is preserved by radial and circumferential deformation in HCM patients. Interestingly, the number of segments with abnormal longitudinal strain has been found to be a predictor of nonsustained ventricular tachycardia in this disease and is more accurate than maximum wall thickness and N-terminal pro-brain natriuretic peptide.¹⁰

LV dysfunction has been increasingly detected with the administration of chemotherapy drugs. This can affect patient care as a drop in EF often influences the decision of whether or not to continue with a given medication. Recent studies in patients receiving chemotherapy have shown a reduction in peak longitudinal strain just before a fall in EF. Preliminary results suggest that the use of beta-blockers and ACE inhibitors during this early stage may prevent progression of LV dysfunction and clinical heart failure in these patients.¹⁶ Larger-scale trials will be needed to determine the role of strain imaging in the management of patients receiving chemotherapy agents.

Despite the promise of this new technology, there are still some limitations that are keeping strain imaging from becoming part of a routine clinical examination. First, acquisition of reliable strain curves requires echocardiographic images of good quality, training, and attention to meticulous technique without which the data loses accuracy and reproducibility. Second, measurements derived from these curves vary among different ultrasound vendors, which limit the establishment of normal ranges. Finally, data are currently lacking regarding how best to use strain measurements in the routine management of a cardiac patient.

Hand-Held Ultrasound Systems

With advancements in digital technology and digital image processing, ultrasound systems became smaller and lighter to where they could be hand-held and carried in a coat pocket. Current hand-held systems provide 2D images and color flow Doppler of diagnostic quality that allow physicians to examine patients at the bedside so they can rapidly assess ventricular and valvular function and screen for pericardial effusion and aortic root pathology (Figure 10).¹⁷ This type of focused examination can hasten the establishment of a cardiac diagnosis, assess LV global and regional function, and streamline the selection of patients who will benefit from a comprehensive echocardiographic examination or a referral to another imaging modality. When properly applied, this approach should reduce cost and improve patient care in both the acute and outpatient settings. However, a hand-held instrument in the hands of an inexperienced physician increases the risk of an inaccurate diagnosis that can harm the patient or increase utilization of expensive imaging tests. Therefore, it is essential that any physician using this exciting new modality receives proper training. Preliminary studies suggest that such a level of training is feasible within a reasonable time period. It is not unreasonable to predict that we will soon see physicians trained to use these devices during their residency or even in medical school. In fact, there are some who predict that these instruments will become the “stethoscope of the future.”

Figure 10. A bedside, focus examination of the heart is performed by a physician using a hand-held device. The patient presented to the emergency department with chest pain suggestive of pericarditis.

Summary

We have presented some of the more recent and exciting technological developments in cardiac ultrasound that are expanding the application of echocardiography in the evaluation of cardiac disorders. In addition, some of these developments are providing new measurements of cardiac function that are enhancing our understanding of myocardial mechanics and their response to altered loading conditions and disease.

In addition to improvements that directly influence imaging capabilities, newer ultrasound systems are lighter, easier to transport, and more ergonomically designed than their predecessors. This is no small matter given that sonographers have been plagued with chronic musculoskeletal disorders related to their profession. With all of these new technologies, echocardiography continues to be the imaging modality of choice for evaluating most cardiac disorders by providing high spatial and time resolution while remaining highly portable. The wide use of hand-held devices will likely change the bedside evaluation of patients and optimize the appropriate use of more costly imaging tests.

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