Reviews

# Speckle Tracking Echocardiography of the Right Atrium: The Neglected Chamber

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ABSTRACT

The right atrium (RA) plays a pivotal role in electromechanical and endocrine regulation of the heart. Its peculiar anatomical features and phasic mechanical function make it distinct from ventricles. Various invasive and noninvasive techniques have been used to elucidate RA structure and function. Of these modalities, echocardiography has distinct advantages over others. Several conventional measures of RA function through echocardiography have been described in the literature, but they are load dependent. A relatively new technique is speckle tracking–derived strain, which is relatively less dependent on loading conditions. Speckle tracking echocardiography tracks acoustic scatters (speckles) of myocardium frame-by-frame to calculate strain or deformation of the myocardium. Speckle tracking echocardiography has been used extensively for strain assessment of the right and left ventricle to detect subtle disease pathology, to gain mechanistic insight, as a marker of ischemic metabolic memory, as an endpoint in clinical trials, and as a functional assessment tool. The RA is a relatively neglected chamber, as it is mostly studied for assessment of atrial mass lesions, for electrophysiological studies, and in animal models for physiological assessment. However, its role in the systolic and diastolic function of the right heart, pulmonary vascular pathology, congenital heart diseases, and combined electromechanical activation phenomena has been less explored or unexplored. Speckle tracking echocardiography is an ideal tool for the assessment of the RA because of its regional and global functional characterization, angle independence, and high temporal resolution.

## Introduction

The right atrium (RA) is located on the anterosuperior aspect of the heart and lies anterior to the left atrium (LA), which forms the most posterior chamber of the heart. The interatrial septum is oblique (at 65 degrees) to the cardiac axis and the tricuspid and mitral valves are located at different levels; therefore, the RA lies anterior and inferior to the LA.

## Anatomy

The RA has unique morphological and physiological characteristics that differentiate it from the other cardiac chambers. It has phasic mechanics. It acts as a reservoir in ventricular systole, a conduit during early ventricular diastole, and a booster pump in late ventricular diastole. It secretes hormones that regulate the cardiovascular and fibrous tissue of the body.[1] Moreover, its ultra-structural features lead to specific atrial mechanics.

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## Histopathology

The RA chamber is organized in the form of layered fiber bundles called trabeculae, which are organized in a specific arrangement to form tracts, cavities, and apertures and to regulate electrical phenomena. On light microscopy, the cardiac trabeculae are composed of cardiomyocytes with abundant sarcomeres.

The RA appendage, crista terminalis, and fossa ovalis are prominent landmarks worth mentioning because they alter the electrical properties and strain of the RA.

***Right Atrial Appendage:*** This small cavity located exterior to the RA has an arrangement of fibers that is much straighter than the rest of the atrium and the right ventricle (RV), thus making it more distensible as compared with the rest of the


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atrium and the ventricles. It is also more prone to fibrosis,[2] and hence to atrial fibrillation (AF) than the rest of the RA chamber. It is the usual site for RA lead placement.

***Crista Terminalis:*** This lies between the venous component and the RA appendage. The crista terminalis is a fibromuscular ridge that incorporates into the RA wall. It has marked myocyte junction anisotropy, which is a substrate for micro-reentry circuits. A distinct entity called cristal atrial reentry tachycardias[3] arises from the crista terminalis because of its unique structural and electrophysiological feature. A ridge, which was considered an embryonic vestigial structure, may give rise to a plethora of arrhythmogenic phenomena. This electrical phenomenon in turn affects RA strain. The crista terminalis can also act as an electrical barrier between the 2 territories that it separates. Its position is variable in the RA, leading to novel electrophysiological phenomena.[4]

***Fossa Ovalis:*** The fossa ovalis is an embryological remnant of septum primum and septum secondum. It closes in postnatal life, leaving a mark-like impression called the foramen ovale. Sometimes it persists, leading to risk of paradoxical embolism, stroke, and migraine.

***Coronary Sinus:*** This is the venous drainage chamber of the myocardium, which opens into the RA, and its opening is guarded by the Eustachian valve.

## Right Atrial Physiology

Atrial mechanics involve the reservoir phase, the conduit phase, and the booster pump (contractile phase). The RA acts as a reservoir during ventricular systole, conduit during early diastole, and contractile pump during late ventricular diastole.[5]

***Reservoir Phase:*** This phase of atrial dilation occurs during ventricular systole. It starts after the closure of the tricuspid valve, when the blood from the superior and inferior vena cavae and coronary sinus enters into the RA. The onset of this reservoir phase coincides with the QRS complex and spans the isovolumic contraction,[6] ventricular systole, and isovolumic relaxation of the ventricle.[7] The RA is a distensible chamber,[8–11] and hence, despite the closure of tricuspid valves, it stretches to accommodate incoming blood. The duration of the reservoir phase and the amplitude of dilatation reflect the potential energy stored in the atria. The RA operates on the Frank-Starling mechanism,[12] with maximum contraction occurring at optimal length. This reservoir function of the RA is 4× more important than its contractile function, as it provides energy needed for atrial kick.

***Conduit Phase:*** This is the passive filling phase, which occurs during the early part of the ventricular diastole. During this phase, the ventricles fill "passively," without active energy expenditure by the atria. It starts from the opening of the tricuspid valves and ends just before the start of active contraction of atria after the P wave on the electrocardiogram. It depends on RV relaxation properties.[5]

***Contractile Phase:*** The active pumping phase of atria contributes about 15% to 30% of stroke volume of the RV. This pumping activity is lost in diseases like AF, in which chaotic movement of atria affects atrial contribution to the ventricles. The reservoir phase depends on intrinsic compliance and RA relaxation properties as RV systolic pressure, which moves the tricuspid annulus upward, acts as an extrinsic force. The contractile phase depends on intrinsic contractility and is affected by RV compliance.[13]

## Exploring Right Atrial Structure and Function Through Various Modalities

The RA is a neglected chamber of the heart. Although it was first described in the 17th century by William Harvey, it was not until 1929, when his famous book was published, that the RA entered the limelight. Even then it remained neglected for a few more decades. The invention of echocardiography by Carl Hellmuth Hertz and Inge Edler opened the way for heart exploration. In 1965, Harvey Feigenbaum and colleagues did some pioneering work on pericardial diseases through M-mode echocardiography,[14] but the RA could not be explored because of the limited views of M-mode echocardiography. Bloomer et al were the first to describe RA dimensions, in 1979. After that there began a series of studies on the structure and functional aspects of this chamber that continues to date.

Compared with other cardiac imaging modalities, echocardiography is less expensive, portable, radiation free, safe, easily available, and has a higher temporal resolution. In addition, the relaxation properties and diastolic phenomena can be investigated very well. However, it is operator dependent and is limited by anatomical views, even on transesophageal echocardiography, and tissue characterization is not possible as it is using magnetic resonance imaging (MRI). In addition to echocardiography, the RA has been explored through cardiac MRI (CMR), computed tomography (CT), electrophysiological studies, angiographic studies, and histopathology studies in humans. Physiological studies have been done on animal models and humans as well. Amparo et al were among the first to use CMR for this purpose. Keller et al used freehand drawing on 3-dimensional (3D) echocardiography and showed good correlations between 3D echocardiography and MRI. This study showed high variability on 1D (124%) and on 2D echocardiography (37%), whereas it is only 11% for 3D echocardiography and comparable for CMR.[15] Two-dimensional echocardiography was compared with cine angiography in 1981 by Schabelman.[16] Cardiac MRI has several advantages over other modalities, namely being operator independent, having good tissue-blood contrast, and ability to acquire extra-anatomical planes. Late gadolinium enhancement imaging is used for investigating atrial fibrosis, remodeling and LA appendage thrombi, and stroke risk assessment. However, studies using MRI for the RA are relatively sparse. Akoum et al used late gadolinium enhancement MRI to show that RA fibrosis correlates with sinus node dysfunction.[17] Fleck et al studied RA function pre- and postablation and showed that atrial contractility returns to normal after ablation.[18]

Multidetector computed tomography is a robust technology for structural and functional assessment of the heart. It has the advantages, like CMR, of being operator independent, a high spatial resolution, and the luxury of extra-anatomical views, but radiation exposure and contrast injection are its drawbacks. The RA has also been studied on


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cine angiography. Transesophageal echocardiography has also been used for atrial assessment. Spontaneous echo contrast on transesophageal echocardiography has been linked to atrial thrombus formation.[19–21] Animal studies studying RA anatomy have been conducted since the 17th century, when the RA was first described by William Harvey and published in his famous manuscript in 1929. Right atrial pressure and stiffness increased, whereas RA diameters decreased, during AF in a murine model.

## Conventional Echocardiographic Measures of Atrial Function

There are several measures of atrial function on "traditional" echocardiography, with some limitations. The most common measure used is atrial volume (which is load dependent) along with transtricuspid inflow velocities[22] and velocity-time integral of the A wave of transtricuspid inflow velocities, but it measures the contractile force of the atria only and is highly dependent on the loading conditions[23] of the heart and diastolic function of the ventricle. Tissue Doppler–based atrial velocities and velocity-time integral also are used, but they have the limitations of being angle dependent and requiring high frame rates for good image resolution. Atrial ejection force[24] is a measure of atrial systole commonly used, but again it is dependent on loading conditions of the heart. Similarly, atrial emptying fraction is also measured instead of ejection fraction (EF), because it is mostly the emptying of the atria rather than ejection.

## Speckle Tracking Echocardiography

Cardiac function is traditionally measured with transthoracic echocardiography via volumetric measures of cavity size (end-diastolic volume and end-systolic volume,[25] mass, and EF). Though they are well validated parameters and have diagnostic and prognostic significance, EF and volume are load dependent.[23] Ejection fraction varies when the heart lengthens or shortens. Moreover, volume, mass, and EF give an estimate of global myocardial function with no or very little information about the regional function of the myocardium. Strain is a measure introduced relatively recently in the cardiac community, which, if considered in 1 dimension, is due to change in length ($L$) of a 1D object relative to its original length. It is described by the formula $E = (L - L_o) \ / \ L_o$, where E indicates strain, $L_o$ indicates original length, and $L$ indicates final length.[1]

## Contractility

Myocardial function depends mainly on 3 factors: preload, afterload, and contractility. Although we can measure loading conditions with reasonable accuracy, the measurement of contractility is fraught with many technical difficulties and challenges, the most notable being its dependence on loading conditions and inotropic state. Several indices of contractility are cardiac output, stroke volume, end-diastolic and -systolic volumes, and EF, but they all have the same technical limitation as mentioned above.

## Methods to Measure Strain

Several methods of strain measurement have been reported in experimental literature,[26–29] but myocardial strain is principally measured through color Doppler methods and, more recently, speckle tracking echocardiography (STE).[30] Doppler-derived strain is a robust, easily available, relatively reproducible technique. However, for accurate data recording it requires a high frame rate[27] (100–150 frames/s) and is angle dependent,[31] as well as being affected by translational movements and tethering.

Speckle tracking echocardiography is a cutting-edge technique with huge potential for transforming cardiology practice.[26] It is robust, reproducible, accurate, and free of angle of insonation, and the frame-rate requirement is not as high (60–90/s). Speckle tracking echocardiography has been shown to have good interobserver and intraobserver variability.[32,33] It has been validated against sonomicrometry and CMR. Speckle tacking echocardiography tracks tissue "signatures" or ultrasound image texture formed by attenuation, reflection, and refraction of sound waves from the myocardium. When sound waves come into contact with the human body, they get scattered by ribs, lungs, myocardium, air, tissue interfaces, and the blood. Some of the sound waves are attenuated by losing their intensity while penetrating the tissues. These waves that are scattered are in decoherent form, which means the crest of one falls over the trough of the other at some places, and vice versa. At some places they cohere (add up), whereas at others they decohere (nullify each other). Despite this coherence and decoherence, there are some waves of very small wavelength smaller than the resolution of the imaging system. They form the "noise" in the imaging process. When subsequent processing steps are applied, these noisy waves have a mottled appearance, and this is what has been called the "speckle pattern." These speckles are assigned a functional unit called a "kernel," which is then used in tracking the myocardium throughout the cardiac cycle. The other half of the picture "tracking" or spatial dislocation is even more interesting. The speckles can be used to track the movement of the underlying myocardium from which they originated. Because these speckles are formed from subresolution wavelength waves, they represent fine fingerprints of underlying Myocardium. Complex algorithms can be applied to track these speckles. Although the algorithms involved are beyond the scope of this article, in essence the statistical methods used are similar to block-matching and autocorrelation techniques.

## Technical Challenges in Measuring Right Atrial Function

Right atrial structure, volume, size, and electrophysiological and endocrine phenomena have been extensively studied, but RA function is difficult to measure because:

1 The RA has thin walls, and contouring the RA is difficult.
2 The RA has many structures fitted into a tight compartment, and the unusual geometry of the chamber makes measurements difficult.
3 So many structures have been fitted within a limited chamber space that functional measurements are all the more difficult.


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4 On echocardiography, the RA can be imaged only in 4-chamber or 5-chamber views. Subcostal views are not routinely acquired in clinical practice due to patient discomfort. The 5-chamber view obliterates the interventricular septum, so accurate calculation of strain is not possible. In the 4-chamber view, the assessment is focused on the LV, and therefore the RA is usually foreshortened due to poor lateral resolution.
5 Image quality is a major issue that renders many interesting studies unsuitable for analysis.
6 Most previous techniques, such as color Doppler, are limited by a high frame rate, angle dependency, tethering artifacts, and complex analysis.

## How Speckle Tracking Can Overcome These Challenges

In STE, set of pixels of very small size is assigned a kernel value, and these kernels are manually drawn on the endocardial border to track the motion of the endocardial during various phases to get the strain curves. It offers the following benefits:

1 An electrical phenomenon is a problem, but averaging of strain over several cardiac cycles can help overcome the problem.
2 With experience, the learning curve of the reader can be improved and it becomes easier to differentiate and maneuver abnormal from normal.
3 Image quality can be optimized by adjusting frame rate, gain, depth, sector width, and other variables.
4 Speckle tracking echocardiography is angle independent and requires medium frame rates. Analysis can be completed in 2 to 3 minutes and, with some vendors, can be performed on the machine.
5 If the apical 4-chamber view can be focused on the RA, it can result in better image quality and best results.

All these reasons prove that the RA can be studied through STE in an efficient manner.

The following diseases would make plausible candidates for the study of the RA through STE:

***Drug Trials of Right Atrium:*** Right atrial function is used in several disease entities,[34–37] including AF, pulmonary hypertension, and obstructive sleep apnea, among others. Right atrial speckle tracking would be an interesting diagnostic entity to study these trials.

***Tricuspid Valve Abnormalities:*** Tricuspid regurgitation increases RA volume significantly and is hypothesized to alter the load independent measures of strain and strain rate. A recent study is in agreement with those findings, and in a cohort of heart failure patients, the RA strain and strain rate have decreased during the reservoir phase in heart failure with reduced ejection fraction (HFREF) patients more than heart failure with normal ejection fraction (HFNEF) patients.[38]

***Congenital Heart Disease:*** Speckle tracking echocardiography has been used in several diseases of the right heart; for example, CMR is the gold standard to measure EF cutoff of 45% in those undergoing surgery for systemic RV and transposition of the great vessels.

The values of EF measured by 2D STE compared with CMR (the gold standard) are quite in harmony with each other.[39] Right ventricular global longitudinal strain and RV circumferential strain have been shown to correlate well with RV pressure overload dynamics in a pediatric congenital heart disease cohort.[40]

As evident, strain rate and strain are load-independent measures of RV function in hypoplastic left heart syndrome after Fontan operation.[41] Similar studies are plausible in the RA as well.

***Patent Foramen Ovale Closure Surgeries:*** The RV function before and after surgery to close the patent foramen ovale (PFO) has prognostic significance. Right ventricular global longitudinal strain and strain rate were increased before PFO surgery and decreased subsequently, in accordance with the hemodynamic parameters, indicating that STE has a role in surgery planning and prognosis in PFO for right heart and possibly the RA.[42]

***Cardiac Resynchronization Therapy Lead Implantation:*** Speckle tracking echocardiography has been used in several studies to measure scar area, the area of latest mechanical activation, prognosis of lead placement, survival rate free from defibrillator therapy, and its correlates with CMR.[43–47] Because the RA is the source of such electrical phenomena, it would be worthwhile to focus on it through STE to elucidate the novel mechanistic insights of electrical activation.

***Pulmonary Hypertension:*** Voigt et al investigated the apical rotation in the RV of pulmonary hypertensive patients, which was associated with deceased free wall longitudinal strain, raised pulmonary artery pressures, decreased tricuspid annular plane systolic excursion, and decreased fractional area contraction.[48] Speckle tracking has also been used in the assessment of RV remodeling in obstructive sleep apnea.[49] On a similar pattern it would be interesting to explore RA deformation patterns.

## Conclusion

Speckle tracking of the RA is an emerging modality with many avenues and vistas for cardiologists to explore.

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