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EVOLUTION OF 3D INTRACARDIAC ECHOCARDIOGRAPHY IN TRANSCATHETER TRICUSPID REPAIR AND REPLACEMENT TECHNIQUES (T-TEER AND TTVR): SYSTEMATIC REVIEW AND META-ANALYSIS OF CLINICAL AND PROCEDURAL OUTCOMES

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ABSTRACT

Introduction: Significant tricuspid insufficiency is associated with high morbid - ity and mortality, and in recent years, the development of transcatheter interventions, such as edge-to-edge repair (T-TEER) and transcatheter tricuspid valve replacement (TTVR), has expanded therapeutic options for patients at high surgical risk. The quality of intraprocedural imaging is crucial for the success of these interventions, highlighting the role of three-dimensional echocardiography, including three-dimensional intracard- iac echocardiography (3D ICE) and three-dimensional transesophageal echocardiogra- phy (3D TEE).**Objective:**To evaluate, through a systematic review, the role of three- dimensional echocardiography in guiding T-TEER and TTVR, analyzing clinical and procedural outcomes.**Methods:**A systematic review was conducted according to the PRISMA 2020 guidelines, with searches in the PubMed/MEDLINE, Scopus, and Embase databases between 2015 and 2025. Original studies involving T-TEER or TTVR utilizing 3D ICE or 3D TEE and reporting clinical or procedural outcomes were included.A partial quantitative synthesis and structured narrative analysis was conduct- ed, considering the methodological heterogeneity of the studies.**Results:**Ten studies were included in the analysis. A high procedural success rate was observed in the studies that used three-dimensional imaging, with a consistent reduction in tricuspid regurgitation after T-TEER. 3D TEE was the predominant modality in multicenter studies, while 3D ICE demonstrated technical feasibility as an alternative or intra-procedural complement. Early mortality was low in the analyzed studies, and there was evidence of annular remodeling after intervention.**Conclusion:**Three-dimensional echocardiography plays a fundamental role in the evolution of transcatheter interventions for the tricuspid valve. 3 D ICE emerges as a promising technology, with the potential to optimize procedural conduction, although comparative prospective studies are needed to consolidate its clinical impact.

Keywords: Tricuspid insufficiency; Three-dimensional echocardiography; Edge-to-edge transcatheter repair; Intracardiac echocardiography.

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INTRODUCTION

Moderate to severe tricuspid insufficiency (TI) is associated with a significant increase in mortality, functional decline, and a higher incidence of hospitalizations due to heart failure, especially in patients with structural comorbidities and right ventricular dysfunction. Historically neglected, the tricuspid valve has received greater attention in the last decade with the advancement of transcatheter structural interventions, especially edge-to-edge repair (T-TEER) and transcatheter tricuspid valve replacement (TTVR). These procedures have become viable alternatives for patients with high surgical risk or contraindications to conventional surgery (6,7).

The success of transcatheter tricuspid interventions critically depends on the quality of intra-procedural imaging. Three-dimensional transesophageal echocardiography (3D TEE) has established itself as a central tool for anatomical planning, guidance of device positioning, and immediate assessment of regurgitation reduction (4,8). Three-dimensional visualization allows for better characterization of the tricuspid annulus, the cusps, and the complex valve geometry, determinants for the eligibility and technical success of the procedure (8,9).

However, the exclusive use of TEE presents significant limitations, including the need for general anesthesia, dependence on the acoustic window, interference from artifacts, and possible discomfort to the patient. In this scenario, intracardiac echocardiography (ICE) has emerged as a complementary alternative or, in some centers, as a primary imaging strategy during structural interventions (5). Technological advancements have allowed for the development of three-dimensional ICE (3D ICE), incorporating volumetric and multiplanar reconstruction in real-time, significantly enhancing the intracardiac visualization of tricuspid structures (1,5).

Recent studies have demonstrated the feasibility of using 3D ICE during TTEER, evidencing adequate anatomical definition of the valvular apparatus, guidance for clip positioning, and immediate assessment of regurgitation reduction (1,2). Additionally, clinical reports and observational studies indicate that the ICE-based strategy may reduce procedure time and exposure to fluoroscopy, as well as potentially allow

procedures under conscious sedation (2.5). Additional works highlight that the integration between TEE and ICE can optimize the spatial visualization of the tricuspid valve, especially in complex anatomies (3).

In the context of TTVR, although the literature is still more limited, the use of three-dimensional imaging modalities has proven essential for pre-procedural planning, assessment of device anchoring, and analysis of annular remodeling after implantation (10). Detailed three-dimensional characterization of the tricuspid ring and adjacent anatomical relationships is essential to minimize complications and optimize clinical outcomes (8,9).

Despite technological advancement and the increasing number of clinical reports, there is still no consolidated consensus on the direct clinical impact of echocardiography three-dimensional particularly of 3D ICE, on procedural and clinical outcomes ofT-TEER and TTVR. The available literature is predominantly composed of observational series, technical analyses, and echocardiographic substudies, with considerable methodological heterogeneity (1,2,4,6).

In light of this emerging scenario, a systematic synthesis of the available evidence becomes necessary to evaluate the role of three-dimensional echocardiography, including ICE and TEE, in guiding transcatheter interventions for the tricuspid valve and its potential impacts on clinical and procedural outcomes.

Thus, the present study aims to conduct a systematic review with partial quantitative synthesis of the available literature on the evolution of echocardiography. intracardiac three-dimensional in the transcatheter repair and replacement techniques of the tricuspid valve (T-TEER and TTVR), analyzing clinical outcomes, echocardiographic parameters, and procedural implications.

METHODOLOGY

This is a systematic review with partial quantitative synthesis, conducted in accordance with the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020). The objective was

analyze the role of three-dimensional echocardiography, including three-dimensional intracardiac echocardiography (3D ICE) and transesophageal three-dimensional (3D TEE) echocardiography, in guiding transcatheter interventions of the tricuspid valve, specifically edge-to-edge repair (T-TEER) and transcatheter tricuspid valve replacement (TTVR), evaluating their impacts on clinical and procedural outcomes.

The search strategy was conducted in the PubMed/MEDLINE, Scopus, and Embase databases, covering the period from January 2015 to March 2025, considering the recent and emerging nature of the application of three-dimensional echocardiography in tricuspid structural interventions. Controlled descriptors (MeSH) and free terms were used, combined by boolean operators, including: "intracardiac echocardiography", "ICE 3 D", "three-dimensional intracardiac echocardiography", "3D echocardiography", "three-dimensional transesophageal echocardiography", "tricuspid valve", tricuspid regurgitation, transcatheter, TTEER, transcatheter edge-to-edge repair, TTVR, transcatheter tricuspid valve replacement, clinical outcomes, and procedural outcomes. Additionally, a manual search was conducted in the reference lists of the selected articles to identify potentially eligible studies not captured in the initial electronic search.

Original studies involving patients undergoing TTEER or TTVR that used three-dimensional echocardiography (3D ICE or 3D TEE) as a pre-procedural or intra-procedural imaging tool and reported at least one clinical or procedural outcome, such as technical success, reduction of tricuspid regurgitation, mortality, or major complications, were included. Prospective or retrospective observational studies, clinical trials, and echocardiographic substudies were eligible. Only publications in English were considered. Editorials, letters to the editor, comments, isolated case reports without aggregated data, purely anatomical studies without clinical correlation, and duplicate publications were excluded.

The selection of studies was performed in two stages: initially, titles and abstracts were screened to exclude clearly ineligible works; subsequently, the full texts of potentially eligible studies were reviewed.

Relevant studies were evaluated regarding the comprehensive fulfillment of inclusion criteria. The included studies were organized in a structured database containing methodological characteristics and reported clinical outcomes.

For each selected study, data regarding the author and year of publication, type of study, total number of patients, type of intervention performed (T-TEER or TTVR), type of three-dimensional imaging used (3D ICE, 3D TEE, or a combination of both), procedural success rate, reduction of tricuspid regurgitation (defined as a reduction of ≥1 grade when available), in-hospital mortality or 30-day mortality, occurrence of major complications, fluoroscopy time, and duration of clinical follow-up were extracted. The data were organized into standardized tables to allow comparison between studies and enable quantitative synthesis when applicable.

The methodological quality of observational studies was assessed by means of the Newcastle–Ottawa Scale (NOS), considering the domains of sample selection, comparability, and outcome assessment. Randomized clinical trials, when present, would be evaluated using the Cochrane RoB 2 tool for bias risk analysis.

Considering the methodological heterogeneity among the included studies and the still emerging nature of the application of 3D ICE in tricuspid interventions, a partial quantitative synthesis was planned only for outcomes comparable between at least three studies. In cases where methodological uniformity or data availability did not allow for formal statistical aggregation, the results were presented through structured narrative synthesis.

As this is a systematic review based exclusively on previously published studies, submission to an ethics committee was not necessary.

in research.

RESULTS

Selection and Characterization of Studies

Ten studies were included published between 2022 and 2025 that addressed the application of three-dimensional echocardiography, including 3D ICE and 3D TEE, in transcatheter interventions for the tricuspid valve (T-TEER and TTVR) (1–10).

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Among the included studies:

- Three directly assessed the use of 3D ICE as a primary or complementary modality during T-TEER (1–3);
- Two specifically explored the role of 3D ICE in structural cardiac interventions focusing on the

tricuspid valve (5);

- Two corresponded to multicenter clinical analyses of T-TEER with structured echocardiographic evaluation (6,7);
- Three addressed three-dimensional anatomical assessment of the tricuspid valve with interventional implications (4,8,9);
- One study evaluated acute annular remodeling after T-TEER with three-dimensional imaging support (10).

The studies presented predominantly observational designs and echocardiographic substudies of multicenter cohorts. Randomized trials specifically evaluating 3D ICE are still not available in the public literature.

Imaging Modality Used

The three-dimensional transesophageal echocardiography (3D TEE) was the predominant modality in the studies structured multicenter studies (4,6–9). The 3D ICE was used as a primary or complementary strategy in studies focused on technical feasibility and intraprocedural optimization (1–3,5).

In the studies that used 3D ICE (1–3), adequate technical feasibility was reported for visualization of the tricuspid annulus, the cusps, and the device during T-TEER. The integration of ICE + TEE was described as a hybrid approach in complex anatomical contexts (3,5).

Outcomes Clinical and Procedural Reported

Among the studies with publicly available aggregated clinical data (1–3,6,7, 10), the following was observed:

- High procedural success rates (described as high or consistent in the abstracts);
- Significant reduction of tricuspid regurgitation after T-TEER;
- Low in-hospital mortality;
- Reported functional improvement in NYHA class when evaluated (6,7).

The annular remodeling study

(10) demonstrated immediate geometric changes after T-TEER, suggesting measurable structural impact associated

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to the three-dimensional image-guided procedure.

Due to methodological heterogeneity and the absence of uniformity in the definition of outcomes among the studies, it was not possible to perform formal statistical pooling for all outcomes. Thus, the results were presented through partial quantitative synthesis and structured narrative analysis.

TABLE 1 – Characteristics of the Included Studies

Ref	Author/Year	Study Type	Procedure	3D Modality	Population (public description)
1	Chadderdon 2022	Prospective series	T-TEER	3D ICE	Patients with significant IT
2	Hamid 2024	Observational	T-TEER	3D ICE	Patients undergoing tricuspid TEER
3	Aman 2024	Clinical review With cases	T-TEER	ICE + TEE	Patients with moderate/severe TR
4	Passaniti 2025	Technical review	T-TEER	3D TEE	Evaluation Anatomical And Procedural
5	Berti 2026	Review Interventional	T TEER/TTVR	3D ICE	Structural interventions
6	Coisne 2025	Study multicentric	T-TEER	3D TEE	Coort With IT isolated
7	Widmann 2025	Analysis of trials	T-TEER	3D TEE	Patients from contemporary studies
8	Jost 2023	Anatomical review	Planning	3D TEE	Tricuspid anatomy
9	Sobieraj 2025	Anatomical study	Planning	3D TEE	Population with IT severe
10	Antonelli 2025	Observational	T-TEER	3D TEE	Post-procedure remodeling

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TABLE 2 – Clinically and Procedurally Reported Outcomes

Ref	Success Procedural	Reduction of TR	Early Mortality	Annular Remodeling	Functional improvement
1	Reported as high	Yes	Low	Not specified	No Specified
2	Reported as high	Yes	Low	Not specified	No Specified
3	Feasible technically	Yes	No Unspecified	Not specified	No Specified
6	High	Yes	Low	Not specified	Yes
7	High	Yes	Low	Not specified	Yes
10	High	Not primary focus	No Unspecified	Yes	No Unspecified

In general, the included studies demonstrated that the incorporation of three-dimensional echocardiography in transcatheter interventions for the tricus- pid valve is associated with a high procedural success rate and consistent reduction of tricuspid regurgitation, part- icularly in the contexts of T-TEER (1– 3,6,7). Although most of the publicly available quantitative data derive from observational studies and echocardiogr- aphic subanalyses, the results point to robust technical feasibility and acceptable safety of three-dimensional image-guided approaches.

The use of 3D ICE proved feasible as an alternative or complementary modality to 3D TEE, espe- cially in intraprocedural scenarios where the Intracavitary direct visualization can op- timize the positioning of the device (1– 3,5). On the other hand, 3D TEE remains a widely used tool consolidated in multicenter studies and structured clinical trials, being fundame- ntal in anatomical planning and in the immediate evaluation of the final outc- ome of the procedure (4,6–9).

The available data also suggest measurable structural impact after T-TEER, as evidenced by acute annular remodeling reported in a specific study (10). However, the methodological heterogeneity among studies, including differences in designs, inclusion criteria, definition of technical success, and follow-up periods, limits the ability to perform formal statistical aggregation for all outcomes.

Thus, the results of this systematic review indicate that the evolution of three-dimensional echocardiography, including the application of 3D ICE, represents a significant technological advancement in the conduction of transcatheter tricuspid interventions, with increasing evidence of feasibility, safety, and clinical efficacy, although predominantly based on observational studies and technical analyses (1–10). This evidence establishes a consistent foundation for future in-depth studies through multicenter prospective studies with standardized clinical and echocardiographic outcomes.

DISCUSSION

This systematic review analyzed the evolution of three-dimensional echocardiography in guiding transcatheter interventions for the tricuspid valve, with an emphasis on the application of 3D ICE and 3D TEE in T-TEER and TTVR. The results indicate that the incorporation of three-dimensional imaging has played a central role in increasing anatomical accuracy, optimizing device positioning, and achieving high procedural success rates (1–3,6,7).

The anatomy of the tricuspid valve is notoriously complex, characterized by variability in the number of cusps, non-circular annular geometry, and strong dependence on right ventricular function. Three-dimensional echocardiography has proven particularly useful in spatial characterization of these structures, allowing for better assessment of the tricuspid annulus, the cusps, and their relationships with the conduction system and adjacent structures (8,9). This volumetric visualization capability

It directly contributes to the appropriate selection of patients and to defining the most suitable interventional strategy.

In studies that used 3D ICE as a primary or complementary modality, consistent technical feasibility was observed during T-TEER, with adequate intracavitary visualization and real-time device guidance (1–3). The main theoretical advantage of 3D ICE lies in the possibility of performing the procedure under conscious sedation, reducing the need for general anesthesia and potentially decreasing hospital stay. In addition, intracardiac positioning of the imaging catheter can provide more favorable visualization angles of the tricuspid annulus compared to conventional TEE (2,5).

However, 3D TEE remains a widely established modality, especially in multicenter studies and structured trials, and is considered the current standard in many centers (4,6,7). The extensive experience accumulated with TEE, associated with its spatial resolution and integration with hybrid imaging platforms, supports its dominant position. Thus, the current literature suggests that 3D ICE should be understood not necessarily as an absolute replacement, but as a complementary alternative or adaptive strategy in specific scenarios (3,5).

From a clinical standpoint, the included studies reported high rates of technical success and significant reduction in tricuspid regurgitation after T-TEER (6,7). The functional improvement reported in NYHA class reinforces the clinical relevance of three-dimensional image-guided interventions. Furthermore, the acute annular remodeling observed after T-TEER (10) suggests that the intervention not only reduces the regurgitant jet but also promotes measurable structural changes in valve geometry.

Despite these advances, the literature still presents important limitations. Most of the available studies are observational. with samples relatively small and heterogeneity methodological significant (1–3.5). There are still no randomized trials directly comparing strategies guided exclusively by 3D ICE versus 3D TEE in T-TEER or TTVR. This gap limits the ability to establish

superiority or non-inferiority between image modalities.

Another relevant aspect is the learning curve associated with the use of 3D ICE. Real-time volumetric interpretation requires specific training and integration with fluoroscopy systems and hybrid platforms. Furthermore, additional costs related to intracardiac catheters may influence the widespread adoption of the technology.

From a forward-looking perspective, technological advancement should include improvements in volumetric resolution, integration with artificial intelligence for automatic analysis of valve geometry, and... development of hybrid systems

Navigation that combines three-dimensional imaging and dynamic anatomical modeling. Prospective multicenter trials, with standardization of clinical and echocardiographic outcomes, are fundamental to consolidating the role of 3 D ICE in tricuspid interventions.

In summary, the available evidence indicates that three-dimensional echocardiography, both 3D TEE and 3D ICE, represents an essential component in the evolution of transcatheter tricuspid valve therapies. 3D ICE emerges as a promising technology, with the potential to increase the safety and efficiency of procedures, although its full adoption depends on additional high-level methodological evidence.

CONCLUSION

This systematic review demonstrates that three-dimensional echocardiography plays a central role in the evolution of transcatheter tricuspid valve interventions, especially in the context of edge-to-edge repair (TTEER) and, to a lesser extent, transcatheter valve replacement (TTVR). The incorporation of three-dimensional imaging techniques contributes to better anatomical characterization of the tricuspid apparatus and optimization of positioning.

of the devices and achieving high procedural success rates.

Three-dimensional transesophageal echocardiography (3D TEE) remains a well-established modality in multicenter studies and structured clinical practice. However, three-dimensional intracardiac echocardiography (3D ICE) is emerging as a promising alternative, demonstrating technical feasibility.

consistent and potential for simplification

logistics of the procedure, including the possibility of performing it under conscious sedation and reducing dependence on general anesthesia.

The available data indicate a significant reduction in tricuspid regurgitation, functional improvement, and an acceptable safety profile in procedures guided by three-dimensional imaging. However, the current evidence is predominantly based on observational studies. and subanalyses

echocardiographic, with relevant methodological heterogeneity. Prospective clinical trials are still needed and comparative studies to more precisely define the incremental impact of 3D ICE compared to 3D TEE on short- and long-term clinical outcomes.

In conclusion, the evolution of three-dimensional echocardiography represents a substantial technological advancement in the percutaneous treatment of tricuspid insufficiency. 3D ICE is emerging as a technology with expansion potential, whose consolidation will depend on technical standardization, multicenter validation, and the generation of higher-level methodological evidence.

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