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INVITED REVIEW OPEN ACCESS

Assessment of the Right Ventricle Function in Patients With Significant Tricuspid Regurgitation: A Review

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ABSTRACT

Tricuspid regurgitation (TR) is an increasingly prevalent condition, especially in older populations, and presents significant challenges due to its association with right heart failure, hospital admissions, and high mortality rates. The management of TR has evolved, with new percutaneous valve repair and replacement techniques emerging alongside traditional surgical approaches. However, accurately assessing right ventricular (RV) function—a key prognostic factor in TR—remains difficult due to the RV's unique anatomy and sensitivity to loading conditions. Current echocardiographic methods, such as Tricuspid Annular Plane Systolic Excursion (TAPSE), S' wave analysis, and RV fractional area change (FAC), offer valuable insights but have limitations, particularly regarding load dependence and incomplete assessment of RV function. Advances in 3D echocardiography and myocardial strain imaging provide more comprehensive evaluations, yet challenges persist in integrating these measures in routine clinical practice. The review highlights the importance of a multimodal approach to RV assessment in TR patients, considering both the right atrium and pulmonary artery interactions, and explores potential future tools such as myocardial work and dynamic testing to improve prognostic accuracy and patient outcomes.

1 | Introduction

Tricuspid regurgitation (TR) is becoming increasingly prevalent, posing significant challenges to healthcare systems worldwide. Although the incidence of severe TR is relatively uncommon in individuals under 60 years old, it rises sharply with age, affecting approximately 2% of those aged 65–74 and up to 4% of individuals over 75 [1–4].

TR is more than just a clinical diagnosis; it can lead to right heart failure and significantly increase the risk of hospital admissions

due to acute heart failure, thereby imposing a considerable financial burden on healthcare systems. These economic pressures remain substantial in the presence of TR, even before the onset of heart failure [5]. Moreover, TR is associated with a high mortality rate, with up to 40% of the most severe cases resulting in death within a year [6]. However, the most pressing concern for patients is the profound impact TR has on their quality of life.

In recent years, TR has been increasingly studied, leading to the emergence of various percutaneous valve repair or replacement techniques, in addition to traditional surgical repair. This

Abbreviations: GLS, global longitudinal strain; RA, right atrium; RV, right ventricle; RV ED, right ventricle end-diastolic area; rV ES, right ventricle end-systolic area; RV FAC, right ventricle fractional area change; RVFWS, right ventricle free wall strain; sPAP, systolic pulmonary artery pressure; TAPSE, tricuspid annular plane systolic excursion; TDI, tissue Doppler imaging; TR, tricuspid regurgitation.

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raises daily concerns about better patient selection in relation to the prognosis of these interventions and the stratification of their prognostic risk. As a result, several risk scores have been developed to enhance clinical risk stratification [7–10].

Additionally, right ventricular (RV) function is a major determinant of prognosis in patients suffering from TR, yet its assessment remains challenging. The RV generates the pressure required to facilitate blood flow through the resistive forces of the pulmonary vasculature. RV function can be influenced by loading conditions, making it crucial to integrate load estimation in the evaluation of RV function. TR increases RV preload through abnormal systolic blood return to the right atrium (RA), leading to atrial and subsequently ventricular volume overload, which also raises diastolic pressure [11, 12].

The anatomy of the RV differs from that of the left ventricle (LV), with a thinner wall thickness and a crescent-shaped morphology. This anatomical difference makes the RV more sensitive to varying loading conditions compared to the LV—responding well to volume overload but poorly to pressure overload [13]. Thus, TR can alter both RV anatomy and function, leading to significant prognostic implications. It underscores the importance of thorough RV assessment for accurate prognostic stratification, determining follow-up frequency, and selecting the aggressiveness and type of treatment.

Assessing RV function is challenging, with no single marker offering perfect diagnostic and prognostic accuracy, necessitating a multiparametric evaluation.

In this context, the review article focuses on methods for assessing RV function with a particular emphasis on advanced echocardiographic techniques. We will discuss both traditional echocardiographic parameters and emerging approaches, and their potential roles in managing patients with TR.

2 | Echocardiographic Assessment of RV Function in TR Patients

Ultrasound imaging is the cornerstone of heart function and remodeling evaluation, especially in patients with TR.

2.1 | Quick Overview: RV Morphology

A healthy RV typically has a crescent shape, characterized by a broad base and a triangular apex. In the case of significant TR, which affects both RV volume and pressure load, the RV loses its triangular shape and turns into an elliptical, like one of the LVs. This morphological change can be visually appreciated in the subxiphoid view and further quantified by measuring the RV diastolic and systolic areas in the apical four-chamber view, which is more reliable than the subxiphoid view for this purpose [14].

Dimensions and surface areas can then be considered abnormal if they exceed the following thresholds: >42 mm for the RV basal diameter; >35 mm for the mid-RV diameter; >25 cm² for the RV end-diastolic area, and >14 cm² for the end-systolic area [15]. Additionally, changes in loading conditions may be reflected in the RV-free wall thickness, which hypertrophies in response

to high pressures. This measurement is taken about 1 cm from the tricuspid annulus in the subxiphoid view, with a RV-free wall hypertrophy being defined as a thickness >5 mm [15, 16] (Figure 1).

2.2 | Keeping It Simple: Longitudinal and Regional Function

TAPSE (Tricuspid Annular Plane Systolic Excursion) is a key parameter for assessing the longitudinal function of the RV, as it reflects the tricuspid annular displacement caused by the shortening of the RV-free and septal walls during systole. The cursor is placed on the lateral annulus, parallel to the free wall, and acquired in M-mode. A TAPSE value of <17 mm in M-mode is considered abnormal and is one of the markers of RV dysfunction. It has been previously shown to correlate well with RV ejection fraction (RVEF) assessed by radionuclide ventriculography [14].

TAPSE is simple, highly reproducible, easy to obtain, and independent of the heart rate. However, it is limited by its load dependence and angle dependence, and it assesses only part of the RV's longitudinal function rather than its overall function [15]. This limitation makes TAPSE an imperfect marker for assessing RV function in significant TR, as it can be overestimated in well-compensated TR patients and may be underestimated when RV function deteriorates [17].

It is also important to note that TAPSE becomes less reliable in patients with any type of prior cardiac surgery [18]. In significant TR, TAPSE has shown prognostic value, with better survival in patients who do not experience TAPSE reduction compared to those with significant TAPSE decline [19]. However, its utility remains controversial in predicting outcomes after tricuspid surgery or percutaneous repair remains controversial [20, 21].

The advancement of Doppler techniques has enabled the development of S' wave analysis using tissue Doppler imaging (TDI) at the tricuspid annulus, which measures systolic excursion velocity. The cursor is placed at the tricuspid annulus or the basal segment of the RV-free wall, and analysis is performed using TDI coupled with pulsed Doppler. A value <9.5 cm/s is considered abnormal. This parameter has shown good reproducibility and a low load dependence, though it remains angle-dependent.

A reduction in the S' wave has been associated with a significant decrease in prognosis for patients with right heart failure; however, it has not been specifically studied in significant TR [22] (Figure 2).

These two parameters are insufficient for assessing global RV function as they only represent a limited portion of the RV (basal lateral segment) and assess only its longitudinal function of the RV. Furthermore, TR-related remodeling and potential changes in RV morphology leading to tricuspid annulus displacement, that can compromise their utility (Table 1).

2.3 | Looking Globally: Global RGV Function

It would be ideal to have an RV parameter equivalent to the left ventricular ejection fraction (LVEF). Although calculation

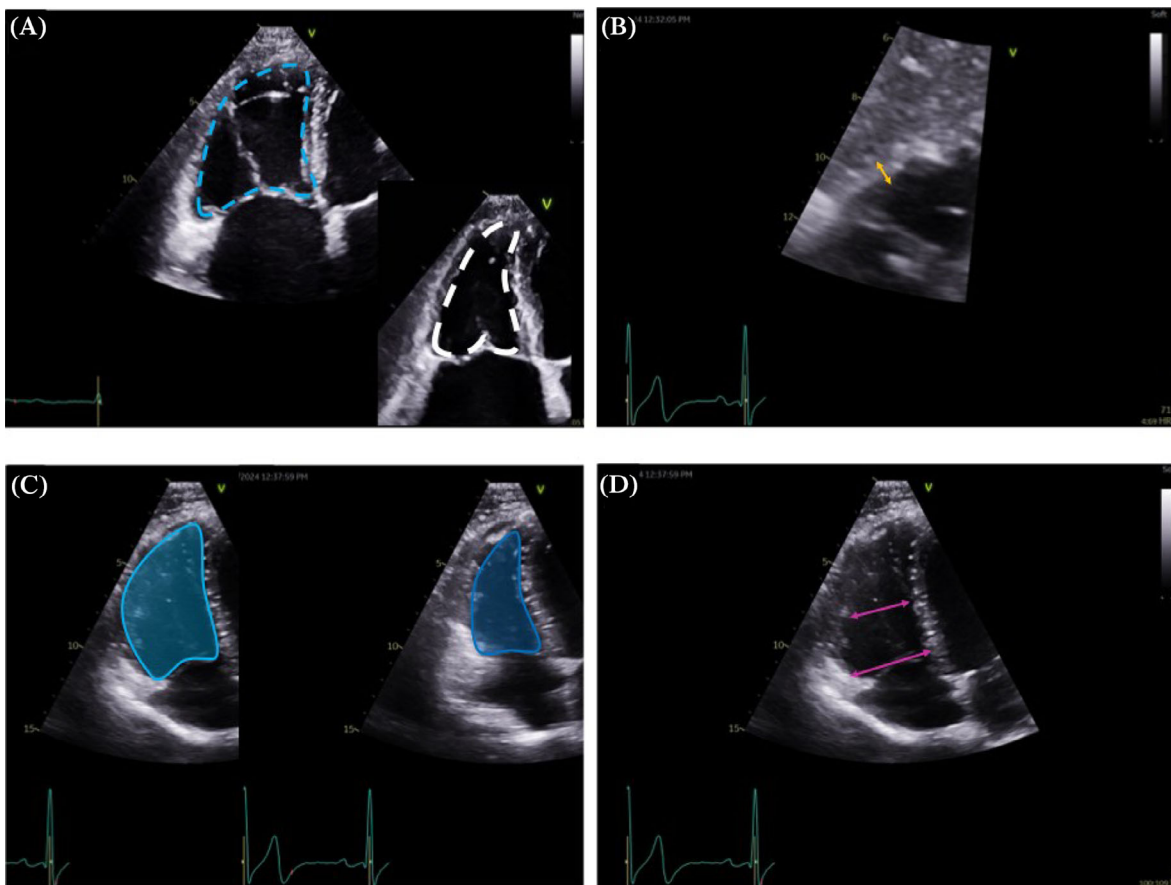


FIGURE 1 | The importance of RV morphology. (A) In cases of severe TR, the RV takes on an elliptical shape rather than its usual crescent shape. (B) Enlargement of the RV wall thickness is a sign of remodeling due to elevated load. (C) RV end-diastolic and end-systolic areas are used to assess RV dilatation. (D) RV basal and mid diameters are used to evaluate RV geometry. RV, right ventricle; TR, tricuspid regurgitation.

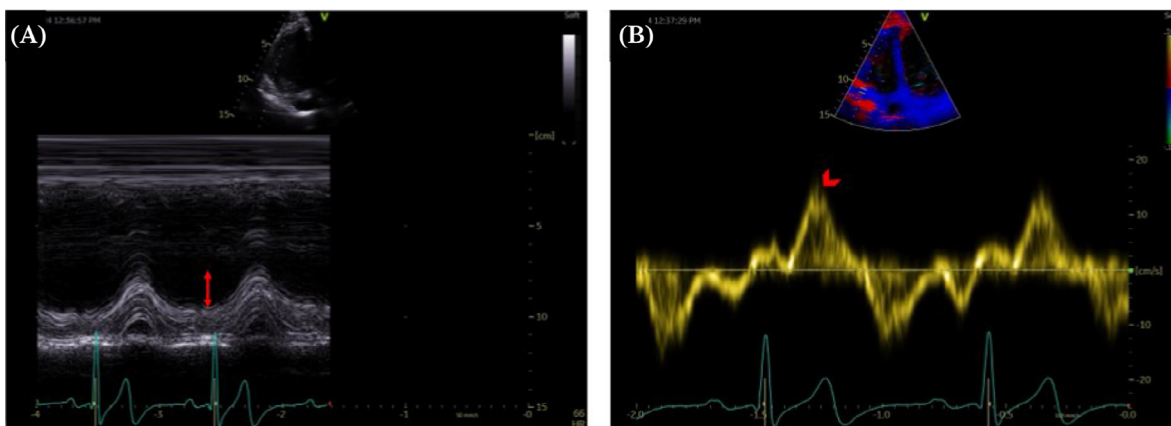


FIGURE 2 | TAPSE and S' TDI as imperfect markers of RV function in TR patients. (A) TAPSE is the most commonly measured parameter in clinical practice, but it has its limitations. (B) The S' TDI is a useful marker of systolic function. S' TDI, systolic wave in tissue Doppler imaging; TAPSE, Tricuspid Annular Plane Systolic Excursion.

of RVEF has been proposed, it remains underdeveloped due to the RV's complex anatomy and the difficulty in accurately determining its volumes. This complexity limits the use of geometric assumptions for reproducible and validated calculations, particularly with techniques like radionuclide ventriculography and, more recently, cardiac MRI. The use of 2D transthoracic echocardiography (TTE)-derived RVEF is not recommended

in clinical practice, particularly in patients with significant TR, which further distorts RV shape and makes it even less predictable.

Therefore, substitutes for RVEF have been developed, notably, the RV fractional area change (FAC), which is based on apical four-chamber area measurements of RV end-diastolic and RV

TABLE 1 | Basic tools for right ventricular function assessment: Advantages, disadvantages, and sources.

TTE parameter	Advantages	Disadvantages	Source
RV morphology (dimensions, area, thickness)	Assesses RV shape changes and dilation under load (e.g., TR).	Provides only a global assessment of the RV, without considering intrinsic myocardial function.	Refs. 14, 15, 16
TAPSE (Tricuspid Annular Plane Systolic Excursion)	Simple, reproducible, easy to obtain, heart rate independent.	Load-dependent, angle-dependent, only assesses part of RV longitudinal function.	Refs. 14, 15, 17, 18, 19
S' TDI (Systolic wave, Tissue Doppler Imaging)	Good reproducibility, predictive of prognosis in right heart failure.	Angle-dependent, not specifically studied in significant TR.	Ref. 22

end-systolic areas (respectively, RVEDA and RVESA). When expressed as a ratio, RV FAC = $(100 \times [RVEDA - RVESA] / RVEDA)$ has shown excellent correlation with radionuclide-determined RVEF [23]. A value <35% is considered abnormal. RV FAC is almost always measurable and is obtained by tracing the RV endocardium in both systole and diastole from the free wall annulus to the apex and then back to the interventricular annulus. This measurement has shown a good correlation with reference RVEF obtained by MRI [24]. Additionally, RV FAC has shown promising prognostic value in tricuspid transcatheter edge-to-edge repair by distinguishing responders from non-responders to the therapy [25].

Although 2D TTE-derived RVEF may be inappropriate, the advent of 3D echocardiography has enabled precise measurements of RV volumes in both systole and diastole, allowing for accurate RVEF calculation. These volumes are well-correlated with those obtained by cardiac MRI [26, 27]. A 3D RVEF <45% is considered pathological and is calculated using the formula $RVEF (\%) = 100 \times (EDV - ESV) / EDV$, with end systolic volume (ESV) and the end diastolic volume (EDV) [28]. The main limitation of this method included its load dependence and image quality due to poor acoustic windows. Volume ratios, provide a global estimate of the RV function. However, they do not provide insight regarding the myocardium intrinsic contractility, which is crucial to account for the varying loading conditions of the TR.

Similar to developments for the LV, myocardial strain imaging appears useful for assessing RV function. Strain imaging describes the deformations occurring during the cardiac cycle. Right ventricular longitudinal strain (RVLS) is calculated as the percentage of systolic shortening of the RV wall from the base to the apex and is expressed with negative values. RVLS is angle-independent and less load-dependent than the aforementioned parameters. Two types of RV strain can be identified: The RV global longitudinal strain (RVGLS) includes six segments (three from the lateral wall and three from the interventricular septum), while the RV-free wall strain (RVFWS) is derived only from the three lateral wall segments. Pathological thresholds are $> -21\%$ for RVGLS and $> -23\%$ for RVFWS. [29] These measurements are more reproducible and less time-consuming than TAPSE, S' TDI, and FAC [30].

RVFWS has shown prognostic significance compared to cardiac CT [31]. It has also demonstrated a strong association with clinical outcomes (i.e., death or heart failure hospitalizations) in

various stages of severe TR [32–34]. Preserved RV strain is likely associated with favorable clinical outcomes [35] (Figure 3).

2.4 | The RV's Interaction With the Left Heart

Of course, the RV is not an isolated entity; it is closely linked to the LV via the interventricular septum. It is estimated that the two structures share common muscle fibers, and 20%–40% of RV ejection force is related to LV fiber action [36]. This leads to an interest in the interactions between the LV and RV. It is well-known that significant changes in load can cause flattening of the interventricular septum [37, 38]. When the RV pressure exceeds the LV pressure, the septum bows, a phenomenon observed primarily in cases of excessive early RV filling and in conditions such as cor pulmonale and RV/LV asynchrony. This septal flattening, with or without asynchrony, has shown prognostic significance [12, 39, 40].

In the context of TR, this septal flattening may be related to the increasing volume overload of the RV. In this case, RV pressure is lower than one from the LV in early systole but exceeds LV pressure in late systole. In severe TR, the LV and RV can no longer eject their volumes effectively. In severe TR, this septal flattening occurs in both systole and diastole and may result from pressure or volume overload. Using TTE, systolic septal flattening is diagnosed by calculating the eccentricity index as a ratio of LV anterior–posterior diameter and LV septolateral diameter in the parasternal short-axis view at the papillary muscle level. The eccentricity index is calculated both in systole and diastole, and when it is >1.0 in both phases, it indicates RV overload [41, 42]. This index appears to be of interest in detecting patients at risk of developing a severe functional TR [43].

Data are lacking regarding the prognostic impact of this parameter in patients with significant TR. A recent study has demonstrated reverse remodeling of the septal curvature after T-TEER therapy, which warrants further attention [44] (Figure 4).

2.5 | RV is Also Coupled to the Pulmonary Artery

The right ventricle–pulmonary artery coupling (RV-PA) is a recently described marker that relates systolic pulmonary artery pressure (sPAP) (representing afterload) to the longitudinal function parameter TAPSE, which is load-dependent when con-

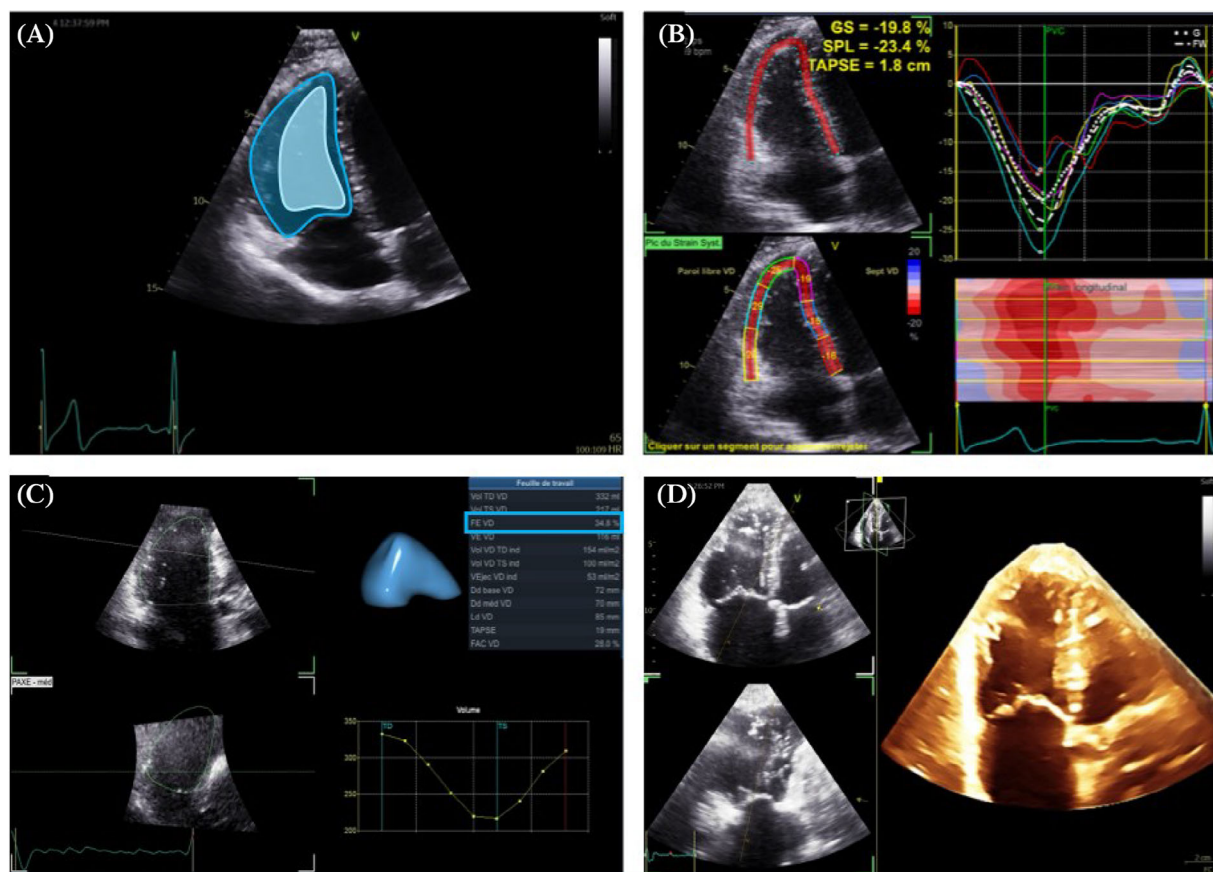


FIGURE 3 | Systolic function: Global more than longitudinal indices? (A) RV end-diastolic and end-systolic areas are used to calculate RV fractional area change as a surrogate for RV ejection fraction. (B) Right ventricular longitudinal strain may be of interest as a surrogate marker of local RV contractility. (C, D) The use of 3D-TTE could help in accurately quantifying volumes and calculating RV ejection fraction without relying on geometric assumptions of the RV. 3D-TTE, 3D transthoracic echocardiography; RV, right ventricle.

sidered in isolation. This marker has demonstrated prognostic value in various cardiac conditions, with different thresholds identified [45, 46].

Initially studied in pulmonary hypertension through invasive evaluation, RV-PA coupling has been increasingly explored in patients with TR [47]. An initial threshold of 0.49, later refined to >0.4 in combination with a dilated RA ($>60 \text{ mL/m}^2$), has been identified as a predictor of cardiovascular events in patients with significant functional TR [48, 49].

This coupling concept appears more functional and less anatomical than usual markers, providing a better prediction of the progression of significant TR than morphological markers of right ventricular severity or TR severity. Another study identified a TAPSE/sPAP threshold <0.31 in patients with RV-PA uncoupling that correlates with a higher incidence of clinical events during follow-up [50].

It is interesting to consider that a marker of right myocardial function as RV FWS, which independently predicts events better than TAPSE, could be even more reliable when combined with the analysis of pulmonary pressures (which represent a component of the RV load). Consequently, the RVFWS/sPAP ratio was initially proposed in pulmonary hypertension and later studied in TR. In

a recent study, Ancona et al. demonstrated that a threshold >0.26 predicted greater event-free survival in patients with severe TR, whereas a baseline RVFWS/sPAP ratio was <0.34 was associated with a higher incidence of events [51, 52] (Figure 5).

A limitation of these indices is the reliability and accuracy of TR maximal velocity in patients with severe TR. Non-invasive (i.e., TTE-derived) measurement of sPAP can be misleading when TR severely alters the pressure dynamics between the right heart chambers. Despite a correlation of around 0.8 in these patients, caution is needed to avoid underestimating echocardiographic pressure compared to invasive measurement [53].

Thus, it is important to consider the right heart as a whole, including both its upstream and downstream structures, to refine risk stratification in patients with TR [54].

A promising tool to evaluate non-invasive sPAP is the ratio between RV forward stroke volume (SV) (i.e., RV SV – regurgitant volume) and RV end-systolic volume (ESV). A study found that a ratio >0.4 is associated with favorable prognosis in patients with significant secondary TR. This may have a stronger prognostic value than previously described RVPa coupling indices [55]. Although these measures require further validation (Table 2).

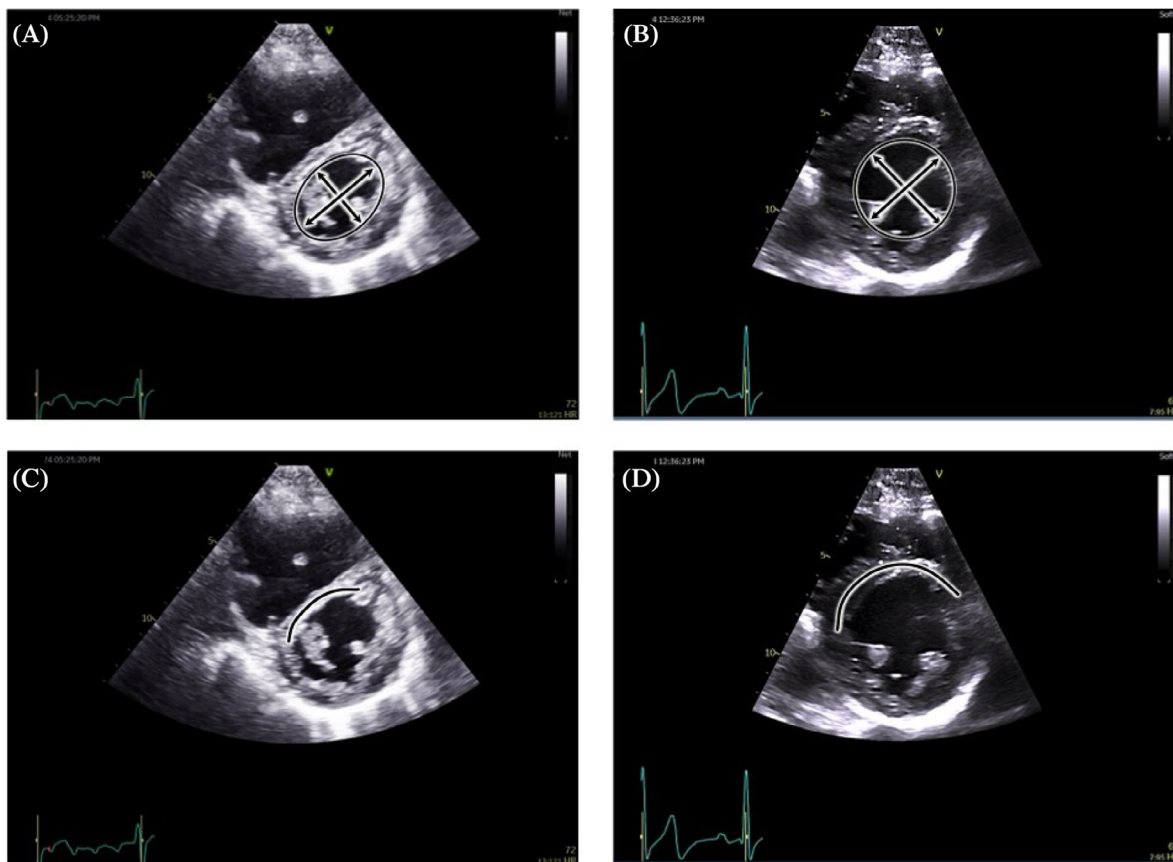


FIGURE 4 | Geometry matters: Septal flattening, eccentricity index. (A, B) The use of the eccentricity index: Elliptical shape of the LV (A) compared to a healthy LV with no elevated RV pressures (B). (C, D) The use of septal curvature to compare a case of increased RV pressures (C) with that of a healthy patient (D). LV, left ventricle; RV, right ventricle.

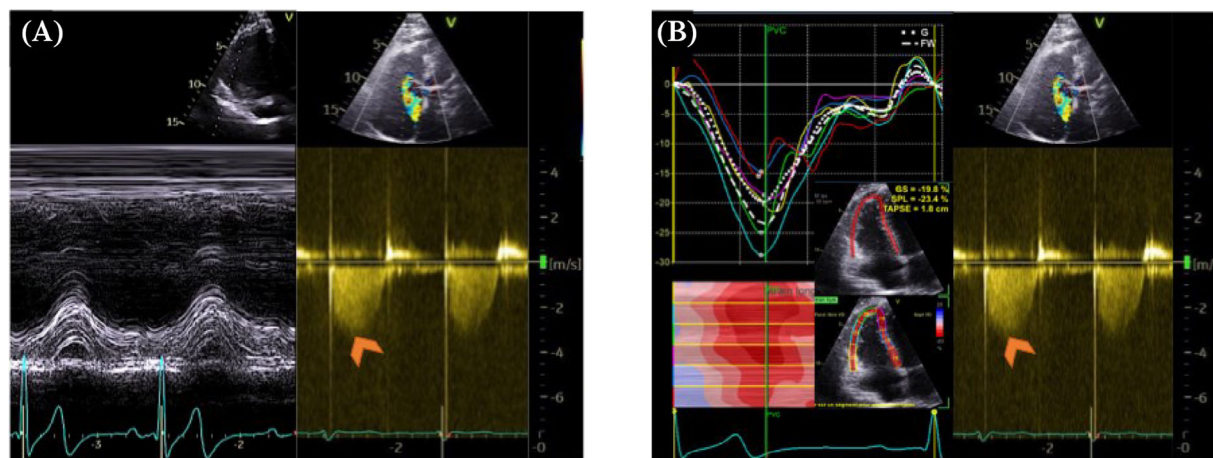


FIGURE 5 | Right ventricle–pulmonary artery coupling: Load-independent? TAPSE/sPAP (A) and RV FWS/sPAP (B) are useful for assessing RV-PA coupling independent of load.

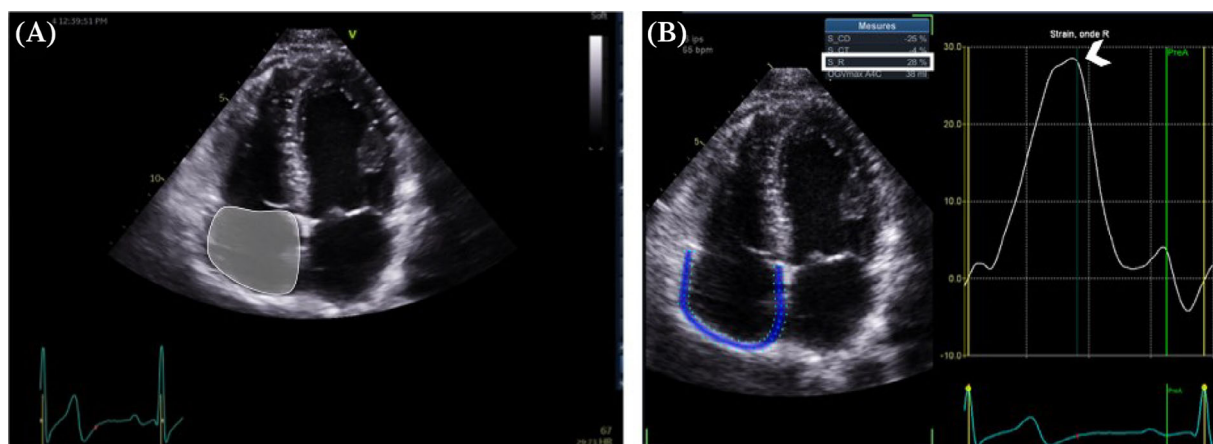
2.6 | Look Upstream: The RA is Also Involved

If the RV and the pulmonary system are integral to understanding the pathophysiological and have prognostic implications, it is equally important not to overlook the upstream circuit involving the RA.

As blood regurgitates into the RA, it is crucial to assess both its morphology and function. These parameters can be evaluated via TTE and are easily accessible. It is recommended to measure the RA area, considering RA dilatation for values $>18 \text{ cm}^2$. Notably, normal TTE ranges for RA volume are $25 \pm 7 \text{ mL/m}^2$ in men and $21 \pm 6 \text{ mL/m}^2$ in women [28].

TABLE 2 | Advanced echocardiographic markers for right ventricular assessment: Advantages, disadvantages.

TTE parameter	Advantages	Disadvantages	Source
RV fractional area change (FAC)	Strong correlation with RVEF measured by CMR, prognostic value in TR.	Load-dependent, limited to the analyzed segments, not a direct measure of myocardial contractility.	Refs. 23, 24, 25
3D RVEF (3D RV ejection fraction)	Allows precise volume measurements and accurate RVEF calculation, well correlated with CMR	Image quality-dependent, requires good acoustic windows, load-dependent.	Refs. 26, 27, 28
RV strain imaging (RVGLS, RVFWS)	Angle-independent, reproducible measurements, correlated with clinical outcomes.	Dependent on equipment and operator training, pathological thresholds not fully standardized.	Refs. 29, 30, 31, 32, 33
Eccentricity index and septal flattening	Indicator of RV overload, useful in assessing significant TR, may predict progression of functional TR.	Limited prognostic data in TR context, more research needed for validation.	Refs. 12, 37, 38, 39, 40
RV-PA coupling (RV-PA coupling)	Functional assessment of RV-PA coupling, accounts for load-dependence compared to morphological markers.	Limited accuracy due to non-invasive pulmonary artery pressure measurements, requiring further validation.	Refs. 45, 46, 47, 48, 49

**FIGURE 6** | The right atrium: More than just an upstream participant. The right atrium (RA) is also important; the RA area (A) and strain (reservoir function) (B) may provide additional prognostic information.

It also appears that the function of the RA, which can be studied using strain imaging, has a prognostic impact on patients with significant TR. A study suggests that an impaired right atrial strain negatively affects the prognosis of patients suffering from TR [35] (Figure 6). However, the optimal cut-off value of RA strain in healthy remains heterogeneous and warrants further investigation.

The RA has gained interest as a marker since secondary TRs have been categorized into atrial and ventricular phenotypes. This distinction is clinically important as it helps to clarify the etiology of the TR and has prognostic implications. As almost 90% of all TR cases are secondary (i.e., not primarily involving of the tricuspid valve itself or cardiac implantable electronic devices related TR), it is crucial to understand the underlying mechanisms to prevent and treat this valvular heart disease [56].

2.7 | Several Classifications of Atrial or Ventricular TR Have Been Proposed [57–61]

A consortium has taken a position to define the criteria for atrial and ventricular forms of secondary TR, while also acknowledging the existence of borderline forms.

The defining characteristics of so-called atrial TR include: tricuspid tenting height ≤ 9 mm, right mid-ventricular diameter ≤ 38 mm, preserved RV systolic function (TAPSE >17 mm, FAC $\geq 35\%$, TDI S' ≥ 9 cm/s), and preserved left ventricular function $\geq 50\%$ [62].

The size of the RA is not part of the definition as studies are discordant on this parameter. Therefore, it does not seem to be the determining factor for classifying a patient in the atrial

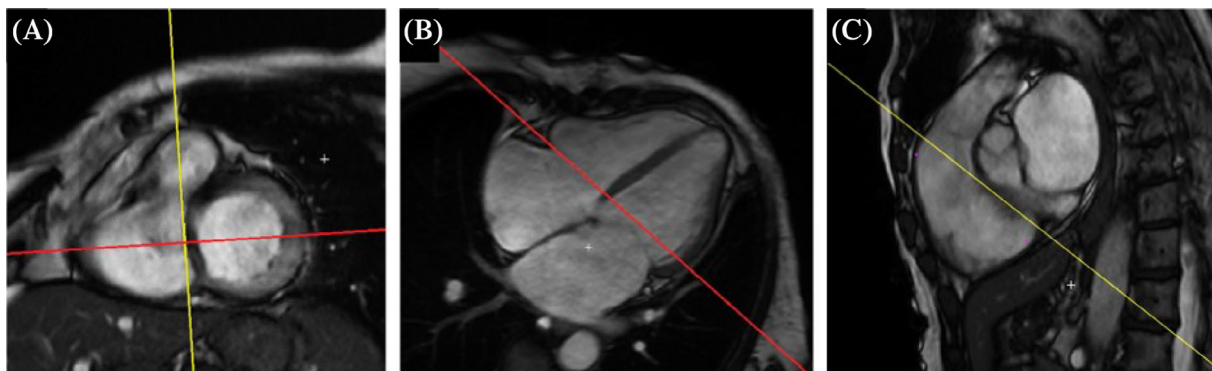


FIGURE 7 | The unconstrained imaging planes of CMR allow for a precise delineation of the complex RV geometry, making it the gold standard for RV volume and EF measure.

phenotype [61, 63]. This point needs further investigation, but an emerging tool using 3D-TTE is the RA:RV volume ratio. A ratio ≥ 1.5 suggests an atrial secondary TR [62, 64].

It is important to adhere to classifying patients with secondary TR, as this has a significant impact on prognosis. It is known that patients with atrial secondary TR have a better long-term prognosis than those with a ventricular phenotype (78% survival for ASTR vs. 46% for VTSR over 10 years in a large series of patients) [60].

3 | Multimodality Imaging of the RV Function in TR Patients

Cardiac magnetic resonance (CMR) is the gold standard in evaluating RV structure and function, particularly in TR. Thanks to unconstrained imaging planes, CMR allows for the visualization of the entire RV and is well suited to the RV's complex geometry, dense myocardial trabeculations, retrosternal position, and peculiar motion. Its unique ability to cross-check measures like SV makes it highly accurate and reproducible [65] (Figure 7).

MR imaging-based RVEF provides independent and incremental prognostic information in patients undergoing corrective surgery for severe functional TR [66]. Patients with reduced echocardiographic TAPSE survive better if CMR RVEF is preserved [21]. Contemporary CMR data suggests that practical RVEF, expressing the net pulmonary flow as a fraction of the end-diastolic volume, is a more robust outcome predictor than RVEF [67].

RV strain offers a non-invasive window on ventriculoarterial coupling and can be obtained by MR feature-tracking during the post-processing of standard cine sequences [68–71]. CMR RV-free wall longitudinal strain appears to be an early marker of RV dysfunction in severe TR, showing additional prognostic information over established parameters such as CMR measurements of RV volumes and RVEF [72].

Despite challenges regarding spatial resolution, CMR-specific ability to characterize myocardial tissues with late gadolinium enhancement (LGE) and extracellular volume mapping (ECV)

could provide more information on RV dysfunction and help implement early TR intervention [73].

Nuclear imaging techniques have historically been the most widely employed for assessing RV function and allow for precise ejection fraction and volume quantification at the cost of low temporal resolution and irradiation [74]. As it is derived from the difference in count densities in end-diastole and end-systole, the radionuclide RVEF measure is independent of the geometric assumption required for other modalities. Both first pass and equilibrium techniques approaches have been extensively validated [75, 76]. However, in the age of MRI and 3D echocardiography, the unique advantage of nuclear imaging lies in the added information about perfusion and metabolism [77, 78]. Alterations in RV metabolism and RV ischemia have been identified as significant contributors to pulmonary hypertension [79]. They may allow a comprehensive assessment of RV function and physiology in patients with significant TR.

Cardiac computed tomography (CCT) offers high spatial resolution in three dimensions, allowing unlimited multiplanar reformats. Thus, CCT's anatomical assessment capabilities make it invaluable for pre-procedural planning of transcatheter tricuspid valve repair and TR related to congenital diseases [80].

Beyond anatomical information, RV volumes and RV EF measured by CCT correlate well with those obtained by CMR imaging. Tanaka et al. used CCT to derive RV EF in symptomatic patients with severe TR undergoing transcatheter tricuspid valve repair, offering incremental prognostic information beyond standard echocardiographic measurements of RV function [25]. Irradiation, limited availability, and the need for iodinated contrast limit the use of CCT for RV EF evaluation in routine practice. Nevertheless, RV EF assessment should be considered in all TR patients undergoing CCT for any purpose [81].

4 | Gaps in Evidence and Future Perspectives

We have seen that the assessment of RV function in the presence of TR relies on a multiparametric approach, and that there is no single non-invasive tool that meets the criteria for accessibility while also providing a reproducible and load-independent evaluation of the RV contractility (Figure 8).

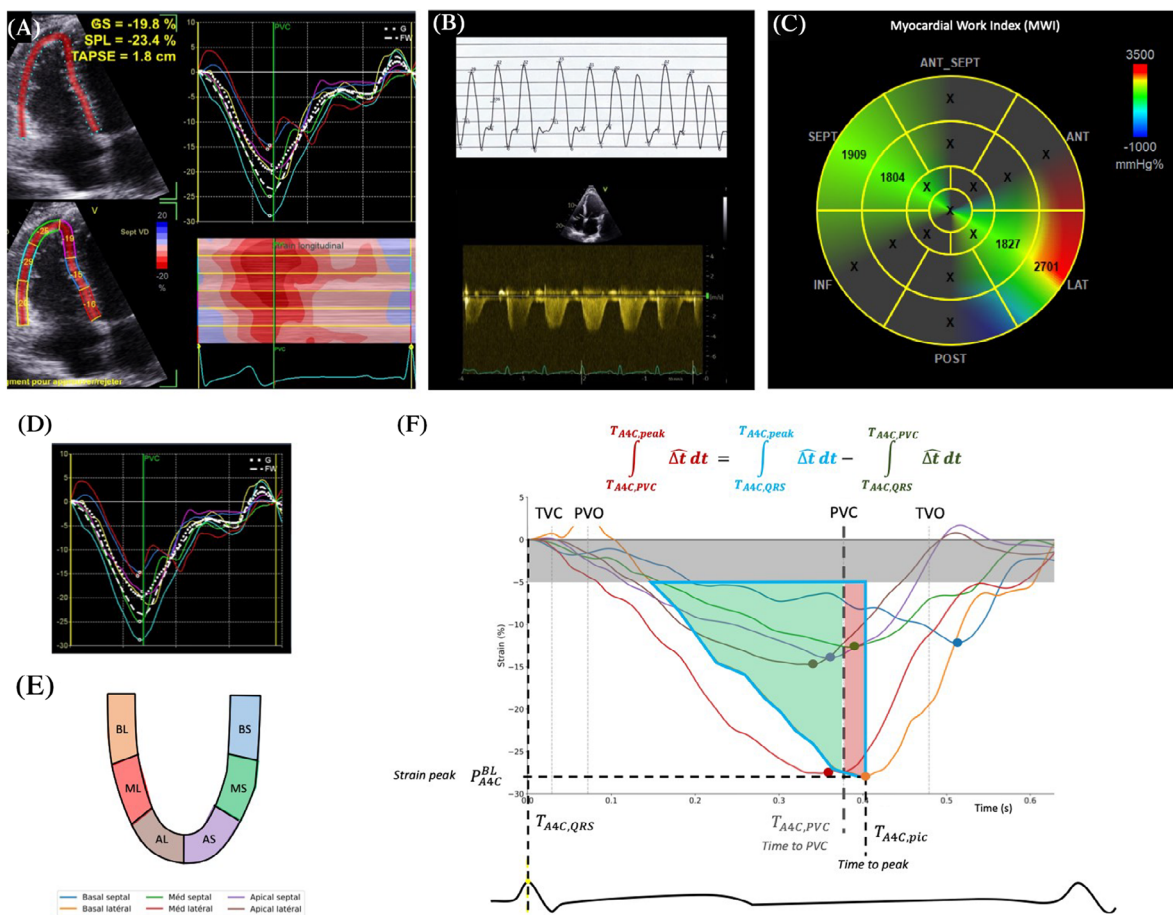


FIGURE 8 | New perspectives in evaluating RV function in the presence of TR? *Upper panel:* The use of RV strain imaging (A) combined with either invasive (B, upper panel) or non-invasive (B, lower panel) pulmonary pressure as a surrogate for RV pressure to obtain RV myocardial work indices (C) using the software dedicated to the LV. *Lower panel:* The application of new indices based on the computation of myocardial RV strain imaging. Each segment can be identified, and curves can be analyzed separately (D, E). Indices such as time to peak or time to pulmonary valve closure can be obtained. Additionally, we can imagine that strain integral analysis could help to characterize total myocardial contraction (F, bold cyan line) as the sum of constructive work (F, green area) and wasted work (F, red area). PVC, pulmonary valve closure; PVO, pulmonary valve opening; TVC, tricuspid valve closure; TVO, tricuspid valve opening.

An interesting tool, initially developed for the LV, could be the application of myocardial work to the RV. This parameter represents the different phases of work performed by the cardiac muscle to ensure blood ejection. It allows for a more physiological and functional assessment of ventricular function than traditional markers by incorporating the load experienced by the ventricle. This parameter is also an excellent reflection of the myocardial oxygen consumption [82, 83].

Although, this parameter can be computed non-invasively in the LV, the technique has not yet been widely validated in routine clinical practice for the assessment of the RV function, although a proof of concept has been undertaken [84, 85]. Small series on the use of RV myocardial work are emerging, particularly in pulmonary hypertension or atrial septal defect [86, 87].

The myocardial work can be used to obtain various markers, such as the RV Global Work Index (mm Hg%), RV Global Constructive Work (mm Hg%), RV Global Wasted Work (mm Hg%), and RV Global Work Efficiency (%). These parameters, derived from computations based on segmental myocardial deformation analysis,

provided promising results in the study of the LV and have only been minimally investigated to study the RV [88].

This parameter is still at an invasive stage, with greater accuracy achieved when the pressures used to generate the curves from which the parameters are derived are invasive pressures. Moreover, estimating right-sided pressures poses a challenge in the case of TR [53].

The variability of pulmonary pressures between the invasive technique and echocardiographic estimation is an issue that remains to be studied, but it appears to be a key determinant of the technique. To overcome this hurdle, another promising parameter could be the use of strain integrals, which have not yet been studied in the RV. These parameters, derived from calculations based on segmental myocardial deformation analyses, have shown promise in the study of the LV but have only been minimally applied to the RV [89].

Another avenue to overcome the load-dependence that complicates the assessment of RV function in the case of significant

TR could be the use of dynamic tests. These tests would be based on the comparison of two different time points where the patient serves as their own control, and the loading conditions are deliberately varied (e.g., during exercise or using the handgrip test). One could even imagine monitoring pressure variations through non-invasive quantification.

These approaches are still exploratory, and the RV remains elusive, despite playing a key role in clinical decision-making and patient prognostication.

References

1. M. Enriquez-Sarano, D. Messika-Zeitoun, Y. Topilsky, C. Tribouilloy, G. Benfari, and H. Michelena, "Tricuspid Regurgitation is a Public Health Crisis," *Progress in Cardiovascular Diseases* 62, no. 6 (2019): 447–451, <https://doi.org/10.1016/j.pcad.2019.10.009>.
2. Y. Topilsky, S. Maltais, J. Medina Inojosa, et al., "Burden of Tricuspid Regurgitation in Patients Diagnosed in the Community Setting," *JACC: Cardiovascular Imaging* 12, no. 3 (2019): 433–442, <https://doi.org/10.1016/j.jcmg.2018.06.014>.
3. J. Nath, E. Foster, and P. A. Heidenreich, "Impact of Tricuspid Regurgitation on Long-Term Survival," *Journal of the American College of Cardiology* 43, no. 3 (2004): 405–409, <https://doi.org/10.1016/j.jacc.2003.09.036>.
4. N. Wang, J. Fulcher, N. Abeysuriya, et al., "Tricuspid Regurgitation is Associated With Increased Mortality Independent of Pulmonary Pressures and Right Heart Failure: A Systematic Review and Meta-Analysis," *European Heart Journal* 40, no. 5 (2019): 476–484, <https://doi.org/10.1093/eurheartj/ehy641>.
5. D. P. Cork, P. A. McCullough, H. S. Mehta, et al., "The Economic Impact of Clinically Significant Tricuspid Regurgitation in a Large, Administrative Claims Database," *Journal of Medical Economics* 23, no. 5 (2020): 521–528, <https://doi.org/10.1080/13696998.2020.1718681>.
6. D. Messika-Zeitoun, P. Verta, J. Gregson, et al., "Impact of Tricuspid Regurgitation on Survival in Patients With Heart Failure: A Large Electronic Health Record Patient-Level Database Analysis," *European Journal of Heart Failure* 22, no. 10 (2020): 1803–1813, <https://doi.org/10.1002/ejhf.1830>.
7. J. Dreyfus, E. Audureau, Y. Bohbot, et al., "TRI-SCORE: A New Risk Score for In-Hospital Mortality Prediction After Isolated Tricuspid Valve Surgery," *European Heart Journal* 43, no. 7 (2022): 654–662, <https://doi.org/10.1093/eurheartj/ehab679>.
8. K. M. Lara-Bretinger, C. G. Scott, V. T. Nkomo, et al., "Tricuspid Regurgitation Impact on Outcomes (TRIO): A Simple Clinical Risk Score," *Mayo Clinic Proceedings* 97, no. 8 (2022): 1449–1461, <https://doi.org/10.1016/j.mayocp.2022.05.015>.
9. T. K. M. Wang, K. Akyuz, A. Mentias, et al., "Contemporary Etiologies, Outcomes, and Novel Risk Score for Isolated Tricuspid Regurgitation," *JACC: Cardiovascular Imaging* 15, no. 5 (2022): 731–744, <https://doi.org/10.1016/j.jcmg.2021.10.015>.
10. D. J. LaPar, D. S. Likosky, M. Zhang, et al., "Development of a Risk Prediction Model and Clinical Risk Score for Isolated Tricuspid Valve Surgery," *Annals of Thoracic Surgery* 106, no. 1 (2018): 129–136, <https://doi.org/10.1016/j.athoracsur.2017.11.077>.
11. F. Haddad, S. A. Hunt, D. N. Rosenthal, and D. J. Murphy, "Right Ventricular Function in Cardiovascular Disease, Part I: Anatomy, Physiology, Aging, and Functional Assessment of the Right Ventricle," *Circulation* 117, no. 11 (2008): 1436–1448, <https://doi.org/10.1161/CIRCULATIONAHA.107.653576>.
12. F. Haddad, R. Doyle, D. J. Murphy, and S. A. Hunt, "Right Ventricular Function in Cardiovascular Disease, Part II: Pathophysiology, Clinical Importance, and Management of Right Ventricular Failure," *Circulation* 117, no. 13 (2008): 1717–1731, <https://doi.org/10.1161/CIRCULATIONAHA.107.653584>.
13. R. T. Hahn, "Tricuspid Regurgitation," *New England Journal of Medicine* 388, no. 20 (2023): 1876–1891, <https://doi.org/10.1056/NEJMr2216709>.
14. S. Kaul, C. Tei, J. M. Hopkins, and P. M. Shah, "Assessment of Right Ventricular Function Using Two-Dimensional Echocardiography," *American Heart Journal* 107, no. 3 (1984): 526–531, [https://doi.org/10.1016/0002-8703\(84\)90095-4](https://doi.org/10.1016/0002-8703(84)90095-4).
15. L. G. Rudski, W. W. Lai, J. Afilalo, et al., "Guidelines for the Echocardiographic Assessment of the Right Heart in Adults: A Report From the American Society of Echocardiography Endorsed by the European Association of Echocardiography, A Registered Branch of the European Society of Cardiology, and the Canadian Society of Echocardiography," *Journal of the American Society of Echocardiography* 23, no. 7 (2010): 685–713, <https://doi.org/10.1016/j.echo.2010.05.010>.
16. R. Prakash and H. Matsukubo, "Usefulness of Echocardiographic Right Ventricular Measurements in Estimating Right Ventricular Hypertrophy and Right Ventricular Systolic Pressure," *American Journal of Cardiology* 51, no. 6 (1983): 1036–1040, [https://doi.org/10.1016/s0002-9149\(83\)80184-2](https://doi.org/10.1016/s0002-9149(83)80184-2).
17. R. T. Hahn, L. P. Badano, P. E. Bartko, et al., "Tricuspid Regurgitation: Recent Advances in Understanding Pathophysiology, Severity Grading and Outcome," *European Heart Journal—Cardiovascular Imaging* 23, no. 7 (2022): 913–929, <https://doi.org/10.1093/ehjci/jeac009>.
18. B. Unsworth, R. P. Casula, A. A. Kyriacou, et al., "The Right Ventricular Annular Velocity Reduction Caused by Coronary Artery Bypass Graft Surgery Occurs at the Moment of Pericardial Incision," *American Heart Journal* 159, no. 2 (2010): 314–322, <https://doi.org/10.1016/j.ahj.2009.11.013>.
19. M. F. Dietz, E. A. Prihadi, P. van der Bijl, N. Ajmone Marsan, V. Delgado, and J. J. Bax, "Prognostic Implications of Staging Right Heart Failure in Patients With Significant Secondary Tricuspid Regurgitation," *JACC: Heart Failure* 8, no. 8 (2020): 627–636, <https://doi.org/10.1016/j.jchf.2020.02.008>.
20. M. F. Dietz, E. A. Prihadi, P. van der Bijl, et al., "Prognostic Implications of Right Ventricular Remodeling and Function in Patients With Significant Secondary Tricuspid Regurgitation," *Circulation* 140, no. 10 (2019): 836–845, <https://doi.org/10.1161/CIRCULATIONAHA.119.039630>.
21. K. P. Kresoja, K. P. Rommel, C. Lücke, et al., "Right Ventricular Contraction Patterns in Patients Undergoing Transcatheter Tricuspid Valve Repair for Severe Tricuspid Regurgitation," *JACC: Cardiovascular Interventions* 14, no. 14 (2021): 1551–1561, <https://doi.org/10.1016/j.jcin.2021.05.005>.
22. J. Meluzín, L. Spinarová, L. Dusek, J. Toman, P. Hude, and J. Krejčí, "Prognostic Importance of the Right Ventricular Function Assessed by Doppler Tissue Imaging," *European Journal of Echocardiography* 4, no. 4 (2003): 262–271, [https://doi.org/10.1016/s1525-2167\(02\)00171-3](https://doi.org/10.1016/s1525-2167(02)00171-3).
23. N. S. Anavekar, D. Gerson, H. Skali, R. Y. Kwong, E. K. Yucel, and S. D. Solomon, "Two-Dimensional Assessment of Right Ventricular Function: An Echocardiographic-MRI Correlative Study," *Echocardiography (Mount Kisco, N.Y.)* 24, no. 5 (2007): 452–456, <https://doi.org/10.1111/j.1540-8175.2007.00424.x>.
24. W. W. Lai, K. Gauvreau, E. S. Rivera, S. Saleeb, A. J. Powell, and T. Geva, "Accuracy of Guideline Recommendations for Two-Dimensional Quantification of the Right Ventricle by Echocardiography," *International Journal of Cardiovascular Imaging* 24, no. 7 (2008): 691–698, <https://doi.org/10.1007/s10554-008-9314-4>.
25. T. Tanaka, A. Sugiura, R. Kavsur, et al., "Right Ventricular Ejection Fraction Assessed by Computed Tomography in Patients Undergoing Transcatheter Tricuspid Valve Repair," *European Heart Journal - Cardiovascular Imaging* 24, no. 11 (2023): 1501–1508, <https://doi.org/10.1093/ehjci/jead102>.

26. Y. J. Shimada, M. Shiota, R. J. Siegel, and T. Shiota, "Accuracy of Right Ventricular Volumes and Function Determined by Three-Dimensional Echocardiography in Comparison With Magnetic Resonance Imaging: A Meta-Analysis Study," *Journal of the American Society of Echocardiography* 23, no. 9 (2010): 943–953, <https://doi.org/10.1016/j.echo.2010.06.029>.
27. L. Sugeng, V. Mor-Avi, L. Weinert, et al., "Multimodality Comparison of Quantitative Volumetric Analysis of the Right Ventricle," *JACC: Cardiovascular Imaging* 3, no. 1 (2010): 10–18, <https://doi.org/10.1016/j.jcmg.2009.09.017>.
28. R. M. Lang, L. P. Badano, V. Mor-Avi, et al., "Recommendations for Cardiac Chamber Quantification by Echocardiography in Adults: An Update From the American Society of Echocardiography and the European Association of Cardiovascular Imaging," *European Heart Journal - Cardiovascular Imaging* 16, no. 3 (2015): 233–270, <https://doi.org/10.1093/ehjci/jev014>.
29. R. T. Hahn, M. K. Lawlor, C. J. Davidson, et al., "Tricuspid Valve Academic Research Consortium Definitions for Tricuspid Regurgitation and Trial Endpoints," *Journal of the American College of Cardiology* 82, no. 17 (2023): 1711–1735, <https://doi.org/10.1016/j.jacc.2023.08.008>.
30. E. Carluccio, P. Biagioli, G. Alunni, et al., "Prognostic Value of Right Ventricular Dysfunction in Heart Failure With Reduced Ejection Fraction: Superiority of Longitudinal Strain Over Tricuspid Annular Plane Systolic Excursion," *Circulation: Cardiovascular Imaging* 11, no. 1 (2018): e006894, <https://doi.org/10.1161/CIRCIMAGING.117.006894>.
31. K. Hirasawa, P. J. van Rosendaal, M. F. Dietz, N. Ajmone Marsan, V. Delgado, and J. J. Bax, "Comparison of the Usefulness of Strain Imaging by Echocardiography Versus Computed Tomography to Detect Right Ventricular Systolic Dysfunction in Patients With Significant Secondary Tricuspid Regurgitation," *American Journal of Cardiology* 134 (2020): 116–122, <https://doi.org/10.1016/j.amjcard.2020.07.063>.
32. E. A. Prihadi, P. van der Bijl, M. Dietz, et al., "Prognostic Implications of Right Ventricular Free Wall Longitudinal Strain in Patients With Significant Functional Tricuspid Regurgitation," *Circulation: Cardiovascular Imaging* 12, no. 3 (2019): e008666, <https://doi.org/10.1161/CIRCIMAGING.118.008666>.
33. R. Hinojar, J. L. Zamorano, A. González Gómez, et al., "Prognostic Impact of Right Ventricular Strain in Isolated Severe Tricuspid Regurgitation," *Journal of the American Society of Echocardiography* 36, no. 6 (2023): 615–623, <https://doi.org/10.1016/j.echo.2023.02.009>.
34. M. Ogawa, K. Kuwajima, T. Yamane, H. Hasegawa, N. Yagi, and T. Shiota, "Effect of Right Ventricular Free Wall Longitudinal Strain on All-Cause Death in Patients With Isolated Severe Tricuspid Regurgitation and Atrial Fibrillation," *Frontiers in Cardiovascular Medicine* 10 (2023): 1188005, <https://doi.org/10.3389/fcvm.2023.1188005>.
35. E. Curtis, L. Lemarchand, K. C. Lee, et al., "Right Atrial and Right Ventricular Strain: Prognostic Value Depends on the Severity of Tricuspid Regurgitation," *European Heart Journal - Cardiovascular Imaging* (2024): jeae182, <https://doi.org/10.1093/ehjci/jeae182>.
36. D. Muraru, K. Haugaa, E. Donal, et al., "Right Ventricular Longitudinal Strain in the Clinical Routine: A State-of-the-Art Review," *European Heart Journal - Cardiovascular Imaging* 23, no. 7 (2022): 898–912, <https://doi.org/10.1093/ehjci/jeac022>.
37. M. R. Movahed, A. Hepner, P. Lizotte, and N. Milne, "Flattening of the Interventricular Septum (D-Shaped Left Ventricle) in Addition to High Right Ventricular Tracer Uptake and Increased Right Ventricular Volume Found on Gated SPECT Studies Strongly Correlates With Right Ventricular Overload," *Journal of Nuclear Cardiology* 12, no. 4 (2005): 428–434, <https://doi.org/10.1016/j.nuclcard.2005.04.004>.
38. M. Feneley and T. Gavaghan, "Paradoxical and Pseudoparadoxical Interventricular Septal Motion in Patients With Right Ventricular Volume Overload," *Circulation* 74, no. 2 (1986): 230–238, <https://doi.org/10.1161/01.cir.74.2.230>.
39. P. Lurz, R. Puranik, J. Nordmeyer, et al., "Improvement in Left Ventricular Filling Properties After Relief of Right Ventricle to Pulmonary Artery Conduit Obstruction: Contribution of Septal Motion and Interventricular Mechanical Delay," *European Heart Journal* 30, no. 18 (2009): 2266–2274, <https://doi.org/10.1093/eurheartj/ehp258>.
40. R. Naeije and R. Badagliacca, "The Overloaded Right Heart and Ventricular Interdependence," *Cardiovascular Research* 113, no. 12 (2017): 1474–1485, <https://doi.org/10.1093/cvr/cvxl60>.
41. S. Abraham and C. G. Weismann, "Left Ventricular End-Systolic Eccentricity Index for Assessment of Pulmonary Hypertension in Infants," *Echocardiography (Mount Kisco, N.Y.)* 33, no. 6 (2016): 910–915, <https://doi.org/10.1111/echo.13171>.
42. N. Galiè, M. Humbert, J. L. Vachiery, et al., "2015 ESC/ERS Guidelines for the Diagnosis and Treatment of Pulmonary Hypertension: The Joint Task Force for the Diagnosis and Treatment of Pulmonary Hypertension of the European Society of Cardiology (ESC) and the European Respiratory Society (ERS): Endorsed by: Association for European Paediatric and Congenital Cardiology (AEPC), International Society for Heart and Lung Transplantation (ISHLT)," *European Heart Journal* 37, no. 1 (2016): 67–119, <https://doi.org/10.1093/eurheartj/ehv317>.
43. H. K. Kim, Y. J. Kim, J. S. Park, et al., "Determinants of the severity of functional tricuspid regurgitation," *American Journal of Cardiology* 98, no. 2 (2006): 236–242, <https://doi.org/10.1016/j.amjcard.2006.01.082>.
44. K. P. Kresoja, S. Rosch, A. R. Schöber, et al., "Implications of Tricuspid Regurgitation and Right Ventricular Volume Overload in Patients With Heart Failure With Preserved Ejection Fraction," *European Journal of Heart Failure* 26, no. 4 (2024): 1025–1035, <https://doi.org/10.1002/ejhf.3195>.
45. M. Guazzi, F. Bandera, G. Pelissero, et al., "Tricuspid Annular Plane Systolic Excursion and Pulmonary Arterial Systolic Pressure Relationship in Heart Failure: An Index of Right Ventricular Contractile Function and Prognosis," *American Journal of Physiology. Heart and Circulatory Physiology* 305, no. 9 (2013): H1373–1381, <https://doi.org/10.1152/ajpheart.00157.2013>.
46. M. I. Brener, P. Lurz, J. Hausleiter, et al., "Right Ventricular-Pulmonary Arterial Coupling and Afterload Reserve in Patients Undergoing Transcatheter Tricuspid Valve Repair," *Journal of the American College of Cardiology* 79, no. 5 (2022): 448–461, <https://doi.org/10.1016/j.jacc.2021.11.031>.
47. K. Tello, J. Wan, A. Dalmer, et al., "Validation of the Tricuspid Annular Plane Systolic Excursion/Systolic Pulmonary Artery Pressure Ratio for the Assessment of Right Ventricular-Arterial Coupling in Severe Pulmonary Hypertension," *Circulation: Cardiovascular Imaging* 12, no. 9 (2019): e009047, <https://doi.org/10.1161/CIRCIMAGING.119.009047>.
48. S. Saeed, J. Smith, K. Grigoryan, V. Lysne, R. Rajani, and J. B. Chambers, "The Tricuspid Annular Plane Systolic Excursion to Systolic Pulmonary Artery Pressure Index: Association With All-Cause Mortality in Patients With Moderate or Severe Tricuspid Regurgitation," *International Journal of Cardiology* 317 (2020): 176–180, <https://doi.org/10.1016/j.ijcard.2020.05.093>.
49. G. L'Official, M. Vely, W. Kosmala, et al., "Isolated Functional Tricuspid Regurgitation: How to Define Patients at Risk for Event?," *ESC Heart Failure* 10, no. 3 (2023): 1605–1614, <https://doi.org/10.1002/ehf2.14189>.
50. F. Fortuni, S. C. Butcher, M. F. Dietz, et al., "Right Ventricular-Pulmonary Arterial Coupling in Secondary Tricuspid Regurgitation," *American Journal of Cardiology* 148 (2021): 138–145, <https://doi.org/10.1016/j.amjcard.2021.02.037>.
51. S. Ünlü, S. Bézy, M. Cvijic, J. Duchenne, M. Delcroix, and J. U. Voigt, "Right Ventricular Strain Related to Pulmonary Artery Pressure Predicts Clinical Outcome in Patients With Pulmonary Arterial Hypertension," *European Heart Journal - Cardiovascular Imaging* 24, no. 5 (2023): 635–642, <https://doi.org/10.1093/ehjci/jeac136>.
52. F. Ancona, D. Margonato, G. Menzà, et al., "Ratio Between Right Ventricular Longitudinal Strain and Pulmonary Arterial Systolic Pressure:

- A Novel Prognostic Parameter in patients With Severe Tricuspid Regurgitation," *International Journal of Cardiology* 384 (2023): 55–61, <https://doi.org/10.1016/j.ijcard.2023.04.056>.
53. L. Lemarchand, V. Auffret, H. Le Breton, et al., "Echocardiographic Estimation of Pulmonary Pressure in Patients With Severe Tricuspid Regurgitation," *Heart (British Cardiac Society)* 110, no. 5 (2024): 366–372, <https://doi.org/10.1136/heartjnl-2023-322893>.
54. C. Bourg, E. Curtis, and E. Donal, "Navigating Upstream and Downstream: Unleashing the Prognostic Potential of RVFWLS/PASP Ratio in Severe Tricuspid Regurgitation," *International Journal of Cardiology* 388 (2023): 131114, <https://doi.org/10.1016/j.ijcard.2023.06.005>.
55. M. Gavazzoni, L. P. Badano, A. Cascella, et al., "Clinical Value of a Novel Three-Dimensional Echocardiography-Derived Index of Right Ventricle-Pulmonary Artery Coupling in Tricuspid Regurgitation," *Journal of the American Society of Echocardiography* 36, no. 11 (2023): 1154–1166 e3, <https://doi.org/10.1016/j.echo.2023.06.014>.
56. D. R. Florescu, D. Muraru, V. Volpato, et al., "Atrial Functional Tricuspid Regurgitation as a Distinct Pathophysiological and Clinical Entity: No Idiopathic Tricuspid Regurgitation Anymore," *Journal of Clinical Medicine* 11, no. 2 (2022): 382, <https://doi.org/10.3390/jcm11020382>.
57. S. Kwak, J. Lim, S. Yang, et al., "Atrial Functional Tricuspid Regurgitation: Importance of Atrial Fibrillation and Right Atrial Remodeling and Prognostic Significance," *JACC: Cardiovascular Imaging* 16, no. 5 (2023): 575–587, <https://doi.org/10.1016/j.jcmg.2022.11.014>.
58. X. Zhou, Y. Otsuji, S. Yoshifuku, et al., "Impact of Atrial Fibrillation on Tricuspid and Mitral Annular Dilatation and Valvular Regurgitation," *Circulation Journal* 66, no. 10 (2002): 913–916, <https://doi.org/10.1253/circj.66.913>.
59. J. J. Silbiger, "Atrial Functional Tricuspid Regurgitation: An Underappreciated Cause of Secondary Tricuspid Regurgitation," *Echocardiography (Mount Kisco, N.Y.)* 36, no. 5 (2019): 954–957, <https://doi.org/10.1111/echo.14327>.
60. X. Galloo, M. F. Dietz, F. Fortuni, et al., "Characterization of Right-Sided Strain Parameters in Atrial and Ventricular Functional Tricuspid Regurgitation," *European Heart Journal—Cardiovascular Imaging* 24, no. S1 (2023): jead119.277, <https://doi.org/10.1093/ehjci/jead119.277>.
61. F. Schlotter, M. F. Dietz, L. Stolz, et al., "Atrial Functional Tricuspid Regurgitation: Novel Definition and Impact on Prognosis," *Circulation: Cardiovascular Interventions* 15, no. 9 (2022): e011958, <https://doi.org/10.1161/CIRCINTERVENTIONS.122.011958>.
62. D. Muraru, L. P. Badano, R. T. Hahn, et al., "Atrial Secondary Tricuspid Regurgitation: Pathophysiology, Definition, Diagnosis, and Treatment," *European Heart Journal* 45, no. 11 (2024): 895–911, <https://doi.org/10.1093/eurheartj/ehae088>.
63. G. Russo, L. P. Badano, M. Adamo, et al., "Characteristics and Outcomes of Patients With Atrial Versus Ventricular Secondary Tricuspid Regurgitation Undergoing Tricuspid Transcatheter Edge-to-Edge Repair—Results From the TriValve Registry," *European Journal of Heart Failure* 25, no. 12 (2023): 2243–2251, <https://doi.org/10.1002/ejhf.3075>.
64. D. R. Florescu, D. Muraru, C. Florescu, et al., "Right Heart Chambers Geometry and Function in Patients With the Atrial and the Ventricular Phenotypes of Functional Tricuspid Regurgitation," *European Heart Journal—Cardiovascular Imaging* 23, no. 7 (2022): 930–940, <https://doi.org/10.1093/ehjci/jeab211>.
65. L. P. Badano, K. Addetia, G. Pontone, et al., "Advanced Imaging of Right Ventricular Anatomy and Function," *Heart (British Cardiac Society)* 106, no. 19 (2020): 1469–1476, <https://doi.org/10.1136/heartjnl-2019-315178>.
66. J. B. Park, H. K. Kim, J. H. Jung, et al., "Prognostic Value of Cardiac MR Imaging for Preoperative Assessment of Patients With Severe Functional Tricuspid Regurgitation," *Radiology* 280, no. 3 (2016): 723–734, <https://doi.org/10.1148/radiol.2016151556>.
67. R. Hinojar, A. G. Gómez, A. García-Martin, et al., "Impact of Right Ventricular Systolic Function in Patients With Significant Tricuspid Regurgitation. A Cardiac Magnetic Resonance Study," *International Journal of Cardiology* 339 (2021): 120–127, <https://doi.org/10.1016/j.ijcard.2021.07.023>.
68. A. Farzaneh-Far and S. Romano, "Measuring Longitudinal Left Ventricular Function and Strain Using Cardiovascular Magnetic Resonance Imaging," *European Heart Journal—Cardiovascular Imaging* 20, no. 11 (2019): 1259–1261, <https://doi.org/10.1093/ehjci/jez097>.
69. N. Kawel-Boehm, A. Maceira, E. R. Valsangiacomo-Buechel, et al., "Normal Values for Cardiovascular Magnetic Resonance in Adults and Children," *Journal of Cardiovascular Magnetic Resonance* 17, no. 1 (2015): 29, <https://doi.org/10.1186/s12968-015-0111-7>.
70. V. T. Truong, K. S. Safdar, D. K. Kalra, et al., "Cardiac Magnetic Resonance Tissue Tracking in Right Ventricle: Feasibility and Normal Values," *Magnetic Resonance Imaging* 38 (2017): 189–195, <https://doi.org/10.1016/j.mri.2017.01.007>.
71. A. Rolf, T. Keller, J. S. Wolter, et al., "Right Ventricular Strain by Magnetic Resonance Feature Tracking is Largely Afterload-Dependent and Does Not Reflect Contractility: Validation by Combined Volumetry and Invasive Pressure Tracings," *Diagnostics (Basel, Switzerland)* 12, no. 12 (2022): 3183, <https://doi.org/10.3390/diagnostics12123183>.
72. S. Romano, D. Dell'atti, R. M. Judd, et al., "Prognostic Value of Feature-Tracking Right Ventricular Longitudinal Strain in Severe Functional Tricuspid Regurgitation: A Multicenter Study," *JACC: Cardiovascular Imaging* 14, no. 8 (2021): 1561–1568, <https://doi.org/10.1016/j.jcmg.2021.02.009>.
73. V. Anastasiou, M. A. Bazmpani, S. Daios, et al., "Unmet Needs in the Assessment of Right Ventricular Function for Severe Tricuspid Regurgitation," *Diagnostics (Basel, Switzerland)* 13, no. 18 (2023): 2885, <https://doi.org/10.3390/diagnostics13182885>.
74. J. D. Rich and R. P. Ward, "Right-Ventricular Function by Nuclear Cardiology," *Current Opinion in Cardiology* 25, no. 5 (2010): 445–450, <https://doi.org/10.1097/HCO.0b013e32833cb252>.
75. L. Bière, M. Audonnet, G. Clerfond, et al., "First Pass Perfusion Imaging to Improve the Assessment of Left Ventricular Thrombus Following a Myocardial Infarction," *European Journal of Radiology* 85, no. 9 (2016): 1532–1537, <https://doi.org/10.1016/j.ejrad.2016.05.017>.
76. J. R. Corbett, O. O. Akinboboye, S. L. Bacharach, et al., "Equilibrium Radionuclide Angiocardiology," *Journal of Nuclear Cardiology* 13, no. 6 (2006): e56–79, <https://doi.org/10.1016/j.nuclcard.2006.08.007>.
77. A. Gómez, D. Bialostozky, A. Zajarias, et al., "Right Ventricular Ischemia in Patients With Primary Pulmonary Hypertension," *Journal of the American College of Cardiology* 38, no. 4 (2001): 1137–1142, [https://doi.org/10.1016/s0735-1097\(01\)01496-6](https://doi.org/10.1016/s0735-1097(01)01496-6).
78. M. Oikawa, Y. Kagaya, H. Otani, et al., "Increased [18F]fluorodeoxyglucose Accumulation in Right Ventricular Free Wall in Patients With Pulmonary Hypertension and the Effect of Epoprostenol," *Journal of the American College of Cardiology* 45, no. 11 (2005): 1849–1855, <https://doi.org/10.1016/j.jacc.2005.02.065>.
79. S. A. van Wolferen, J. T. Marcus, N. Westerhof, et al., "Right Coronary Artery Flow Impairment in Patients With Pulmonary Hypertension," *European Heart Journal* 29, no. 1 (2008): 120–127, <https://doi.org/10.1093/eurheartj/ehm567>.
80. B. B. C. Lopes, G. Hashimoto, V. N. Bapat, P. Sorajja, M. D. Scherer, and J. L. Cavalcante, "Cardiac Computed Tomography and Magnetic Resonance Imaging of the Tricuspid Valve: Preprocedural Planning and Postprocedural Follow-up," *Interventional Cardiology Clinics* 11, no. 1 (2022): 27–40, <https://doi.org/10.1016/j.iccl.2021.09.004>.
81. A. Vahanian, F. Beyersdorf, F. Praz, et al., "2021 ESC/EACTS Guidelines for the Management of Valvular Heart Disease," *European Heart Journal* 43, no. 7 (2022): 561–632, <https://doi.org/10.1093/eurheartj/ehab395>.
82. K. Russell, M. Eriksen, L. Aaberge, et al., "A Novel Clinical Method for Quantification of Regional Left Ventricular Pressure–Strain Loop Area: A Non-Invasive Index of Myocardial Work," *European Heart Journal* 33, no. 6 (2012): 724–733, <https://doi.org/10.1093/eurheartj/ehs016>.

83. K. Russell, M. Eriksen, L. Aaberge, et al., "Assessment of Wasted Myocardial Work: A Novel Method to Quantify Energy Loss Due to Uncoordinated Left Ventricular Contractions," *American Journal of Physiology-Heart and Circulatory Physiology* 305, no. 7 (2013): H996–H1003, <https://doi.org/10.1152/ajpheart.00191.2013>.
84. S. C. Butcher, F. Fortuni, J. M. Montero-Cabezas, et al., "Right Ventricular Myocardial Work: Proof-of-Concept for Non-Invasive Assessment of Right Ventricular Function," *European Heart Journal–Cardiovascular Imaging* 22, no. 2 (2021): 142–152, <https://doi.org/10.1093/ehjci/jeaa261>.
85. L. E. Sade, A. Colak, S. A. Duzgun, et al., "Approach to Optimal Assessment of Right Ventricular Remodelling in Heart Transplant Recipients: Insights From Myocardial Work Index, T1 Mapping, and Endomyocardial Biopsy," *European Heart Journal–Cardiovascular Imaging* 24, no. 3 (2023): 354–363, <https://doi.org/10.1093/ehjci/jeac108>.
86. J. Wu, X. Huang, W. Chen, et al., "Noninvasive Right Ventricular Work in Patients With Atrial Septal Defects: A Proof-of-Concept Study," *Cardiovascular Ultrasound* 21, no. 1 (2023): 10, <https://doi.org/10.1186/s12947-023-00306-8>.
87. J. Wang, C. Ni, M. Yang, et al., "Apply Pressure-Strain Loop to Quantify Myocardial Work in Pulmonary Hypertension: A Prospective Cohort Study," *Frontiers in Cardiovascular Medicine* 9 (2022): 1022987, <https://doi.org/10.3389/fcvm.2022.1022987>.
88. N. Marzlin, A. G. Hays, M. Peters, et al., "Myocardial Work in Echocardiography," *Circulation: Cardiovascular Imaging* 16, no. 2 (2023): e014419, <https://doi.org/10.1161/CIRCIMAGING.122.014419>.
89. A. Bernard, E. Donal, C. Leclercq, et al., "Impact of Cardiac Resynchronization Therapy on Left Ventricular Mechanics: Understanding the Response Through a New Quantitative Approach Based on Longitudinal Strain Integrals," *Journal of the American Society of Echocardiography* 28, no. 6 (2015): 700–708, <https://doi.org/10.1016/j.echo.2015.02.017>.