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Recent technological advancements in cardiac ultrasound imaging

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ABSTRACT

About 92.1 million Americans suffer from at least one type of cardiovascular disease. Worldwide, cardiovascular diseases are the number one cause of death (about 31% of all global deaths). Recent technological advancements in cardiac ultrasound imaging are expected to aid in the clinical diagnosis of many cardiovascular diseases. This article provides an overview of such recent technological advancements, specifically focusing on tissue Doppler imaging, strain imaging, contrast echocardiography, 3D echocardiography, point-of-care echocardiography, 3D volumetric flow assessments, and elastography. With these advancements ultrasound imaging is rapidly changing the domain of cardiac imaging. The advantages offered by ultrasound imaging include real-time imaging, imaging at patient bed-side, cost-effectiveness and ionizing-radiation-free imaging. Along with these advantages, the steps taken towards standardization of ultrasound based quantitative markers, reviewed here, will play a major role in addressing the healthcare burden associated with cardiovascular diseases.

Contents

Abbreviations: ARFI, acoustic radiation force impulse; CE, contrast echocardiography; CT, computed tomography; EBD, endocardial border definition; ED, emergency department; EF, ejection fraction; FoCUS, focused cardiac ultrasound; HFpEF, heart failure with preserved ejection fraction; HFrEF, heart failure with reduced ejection fraction; ICU, intensive care unit; MI, mechanical index; MPI, myocardial perfusion imaging; MR(I), magnetic resonance (imaging); LV, left ventricle/ventricular; LVO, Left ventricular opacification; PET, positron emission tomography; POCUS, point-of-care ultrasound; RV, right ventricle/ventricular; SHOC, sonography in hypotension and cardiac arrest; SWEI, shear wave elasticity imaging; SWI, shear wave imaging; SPECT, single-photon emission computed tomography; STE, speckle-tracking echocardiography; TDI, tissue Doppler imaging; TEE, transesophageal echocardiography.

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1. Introduction

Confucius enunciated "I hear and I forget. I see and I remember...". Interestingly, in cardiology, from utilizing sound for diagnosis based on auscultations [1] (from the Hippocratic period: 460 to 370 BCE; still used in clinical practice today), techniques have evolved to translate ultrasound into images for characterization of cardiac function. Medical use of ultrasound dates back to the 1940s with the use of ultrasound in cardiology being reported in the 1950s [2,3]. Since then advancements in electronics and ultrasound transducers, coupled with signal and image processing algorithms have rapidly propelled the use of medical ultrasound with echocardiography regarded as one of cardiology's 10 greatest discoveries of the 20th century [4].

Out of several imaging modalities available today for cardiac imaging, advantages associated with ultrasound include real-time imaging, imaging at patient bed-side (point of care), cost-effectiveness and ionizing-radiation-free imaging [5,6]. The cost of other cardiac imaging modalities exceed that of 2D echocardiography by a factor of 3.1–14.0, whereas the cost of right and left heart catheterization, performed often to obtain diagnostic information, is greater by almost a factor of 20 [5]. As per the latest data from the American Heart Association, about 92.1 million Americans (more than 1 in 3 Americans) suffer from at least one type of cardiovascular disease [7]. Worldwide, cardiovascular diseases are the number one cause of death (about 31% of all global deaths) [8]. Further, it is estimated that by 2030, the total annual cost associated with cardiovascular diseases in the United States will exceed $900 billion [7].

In briefly reviewing basic cardiac function, the heart is designed to respond to different loading (filling) conditions in the form of varying blood volumes and varying magnitudes of flow resistance. As a dynamic cyclic pump that is able to respond and adapt to varying flow requirements and pressure conditions, measuring the characteristics and functional parameters of the heart muscle becomes clinically relevant for assessing heart failure and myocardial ischemia (due to reduced blood flow to the heart). Abnormalities in the compliance of the heart muscle during the filling stage of the cardiac cycle (diastole) cause diastolic dysfunction and heart failure with preserved ejection fraction (HFpEF). Abnormalities in the pumping ability of the heart during the contraction of the heart muscle in the cardiac cycle (systole) causes systolic heart failure also known as heart failure with reduced ejection fraction (HFrEF).

Keeping in mind the advantages offered by ultrasound imaging and the healthcare burden of cardiovascular diseases, technological advancements have expanded the role of ultrasound in cardiac imaging. This review article will serve as an overview of some of these recent technological advancements in cardiac ultrasound including tissue Doppler imaging, strain imaging, contrast echocardiography, 3D echocardiography, point-of-care echocardiography, 3D volumetric flow assessments, and elastography.

2. Tissue doppler imaging (TDI)

For more than 50 years, since the first measurement of motion as well as flow in the heart was performed in Japan in the 1950's by Satomura, the clinical use of ultrasound imaging has expanded dramatically [9,10]. While ultrasound scanners have been detecting echoes scattered from blood based on the Doppler effect for most of that time [11], it was only in the late 1980's that the concept of tissue Doppler imaging (TDI) for echocardiography (sometimes also referred to as Doppler myocardial imaging) emerged [12–14]. Conventional Doppler systems rely on high-pass filters to extract the high frequency, low amplitude signals caused by blood flow, but by inverting the signal processing TDI employs low-pass filters to isolate the low frequency, high amplitude signals associated with myocardial motion, in particular, the longitudinal component of the myocardial contraction [12,13].

Tissue Doppler imaging measurements are performed using either the pulsed wave or the color coded modes. Pulsed wave TDI directly measures the instantaneous tissue velocity within a small (1–5 mm) sampling volume, while color coded TDI allows simultaneous interrogation of the entire color box (i.e., over a large region of interest; ROI), but necessitates post-processing to compensate for variations in the angle of interrogation across the color box in order to extract the mean tissue velocity (typically some 25% lower than the pulsed wave TDI values) [12,13]. Both these modes rely on the pulsed Doppler principle but differ from one another based on the size of the region from which velocity measurements are performed, and how the resultant values are calculated and displayed. Consensus statements from a number of echocardiographic societies around the globe recommend quantitative TDI evaluations for assessment of systolic and diastolic left ventricular (LV) and right ventricular (RV) function, LV filling pressures and ventricular dyssynchrony, and for monitoring the treatment of patients with heart failure [15–18].

Over a cardiac cycle the pulsed wave TDI signal contains three peaks corresponding to the peak myocardial velocities during systole (s' signifying myocardial contraction), early diastole (e' signifying myocardial relaxation) and late diastole (a' signifying active atrial contraction) (Fig. 1). Additionally, isovolumetric contraction and relaxation peaks can also be identified. Normal pulsed wave TDI values for s', e' and a' can be found in the literature [12]. Quantitative TDI measurements can be used to characterize global and regional myocardial function and can provide prognostic markers for a number of cardiac diseases including coronary artery disease, heart failure and valvular heart diseases [12].

The use of TDI measurements has also been evaluated for prognosis post cardiac resynchronization therapy (a pacemaker based therapy for resynchronizing ventricular contractions). A meta-analysis of 8 cardiac resynchronization therapy studies involving over 4000 patients found that TDI had an 87–97% sensitivity and 55–100% specificity for differentiating between responders and non-responders [18]. However, these results were not confirmed by the prospective, multi-center PROSPECT trial, which resulted in sensitivities of 42–74% and specificities of 35–60% based on TDI assessments of responses to cardiac resynchronization therapy amongst 498 patients [19]. A meta-analysis of studies looking at detection of coronary artery disease concluded that TDI velocities provided significant separation amongst patients with and without coronary artery disease before and after stress tests [13]. However, while at rest these differences were expressed in the peak systolic velocity (i.e., s' amplitude) and post stress differences appeared in the early diastolic velocity (i.e., e' amplitude) [13]. Early diastolic velocities by TDI are also frequently used to estimate filling pressures; however, in a recent meta-analysis of 24 studies, Sharifov and colleagues found a poor to mediocre correlation of the TDI-based technique with invasively-determined LV filling pressures [20].