REVIEW ARTICLE

# Perioperative Echocardiographic Assessment of Atrial Septal Defect: Key Learning Points for Fellows/Residents in Training

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## Abstract

Atrial septal defect (ASD) is a common variety of acyanotic congenital heart defects and accounts for a significant portion of the operative volume in a cardiac surgical setup. Transthoracic echocardiography (TTE) has class I recommendation for initial and follow-up assessment of all congenital heart diseases. It has an indispensable role for diagnosis, assessment of hemodynamics as well as ventricular function, and ruling out other associated cardiac anomalies. Transesophageal echocardiography (TEE) is particularly useful for evaluation for transcatheter closure of ASD as well as for guidance during transcatheter or surgical closure of ASD. Three-dimensional echocardiography is now increasingly used for better assessment of ASD location, shape and dimensions, surrounding structures, rims as well as for real-time procedural guidance of percutaneous ASD closure. We provide a discussion on perioperative and peri-interventional transthoracic as well as transesophageal echocardiographic assessment of ASD, directed towards trainee cardiac anesthesia fellows/residents providing perioperative and peri-interventional anesthetic care as well as echocardiographic guidance in the operating room and cardiac catheterization laboratory.

**Keywords:** Atrial septal defect, Perioperative echocardiography, Pulmonary veins, Transesophageal echocardiography, Transthoracic echocardiography.

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Atrial septal defect is a defect of variable size in the atrial septum. In the Indian population, ASD accounts for 19–21% of congenital heart diseases, and a significant portion of operative and interventional volume.[1,2] It is usually more common in the female population over the male. ASD can be present as an isolated, single defect in a patient or it can be a part of a more complex congenital heart defect.

Based on location and on embryological basis, ASD is classified as ostium primum type, ostium secundum type, sinus venosus type, and coronary sinus type.[3] Among these, ostium secundum is the most common type of ASD. It occurs due to a true deficiency of embryonic septum primum tissue. Ostium primum type of ASD is a part of the spectrum of atrioventricular canal defect, occurring due to failure of fusion of endocardial cushions. Sinus venosus type of ASD occurs as a result of deficiency of the wall between the right upper pulmonary vein and superior vena cava (SVC type) or that between the right middle/lower pulmonary vein and inferior vena cava (IVC type). Coronary sinus type occurs due to deficiency in the wall between the coronary sinus and left atrium (LA) and is the least common variety.

In patent foramen ovale (PFO), there is no true deficiency of atrial septal tissue, rather, it is a potential gap between the septum secundum and the flap of septum primum. Up to 20–25% of the normal adult population can have PFO,[4] which can cause paradoxical embolization due to intermittent shunting from the right atrium (RA) to LA due to intermittent difference of pressures between the two chambers.

## Pathophysiology

The pathophysiologic consequence of ASD depends upon the degree of left-to-right shunting, which, in turn, depends mainly upon the size of ASD and the relative compliance of the right and left ventricles (LVs). There is diastolic volume overload of RA and right ventricle (RV), which leads to enlargement of the right-sided chambers. Unlike other left-to-right lesions like ventricular septal defect, patent ductus arteriosus, there is isolated volume overload of the pulmonary circuit in ASD. Therefore, the onset of pulmonary arterial hypertension (PAH) usually has a delayed, gradual onset in the natural history of ASD. Significant PAH usually starts developing after 25 years of age and the incidence rises to nearly 35% in patients after 40 years of age.[5] ASD with significant PAH at a younger age should initiate the search for other concomitant lesions known to cause PAH and evaluation for primary pulmonary hypertension.

Chronic right ventricular volume overload with/without pressure overload leads to tricuspid annular dilatation, tricuspid regurgitation (TR), flattening of interventricular septum, and RV dysfunction. Right atrial dilation can predispose to atrial arrhythmias.

## Echocardiographic Assessment of ASD

Transthoracic echocardiography has class I recommendation for initial and follow-up assessment of all congenital heart diseases.[6] It has an indispensable role for diagnosis, assessment of hemodynamics as well as ventricular function, and ruling out

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other associated cardiac anomalies in congenital heart lesions. Intraoperative TEE also has got class I recommendation for guiding surgical repair of congenital heart diseases.[6]

For ASD also, TTE is the preferred initial diagnostic modality and is very useful in small children, where it can be used as a full diagnostic modality. TEE is particularly useful for evaluation for transcatheter closure of ASD as well as for guidance during transcatheter or surgical closure of ASD.

The American Society of Echocardiography (ASE) has laid down guidelines for the echocardiographic assessment of ASD and PFO.[7] The following parameters should be evaluated while assessing ASD by echocardiography:

- Atrial septal defect type, number
- Direction of shunt
- Presence/absence of atrial septal aneurysm (ASA)
- Associated findings
- Atrial septal defect size: Both maximal and minimal sizes in a cardiac cycle
- Location
- Measurement of rims
- Shape/fenestrations

Apart from assessment of the ASD itself, evaluation should also be done regarding[7,8]:

- Mitral valve structure, function; annulus measurement
- Tricuspid valve structure, function; annulus measurement
- Morphology, function of pulmonary valve; pulmonary artery (PA) size
- Pulmonary arterial pressure estimation
- Right atrium/RV enlargement
- Pulmonary venous drainage—any anomalies
- Presence of left-sided SVC with/without unroofing of the coronary sinus
- Left ventricle/RV function

During surgical repair of ASD, perioperative TTE as well as TEE are particularly useful for[9,10]:

- Preoperative period
  - Confirmation of size and location of ASD
  - Rule out/evaluate associated cardiac lesions
    - Left-sided SVC (LSVC)
      - Absolutely necessary for coronary sinus type of ASD
    - Mitral regurgitation (MR)
    - Pulmonary valve stenosis
    - Partial anomalous pulmonary venous connection (PAPVC)
  - Assess ventricular sizes and functions
  - Estimation of PA pressure
- Adequate and complete de-airing of cardiac chambers before coming off cardiopulmonary bypass (CPB)
- Postoperative period
  - Residual shunt
  - Assessment of vena cavae
  - Assessment of pulmonary venous stenosis (sinus venosus)
  - Assessment of mitral cleft/left ventricular outflow tract (LVOT) obstruction (primum)
  - Residual valvular regurgitation
  - Ventricular function
- Assessment and management of hemodynamic perturbations throughout the perioperative period

Assessment of rims, that is, the atrial septal tissue surrounding and bordering the ASD of an ostium secundum ASD is essential for determining the feasibility of performing transcatheter device closure of ASD. Conventionally, based on the cardiac structure present in proximity, there are six named rims of an ostium secundum ASD[7]:

- Aortic rim: Between the ASD and the aortic valve annulus and aortic root; located superiorly and anteriorly (Fig. 1)
- Atrioventricular (AV) valve rim: Between the ASD and the AV valves; located inferiorly and anteriorly (Fig. 2)
- Superior vena cava rim: Between the ASD and the SVC; located superiorly and posteriorly (Fig. 3)
- Inferior vena cava rim: Between the ASD and the IVC; located inferiorly and posteriorly (Fig. 3)
- Posterior rim: Between ASD and posterior atrial walls; located posteriorly (Fig. 1)
- Right upper pulmonary vein (RUPV) rim: Between the ASD and the RUPV; located posteriorly (Fig. 4)

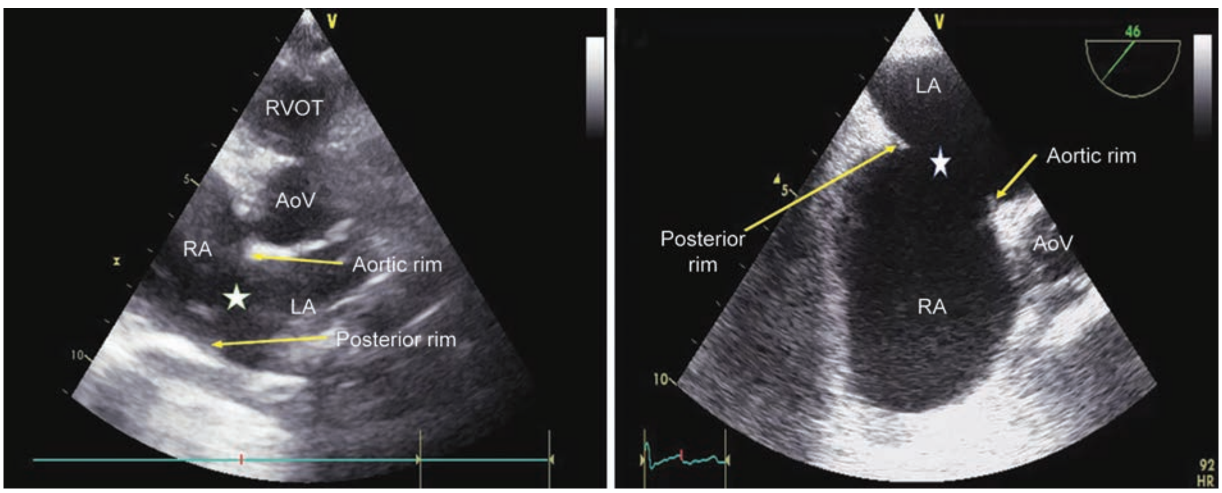


**Fig. 1:** Left panel—parasternal aortic-valve short axis view showing ASD (asterisk) and the aortic and posterior rims; Right panel—ME aortic valve short axis view showing ASD (asterisk) and the aortic and posterior rims. RA, Right atrium; LA, Left atrium; RVOT, Right ventricular outflow tract; AoV, Aortic valve

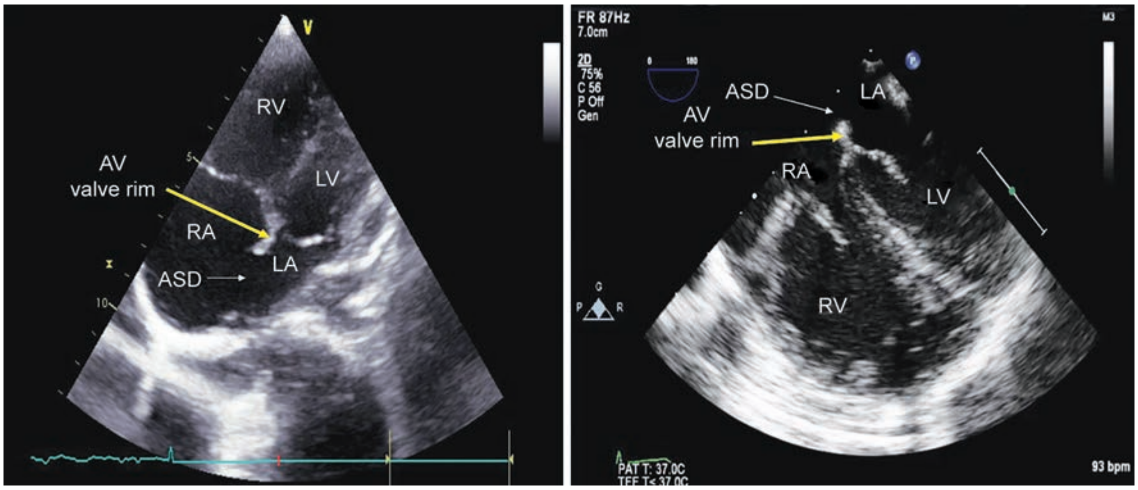


**Fig. 2:** Left panel—apical four-chamber view, showing ASD and the AV valve rim; Right panel—ME four-chamber view, showing ASD and the AV valve rim. RA, Right atrium; LA, Left atrium; RV, Right ventricle; LV, Left ventricle

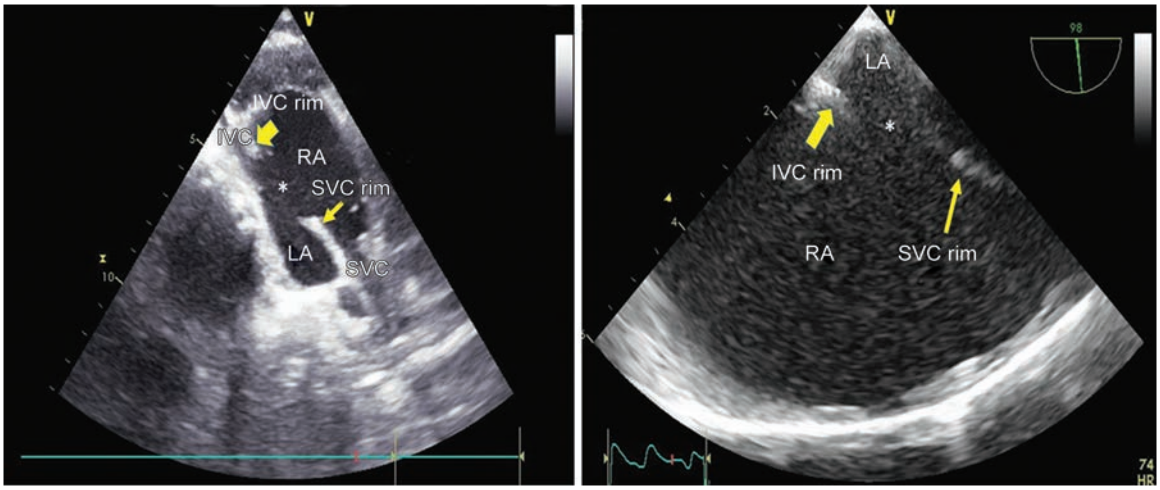


**Fig. 3:** Left panel—subcostal sagittal view showing ASD (asterisk) and the SVC and IVC rims; Right panel—ME bicaval view, showing ASD (asterisk) and the SVC and IVC rims. RA, Right atrium; LA, Left atrium; SVC, Superior vena cava; IVC, Inferior vena cava

A rim length of 5 mm or more is considered adequate. The presence of adequate SVC, IVC, RUPV, and AV valve rims is necessary for successful transcatheter ASD device closure.[7]

Multiple views of TTE are necessary for a full evaluation of ASD, the remaining atrial tissue, and the surrounding structures.[8] Additional views are necessary for assessing the associated anomalies as well as the hemodynamic consequences of ASD. The most useful TTE views for evaluation of ASD are[7,8]:

- Subxiphoid/subcostal four-chamber view (Video 1):
  - Preferred view
  - Images along anteroposterior axis of interatrial septum (IAS)
  - Atrial septum perpendicular to echo beam: minimal dropout artifact
  - Assessment of RUPV rim
- Subxiphoid/subcostal sagittal view (Video 2):
  - Turn the probe 90° clockwise from the subcostal four-chamber view
  - Images along the superoinferior axis of IAS
  - Assessment of SVC and IVC rims
  - Excellent for imaging sinus venosus ASD
- Subcostal left anterior oblique view:
  - Turn probe approximately 45° anticlockwise from subcostal four-chamber view
  - Ideal view for identification and assessment of ostium primum ASD
  - Delineation of the relation between ASD and SVC
  - Viewing the drainage of the right upper pulmonary vein: anomalous drainage can be detected
- Apical four-chamber view (Video 3):
  - Assess RA, RV size, RV pressure by TR jet, RV, and LV function
  - Detection of right to left shunt by injecting agitated saline contrast
  - Artifactual dropout of IAS—measurement of ASD should not be done
- Modified apical four-chamber view:
  - Slide probe to medial side from apical four-chamber view to the left sternal border
  - Alternate to subcostal view

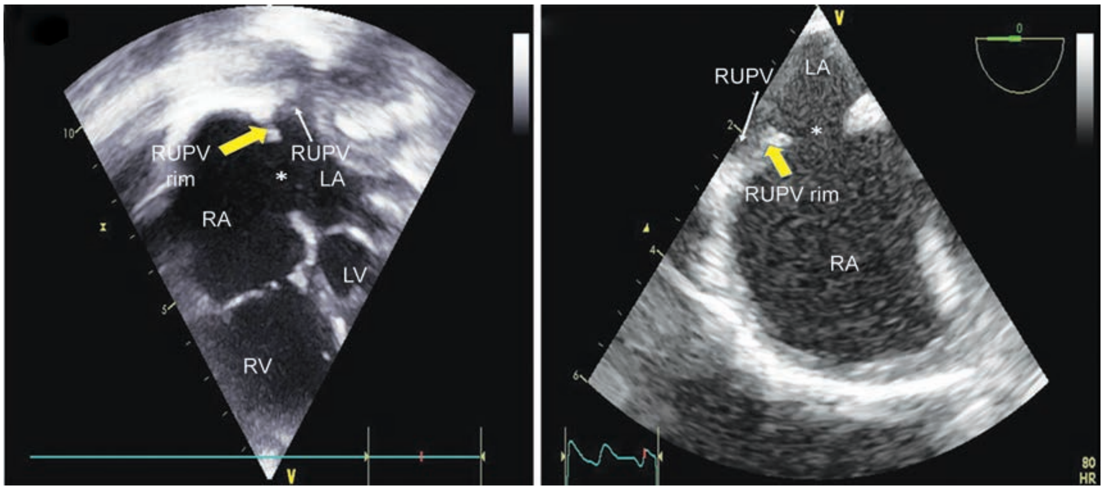


**Fig. 4:** Left panel—apical RV focused view (up/down invert) showing ASD (asterisk) and the RUPV rim; Right panel—ME view, obtained by clockwise rotation and withdrawal of probe from ME four-chamber view, showing ASD (asterisk) and the RUPV rim. RA, Right atrium; LA, Left atrium; RV, Right ventricle; LV, Left ventricle; RUPV, Right upper pulmonary vein

- Parasternal short axis view (Video 4):
  - Assessment of the aortic and posterior rims
  - Atrial septal defect size should not be measured
- High right parasternal view:
  - Patient in right lateral decubitus, probe placed parasagitally in anteroposterior direction
  - Interatrial septum perpendicular to the beam
  - Alternate to subcostal four-chamber bridge, if subcostal views are not adequate
  - Good for detection and assessment of sinus venosus defects

Similar to TTE, multiple views of TEE are also necessary to completely evaluate the ASD, its relation to surrounding structures, and the hemodynamic consequences. ASE recommends sweeping the areas of interest with 15° increments of omniplane angle.[7] The color Doppler scale settings should be kept at 35–40 cm/s for being able to appreciate low velocity flows across the ASD, PFO, or fenestrations.[7] TEE is especially useful for assessment of the rims of ASD and is recommended prior to undertaking transcatheter device closure of ASD. Each rim should be evaluated in at least three sequential related omniplane views at 15° increments.[7] There are five recommended key views of TEE for anatomical assessment of ASD and related structures.[7] The views are:

- Upper esophageal short axis view (Video 5):
  - Superior aspect of IAS; roofs of RA and LA; SVC and ascending aorta; and drainage of right pulmonary veins
  - Superior vena cava type sinus venosus ASD
- Midesophageal (ME) aortic valve short axis view (Video 6):
  - Aortic and posterior rims; anteroposterior diameter of ASD; and overlapping of septum primum and secundum in presence of a PFO
- Midesophageal four-chamber view (Video 7):
  - Evaluation of AV septum and detection and evaluation of ostium primum ASD
  - Relationship of ASD to AV valves and AV valve rim of OS ASD

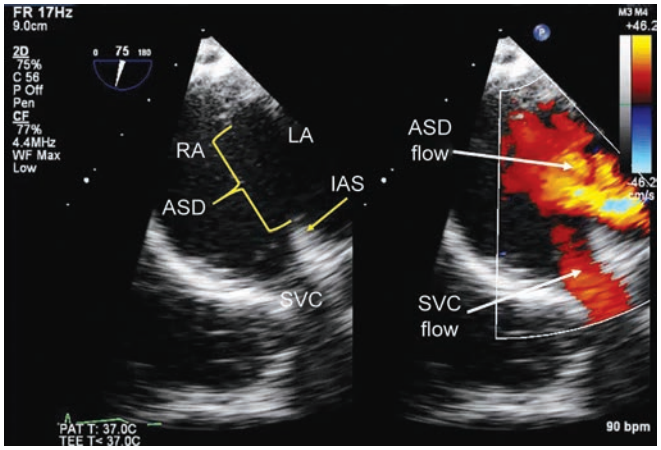


**Fig. 5:** Deep transgastric atrial septal view (color compare) showing ASD and its flow, also showing the drainage of SVC and its flow. RA, Right atrium; LA, Left atrium; SVC, Superior vena cava; IAS, Inter atrial septum

- Midesophageal bicaval view (Video 8):
  - Inferior and superior aspects of IAS
  - Superior vena cava and RUPV
  - Superior vena cava type ASD and PAPVC, over-riding of IAS by SVC is seen
  - Dome of RA
- Midesophageal long axis view:
  - Roof or dome of LA
  - Drainage of left pulmonary veins

Apart from these views, deep transgastric (DTG) atrial septal view is also useful for evaluation of IAS and ASD.[7] From DTG five-chamber view, the probe is slightly withdrawn with slight clockwise rotation and omniplane angle increased to 50–90° to obtain DTG right ventricular outflow tract (RVOT) view. From this view, the omniplane angle is increased to 80–90° and the probe is rotated clockwise till SVC, RA, RA appendage, LA, and IAS are seen, thus producing the DTG atrial septal view (Fig. 5, Video 9). SVC flow can be visualized and interrogated using spectral Doppler, as the flow is parallel to the echocardiographic beam in

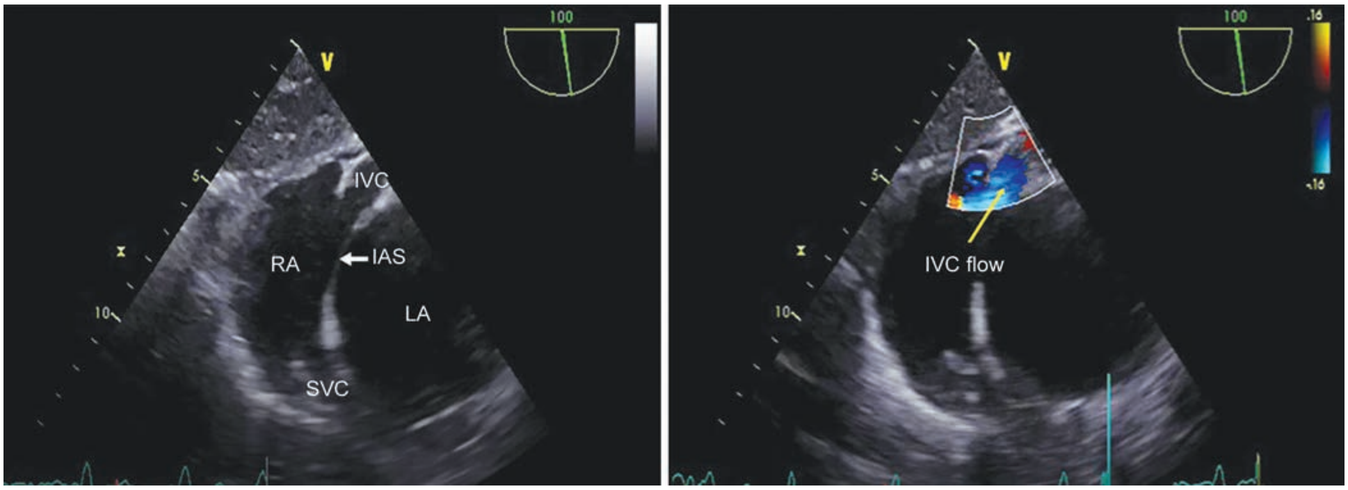


**Fig. 6:** Deep transgastric atrial septal view (color compare), showing IVC drainage and its flow. RA, Right atrium; LA, Left atrium; SVC, Superior vena cava; IAS, Inter atrial septum; IVC, Inferior vena cava

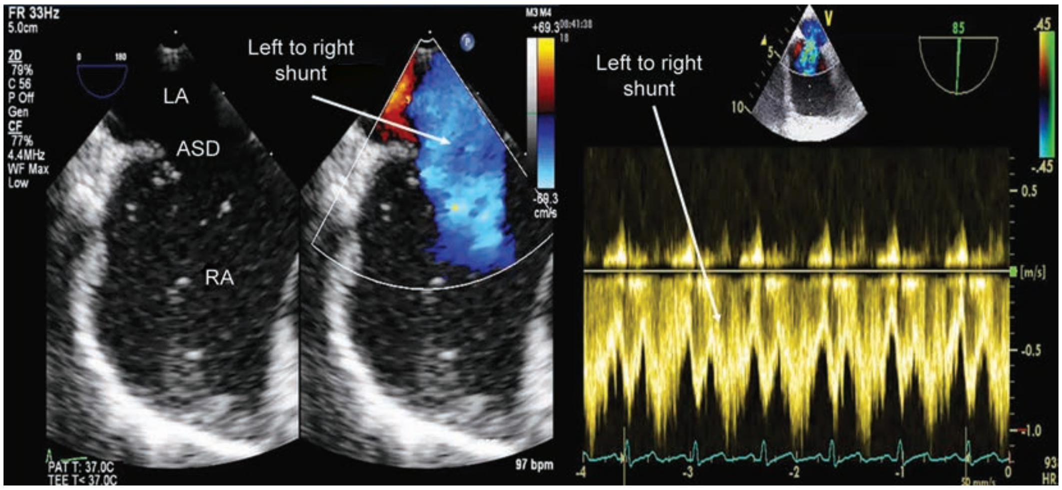


**Fig. 7:** Color Doppler (left panel) and spectral Doppler (right panel) examination of ASD showing left-to-right shunt. RA, Right atrium; LA, Left atrium

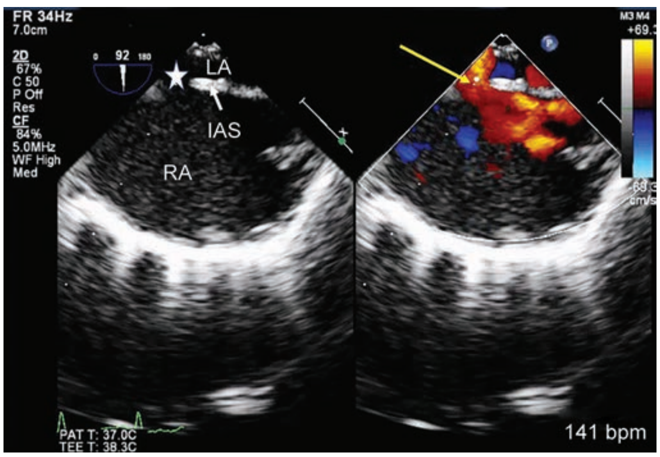


**Fig. 8:** ME bicaval view (color compare) showing right-to-left shunt [yellow arrow through ASD (asterisk)]. This finding should lead to a search for the presence of TAPVC. RA, Right atrium; LA, Left atrium; IAS, Interatrial septum

this view.[7] The entrance of IVC into the RA can also be viewed by advancing the probe slightly from this view and increasing the omniplane angle to 100–120° (Fig. 6). Changing the omniplane angle to 0–10° at this point, the IAS can be seen orthogonally, alongwith RA, entry of left and right pulmonary veins into LA, and both the ventricles and AV valves.

## Color and Spectral Doppler Assessment

Color and spectral Doppler assessment are used to evaluate[7–10]:

- Direction of shunting through ASD (Fig. 7)
    - Predominantly left-to-right shunt
    - In presence of high PA pressure, the shunt may become bidirectional or even right to left in case of Eisenmengerization
    - Presence of a pure right to left shunt through an ASD should always initiate a search for excluding total anomalous pulmonary venous connection (TAPVC) (Fig. 8)
- Locating and interrogating pulmonary venous flow (Figs 9 and 10, Videos 10 and 11):
    - Pulmonary venous spectral Doppler usually shows higher baseline velocities with preserved pulsatility in ASD patients, due to increased pulmonary blood flow. Due to increased pulmonary blood flow, the S and D antegrade waves normally seen in the pulmonary venous flow pattern are replaced by a continuous antegrade wave in ASD. Atrial reversal wave is also reduced. The venous waveform becomes normal after ASD closure (Fig. 11)[11].

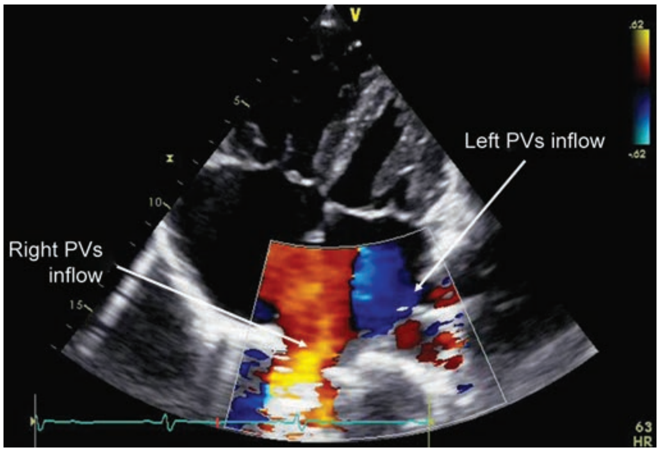


**Fig. 9:** Apical four-chamber color Doppler view showing right- and left-sided pulmonary venous inflows

- Grading of MR/TR:
  - By using standard color/spectral Doppler criteria
- Estimation of PA pressure (Fig. 12):
  - Using TR and/or pulmonary regurgitation jet for estimation of peak and/or mean PA pressures, respectively, using a standard formula
  - Pulmonary artery acceleration time (PAAT) (Fig. 13)
- Assessment of pulmonary stenosis:
  - Increased pulmonary blood flow due to ASD itself can give rise to flow across the pulmonary valve up to 2.5 m/se

## Assessment of Shunting

- Indicators of the presence of significant left-to-right shunt:

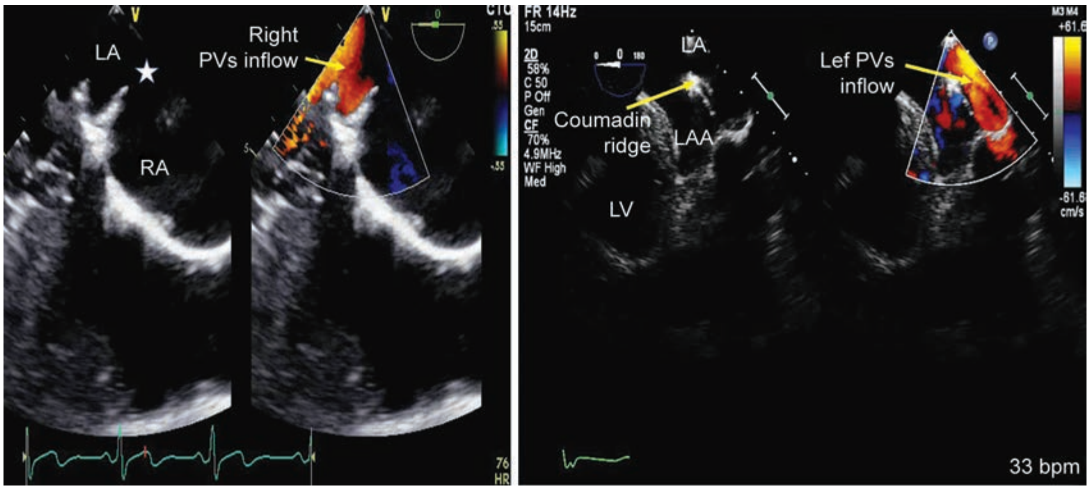


**Fig. 10:** Left panel—view obtained by clockwise rotation and withdrawal of probe from ME four-chamber view showing secundum type ASD (asterisk) and right-sided pulmonary venous inflow; Right panel—view obtained by counterclockwise rotation and withdrawal of probe from ME four-chamber view showing left-sided pulmonary venous inflow from behind the Coumadin ridge. RA, Right atrium; LA, Left atrium; PV, Pulmonary vein; LV, Left ventricle; LAA, Left atrial appendage

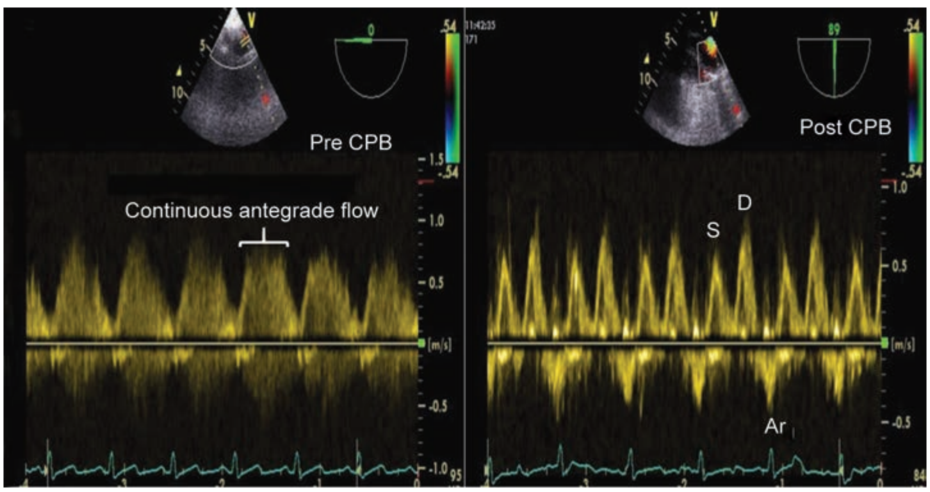


**Fig. 11:** Spectral Doppler interrogation of pulmonary venous inflow in presence of ASD, left panel—waveform prior ASD closure shows continuous antegrade flow; Right panel—waveform post-ASD closure shows return to normal systolic (S), diastolic (D), and atrial reversal (Ar) waves

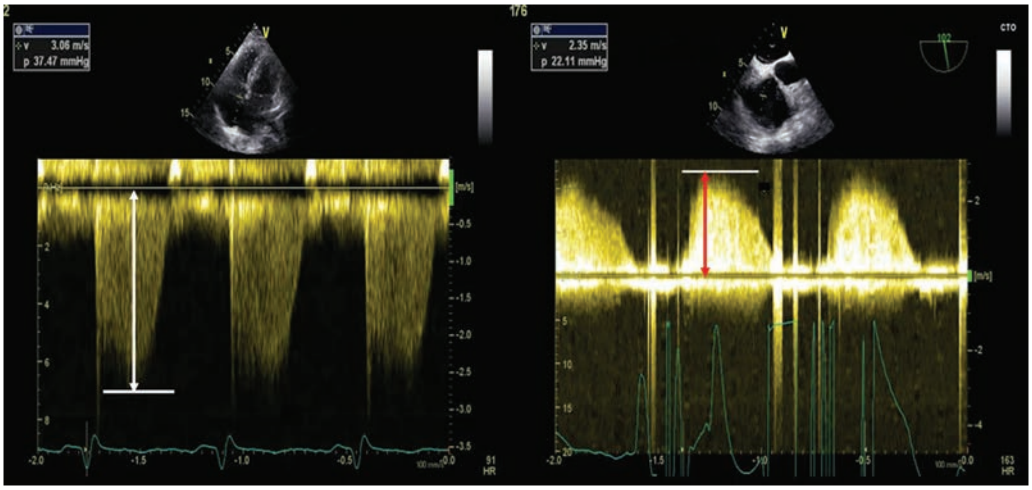


**Fig. 12:** Spectral Doppler interrogation of TR jet velocity for estimation of pulmonary artery systolic pressure (PASP), left panel—from apical four-chamber view; Right panel—from ME modified bicaval view

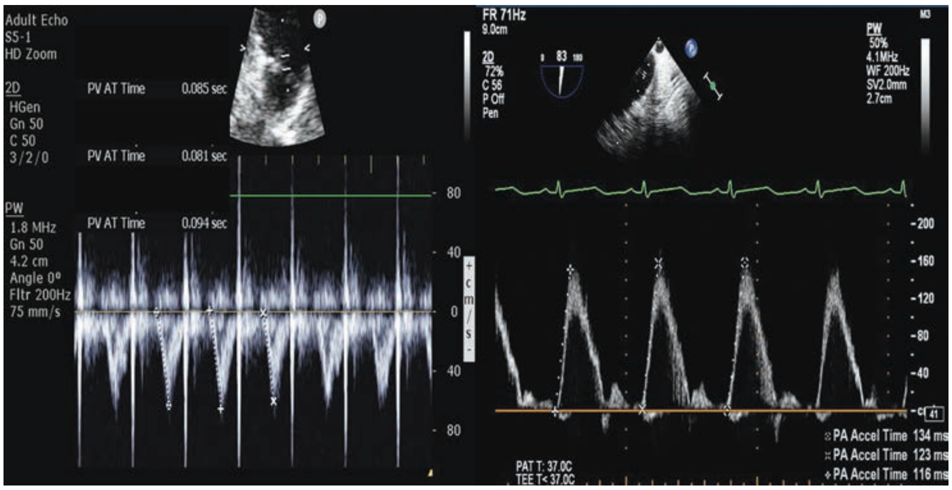


**Fig. 13:** Estimation of pulmonary artery acceleration time (PAAT) by placing pulsed wave Doppler aligned to pulmonary arterial blood flow with sample volume placed just proximal to pulmonary valve. Left panel—parasternal aortic valve short axis view, zoomed over pulmonary valve; Right panel—upper esophageal aortic arch short axis view

  - Enlargement of RA, RV, and/or PA
  - Diastolic flattening of the interventricular septum
- Direction of shunting:
  - Using color (scale 25–40 cm/s) and spectral Doppler
  - Predominantly left-to-right shunt
  - Increased velocity of left-to-right shunting can be found in conditions associated with increased LA pressures, for example:
    - Mitral stenosis or supramitral ring
    - Impaired LV diastolic compliance
    - Left ventricle outflow obstruction, for example, subaortic membrane and aortic stenosis
    - Associated coarctation of aorta
  - Bidirectional shunting or right - to left shunt can be present in presence of:
    - Significant PAH
    - Impaired RV compliance
  - Pure right to left shunt across an ASD, especially in infants or young children should raise the suspicion of TAPVC (Fig. 8)
  - Quantitative estimation of left-to-right shunting (Fig. 14)
    - Expressed as a ratio of pulmonary (Qp) and systemic (Qs) blood flow
    - Qp:Qs ratio may be measured by echocardiography by estimating the ratio between RV and LV stroke volume:
      - Right ventricle stroke volume = RVOT area × RVOT velocity time integral (VTI)
      - Left ventricle stroke volume = LVOT area × LVOT VTI
      - Right ventricular outflow tract and LVOT areas are derived from the respective diameters measured from 2D imaging [area = pi × $(\text{diameter}/2)^2$]
      - Ratio between RV and LV inflow volumes has also been reported to be correlating with the gold standard oximetry method (Inflow stroke volume = AV valve area in diastole × AV inflow VTI)
- Shunt across PFO:
  - Color Doppler: Shunt may not be visible as it is intermittent and is of small magnitude
  - Bubble study[7]:

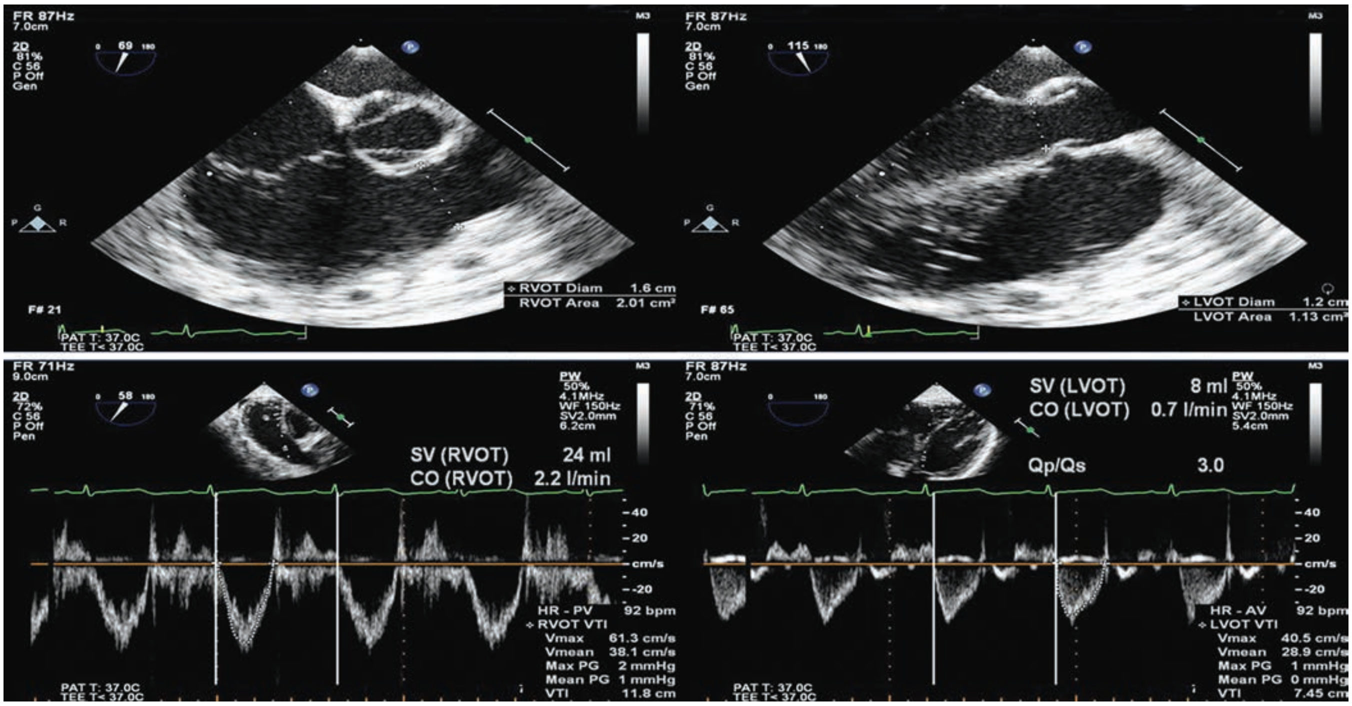


**Fig. 14:** Estimation of ratio of pulmonary and systemic blood flow (Qp:Qs ratio). Left upper panel—RVOT diameter measurement from ME RV inflow-outflow view; Right upper panel—LVOT diameter measurement from ME aortic valve long axis view; Left lower panel—estimation of RVOT VTI from transgastric RV inflow-outflow view; Right lower panel—estimation of LVOT VTI from DTG long axis view. RVOT, Right ventricular outflow tract; LVOT, Left ventricular outflow tract; VTI, Velocity time integral

  - Use of agitated saline as contrast and/or utilizing physiologic maneuvers to provoke right - to left shunting
  - Increased sensitivity for detecting a shunt
  - Usual protocol[7]:
  - Use of a large-bore intravenous (i.v) catheter, preferably in the antecubital vein
  - Preparation of contrast: either 1 mL air + 1 mL patient's blood + 8 mL normal saline or 1 mL air + 9 mL normal saline → to be mixed rapidly back and forth, using two 10 mL syringes connected *via* a three-way stopcock
  - Set a long clip length in the echocardiography system (typically 10 seconds or at least 10 cardiac cycles); views: apical four-chamber (TTE), ME bicaval/ME view between 30 and 100° with the best profiling of IAS (TEE). The use of biplane imaging increases sensitivity
  - Push the agitated saline rapidly through the i.v catheter, while recording the echocardiographic clip
  - Opacification of RA followed by LA within three to six cardiac cycles is considered indicative of the presence of PFO. Often passage of bubbles from RA to LA can be seen
  - Provocative maneuver: utilized when no shunting can be demonstrated by the procedure described above. The same steps described above are followed concurrently with the following maneuvers:

- In awake patient: Valsalva held in expiration followed by release
- In ventilated patient: Breath held in inspiration followed by release
- False positive bubble test can be present in presence of:
- Sinus venosus type or other unidentified ASD:
  - Leg vein saline injection can be tried to identify/rule out IVC type sinus venosus ASD
  - Pseudocontrast (also known as spontaneous contrast) in LA due to stagnation of blood during Valsalva
  - False negative bubble test can occur due to:
  - Inadequate opacification of RA
  - Inadequate Valsalva maneuver
  - Presence of prominent Eustachian valve:
  - Leg vein saline injection can be utilized
  - Conditions associated with increased LA pressure

## Assessment of RA and RV

A significant left-to-right shunt across ASD leads to RA and RV enlargement. Assessment and quantification of RA and RV enlargement can be done in the following views[8]:

- TTE:
  - Apical four-chamber view (recommended for RA dimension) (Fig. 15)
  - Right ventricle-focused apical four-chamber view (the best view for RV dimensions)[12]
- TEE:
  - Midesophageal four-chamber view with clockwise rotation of probe to focus on RA (for RA dimensions) and RV (for RV dimensions) (Fig. 15)

The criteria for RA and RV enlargement (adult)[12]:

- Right atrium area >18 $cm^2$
- Right atrium major dimension (length) [maximum end-diastolic RA dimension parallel to IAS] >53 cm

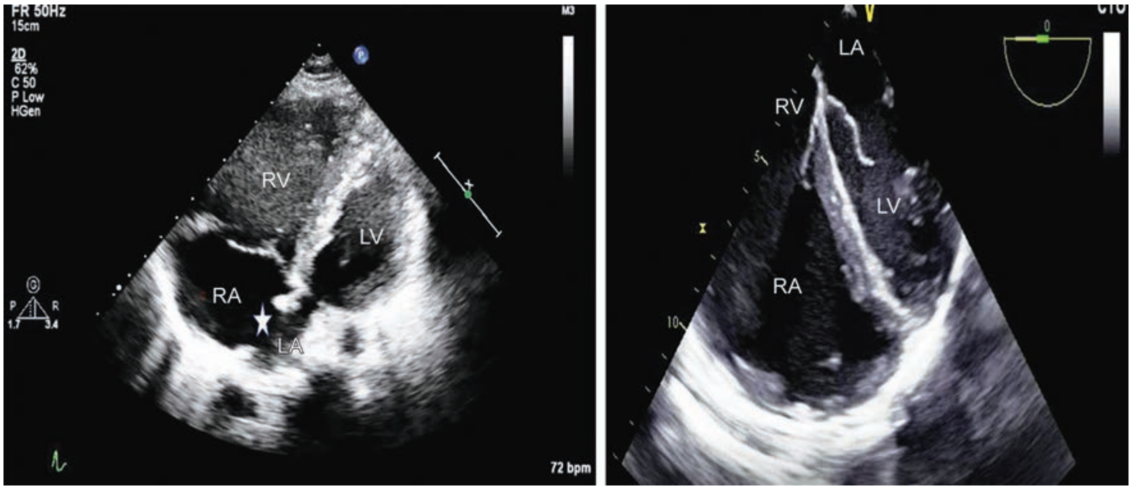


**Fig. 15:** Right ventricular enlargement seen in presence of ASD (asterisk) in the left panel—apical four-chamber view (also showing right atrial enlargement), Right panel—ME four-chamber view. LA, Left atrium; RA, Right atrium, LV, Left ventricle; RV, Right ventricle

- Right atrium minor dimension (RA diameter) [maximum end-diastolic RA dimension perpendicular to IAS] >44 mm
- Right ventricle diameter >42 mm (base), >35 mm (midlevel), and >86 mm (longitudinal)

The different available criteria and their respective cut-off values for RV systolic dysfunction are[12,13]:

- Right ventricular index of myocardial performance (RIMP): >0.4 (pulsed wave technique) and >0.55 (tissue Doppler)
- Tricuspid annular plane systolic excursion: <16 mm
- Two-dimensional fractional area contraction: <35%
- Tissue Doppler-derived tricuspid annular plane systolic velocity (S'): <10 cm/s
- Tricuspid valve dP/dT: <400 mm Hg/s
- Tissue Doppler imaging derived isovolumic myocardial acceleration: <1.0 m/s$^2$
- 3D RV ejection fraction: <45%
- Right ventricle global longitudinal strain: >–10%

Right ventricle diastolic function can be assessed using the following parameters[12,13]:

- Tricuspid valve inflow E velocity, A velocity, and E/A ratio
- Tissue Doppler derived tricuspid annular e' velocity, a' velocity, e'/a' ratio, and E/e' ratio

## Assessment of LV function

The presence of significant LV diastolic dysfunction increases LA pressure, which increases left-to-right shunt. Closure of ASD in patients with significant LV diastolic dysfunction can lead to acute pulmonary edema. Due to the presence of left-to-right shunt at the atrial level, RA and RV enlargement, the LA volume, and TR jet velocity assessments are confounded. Assessment of mitral inflow velocities and the tissue Doppler-derived mitral annular velocities are usually able to identify patients at risk of developing postclosure pulmonary edema.

## Assessment of PAH

Pulmonary arterial hypertension usually starts developing in ASD patients after 18–25 years of age and is present in more than 35% of patients of age more than 40 years. Estimation of PA pressures is an essential portion of echocardiographic assessment of ASD. The various techniques available in this purpose are[12,13]:

- Pulmonary artery systolic pressure = 4 × (peak TR jet velocity)$^2$ + estimated RA pressure (Fig. 12)
- Pulmonary artery diastolic pressure = 4 × (end pulmonary regurgitation velocity)$^2$ + estimated RA pressure
- Pulmonary artery mean pressure = 4 × (peak pulmonary regurgitation velocity)$^2$ + estimated RA pressure
- Pulmonary arterial acceleration time, the time interval from onset of RV ejection to peak flow velocity, has high sensitivity and specificity for detection of PAH, especially when measured at RV outflow tract (Fig. 13)[14]. PAAT is inversely correlated with the degree of PAH. Mean PA pressure can be estimated from PAAT, using the following equations[15]:
    - Mean pulmonary arterial pressure (PAP) = 79 – (0.45 × PAAT)
    - Mean PAP = 90 – (0.62 × PAAT) for PAAT <120 ms
    - Usually, PAAT <80 ms indicates the presence of severe pulmonary hypertension
- Although the gold standard for measurement of pulmonary vascular resistance (PVR) is catheterization study, the following equation has been shown to be moderately correlating with the catheter-based measurement of PVR:
    - Pulmonary vascular resistance = 10 × (TR jet velocity in ms$^{-1}$/RVOT VTI in cm) + 0.16 Wood unit[16]
    - An indexed PVR >8 Wood units usually preclude ASD closure

## Assessment of Pulmonary Venous Drainage

Partial anomalous pulmonary venous connection is usually associated with 85% of cases of sinus venosus type and 10–15% cases of ostium secundum type ASD.[9,10] Therefore, the pulmonary venous connections have to be checked in all cases of ASD (Fig. 16). The right- and left-sided venous drainages can be visualized ME right and left pulmonary vein views, respectively (Figs 9 and 10, Videos 10 and 11)[17]. Rotating the probe in clockwise and counterclockwise directions from ME bicaval view also visualizes the right- and left-sided pulmonary veins, respectively.

In the right pulmonary vein view, the presence of an anomalously draining right upper lobar pulmonary vein gives rise to "teardrop" appearance (Fig. 17)[18].

Color and spectral Doppler interrogation of the pulmonary venous inflows are necessary to rule out any associated pulmonary vein stenosis. Increased maximum pulmonary venous Doppler

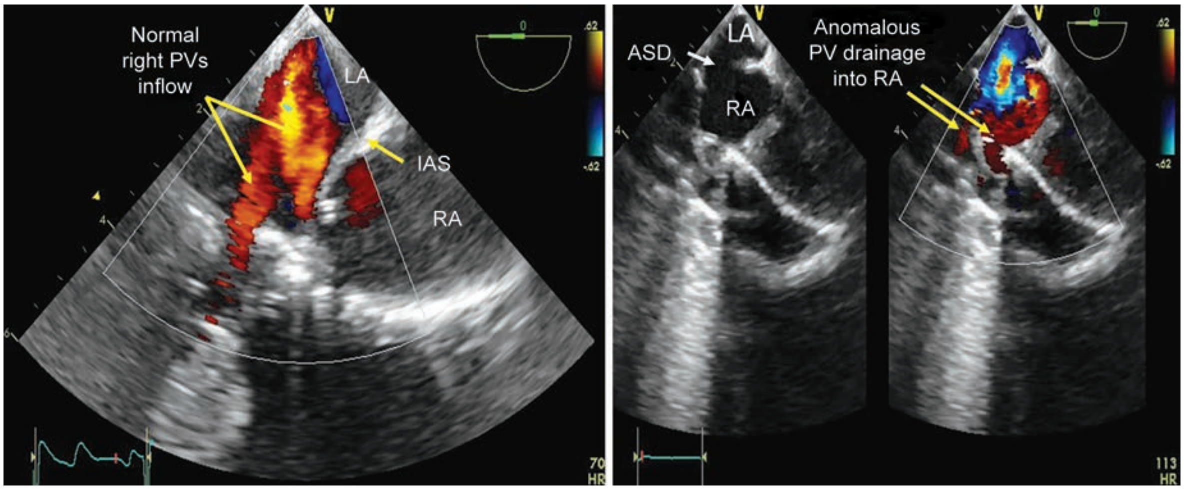


**Fig. 16:** Upper esophageal short axis view (obtained by clockwise rotation and withdrawal of probe from ME four-chamber view) showing: Left panel—normal right-sided pulmonary venous drainage into LA; Right panel—anomalous right-sided pulmonary venous drainage into RA. LA, Left atrium; RA, Right atrium, IAS, Interatrial septum; PV, Pulmonary vein

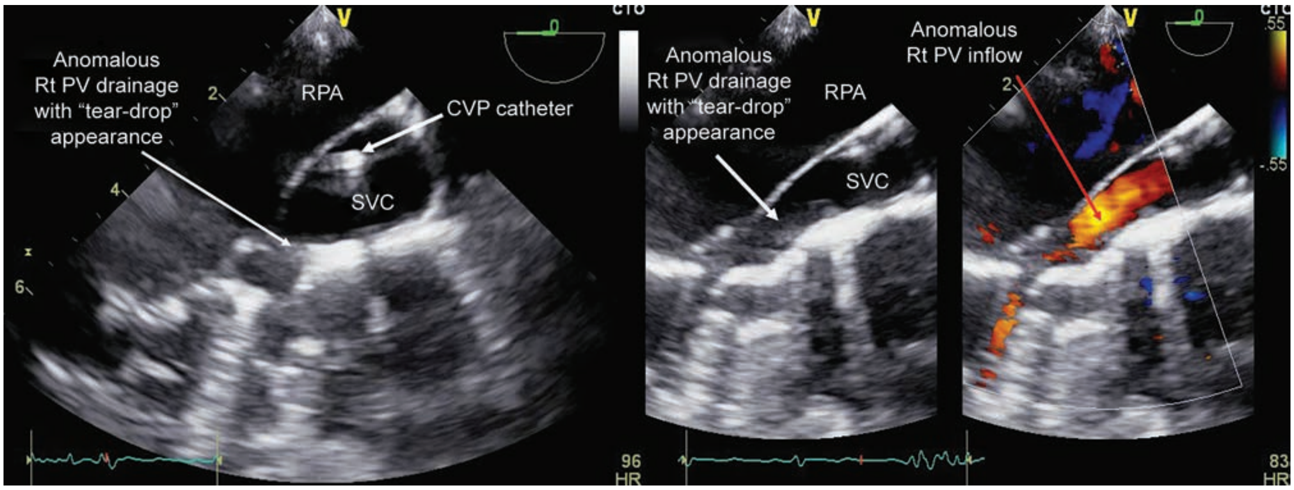


**Fig. 17:** Obtained by clockwise rotation and withdrawal of probe from ME four-chamber view to upper esophageal level showing: anomalous drainage of right upper pulmonary vein to SVC, resulting in "teardrop" appearance. SVC, Superior vena cava; RPA, Right pulmonary artery; PV, Pulmonary vein

flow velocity (>1.1 m/s) combined with color Doppler turbulence is usually a reliable index for diagnosing pulmonary vein stenosis.[17,19]

## 3D Assessment of ASD

3D assessment of ASD provides a better assessment of the following[7,19] (Videos 12 and 13):

- ASD location and type, shape, and dimensions
- Surrounding structures and rims
- Anatomy of AV valves
- Real-time procedural guidance of percutaneous ASD closure
- Visualization and management of complications of percutaneous device closure
- Detection, characterization, and management of residual shunt after surgical closure

For 3D assessment of IAS and ASD, narrow-angled, zoomed, and wide-angled acquisition of 3D data are recommended from multiple views[7,20]:

- At ME level at 0° scan angle, the probe is rotated to center the IAS/ASD. Both narrow- and wide-angled acquisitions are made
- At ME level, between 30 and 60° omniplane angle, narrow/zoomed/wide angled acquisitions are made. Can be used to generate an en face view of ASD, assess relationship to the aorta and measure the aortic rim, guide transcatheter device closure, and precise measurement of size, shape, dynamic change, flow characteristics
- Midesophageal bicaval view: adjustments of datasets allows to visualize the en face perspectives of the IAS and ASD from both the left and right atrial side
- Deep transgastric atrial septal view: same perspectives as of ME bicaval view

There are three well-described protocols for viewing the ASD in anatomically correct orientation[21,22]:

- Turn-Up-Then-Left (TUPLE) maneuver:
  - 3D zoom mode acquisition of IAS/ASD at ME 0°
  - Initial image generated in the same orientation as the corresponding 2D image (IAS in long axis)
  - Upward tilting of the image along the horizontal axis (en face view from RA side with the superior portion of ASD (SVC)

- at top of the screen and anterior portion (aortic valve and ascending aorta) along the right side of screen)
- Leftward tilting of image by 180° along the vertical axis (en face view from LA side with SVC rim at the top, aortic rim at the left side, and ostia of right pulmonary veins on the right side of the screen).

- Turn-Up-Then-Left plus Rotate-Left-in-Z-Axis (TUPLE plus ROLZ) maneuver:
  - Acquisition of initial 3D zoom mode image of IAS/ASD at ME bicaval view
  - Initial image with SVC rim at the right side of the screen
  - Tilt up along horizontal axis (en face from RA side)
  - Rotate clockwise by 90° along Z axis to obtain anatomically oriented en face view from RA side (SVC rim at the top and aortic rim at the right-hand side of screen)
  - Leftward tilting along vertical axis by 180° (anatomically oriented en face view from LA side with SVC rim at the top and aortic rim on the left side of the screen).
- Rotate-Anticlockwise-Tilt-Left for 90° (RATLe-90) maneuver:
  - Activation of 3D zoom mode at ME bicaval view, with the zoom box optimized in the lateral plane to include the ostia both of vena cava and in the elevation plane to include the aortic valve as well as the posterior atrial wall
  - Acquisition of volume, with SVC opening towards the right side of the screen
  - Anticlockwise rotation of the volume by 90°, resulting in SVC opening pointing superiorly
  - Leftward tilt of the volume by 90°, resulting in anatomically oriented en face view of the IAS from the RA perspective
  - Reduction of total gain in order to show the anatomical structures inside the RA.

## De-airing after Release of Aortic Cross Clamp

Adequate and complete de-airing of the cardiac chambers is mandatory before weaning from CPB. As air floats upwards, it is important to rule out the presence of air in the non-dependent areas of the heart before weaning from CPB. After gross air is evacuated from within the cardiac chambers, the following locations are to be looked upon specifically for being sure about complete de-airing:

- LA side of the IAS (ME 0° and ME bicaval views)
- Left atrial appendage (ME left atrial appendage view)
- Openings of all four pulmonary veins into LA (ME right and left pulmonary vein views)
- Roof of LA (ME Long axis view)
- Along anteroseptal wall of interventricular septum (ME long axis view)

It is useful to look at the descending thoracic aorta (DTA) short axis view to look for the passage of air bubbles. As long as air bubble passage can be seen through DTA, the presence of a significant amount of intracardiac air can be assumed and should lead to an extensive search for the same, especially in the non-dependent hidden locations of the heart, as mentioned above.

## Postoperative/Postprocedural Assessment after Surgical/Device Closure of ASD

The following points should be looked upon after surgical/transcatheter closure of ASD[9,10]:

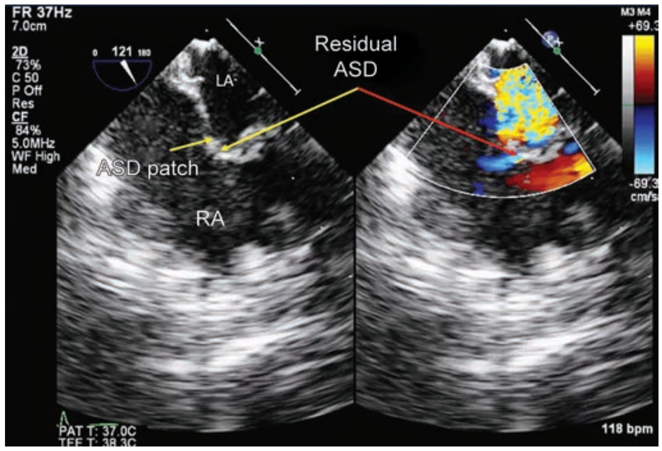


**Fig. 18:** ME bicaval view showing a small residual ASD and its flow. LA, Left atrium; RA, Right atrium

- Confirm complete ASD closure and verify absence of any residual/additional interatrial communications
- Thorough 2D, color Doppler, and spectral Doppler assessment at multiple planes (Fig. 18). Bubble contrast study is preferable for reliably excluding any residual shunt. Use of 3D as well as 3D color Doppler examination is especially useful for assessing the device/patch from multiple perspectives from both the RA and the LA side.[20]

The presence of any residual or additional interatrial communication should be immediately notified to the surgeon. A thorough examination, preferably using 3D, should be done to specify the exact location, size, and morphology of the residual/additional lesion. The hemodynamic significance of the residual/additional shunt should be determined by Qp/Qs calculation.

- After a device closure, the stability of the device and proper engagement of the device on all the rims should be confirmed. The surrounding structures, for example, pulmonary veins, aortic valve, ascending aorta, SVC, IVC, coronary sinus, tricuspid valve, and mitral valve have to be examined to rule out any obstruction/impingement of the structures by the device[10,17]
- The IVC's drainage into RA should be confirmed post ASD closure, as in presence of a large Eustachian valve, IVC can be mistakenly routed into LA during surgical closure (Fig. 19)
- Assessment of LV and RV function as well as the function of both the AV valves
- Assessment of PA pressure
- If a concomitant tricuspid valve repair has been done, assessment for residual TR is to be done along with ruling out iatrogenic tricuspid stenosis
- After an ostium primum ASD repair, the following is to be looked for specifically[10,17]:
  - Residual MR following mitral valve cleft repair. As the repair is often difficult, more than mild MR is often accepted to avoid MVR at an early age. Again, as the MR is often eccentric and/or multiple, grading is difficult. Simultaneous use of multiple qualitative and quantitative techniques is required to accurately grade the severity. Use of 3D along with color Doppler can be an extremely useful modality here
  - Assess for LV outflow tract obstruction due to acquired long tunnel-like shape of LV outflow tract, as a result of primary repair of ASD

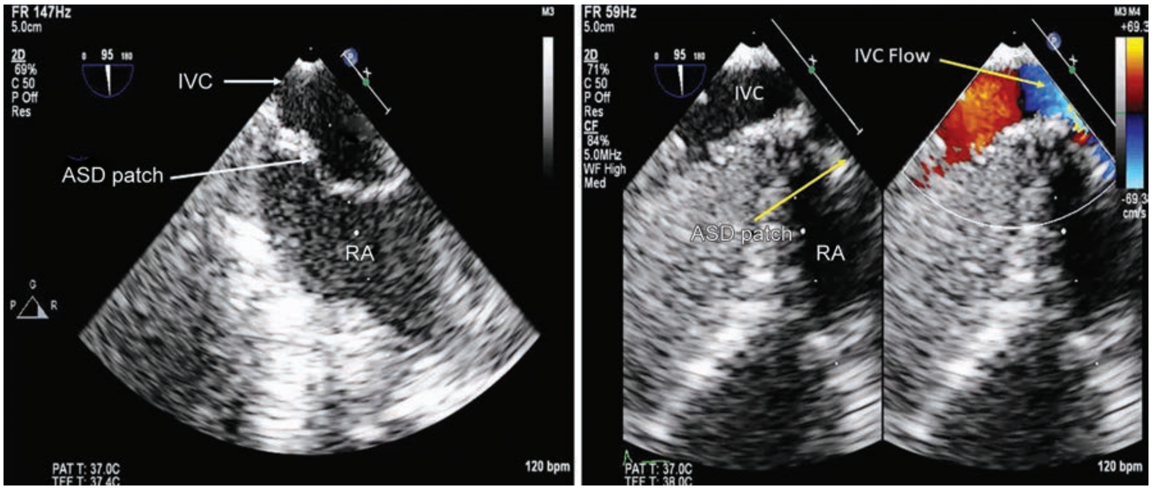


**Fig. 19:** TEE in post-CPB period showing IVC misdirection into LA. LA, Left atrium; RA, Right atrium; IVC, Inferior vena cava

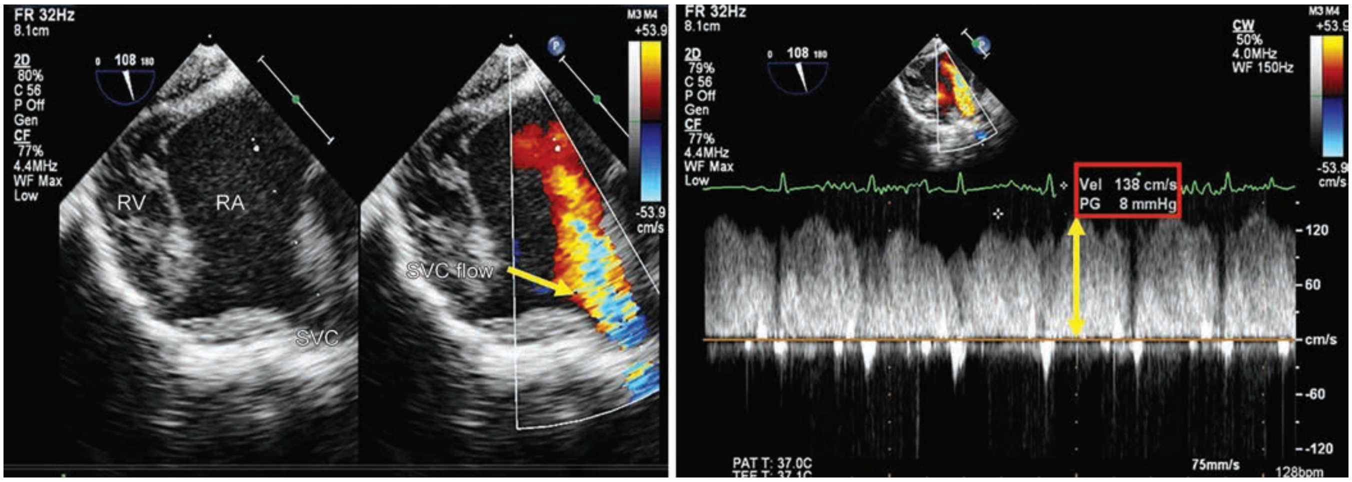


**Fig. 20:** Transgastric right ventricular inflow view in post-CPB period after sinus venosus type ASD repair shows: Left panel—turbulence in SVC inflow in color Doppler; Right panel—elevated (8 mm Hg) gradient across SVC inflow, suggestive of SVC inflow obstruction. RA, Right atrium; RV, Right ventricle; SVC, Superior vena cava

- After SVC type ASD repair, the following should be assessed specifically[10,17]:
  - Confirming the re-routing of the anomalous pulmonary veins into LA
  - Ruling out any obstruction of the re-routed pulmonary veins. Flow through the re-routed pulmonary veins should be laminar and should display a typical pulmonary venous waveform on spectral Doppler assessment. The peak gradient of re-routed pulmonary venous inflow should be <2 mm Hg to be acceptable. A higher gradient and/or failure of the venous inflow profile to touch baseline indicates significant stenosis
  - Ruling out obstruction of SVC or IVC inflow into RA, following repair of SVC and IVC type sinus venosus ASD, respectively. Obstruction is to be suspected in presence of turbulent color Doppler flow at the cavo-atrial junction in ME bicaval view. The SVC inflow can be aligned parallel to the Doppler beam in DTG atrial septal view and transgastric RV inflow view—this allows spectral Doppler interrogation of the same. The acceptable peak gradient across the SVC-RA junction is <5 mm Hg. Loss of biphasic pattern of SVC inflow is said to have a more indicative value for obstruction (Fig. 20)[10,17]
- After coronary sinus ASD closure, closure of the coronary sinus ostium is to be confirmed in patients without LSVC. In patients with an LSVC with unroofed coronary sinus, the drainage of CS into RA and the closure of communication between coronary sinus and LA is to be confirmed

## Conclusion

Perioperative transthoracic and TEE help in establishing and confirming the diagnosis, diagnosing other associated lesions, formulating a surgical plan, periprocedural guidance, evaluation of surgical/procedural repair, detection of residual lesion, and perioperative hemodynamic management. Use of 3D echocardiography may be additionally helpful for the guidance of surgery and/or transcatheter procedures.

Video 1: Subcostal four-chamber color compare view showing ASD (yellow arrow—left panel) and its shunting (yellow arrow—right panel). LA, Left atrium; RA, Right atrium; LV, Left ventricle; RV, Right ventricle

Video 2: Subcostal sagittal view with color compare (left panel) and its Mirror image view with color compare (right panel), showing ASD (yellow arrow in left subpanels) and its shunting (yellow arrow right subpanels). LA, Left atrium; RA, Right atrium; RV, Right ventricle

Video 3: Apical four-chamber view showing ASD (Yellow arrow). LA, Left atrium; RA, Right atrium; RV, Right ventricle

Video 4: Parasternal aortic valve short axis view showing ASD (Yellow arrow). LA, Left atrium; RA, Right atrium; RV, Right ventricle, AoV, Aortic valve; RVOT, Right ventricle outflow tract

Video 5: Upper esophageal short axis view (obtained by clockwise rotation and withdrawal of probe from ME four-chamber view) showing a sinus venosus type of ASD (yellow arrow). LA, Left atrium; RA, Right atrium; IAS, Inter atrial septum

Video 6: ME aortic valve short axis view showing ASD (yellow arrow). LA, Left atrium; RA, Right atrium; AoV, Aortic valve

Video 7: ME four-chamber color compare view showing an ostium primum type of ASD (yellow arrows). LA, Left atrium; RA, Right atrium; RV, Right ventricle

Video 8: ME bicaval color compare view showing ostium secundum type of ASD (asterisk) and its shunting (arrow). LA, Left atrium; RA, Right atrium; SVC, Superior vena cava

Video 9: DTG atrial septal view. Left panel—in presence of intact atrial septum, showing the opening of the SVC and IVC. Right panel—in presence of ASD, showing the ASD and its shunting (yellow arrows) and the SVC flow. LA, Left atrium; RA, Right atrium; SVC, Superior vena cava; IVC, Inferior vena cava; IAS, Inter atrial septum

Video 10: Apical four-chamber view showing both right- and left-sided pulmonary venous drainage into LA. LA, Left atrium; RA, Right atrium; LV, Left ventricle; RV, Right ventricle; PV, Pulmonary vein

Video 11: Left panel—view obtained by clockwise rotation and withdrawal of probe from ME four-chamber view showing secundum type ASD (asterisk) and right-sided pulmonary venous inflow; Right panel—view obtained by counterclockwise rotation and withdrawal of probe from ME four-chamber view showing left-sided pulmonary venous inflow from behind the Coumadin ridge. RA, Right atrium; LA, Left atrium; PV, Pulmonary vein, LV, Left ventricle; LAA, Left atrial appendage

Video 12: 3D video clip oriented to image interatrial septum from left atrial side showing ASA and the ASD

Video 13: 3D video clip oriented to image interatrial septum from right atrial side (after performing RATLe-90 maneuver) showing ASD and entry of SVC into RA. SVC, Superior vena cava; RA, Right atrium

## Supplementary Material

The supplementary Video 1-13 are available online on the website of www.jpecardio.com

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