Review Article

Role of Transthoracic Echocardiography in Percutaneous Closure of Ventricular Septal Defect

João Batista Masson Silva,[1,2] *Cloves Geraldino da Silva Junior*[2,3]
Universidade Federal de Goiás (UFG),[1] *Goiânia, GO – Brazil*
Hospital das Clínicas da Universidade Federal de Goiás (UFG), Empresa Brasileira de Serviços Hospitalares (EBSERH),[2] *Goiânia, GO – Brazil*
Clínica MEDCORE,[3] *Goiânia, GO – Brazil*

Abstract

Ventricular septal defect (VSD) is the most common congenital heart defect, and its management has evolved with percutaneous closure, a minimally invasive alternative to surgery. In this context, echocardiography has established itself as the primary imaging tool, crucial in all phases of the procedure. Transthoracic echocardiography (TTE) is essential for diagnosis, anatomical classification (perimembranous, muscular, inlet and outlet), initial hemodynamic assessment, and long-term follow-up. Indication for closure is based on such criteria as the left ventricular (LV) volume overload, with Qp:Qs ≥ 1.5:1. For detailed planning and intraprocedural guidance, transesophageal echocardiography (TEE), especially with three-dimensional (3D) reconstruction, is the gold standard. 3D TEE offers an accurate measurement of defect diameters, a border analysis for safe device anchorage, and an assessment of the relationship with adjacent structures, such as the aortic and tricuspid valves. The success of the intervention, both in congenital VSDs and in the rare and complex post-infarction VSDs, depends directly on the quality of the echocardiographic evaluation. The multimodal approach, which integrates TTE and TEE, ensures appropriate patient selection and safe procedure management, optimizing outcomes and expanding the realms of percutaneous VSD treatment.

Introduction

Ventricular septal defect (VSD) is the most prevalent congenital heart defect, accounting for approximately 40% of all cardiac malformations. The global prevalence is approximately 9/1,000 live births, but the exact incidence may be underestimated due to the high frequency of spontaneous closure. The diagnosis and characterization of VSD depend on its location and hemodynamic consequences, with echocardiography being the primary tool for this assessment.[1,2]

Keywords

Ventricular Heart Septal Defects; Echocardiography; Transesophageal Echocardiography

Mailing Address: João Batista Masson Silva •
Hospital das Clínicas da Universidade Federal de Goiás (UFG). Primeira Avenida S/N. Postal Code: 74605-065. Goiânia, GO – Brazil
E-mail: jbmasson@ufg.br
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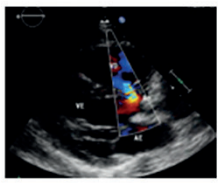
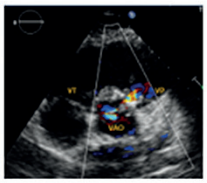
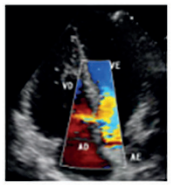
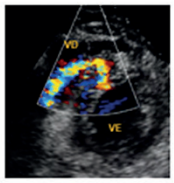
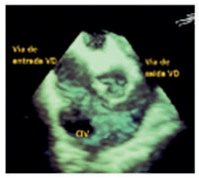
VSD classification is based on its anatomy, following the consensus of the International Society for the Nomenclature of Pediatric and Congenital Heart Diseases (*Sociedade Internacional para a Nomenclatura de Doenças Cardíacas Pediátricas e Congênitas* – ISNPCHD). VSDs are categorized into four main types, depending on their location and borders from the right ventricle (RV) perspective.[2-4]

- **Perimembranous VSD**:
  - ◇ The most common type (80% of all VSDs).
  - ◇ Located in the membranous septum (adjacent to the aortic and tricuspid valves).
  - ◇ Perimembranous VSD may extend to the inlet, outlet, or trabecular portions of the muscular septum.
  - ◇ May be associated with aortic valve leaflet prolapse (aortic regurgitation).
  - ◇ Often referred to as **infracristal** (located below the supraventricular ridge).
  - ◇ The proximity of the atrioventricular (AV) conduction system to the posteroinferior border of the perimembranous VSD makes it vulnerable to injury, with the risk of heart block, during surgery or percutaneous intervention.

- **Muscular (or trabecular) VSD**:
  - ◇ This type constitutes 5-20% of all VSDs.
  - ◇ Completely surrounded by muscle tissue.
  - ◇ They may be single or multiple (“Swiss cheese”) defects.
  - ◇ This type of VSD has a high rate of spontaneous closure (up to 2/3 of muscle defects can close without intervention).

- **Outflow tract (or subarterial) VSD**:
  - ◇ Located in the RV outflow tract, adjacent to the pulmonary and aortic valves.
  - ◇ Least common type in the West (approximately 6%).
  - ◇ May represent up to 33% of cases in the Asian population.
  - ◇ Is frequently associated with aortic cusp prolapse and aortic regurgitation.
  - ◇ Also referred to as supracristal, as it is located above the supraventricular ridge.

Central Illustration: Role of Transthoracic Echocardiography in Percutaneous Closure of Ventricular Septal Defect

1 – Diagnosis and Anatomic classification of the VSDs (2D and 3D TTE)				
Congenital				Acquired
Perimembranous	inlet	outlet	Muscular	Post-infarction
				
2 – Evaluation of the Hemodynamic Repercussion (2D and 3D TTE)				
QP:QS – pulmonary hyperflow	PH signs	Eisenmenger	LA and LV overload volume	
3 – Criteria for percutaneous closure (2D and 3D TEE/TTE)				
Muscular – Highly indicated	Perimenbranous – selected cases (VSD border – AO valve > 2-3 mm)	Outlet (not recommended)	Inlet (not recommended)	Pós-AMI Evaluate time of AMI, location, and tissue friability
4 – Intraoperative (2D and 3D TEE/TTE)				
Choice of Prosthesis		Implant		Pre-release
Congenital VSD – Overestimate 1-2 mm of the maximum measured diameter; Post-IM VSD – the degree of overestimation depends on tissue friability.		Evaluate: Passage of the catheters Opening of the discs Positioning of the septum		Check stability
5 – Post-release (2D and 3D TTE)				
Maintenance of positioning		Residual shunt	Reverse remodeling	

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How to perform echocardiographic evaluation in a percutaneous closure of ventricular septal defect.

- **Inlet VSD (or atrioventricular canal-type):**
  - ◇ Located in the inlet of the RV (near the atrioventricular valves).
  - ◇ May be part of an atrioventricular septal defect (AVSD).
  - ◇ Less common type (approximately 8% of all VSDs).

The natural history of untreated VSDs varies considerably. Small VSDs (diameter of less than 1/3 of the aortic root diameter) and restrictive VSDs (peak pressure gradient greater than 64 mmHg), which do not cause left ventricular volume overload or pulmonary hypertension (PH), can remain asymptomatic for decades. However, an unknown percentage of patients may develop long-term complications. VSDs with large shunts can cause LV volume overload and PH, leading to ventricular dysfunction, arrhythmias, aortic regurgitation, and heart failure.[2,5]

A restrictive VSD that does not close spontaneously may be predisposed to late sequelae, such as LV dilation, arrhythmias, aortic regurgitation, PH, and endocarditis. By contrast, large and non-restrictive VSDs can lead to PH, with increased pulmonary vascular resistance (PVR), culminating in flow reversal (right-to-left shunt) and the development of Eisenmenger syndrome.[6]

Post-infarction ventricular septal defect (PIVSD) is a rare mechanical complication of acute myocardial infarction (AMI), with an incidence of approximately 0.17% to 0.34% in the reperfusion era. However, this represents a devastating condition, with mortality that can exceed 90% in the absence of intervention. The pathophysiology of the rupture results from transmural myocardial necrosis, typically occurring 3 to 5 days after the ischemic event. During this phase, inflammation and enzymatic degradation of the collagen matrix by metalloproteinases result in necrotic septal tissue, which is extremely friable and mechanically incompetent to withstand the interventricular pressure gradient. The echocardiographic report, in this context, should be more than descriptive and must be interpretive, offering the multidisciplinary team an opinion on the feasibility of anchoring the device, which directly impacts the choice between an immediate percutaneous approach or stabilization for delayed surgery.[8]

The immediate consequence is the formation of an acute left-to-right shunt, leading to biventricular volume overload, hemodynamic collapse, and often rapid progression to cardiogenic shock and multiple organ failure. The anatomical complexity of VSD is a critical factor, ranging from simple, apical defects associated with anterior infarctions to complex ruptures with serpiginous and irregular courses, located at the septal base in inferior infarctions. Therefore, detailed assessment of the defect morphology, the quality of the adjacent necrotic tissue, and its relationship to adjacent valvular structures is essential for prognosis and planning of the therapeutic approach.[8]

Transthoracic echocardiography (TTE) is the primary imaging method used for the diagnosis and characterization of VSDs, providing essential anatomical and hemodynamic assessments to guide clinical management. Three-dimensional (3D) echocardiography, in particular, enhances this assessment by allowing en face visualization of the interventricular septum, which is useful for accurate analysis of the size, shape, and relationship of the defect to adjacent structures. This technique allows for a more accurate assessment of maximum and minimum diameters, delineation of borders, and visualization of the defect's course through the septum, overcoming the limitations of two-dimensional imaging, especially in funnel-shaped VSDs. TTE can be complemented by other imaging techniques, such as transesophageal echocardiography (TEE), cardiovascular magnetic resonance (CMR), and cardiovascular computed tomography (CCT), especially in cases of complex anatomy, inadequate acoustic windows, or for a more detailed assessment of extracardiac and ventricular structures.[2,9]

Although TTE is an indispensable first-line tool for the initial diagnosis and follow-up of patients with VSD, its limitations must be recognized, especially in the adult population and in cases of complex anatomy. Suboptimal acoustic windows can compromise complete visualization of the interventricular septum, and accurate assessment of the defect's edges – particularly the aortic rim, crucial for planning percutaneous closure – can be challenging. In these scenarios, TEE becomes essential, offering superior image resolution for detailed anatomical delineation, and is considered the gold standard for intraprocedural guidance. 3D echocardiography, both transthoracic and transesophageal, further enhances this assessment by allowing en face visualization of the defect, precise measurements of its maximum and minimum diameters, and a clear understanding of its spatial relationship with the aortic and tricuspid valves. Thus, a multimodal approach is consolidated, in which TTE serves as the main diagnostic and monitoring tool, while TEE, often with 3D reconstruction, is essential for the definitive planning and safe conduct of percutaneous intervention.[2]

General criteria for indicating closure of ventricular septal defect

The decision to intervene in a VSD in adult patients is multifactorial, based on a careful assessment of the defect's anatomy, its hemodynamic repercussions, and the patient's clinical status. The main indication for VSD closure is the presence of left ventricular volume overload with a hemodynamically significant left-to-right shunt, defined by a pulmonary to systemic flow ratio (Qp:Qs) ≥1.5:1. Intervention is recommended regardless of symptoms, as long as pulmonary vascular resistance remains low (less than one-third of systemic vascular resistance [SVR] or <3 Wood Units) and pulmonary artery systolic pressure (PASP) is less than 50% of systemic systolic pressure.[9,10]

There are also specific indications that justify intervention even in the absence of significant volume overload:

- **Aortic valve dysfunction**: Surgical closure is reasonable in adults with perimembranous or supracristal VSDs that have prolapse of an aortic leaflet resulting in progressive aortic regurgitation.[10]
- **Infective endocarditis (IE)**: Closure may be considered in patients with a history of repeated episodes of infective endocarditis attributed to VSD, even if the shunt is not hemodynamically significant.[10]

The presence of pulmonary hypertension makes the decision more complex. Closure may be considered in patients with moderate PH (PVR 3–5 Wood Units or PASP ≥ 50% of systemic) if a significant left-to-right shunt (Qp:Qs > 1.5) persists. However, intervention is contraindicated in severe PH and advanced pulmonary vascular disease (Eisenmenger physiology), defined by a PVR > two-thirds of SVR (or ≥ 5 Wood Units), predominant right-to-left shunt, or oxygen desaturation during exercise.[1,9,10]

Treatment Modalities: Surgery vs. Percutaneous Intervention

Surgical closure continues to be the treatment of choice for most VSDs that require intervention, with low operative mortality and good long-term outcomes. However, percutaneous intervention has emerged as a viable and effective alternative for selected cases, avoiding the need for sternotomy and cardiopulmonary bypass.[5]

The choice of modality depends primarily on the anatomy of the defect:

- **Surgery**: This is the standard for most perimembranous, inlet, and outlet/supracristal VSDs, and for patients requiring concomitant cardiac procedures.
- **Percutaneous treatment**: This is preferred for specific defects, such as muscular VSDs, postoperative residual VSDs, and defects in difficult-to-access surgical locations.

Percutaneous Treatment: Indications and Contraindications[5,9-11]

Despite advances, percutaneous treatment of VSD has well-defined indications and limitations.

Indications:

Percutaneous closure is considered reasonable and effective in the following scenarios:

1. **Muscular VSDs**: This is the main indication, especially for defects located in the mid- or apical trabecular septum, provided there are adequate edges for device anchorage. The Amplatzer Muscular VSD Occluder is the only FDA-approved device for this purpose in the US.
2. **Postoperative residual VSDs**: This is an excellent option for treating residual shunts that persist after surgical closure.
3. **Selected perimembranous VSDs**: Although technically feasible, the percutaneous approach is controversial due to its risks. It is an option in selected cases, especially in the presence of a membranous septal aneurysm, which can facilitate device implantation and protect adjacent structures.

Contraindications and Limitations:

The main limitations of the percutaneous approach are anatomical and related to the risk of complications:

- **Defect location**: Inlet and outlet/supracristal VSDs are generally not considered suitable for device closure due to their proximity to the atrioventricular and semilunar valves.
- **Proximity to valve structures**: An inadequate distance between the defect edges and the aortic or tricuspid valves is a significant contraindication due to the risk of interfering with valve function, which may cause or worsen regurgitation.
- **Risk of complete atrioventricular block (AVB)**: This is the main concern and the greatest limitation for percutaneous closure of perimembranous VSDs due to their proximity to the cardiac conduction system. The rates of complete AVB requiring a permanent pacemaker after the procedure range from 2% to 22%, a considerably higher risk than with surgery.
- **Hemodynamic contraindications**: The same ones that apply to surgery, such as the presence of severe PH with elevated PVR and right-to-left shunt (Eisenmenger syndrome), are absolute contraindications for percutaneous closure.

Selecting the appropriate device is critical to the success of the procedure and depends on the specific anatomy of the defect. Table 1 summarizes the main available devices and their indications.

Detailed Echocardiographic Analysis for Percutaneous Closure of VSDs[3,4,10,11]

Echocardiography is the core and crucial imaging modality that governs all phases of percutaneous closure of VSDs, from strategic planning to confirmation of therapeutic success and long-term follow-up. The technical rigor of the evaluation and the choice of echocardiographic modality (transthoracic vs. transesophageal; 2D vs. 3D) are tailored to the etiology of the defect – congenital or post-myocardial infarction – and the phase of patient management.[3]

Pre-procedure Assessment: Anatomical and Hemodynamic Mapping for Therapeutic Decision-making

The pre-procedure phase is crucial in determining the feasibility of the percutaneous approach, selecting the ideal device, and anticipating technical challenges.

Congenital VSD (elective planning):

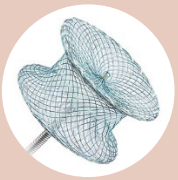
2D transthoracic echocardiography (TTE) with Doppler is the first-line tool for diagnosis and initial evaluation. Technical analysis should include:

- **Anatomical mapping**: Using multiple views (parasternal, apical, subcostal), the TTE classifies the type of VSD (perimembranous, muscular, outlet, inlet), defines the number of defects, and measures their diameter in at least two orthogonal planes.
- **Hemodynamic assessment**: The indication for closure is confirmed by shunt quantification. The pulmonary to systemic flow ratio (Qp/Qs) is calculated, and a value ≥ 1.5 is considered hemodynamically significant. Right ventricular systolic pressure (RVSP) is estimated by the VSD jet velocity or tricuspid regurgitation velocity, using the simplified Bernoulli equation ($\Delta P = 4v2$). Left ventricular volume overload is quantified by measuring its diameters and volumes.

2D, and especially 3D, transesophageal echocardiography (TEE) is essential for detailed planning of percutaneous interventions, especially in adults or when the TTE window is suboptimal. 3D TEE offers technical superiority for:

- **Accurate sizing**: 3D TEE allows for the projection of an en face view of the defect, enabling an accurate measurement of maximum and minimum diameters, regardless of its spatial orientation. This is crucial for complex or oval-shaped defects, where 2D imaging may underestimate the maximum diameter, leading to the selection of an undersized device and the risk of embolization.
- **Edge analysis**: 3D TEE allows for simultaneous visualization of all defect edges, providing a clear spatial assessment of the "anchoring zone." Measurement of the aortic edge is mandatory; a deficient edge (<2-3

Table 1 – Main devices used for percutaneous closure of ventricular septal defect

Prosthesis Model	Defect Type (Anatomical Location)	Specific Clinical Recommendations	Prosthesis Diameters (Waist / Discs)
Amplatzer™ Muscular VSD Occluder 	**Congenital Muscular VSD:** Muscular portion of the septum (apical, mid-septal, anterior). May be used to treat multiple defects ("Swiss cheese").	Patients with complex and significantly sized muscular VSD, who are considered high risk for conventional surgery.	**Belt Diameter:** 4-18 mm **Disc Diameter:** 9-26 mm **Disc Separation Height:** 7 mm
Amplatzer™ P.I. Muscular VSD Occluder 	**Muscular VSD Post-Acute Myocardial Infarction (Post-AMI):** Defects that arise as a complication of an infarction.	Closure of post-AMI muscular VSDs in patients who are not satisfactory surgical candidates. This is contraindicated for congenital or perimembranous defects.	**Belt Diameter:** 16-24 mm **Disc Diameter:** 26-34 mm **Disc Separation Height:** 10 mm
Amplatzer™ Membranous VSD Occluder 	**Perimembranous VSD:** The most common type of VSD, located in the thin, membranous portion of the septum, near the heart valves.	Closure of perimembranous VSDs with significant hemodynamic repercussions. The asymmetric design seeks to avoid compression of the aortic and tricuspid valves.	**Belt Diameter:** 4-12 mm **Disc Diameters (Right):** 8-16 mm **Disc Diameters (Left):** 10-18 mm **Disc Separation Height:** 3 mm
Cera™ / CeraFlex™ VSD Occluders  **Perimembranous**  **Congenital muscular**  **Muscle post-AMI**	**Muscular and Perimembranous VSD:** Specific models are available for both types. For perimembranous defects, symmetrical, asymmetrical, and eccentric designs are available to adapt to complex anatomy.	Recommended for percutaneous closure of muscular and perimembranous VSDs. The variety of geometries for membranous defects allows for more precise selection to protect adjacent cardiac structures.	**Belt Diameter:** 4-24 mm **Disc Diameters:** Vary by model, from 8 mm to 31.6 mm **Disc Separation Height:** 3 mm

KONAR-MF™ VSD Occluder

Perimembranous and Muscular VSD:

Designed to be versatile, treating both types of defects, with a special focus on perimembranous defects.

Recommended for complex cases in which flexibility and low radial force are key to minimizing the risk of atrioventricular block (AVB). It is also a viable option for young children (<10 kg).

Belt Diameter (Right/Left):
3-12 mm / 5-14 mm

Disc Diameter:
10-18 mm

Cocoon® VSD Occluder

Muscular and Perimembranous VSD:

The availability of multiple waist lengths (4 mm, 7 mm, and 10 mm) makes the device adaptable to septal defects of varying thicknesses.

Occlusion of hemodynamically significant VSDs. The variety of waist sizes allows the physician to choose the prosthesis that best fits the thickness of the septum, whether muscular (thicker) or membranous (thinner).[6]

Belt Diameter:
3,25-12 mm

Disc Diameter:
10-18 mm

MemoPart™ VSD Occluder

Muscular

Muscular

Muscular and Perimembranous VSD:

Offers different models for each type of defect.

The recommendations are similar to those of the Amplatzer line.

The muscular model is for high-risk surgical patients, and the membranous model is for minimally invasive closure of perimembranous VSDs.

Belt Diameter:
4-20 mm

Disc Diameter E :
8-26 mm

Disc Diameter 4:
8-24 mm

Disc Separation Height:
2,6 - 7 mm

Perimembranous

mm) requires the use of an asymmetrically designed device to avoid interference with the aortic valve. The rule of thumb for device sizing is that its waist should be 1-2 mm larger than the maximum defect diameter.

Post-myocardial infarction VSD:

In this scenario, echocardiography is an emergency tool for diagnosis and risk stratification in a critically ill patient.

- **2D transthoracic echocardiography (TTE)**: This is the modality of choice for rapid bedside diagnosis. Its technical objectives are to confirm septal rupture with color Doppler, assess biventricular function, and, primarily, rule out other mechanical complications, such as papillary muscle or free wall rupture.
- **2D and 3D transesophageal echocardiography (TEE)**: This is essential for detailed anatomical characterization. Post-AMI VSD typically has an irregular and serpiginous course. 3D TEE is superior in assessing the quality of the surrounding tissue, identifying the extent of necrotic and friable myocardium, which is the main determinant of the viability of percutaneous device anchorage. Assessment of right ventricular function is of paramount prognostic importance, given the sudden volume and pressure overload.

  In the evaluation of post-infarction VSD, echocardiography transcends simple defect identification, assuming a key prognostic and strategic planning role. The echocardiographer's main priority is to assess the quality of the adjacent tissue, as the pathophysiology of the rupture involves transmural necrosis, resulting in an extremely friable and mechanically incompetent myocardium. TEE, especially with 3D imaging, is superior to TTE for this analysis, enabling a detailed characterization of the extent of necrosis and the integrity of the defect's edges. A wide, fragile edge is a strong predictor of percutaneous closure failure, increasing the risk of complications, including device embolization. Therefore, detailed echocardiographic assessment of the rupture morphology and the viability of the surrounding septal tissue is the determining factor in deciding whether a patient is a viable candidate for a percutaneous approach or whether hemodynamic stabilization for delayed surgery, allowing fibrotic maturation of the defect, would be the best strategy.[12]

Intraprocedural Assessment: Guiding the Intervention and Prosthesis Sizing[4,5,10,11]

Intraprocedural echocardiography is the cornerstone of implant safety and accuracy. Transesophageal echocardiography is traditionally considered the gold standard and the most widely used modality to guide the procedure, often described as "the interventionist's eye." Its superiority lies in its high image resolution, especially for posterior structures, and its ability to accurately assess defect edges and valve function, making it crucial in patients with limited transthoracic acoustic windows. In Brazil, most studies and position papers from societies such as the Brazilian Society of Cardiology (SBC) and the Brazilian Society of Cardiology (SBHCI) describe the procedure as being performed under TEE monitoring.

Regardless of the chosen modality, the role of intraprocedural echocardiography is multifaceted and governs the critical stages of the intervention:

- **Final prosthesis sizing**: Echocardiography (primarily TEE) performs the final and definitive measurement of the defect under the hemodynamic conditions of the procedure. The rule of thumb is to select a device whose waist is 1 to 2 mm larger than the maximum measured diameter to ensure secure anchorage. In post-AMI VSD, due to tissue friability, "significant oversizing" is often recommended. It is crucial to note that, unlike congenital VSDs, this "significant oversizing" is a qualitative, not quantitative, concept; the final decision depends on the intraprocedural assessment of defect morphology and tissue integrity, guided by the operator's experience rather than a fixed formula. It is important to note that the balloon sizing technique, common in ASD closure, is not used for VSDs due to the inelastic nature of the septum and the risk of widening the rupture in post-AMI cases.
- **Guidance and positioning**: Echocardiographic imaging actively guides every step, from the safe passage of guidewires and sheaths through the defect, avoiding injury to adjacent structures, such as the tricuspid valve chordae tendineae, to monitoring the sequential opening of the prosthesis discs and their correct positioning in the interventricular septum.
- **Pre-release critical evaluation**: Before definitive detachment of the prosthesis, echocardiography performs a crucial safety check, a true "point of no return." At this stage, the stability of the device, the presence of significant residual shunt, and, primarily, the absence of new aortic and tricuspid valve dysfunction are assessed.

Although TEE is the standard, TTE has emerged as a viable and effective alternative for guiding the entire procedure in selected cases. Studies have shown that, in patients with a good acoustic window (often children and young adults), TTE-only guidance can achieve success rates and residual shunt that are similar to TEE. The advantages of using TTE include the elimination of general anesthesia and intubation, as well as reduced procedure and fluoroscopy time. However, this approach is selective and requires considerable operator expertise, as it is best suited for patients weighing more than 10 kg and with defects smaller than 8 mm.

More recently, intracardiac echocardiography (ICE) has emerged as a promising emerging technology for procedural guidance. ICE also eliminates the need for general anesthesia and, in some cases, can offer superior visualization of certain defect edges when compared to TEE. Its adoption represents a significant advance in making percutaneous closure an even less invasive procedure.

Post-procedure Evaluation: Monitoring the Therapeutic Outcome

Post-procedure follow-up assesses the success of the intervention and monitors long-term progress.

- **2D transthoracic echocardiography and Doppler**: This is the primary modality for follow-up.
- **Immediate (pre-discharge) assessment**: A TTE is performed to confirm stable prosthesis position, quantify any immediate residual shunt, and rule out acute complications, such as pericardial effusion.
- **Short-term and long-term follow-up**: Serial echocardiographic follow-up (e.g., at 1, 6, and 12 months, and then every 2–5 years if stable) is recommended to monitor complete shunt occlusion (as device endothelialization occurs), ventricular function and remodeling (normalization of chamber dimensions), and valve function, as well as to detect late complications. Patients with significant residual findings require more frequent follow-up.

To emphasize the multifaceted role of echocardiography throughout the process, the Central Illustration presents a flowchart summarizing the main steps of the assessment.

Conclusion

Percutaneous closure of VSDs has established itself as an effective alternative to surgery in selected cases, and echocardiography is the core and crucial imaging modality in all phases of this procedure. Transthoracic echocardiography has established itself as the primary tool for diagnosis, classification, initial hemodynamic assessment, and long-term follow-up. However, for detailed intervention planning and, especially, intraprocedural guidance, TEE, especially with 3D technology, is the gold standard, ensuring the precision and safety necessary for therapeutic success. Careful patient selection, detailed anatomical characterization, and rigorous monitoring of adjacent structures, all guided by echocardiography, are the pillars that allow us to expand the realms of minimally invasive VSD treatment, in turn optimizing patient outcomes.

Challenges and future perspectives6

Despite remarkable advances, the field of percutaneous VSD closure still faces significant challenges that direct future innovations.

1. **Reducing the risk of atrioventricular block**: The main obstacle to the widespread adoption of percutaneous closure in perimembranous VSDs continues to be the risk of complete AV block. Future research should be focused on developing prostheses with more flexible designs and lower radial force, such as the *Nit-Occlud Lê VSD Coil* and the *KONAR-MF™ VSD Occluder*, which aim to minimize trauma to the conduction system.
2. **Improving imaging and guidance**: Although TEE is the standard, ICE is emerging as a promising alternative that eliminates the need for general anesthesia, potentially reducing procedure time and risk. The integration of fusion imaging, combining fluoroscopy and real-time echocardiography, as well as the development of artificial intelligence software to aid in implant sizing and simulation, are the next steps to further increase accuracy and safety.
3. **Development of bioresorbable devices**: The most transformative long-term prospect is the creation of fully bioresorbable occluders. Currently, research in this area is most advanced for the closure of low-pressure defects, such as atrial septal defects (ASD), with devices like the Carag Bioresorbable Septal Occluder already being used in clinical trials. Expanding this technology to VSDs is the next major challenge. This will require the development of polymers with greater mechanical strength, capable of withstanding the high interventricular pressure gradient and high shear stress, ensuring structural stability during the absorption and endothelialization process. Successful development of such devices would eliminate the risks associated with permanent implants, such as erosion and late thrombosis, representing the next frontier in the treatment of congenital heart disease.

Author Contributions

Conception and design of the research: Masson-Silva JB. Writing of the manuscript: Masson-Silva JB, Silva Junior CG. Critical revision of the manuscript for intellectual content: Masson-Silva JB, Silva Junior CG.

Potential conflict of interest

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Study association

This study is not associated with any thesis or dissertation work.

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Use of Artificial Intelligence

During the preparation of this work, the author(s) used Gemini for grammar and agreement corrections in Portuguese, as well as for assistance with translations from other languages. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data Availability

The underlying content of the research text is contained within the manuscript.

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