Transesophageal Echocardiography

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Introduction

From its introduction into clinical practice in the early seventies using monoplane probes to the development of real three-dimensional (3D) imaging technology, transesophageal echocardiography (TEE) (Fig. 1) has gain a key role in the perioperative and acute care settings. The decreased in cost of TEE probes, the availability of single used ones and the increased availability of portable more affordable Ultrasound (US) systems has contributed to the spread of this imaging modality outside Cardiology and Cardiac Anesthesia. Nevertheless, the availability of image storage systems and expertise among anesthesiology and critical care physicians still constitutes the main burden for further spread of this imaging modality.

TEE (Figs. 2 and 3) has become standard of care in the intraoperative management of patients undergoing cardiac surgical procedures. In the hand of cardiac anesthesiologists, it is used to confirm indication, to guide surgical and catheter-based intervention, to assess results and to monitor hemodynamics [1, 2]. This requires advanced TEE competences, typically acquired through a Cardiac anesthesia fellowship and subsequent Board Certification and imply performing a comprehensive intraoperative examination. A simplified TEE examination has also

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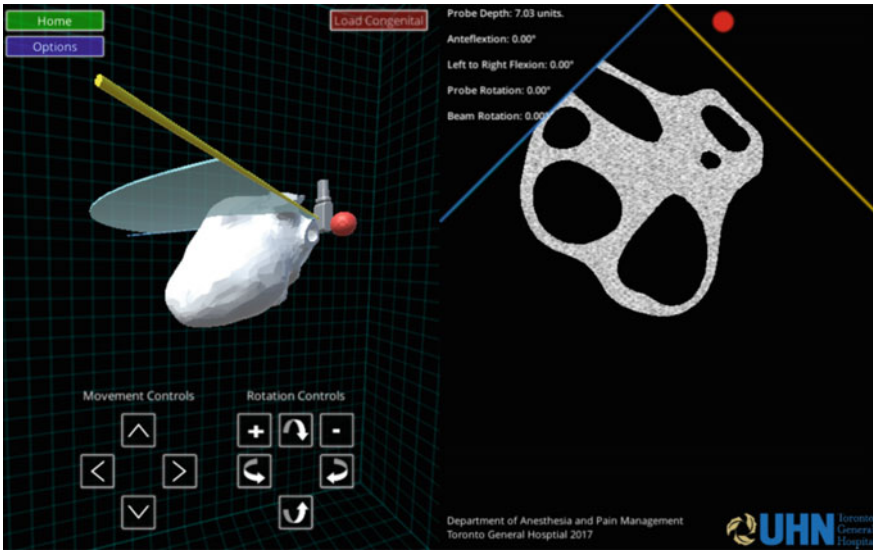


Fig. 1 On-line TEE simulator displaying (on the left) a 3D rendering of the TEE probe head, the ultrasound scanning plane and the heart. On the right is a simulation of the ultrasound imaging. (https://apil.ca/echocardiography-simulator/)

been defined to be used outside of cardiac surgery as a "basic" TEE examination [3] (Fig. 1) to define gross structural and functional cardiac abnormalities and provide hemodynamic monitoring. Furthermore, Focused TEE, including only five views, has been successfully introduced in emergency medicine as an effective tool to answer dichotomous questions and guide treatment in hemodynamically unstable patients [4]. Each application of TEE in the intraoperative or acute care setting mandate clear definition of scope of practice that include indication, imaging protocol, training pathway and quality assurance. In this chapter we will provide a practical overview of intraoperative Advanced and Basic TEE for novices.

Probe Manipulation and Standard Views

The TEE probe has been developed by integrating a single line of piezoelectric crystals on the tip of a gastroscope. The TEE probe head is a phased array that generated a single 2D pie-shaped US scanning plane, similarly to transthoracic echocardiography (Fig. 2). Different TEE scanning planes were obtained by rotating the probe right and left, withdrawing and advancing the probe in the esophagus. The probe's tip can be anteflexed, retroflexed, bent right and left bending, through the knobs of a gastroscope. TEE probes also allow to rotate the scanning plane clockwise (if facing the probe) by increments of one degree from 0

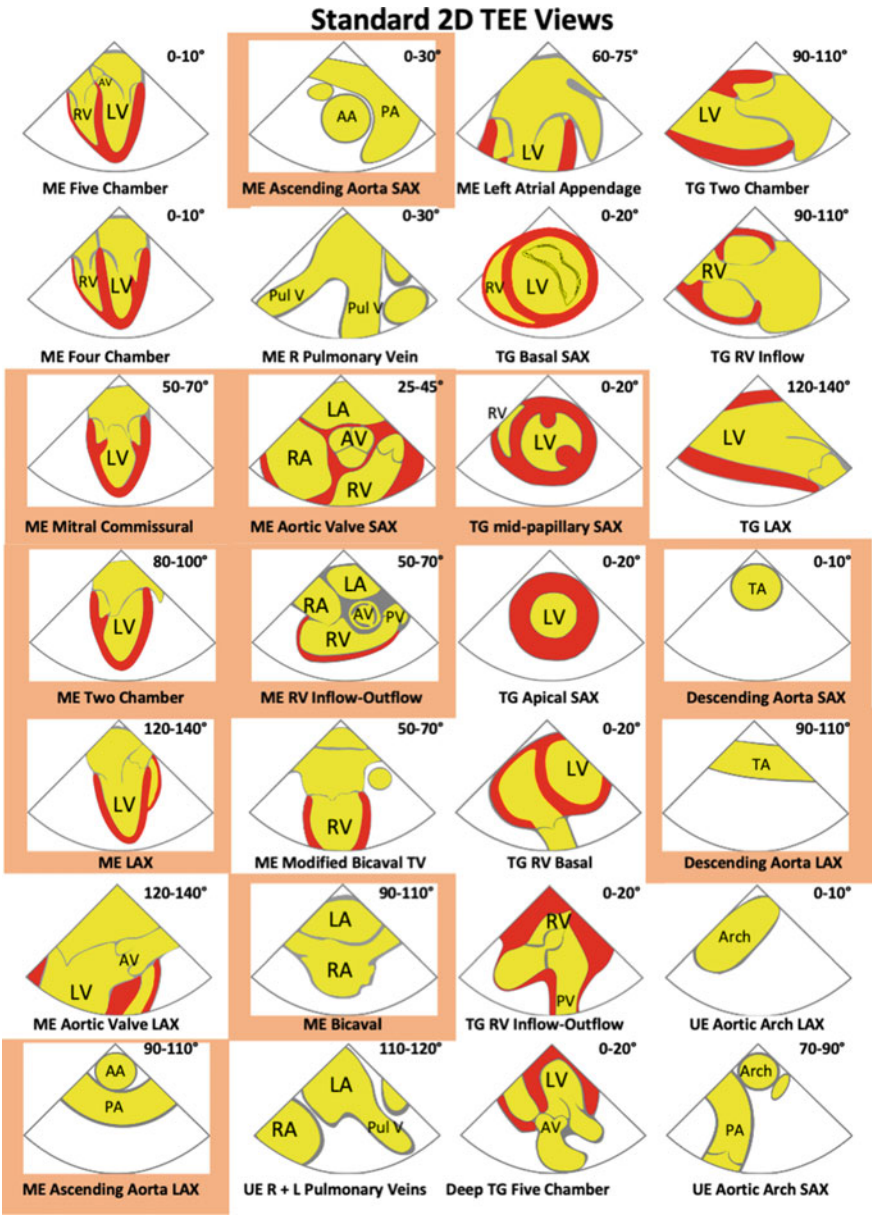


Fig. 2 28 Standard TEE View. The 11 Basic views are highlighted. ME: Mid Esophageal; UE: Upper esophageal; TG: Trans gastric; SAX: Short Axis; LAX: long Axis; LV: Left Ventricle; RV: Right Ventricle; AV: Aortic Valve; AA: Ascending Aorta; PA: Pulmonary Artery; Pul V: Pulmonary vein; LA: Left Atrium; RA: Right Atrium; PV: Pulmonic Valve; TA: Thoracic Aorta; TV: Tricuspid Valve; Arch: Aortic Arch

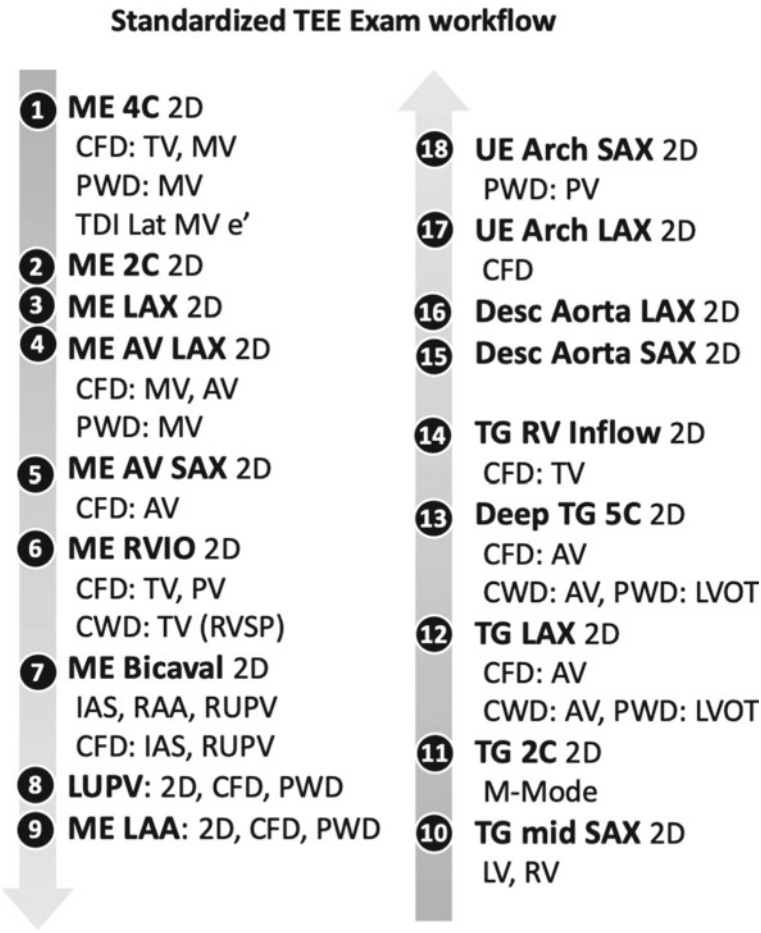


Fig. 3 TEE examination workflow. ME: Mid Esophageal; 4C: Four chambers; CFD: Color Flow Doppler; PWD: Pulsed Wave Doppler; TDI: Tissue Doppler; Lat: Lateral; E′: E′wave; 2C: Two Chambers; RVIO: Right Ventricle Inflow-outflow; RVSP: Right Ventricular Systolic pressure; CWD: Continuous Wave Doppler; IAS: Interatrial Septum; RAA: Right Atrial Appendage; RUPV: Right Upper Pulmonary Vein; LUPV: Left Upper Pulmonary Vein; LAA: Left Atrial Appendage; Arch: Aortic Arch; Desc: Descending; 5C: Five Chambers; LVOT: Left Ventricular Outflow Tract; UE: Upper esophageal; TG: Trans gastric; SAX: Short Axis; LAX: long Axis; LV: Left Ventricle; RV: Right Ventricle; AV: Aortic Valve; AA: Ascending Aorta; PA: Pulmonary Artery; LA: Left Atrium; RA: Right Atrium; PV: Pulmonic Valve; Aorta; MV: Mitral Valve; TV: Tricuspid Valve

to 180°, where 180° would be a mirror image of 0. A single line of 64–128 Ultrasound crystals is rotated by an eclectically powered motor. Modern TEE probes utilize Matrix arrays where the piezoelectric crystals are organized in a checkerboard of 50 by 50 micro elements in less than a centimeter square. Matrix arrays can generate a single or simultaneous two-dimensional US scanning planes.

The scanning planes are rotated electronically by activating different lines of crystals without any mechanically moving parts. These probes also generate real-time 3D images.

The TEE probe is introduced into the esophagus and advanced to the stomach. Through this path the probe's tip can be moved from the aortic arch to the apex of the left ventricle (LV).

Images of the heart are obtained at four levels: upper-esophageal (above the aortic valve), mid-esophageal (at the level of the left atrium), trans-gastric (in the stomach), deep trans-gastric (at the level of the LV apex). At any given level right and left rotation, as well as change in the scanning plane angle allows to obtain infinite cuts of the heart. Three basic movements (insert/withdraw, turn right/left and angle change) with anteflexion when the probe is advanced into the stomach allow navigation through all of the standard views (Fig. 4). In order to set a standardization and comparison between studies a number of standard cutting planes have been defined for a complete TEE exam [2]. A comprehensive exam includes 28 scanning planes, a basic 11 [3] and a focused 5 (Fig. 1).

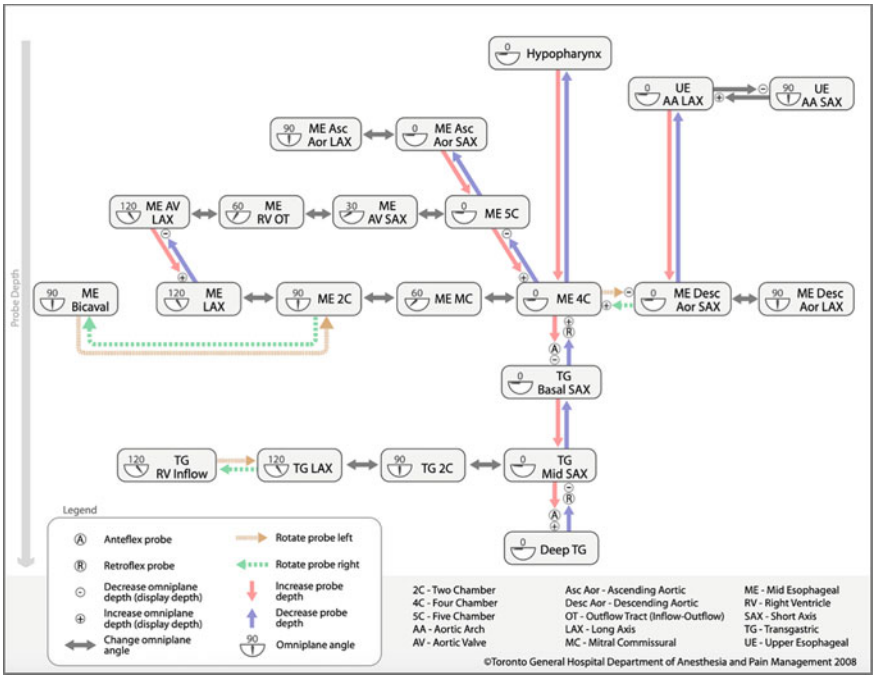


Fig. 4 Navigation between view (www.pie.med.utoronto.ca)

Safety and Indications

Although routinely performed, intraoperative TEE is relatively invasive and carries a risk of overall complication of 0.2%. The majorities of reported complications are mechanical and are related to the introduction and the manipulation of the probe. The most feared one is an esophageal perforation, that occurs between 0 and 0.3% of cases and carries a very high morbidity and mortality. Other complications include: dental damage, oral bleeding, endotracheal tube displacement, postoperative dysphagia and dysphonia. Absolute contraindications for TEE are: perforated viscus, esophageal strictures/perforation/tumor/diverticulum and active esophageal bleed. Hiatus hernia, esophageal/gastric surgery, esophagitis, coagulopathy are considered only relative contraindications [2].

The indication for an intraoperative TEE exam [2] varies depending on the type of exam. According to the American guidelines, a comprehensive intraoperative TEE exam is indicated in all types of open-heart surgeries, in some coronary artery bypass surgeries and in non-cardiac surgery when the patient is known to have cardiac pathology. TEE is also indicated when TTE to guide transcatheter cardiac interventional procedures such as interatrial septal and left atrial appendage closures, valve implantation and clipping. Basic TEE exam is indicated on a case-to-case base to qualitatively assess left ventricular function, wall motion abnormalities, right ventricular function, pulmonary embolism, pericardial effusion, thoracic trauma, gross valvular abnormalities and air in course of neurosurgical procedures [3]. TEE is finally indicated outside the operating room whenever transthoracic echocardiography provided suboptimal images.

Left Ventricular Function

Assessment of LV function remains one of the most common indications for the use of TEE in and outside the operating room. Assessment of LV includes assessment of LV morphology, size, global and regional systolic and diastolic function. Assessment of diastolic dysfunction by TEE is complex and has at the moment minimal impact in clinical decision making in the operating room therefore will be omitted in this chapter. The LV has a grossly oval shape that can be simplified to the geometrical shape of an ellipsoid. It has four walls: anterior, inferior, septal and lateral and is divided into three segments from the base to the apex (basal, mid and apical) plus an apical cap (Fig. 5). The septal and lateral segments at the basal and mid-level are further divided into antero/infero septal and antero/infero lateral. These altogether with the apical cap constitute the 17 segments. For a full assessment of wall motion abnormality all 17 segments must be evaluated. This requires a minimum of three TEE views: mid esophageal four chamber (ME4C), mid esophageal two chamber (ME2C) and mid esophageal long axis (MELAX) [5].

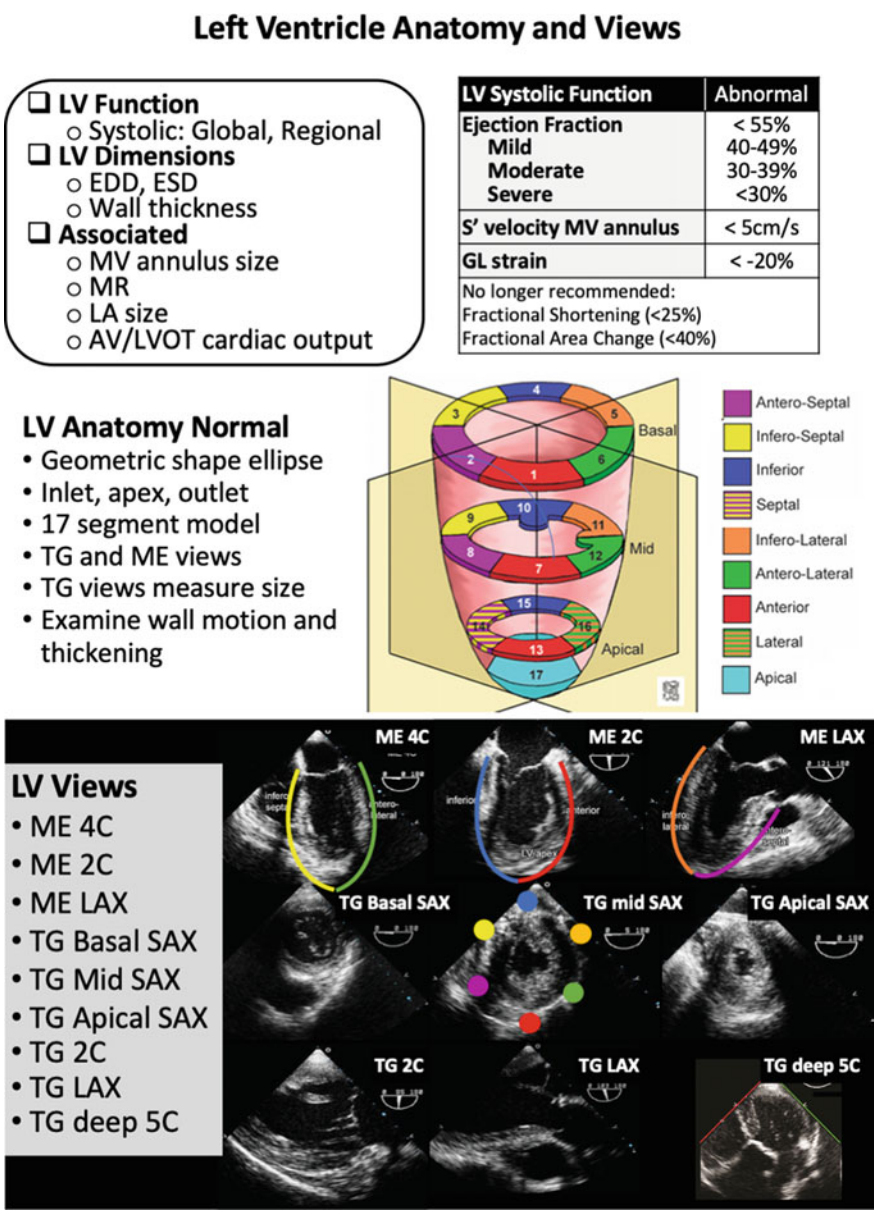


Fig. 5 Left Ventricular Anatomy and Views. LV: Left Ventricle; EDD: End Diastolic Diameter; ESD: End Systolic Diameter; MV: Mitral Valve; MR: Mitral Regurgitation; LA: Left Atrium; AV: Aortic Valve; LVOT: Left Ventricular Outflow Tract; S': S' Doppler Wave; GL: Global Longitudinal; ME: Mid-Esophageal; TG: Trans Gastric; 4C: Four Chambers; 2C: Two Chambers; SAX: Short Axis; LAX: Long Axis; 5C: Five Chambers

It is important to optimize each of these views to make the endocardium and the epicardium visible to assess myocardial contractility and cut through the true apex of the heart to avoid LV foreshortening. The LV contraction results in the displacement of the mitral valve (MV) and the base towards the apex therefore the latter remain relatively still. Movement of the apex means that the view is cutting through the lateral wall and not the real apex therefore resulting in foreshortening of the LV chamber. For each segment we need to assess systolic thickening of the myocardium resulting in displacement of the endocardium towards the center of the ventricle. Reduced thickening in comparison to adjacent segment is defined as hypokinesis, lack of movement as akinesia and outward movement as dyskinesia. New onset of hypo/akinesia typically represent coronary ischemia. Each of the mid-esophageal views only allow assessment of two coronary territories at each time. The trans-gastric midpapillary short axis view (TG mid SAX) displays all three coronary territories at the mid papillary level at the same time. For this reason, this view is the view of choice for monitoring myocardial ischemia. Automatic endocardial detection and speckle tracking strain further enhance the ability to assess wall motion abnormalities by simple eyeballing.

LV diameter is measured in the trans-gastric long axis view (TG LAX) at the level of the papillary muscle tips. Normal values are approximately <5 cm. LV thickness is measured in the TG mid SAX at the septum and the inferolateral walls, normal values are approximately <1 cm. LV chamber dilatation and hypertrophy (thickness > 1) are always the result of a chronic process which etiology should be identified.

Quantification of LV function (Fig. 6) relies on measurement of ejection fraction (EF). EF is the ratio of LV stroke volume (SV) and LV end diastolic volume (EDV). In order to estimate volumes from 2D LV cuts we use two perpendicular views (ME 4C and ME 2C) and assume the LV is a stack of disks constituting an ellipsoid. Modern echocardiographic system simply require manual tracing of the endocardium in systole and diastole in these two views and the LV volume is automatically calculated. Speckle tracking technology further simplifies this process by automatically identifying the blood-tissue interface. As previously mentioned, the LV systolic contraction results in the displacement of the MV towards the apex of the heart. The velocity of systolic displacement of the MV annulus is directly related to the strength of LV contraction. Tissue doppler is a technology that uses the Doppler signal to quantify the movement of the cardiac tissues. In the ME 4C the velocity of displacement of the lateral MV annulus can be measured and provides a reliable estimation of global LV function.

Finally, speckle tracking strain is a semi-automated technology that allows following the grey speckles within the myocardium to quantify their movement in respect to each-others. When we follow the movement of two speckles at the proximal and at the distal end of each LV segment in any mid-esophageal view, we can detect the shortening of the longitudinal myocardial fibers. In systole the base of the heart moves towards the apex and the longitudinal fibers shorten resulting in a negative strain value that can also be expressed as an absolute percentage. Different strain values for adjacent LV segments would detect wall motion abnormalities while the average longitudinal strain (global longitudinal strain) correlates with LVEF.

Left Ventricle Size and Systolic Function

LV Size	Female				Male			
Diameter Index (diameter/BSA)	Refer. range	Mild	Moderate	Severe	Refer. range	Mild	Mod	Severe
Diastole, cm	3.8-5.2	5.3-5.6	5.7-6.1	**> 6.2**	4.2-5.8	5.9-6.3	6.4-6.8	**> 6.8**
Diastole index, cm/m^2	2.2-3.1	3.2-3.4	3.5-3.7	**> 3.7**	2.2-3.0	3.1-3.3	3.4-3.6	**> 3.6**
Systole, cm	2.2-3.5	3.6-3.8	3.9-4.1	**> 4.1**	2.5-4.0	4.1-4.3	4.4-4.5	**> 4.5**
Systole index, cm/m^2	1.3-2.1	2.2-2.3	2.4-2.6	**> 2.6**	1.3-2.1	2.2-2.3	2.4-2.5	**> 2.5**
LV volume								
Diastolic, mL	46-106	107-120	121-130	**> 130**	62-150	151-174	175-200	**> 200**
Diastolic index, mL/m^2	29-61	62-70	71-80	**> 80**	34-74	75-89	90-100	**> 100**
Systolic, mL	14-42	43-55	56-67	**> 67**	21-61	62-73	74-85	**> 85**
Systolic index, mL/m^2	8-24	25-32	33-40	**> 40**	11-31	32-38	39-45	**> 45**

Simpson's (EF)
- Acquire 2D ME 4C + 2C
  - Increase gain to highlight endocardial border
- Use software to trace endocardial border in S and D
  - Identify LV apex
  - Exclude papillary muscles
- Obtain EDV, ESV, stroke volume, EF

Speckle Tracking (EF)
- Acquire 2D ME 4C + 2C, FR > 50Hz, similar HR
  - Increase gain to highlight endocardial border
- Use software (2DQ)
  - Identify MV annular and LV apex points
- Software automatically tracks, edit if needed
- Obtain EDV, ESV, stroke volume, EF

S' velocity MV lateral annulus
- ME 4C use TDI pre-set
- Narrow sector, TDI color to identify myocardium
- PW Doppler on myocardium below annulus
- Obtain spectral trace and measure S' velocity

Global Longitudinal Strain (GLS)
- Acquire 2D ME views (4C, 2C, LAX)
- Open CMQ software
- Position points at mitral annulus + LV apex
- Software automatically tracks, edit if needed
- Display bull's eye for regional and GLS

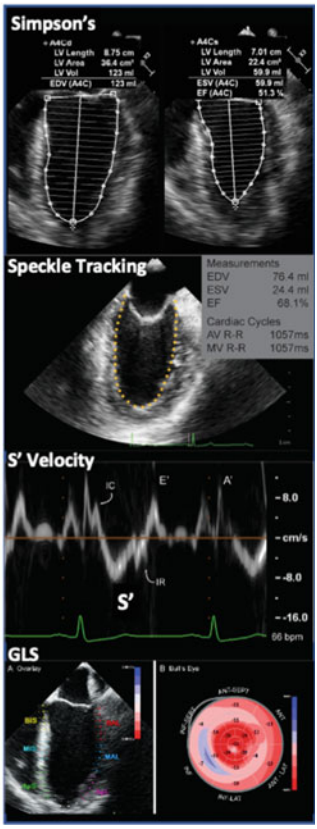


Fig. 6 Left Ventricular Size and Sunction. BSA: Body Surface Area; LV: Left Ventricle; EF: Ejection Fraction; ME: Mid-Esophageal; 4C: Four Chambers; 2C: Two Chambers; LAX: Long Axis; MV: Mitral Valve; EDV: End Distolic Volume; ESV: End Systolic Volume; GLS: Global Longitudinal Strain

Right Ventricular Function

The right ventricle (RV) (Fig. 7) wraps anteriorly around the conical LV. Its shape is irregular: triangular in the coronal plane (ME 4C) and a crescent in the transverse plane (TG mid SAX). Typical anatomical features of the RV are: the attachment of the septal leaflet of the tricuspid valve (TV), presence of a muscle bundle across the apex (moderator band) outflow into the pulmonary artery (PA).

It comprises three portions: the inflow under the tricuspid valve (TV), the apex and the outflow under the pulmonic valve (PV). In the ME 4C the RV appears smaller than the LV and the cardiac apex belongs to the LV. In case of moderate dilatation the RV is as big as the LV and bigger then the LV in case of severe dilatation. The RV diameter is measured at mid ventricle in the ME 4C view. The RV is the only chamber of the heart that can dilate as a result of an acute process. To distinguish between acute and chronic dilatation we need to evaluate right ventricular wall thickness and right atrial (RA) size. RV hypertrophy (thickness in ME 4C, one cm below the TV > 5 mm) and RA dilatation (RA bigger than left atrium) indicate a chronic process. RV dilatation can also be observed in the TG mid SAX where dilatation of the RV would result into flattening of the interventricular septum. Flattening of the septum can occur only in one phase of the cardiac cycle. Systolic flattening would indicate pressure overload (e.g. pulmonary hypertension, PV stenosis or pulmonary embolism), diastolic flattening volume overload (PV insufficiency).

RV contraction results in a displacement of the TV annulus towards the apex, inward movement of the RV free wall and contraction of the outflow. While RV EF can only be measured using 3D TEE, RV function is typically quantified on partial measures such as the displacement of the TV annulus or the percentage change of the coronal plane (Fig. 8) [5].

Tricuspid annular plane systolic excursion (TAPSE) measures the displacement of the lateral TV annul towards the apex in systole. It is measured in the ME 4C using anatomical M Mode (not available on all echo systems) and positioning the M Mode cursor along the RV free wall through the RV apex. Normal values are >1.7 mm. RV fractional area change (FAC) is also measured in the ME 4C by tracing the RV endocardium in end systole and end diastole. Speckle tracking technology allow to trach the myocardial speckles in the free wall of the RV and determine the percentage of shortening of the Myocardial fibers along the RV free wall. Similar to the LV, we observe a shortening of the myocardial fibers in Systole that result in a negative strain value. RV free wall strain seems to allow a more sensitive quantification of RV function. All the above measures of RV function only provide a qualitative assessment that allow classification into normal and abnormal.

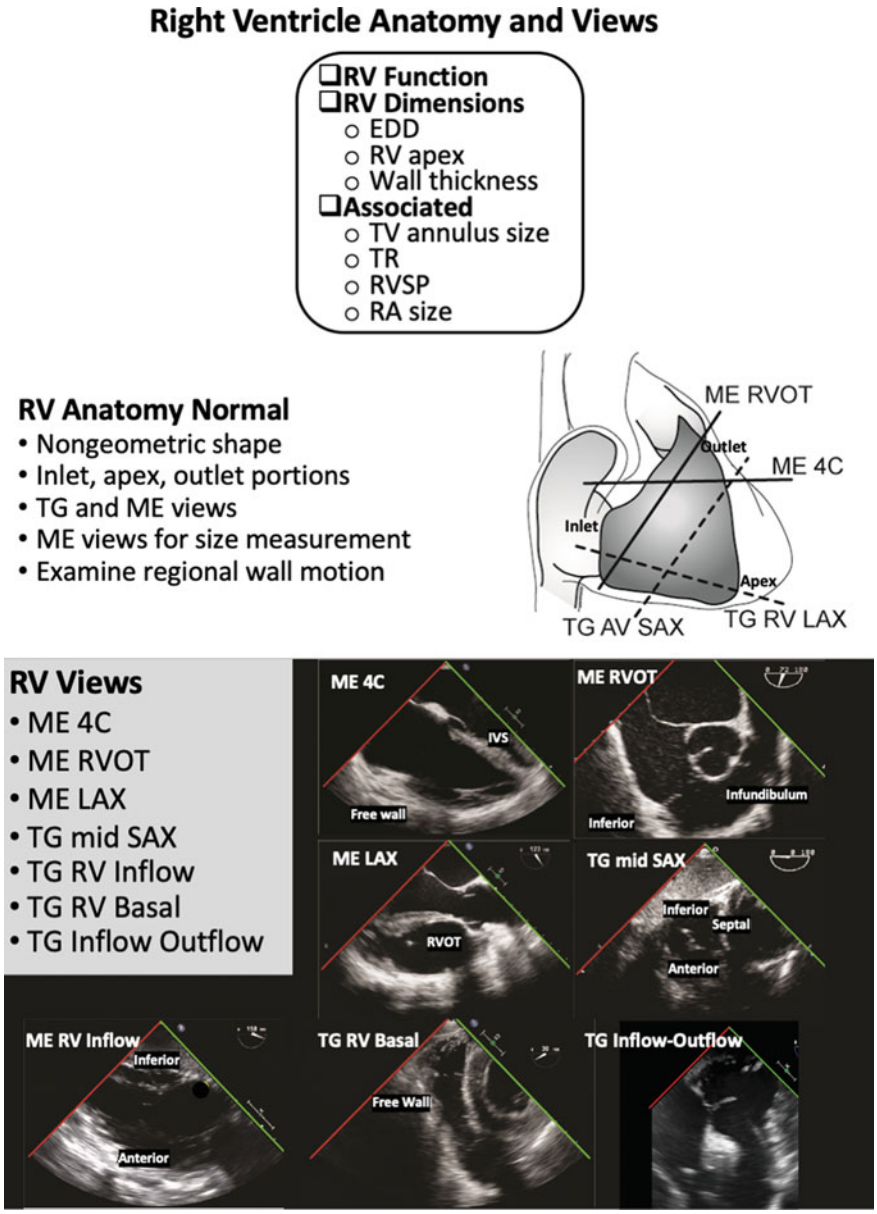


Fig. 7 Right Ventricular Anatomy and Views. RV: Right Ventricle; EDD: End Diastolic Diameter; TV: Tricuspid Valve; TR: Tricuspid Regurgitation; RVSP: Right Ventricular Systolic Pressure; RA: Right Atrium; ME: Mid Esophageal; TG: Trans Gastric; 4C: Four Chambers; RVOT: Right Ventricle Inflow outflow; LAX; Long Axis, SAX: Short Axis; AV: Aortic Valve

Right Ventricle Function and Size

Parameter [Ref 2]	Abnormal
FAC	< 35%
TAPSE	< 17 mm
S' Velocity TV annulus	< 9.5 cm/s
GLS Free Wall	< -20

Measures (mm)	Abnormal
EDD Basal (ME 4C)	> 42
EDD Mid (ME 4C)	> 35
Wall Thickness (TG)	> 5

Fractional Area Change (FAC)
- Acquire 2D ME 4C rotate to show RV
  - Increase gain (endocardium)
  - Retroflex (RV apex)
- Trace endocardial border to TV annulus in S + D
  - Exclude papillary muscles
  - Obtain ED and ES areas
- Calculate **FAC = EDA – ESA / EDA**

Speckle Tracking FAC
- Acquire 2D ME 4C view of RV as above
- Use software (2DQ)
  - Change to area from volume measurement
  - Mark points TV annulus + RV apex
- Software tracks RV area, display FAC
  - Edit if needed to track endocardium

Tricuspid Annular Plane Systolic Excursion (TAPSE)
- Acquire 2D ME 4C view of RV
  - Narrow sector size to TV lateral annulus
- Activate m-mode sample line
  - Align parallel to annular movement
  - Use anatomic m-mode (if available)
- Measure TAPSE
  - Identify similar lower + upper portions

Global Longitudinal Strain (GLS) Free Wall
- Acquire ME 4C 2D view of RV
- Activate CMQ pre-set
  - Mark points TV annulus + RV apex
- Software automatically tracks, edit if needed
  - Obtain GLS that includes IVS
  - Edit to eliminate the IVS for GLS free wall

S' Velocity TV lateral annulus
- TG RV LAX as difficult alignment in ME 4C
- Activate TDI
  - Use TDI color to identify myocardium
- PW Doppler
  - Sample volume on myocardium parallel to motion
- Obtain spectral trace
- Measure S' velocity

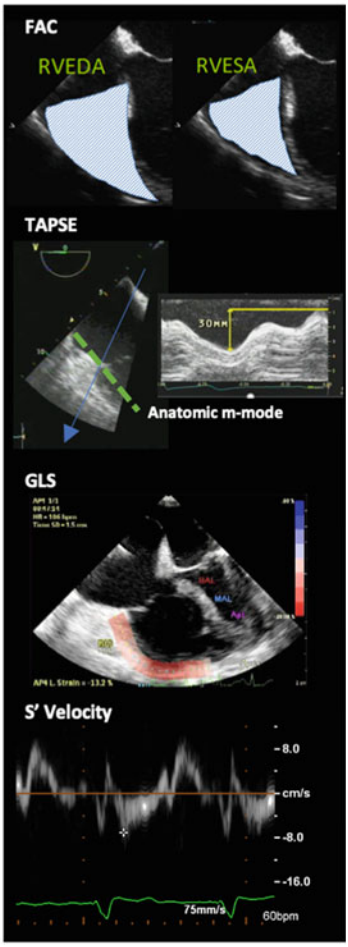


Fig. 8 Right Ventricular Function and Size. RV: Right Ventricle; FAC: Fractional Area Change; TAPSE: Tricuspid Valve Annular Plane Systolic Excursion; S': S' Doppler wave; TV: Tricuspid Valve; GLS: Global Lungitudinal Strain; ME: Mid Esophageal; 4C: Four Chambers; EDA: End Diastolic Area; ESA: End Systolic Area; TG: Trans Gastric; LAX: long Axis; TDI: Tissue Doppler

Aortic Valve

The aortic valve (AV) (Fig. 9) comprises three cusps that correspond to the three sinuses: left, right and non-coronary. The most anterior cusp is the right which explains the risk of right coronary air embolism in a supine patient. The non-coronary cusp is adjacent to the interatrial septum and the left in between. The AV annulus is in close proximity to the posterior MV and to the anterior PV annulus. The PV annulus is rotated 90 degrees in respect to the AV therefore when one is displayed in its short axis the other is in the long axis and vice versa. The only exception is transposition of the great arteries when these valves are on the same plan. The AV functions within a complex of structures that includes: the left ventricular outflow tract, the AV annulus, the AV cusps, the aortic sinuses and the sino-tubular junction (STJ). Alteration of any of these structures would result in AV pathology. Assessment of the AV involves measurement of AV size, leaflet morphology, leaflet function and flow across the valve. The mid-esophageal AV long axis view (ME AV LAX) is the best view to assess leaflet morphology and for measurements. The LVOT and AV annulus should be measured in mid Systole while the aortic sinuses and STJ at end diastole. In the ME AV LAX the more distal, lower cusp is invariably the right while the upper cusp can be the non or the left. In order to obtain the widest AV annular diameter slight movement right and left would allow to cut in the commissure between the non and the left cusps that can be identified by poor definition of the upper cusp. Aortic cusp calcification is typical of degenerative aortic stenosis (AS) it appears as hyperechoic bright cusps that cast a dark shadow and have limited movement. By subtracting 90 degree to the scanning plane of ME AV LAX we can obtain a short axis view of the AV in the mid-esophageal AV short axis view (ME AV SAX) which displays all three cusps and allows tracing the AV opening in systole to estimate aortic valve area. This measure is though not very precise due to the geometry of the AV opening therefore does not constitute the gold standard.

The AV flow cannot be measured in the middle-esophageal views because it is perpendicular to the ultrasound (US) beam therefore, we can only use qualitative color flow Doppler (CFD) assessment. In order to position the Doppler beam though the LVOT and the AV we need to advance the probe in the stomach [6]. CFD is used to quantify the degree of aortic insufficiency (AI) [7] by measuring the width of the regurgitant jet right below the AV (Vena Contracta) which is also further compared to the LVOT diameter. The deep trans-gastric 5 chamber view (DTG) is obtain by advancing the probe deep in the stomach and apply anteflexion. Alternatively, the trans gastric log axis view can be used. It typically allows the best alignment of the doppler beam with the blood flow through the AV. Continuous wave Doppler (CW) is used to assess the flow through the AV and pulse wave Doppler to assess the flow though the LVOT. Based on the principle of conservation of mass the same SV flows through each portion of the heart therefore the SV in the LVOT be the same as through the AV. The SV is the cylinder of blood which base is the LVOT cross-sectional area and the height is the velocity time

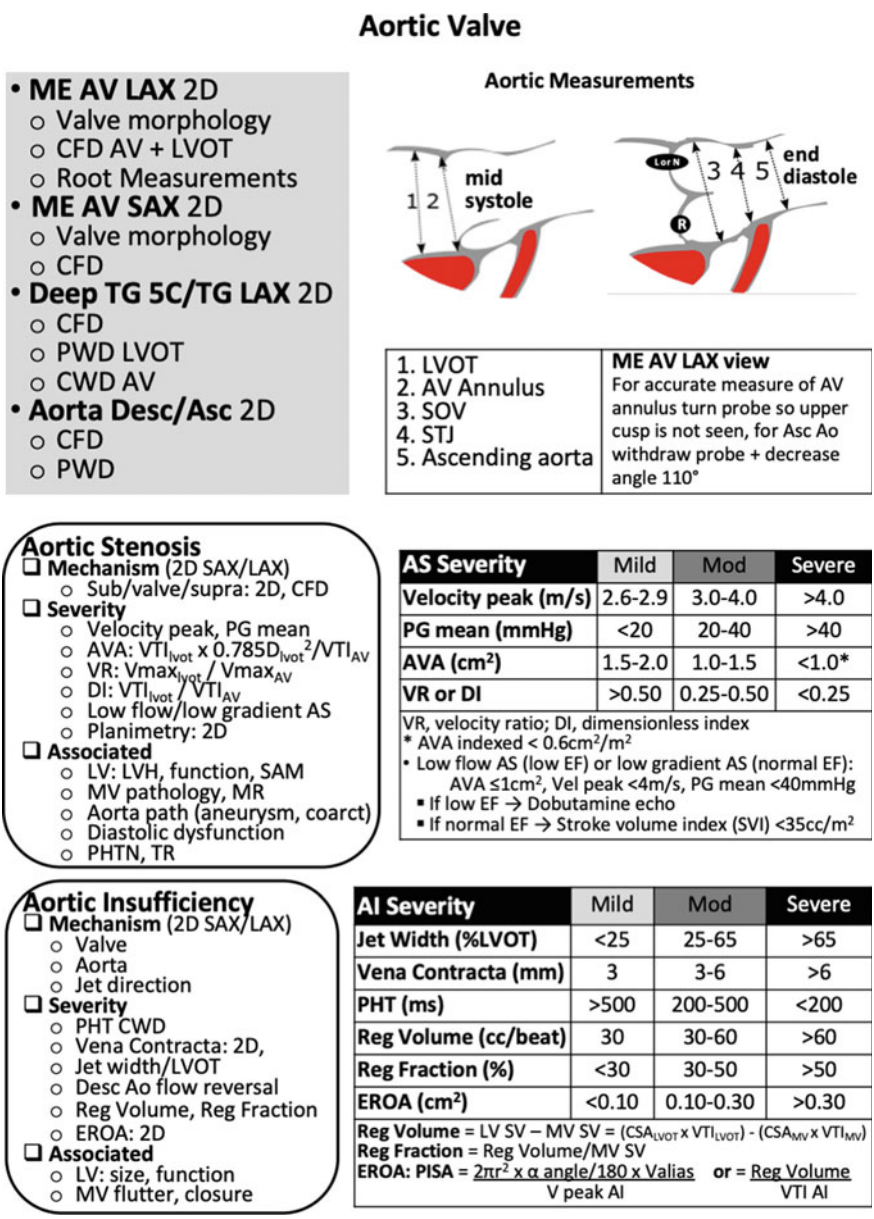


Fig. 9 Assessment of the Aortic Valve. ME: Mid Esophageal; AV: Aortic Valve; SAX: Short axis, LAX: Long Axis; CFD: Color Flow Doppler; LVOT: Left Ventricular Outflow Tract; SAX: Short Axis; TG: Transgastric; 5C: Five Chambers; PWD: Pulsed Wave Doppler, CWD: Continuous Wave Doppler; Desc: Descending; Asc: Ascending; AVA: Aortic Valve Area; VR: Velocity Ratio; VTI: Velocity Time Integral; LV: Left Ventricle; LVH: Left Ventricular Hypentrophy; MV: Mitral Valve; MR: Mitral Regurgitation; SAM: Systolic Anterior Motion; PHTH: Pulmonary Hypertension; TR: Tricuspid Regurgitation; PHT: Pressure Half Time; EROA: Effective Regurgitant Orifice Area; DI: Dimensionless Index; AS: Aortic Stenosis; AI: Aortic Insufficiency; Reg: Regurgitation; V: Velocity; PISA: Proximal Isovelocity Surface Area

integral (VTI), which is automatically calculated in cm by tracing the PW doppler trace at the LVOT level. If we obtain the AV VTI by tracing the CW AV velocity envelope, we can derive the AV area (AVA). We define this as the continuity equation, and it is suggested to be used to estimate AVA. Subtracting the SV measured through the MV to that measure in the LVOT allows computation of the AI regurgitant volume and fraction. In case of AI, CW would display the regurgitant diastolic flow. The steep of the AI regurgitant flow velocity in diastole is directly relates to the degree of AI and it is quantified using the Pressure half time. The most precise measurement of AI remains though the measurement of AV effective regurgitant orifice area (EROA). This can be calculated using proximal iso velocity surface area (PISA). This requires the CFD in the DTG and adjusting the lower velocity to approximately 30 cm/s. This will create a blue hemisphere above the AV. The radius of the hemisphere and the upper CFD velocity allows in central jets to precisely estimate the AV EROA.

Mitral Valve

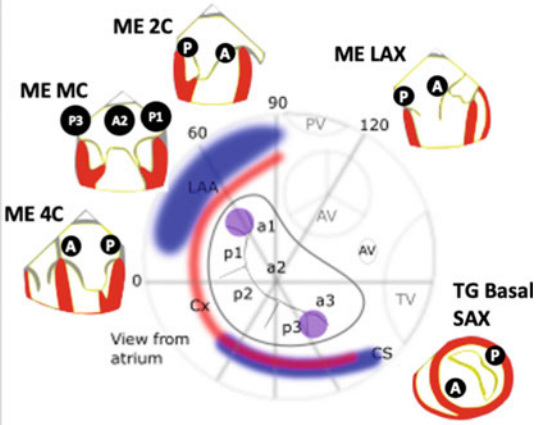
The MV (Fig. 10) is located between the left atrium (LA) and the LV. It comprises two leaflets (anterior and posterior) and a saddle shaped annulus. According the Carpentier's nomenclature the leaflets are further divided into three scallops (P/A 1–3) where P1 is lateral and P3 medial. The mitral valve leaflets, the annulus, the chordae, the papillary muscles and the LV constitute the MV complex. Alteration of any of its components would result in MV regurgitation (MR). The MV is in a favorable location for US imaging, perpendicular to the US beam and proximal to the probe. Starting from ME 4C view with progressive increase of the scanning angle we can display all segments of both leaflets.

The mitral valve annulus antero-posterior diameter is normally smaller and is to be measured in diastole in ME LAX; the mediolateral in the mid esophageal mitral valve commissural view (ME MC).

MR is the commonest MV pathology in the developed world. It leads to volume overload resulting in LA and LV dilatation. Intraoperative TEE should aim at identifying the mechanism of regurgitation and precisely locating structural leaflet abnormalities. Assessment of MR severity is based on CFD and spectral Doppler measurements. A simple and reliable measurement is the Vena Contracta (VC), the width of the regurgitant jet at the narrowest point above the MV [7]. Given the lack of valves between the LA and the pulmonary vein (PV), the PV flow reflects the change in pressure in the LA. The blood normally flow from the PV into the LA but in case of severe MR the PV flow would be reversed in systole. Similarly to what previously described for the assessment of AI, PISA method can be applied to MV to estimate the size of the MR EROA. Knowing the EROA and multiplying it by the VTI from the tracing the CW spectral trace of the MR jet, the regurgitant Volume and fraction can be calculated. Mitral Valve stenosis (MS) is typically the consequence of Rheumatic fever. It leads to a thickening of the MV leaflets that

Mitral Valve

- **ME 4C** 2D
- **ME MC** 2D
- **ME 2C** 2D
- **ME AV LAX** 2D
- Zoom or reduce depth
- In any view assess
  - Leaflet motion
  - CFD (50-60cm/s)
  - Annulus diameter
  - PWD MV or CWD MR
- **LAA** 2D, CFD, PWD
- **RUPV/LUPV** CFD, PWD
- **ME Bicaval** 2D, CFD
- **TG Basal SAX** 2D, CFD
- **TG mid SAX** 2D
- **TG 2C** 2D **MV**



Mitral Stenosis

- ❑ **Mechanism**
  - Rheumatic, calcific
- ❑ **Severity**
  - PG mean
  - MVA: planimetry, PHT, PISA
  - PAP (RVSP)
- ❑ **Associated**
  - LA size, SEC, thrombus
  - PHTN, TR, RV dilated
  - MR

MS Severity	Mild	Mod	Severe
MVA (cm^2)	>1.5	1.0-1.5	< 1.0
PG mean (mmHg)**	<5	5-10	>10
PAP (mmHg)	<30	30-50	>50

**HR dependent, values shown for HR 60-90, NSR

MVA: PISA = $\frac{2\pi r^2 \times \alpha \text{ angle}/180 \times \text{Valias}}{\text{V peak MS}}$ **or** = $\frac{220}{\text{PHT}}$

Mitral Regurgitation

- ❑ **Mechanism**
  - Valve (1°)
  - Functional (2°)
- ❑ **Severity**
  - Vena Contracta: 2D,
  - Flow Convergence (PISA)
  - Pulmonary Vein Doppler
  - Reg Volume, Reg Fraction
  - EROA
  - CWD: signal strength, shape
- ❑ **Associated**
  - LV: size, function
  - LA dilated
  - TV annulus, TR

MR Severity	Mild	Mod	Severe
Jet Area	small	variable	large
Vena Contracta (mm)	3	3-6	≥7
Flow Convergence (cm)	<0.3	Inter	≥1.0
Pulmonary Vein	normal	blunt	reverse
Reg Volume (cc/beat)	30	30-59	≥60
Reg Fraction (%)	<30	30-49	≥50
EROA (cm^2)	<0.20	0.20-0.39	≥0.40

Reg Volume = LV stroke volume – AV SV or LVOT SV

Reg Fraction = Reg Volume/LV SV

EROA: PISA = $\frac{2\pi r^2 \times \alpha \text{ angle}/180 \times \text{Valias}}{\text{V peak MR}}$ **or** = $\frac{\text{Reg Volume}}{\text{VTI MR}}$

Fig. 10 Assessment of the Mitral Valve. ME: Mid Esophageal; 4C: Four Chambers; MC: Mitral Commissural; 2C: Two Chambers; AV: Aortic Valve; LAX Long Axis, TG: Transgastric; SAX: Short Axis. A: Anterior; P: Posterior; CFD: Color Flow Doppler; MV: Mitral Valve; MR: Mitral Regurgitation; MS: Mitral Stenosis; PWD: Pulsed Wave Doppler; CWD: Continuous Wave Doppler; LAA: Left Atrial Appendage; RUPV: Right Upper Pulmonary Vein; LUPV: Left Upper Pulmonary Vein; MVA: Mitral Valve Area; PHT: Pressure Half Time; PISA: Proximal Isovelocity Surface Area; PAP: Pulmonary Artery Pressure; RSVP: Right Ventricular Systolic Pressure; TR: Tricuspid Regurgitation, RV: Right Ventricle; PG: Peak Gradient; MVA: Mitral Valve Area; PHTH: Pulmonary Hypertension; EROA: Effective Regurgitant Orifice Area; Reg: Regurgitant; VTI: Velocity Time Integral

won't be fully opening and assume a hockey stick appearance in Diastole. It is always associated with a severe LA dilatation and slow flow in the LA, especially in presence of atrial fibrillation that appears as spontaneous echo contrast (smoke-like). MS severity grading is based on the diastolic pressure gradient through the MV measured using CW and estimation of MV area (MVA) [6]. MVA can also be estimated by tracing the diastolic MV flow steep and calculating the time needed to decrease the pressure to half (pressure half time) (automatically calculated by the echo machine). 220 divided by the pressure half time give an estimation of the MVA. Alternatively, we can use the PISA method using the hemisphere of flow acceleration that can be seen above the MV in diastole.

In case of hypovolemia, especially in presence of LV hypertrophy the anterior leaflet of the LV is pulled into the LVOT in systole and result into MR. This phenomenon is called Systolic Anterior Motion (SAM), can also be observed after MV repair and it is best displayed in the ME LAX. LA dilatation almost invariably results into atrial fibrillation which leads to thrombus formation in the LA appendage that needs to be carefully inspected in case of MR and MS.

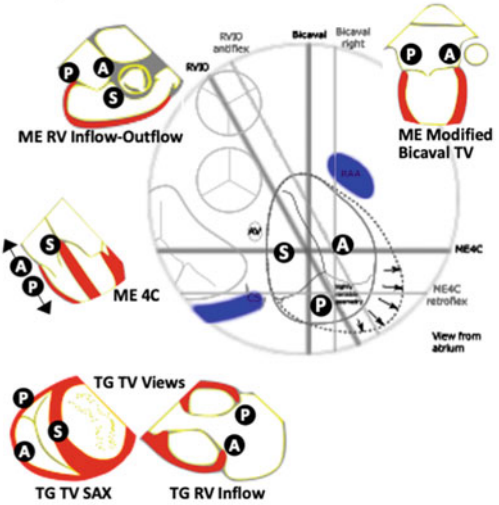
Tricuspid and Pulmonic Valve

The tricuspid valve (TV) (Fig. 11) comprises three leaflets (anterior, posterior and septal) and is the biggest of all valves. Assessment of the TV consists in the assessment of valve size and leaflet morphology. Precise leaflet identification with standard TEE views is difficult and one of the two leaflets cannot be clearly identified. The TV annulus is measured at end diastole in the ME 4C view. A normal TV annulus is <4 cm. The most common TV pathology is functional TV regurgitation (TR) which is the result of TV dilatation. TV annular dilatation result in the lateral displacement of the anterior and posterior leaflets that will no longer get in contact with the septal leaflet in Systole and therefore leave a gap. Assessment of TR severity is done in a similar fashion as for MR [7]. TR results invariably into RA dilatation and the increased systolic RA pressure, in case of severe TR, will result in a reverse systolic hepatic vein flow. The measurement of peak MR jet flow velocity squared and multiplied by four (simplified Bernoulli equation) added to the central venous pressure provides an estimate of RV systolic pressure which, in absence of pulmonary valve (PV) pathology, corresponds to the systolic pulmonary pressure. TV stenosis (TS) is a rate pathology and can also be caused by rheumatic fever. TS is identified by measuring the TV diastolic pressure gradients, with the continuity equation or dividing 190 by the TV pressure half time [6].

The PV (Fig. 12) is the most anterior of all cardiac valves. Its annulus is adjacent to that of the AV and it is normally rotated 90 degree from it. The PV comprises three cusps (anterior, left and right), the PV annulus is measured in the ME RV in–out and the flow can be measured either in the Transgastric RV inflow outflow view (TG RV in–out) or in the upper esophageal Aortic arch short axis view. PV stenosis (PS) and PV insufficiency (PI) are quantified in a similar fashion as AS and AI [6, 7].

Tricuspid Valve

- **ME 4C** 2D
- **ME RV In/Outflow** 2D
- **ME Bicaval mod TV** 2D
- **ME CS LAX** 2D
- Zoom or reduce depth
- In any view assess
  - Leaflet motion
  - CFD (50-60cm/s)
  - CWD TR
  - Annulus diameter (0°)
- **IVC LAX:** 2D, CFD
  - PWD hepatic vein
- **TG Basal SAX** 2D, CFD
- **TG RV Inflow** 2D, CFD



Tricuspid Stenosis

- ❑ **Mechanism** (2D)
  - Rheumatic, congenital
- ❑ **Severity**
  - PG mean
  - TV inflow VTI
  - TV Area (PHT, continuity)
  - PHT
- ❑ **Associated**
  - TR
  - RA size, SEC, thrombus
  - IVC dilated

TS Severity	Significant
PG mean (mmHg)*	≥ 5
TV Inflow VTI (cm)	> 60
PHT (msec)	≥ 190
TVA (cm^2)	≤ 1.0

*NSR 70-80bpm

TVA: Continuity = $\frac{\text{AV VTI} \times 0.785(\text{AV diam})^2}{\text{TV VTI}}$ **or** = $\frac{190}{\text{PHT}}$

Supportive: dilated RA, IVC

Tricuspid Regurgitation

- ❑ **Mechanism** (2D SAX/LAX)
  - Functional (2°):
    - Annulus: 2D
  - Valve (1°)
- ❑ **Severity**
  - TR CWD density
  - Jet area
  - Vena Contracta: 2D
  - PISA radius
  - EROA: 2D
  - Reg Volume
  - Hepatic Vein S wave PWD
- ❑ **Associated**
  - RV: size, function
  - RA size
  - IVC dilated

TR Severity	Mild	Mod	Severe
CWD TR	soft	dense	dense
Jet Area (cm^2)	<5	5-10	>10
Vena Contracta (mm)	NA	<7	>7
PISA radius (mm)	<5	6-9	>9
EROA (cm^2)	NA	NA	>4
Reg Volume (cc/beat)	NA	NA	>50
Hepatic Vein S wave	Norm	Blunted	Reverse

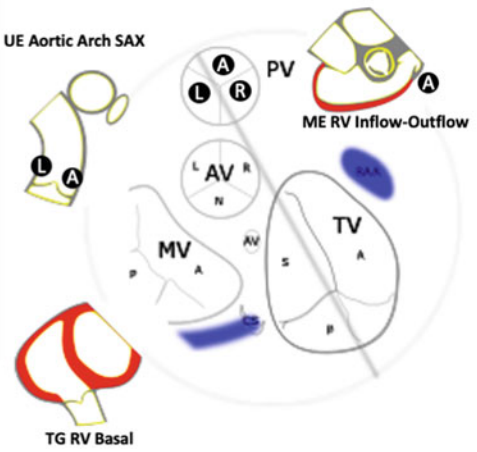
Reg Volume = TV VTI x TVA – RV (or LV) stroke volume

EROA: PISA = $\frac{2\pi r^2 \times \alpha \text{ angle}/180 \times \text{Valias}}{\text{Peak V TR}}$ **or** = $\frac{\text{Reg Vol}}{\text{VTI TR}}$

Fig. 11 Assessment of the Tricuspid Valve. ME: Mid Esophageal; 4C: Four Chambers; AV: Aortic Valve; LAX Long Axis, TG: Trans gastric; SAX: Short Axis; mod: modified; CS: Coronary Sinus; IVC: Inferior Vena Cava, A: Anterior; P: Posterior; S: Septal CFD: Color Flow Doppler; TV: Tricuspid Valve; TR: Tricuspid Regurgitation; TS: Tricuspid Stenosis; RA: Right Atrium; PWD: Pulsed Wave Doppler; CWD: Continuous Wave Doppler; PHT: Pressure Half Time; PISA: Proximal Isovelocity Surface Area; PAP: Pulmonary Artery Pressure; RV: Right Ventricle; PG: Peak Gradient; TVA: Tricuspid Valve Area; NSR: Normal Sinus Rhythm; EROA: Effective Regurgitant Orifice Area; Reg: Regurgitant; VTI: Velocity Time Integral

Pulmonic Valve

- **ME RVIO** 2D
- **UE Ao Arch SAX** 2D
- **TG RV Basal** 2D
- Zoom or reduce depth
- In any view assess
  - Leaflet motion
  - CFD (50-60cm/s)
  - Annulus diameter
  - PWD/CWD PV Inflow
- **ME 4C** 2D
  - TV: CFD, CWD, annulus
  - RV: size, function



Pulmonic Stenosis

- ❑ **Mechanism** (2D)
  - Calcific, congenital
  - Previous surgery
- ❑ **Severity**
  - Velocity peak
  - PG peak
- ❑ **Associated**
  - RV size, RVH
  - RV function
  - PI
  - TV morphology
  - TR (RVSP)
  - PA morphology

PS Severity	Mild	Mod	Severe
Leaflets	N	Abn	Abn
RV Hypertrophy	N	Mild	Mod
Velocity peak (m/s)	<3	3-4	>4
PG peak (mmHg)	<36	36-64	>64

Pulmonic Insufficiency

- ❑ **Mechanism** (2D)
  - Valve
    - Previous surgery
  - Functional (PHTN)
- ❑ **Severity**
  - Jet length
  - Jet width (JW)/RVOT
  - CWD density
  - PV annulus
- ❑ **Associated**
  - RV size: EDD, ESD
  - RV function
  - RA size
  - TR (RVSP)
  - TV morphology
  - PA morphology

PI Severity	Mild	Mod	Severe
Leaflets	N	± Abn	Abn
RA/RV/annulus (mm)	N	± Abn	Dilated
Jet length (mm)	<10	10-20	>20
JW/RVOT diam (%)	<34	35-74	>75
CWD signal	Soft	Dense	Dense
Deceleration rate	Slow	Variable	Steep
Other Indicators Severe PI			
• PI jet deceleration time < 100ms • Ratio PI jet width/pulmonary annulus > 0.7 • Pressure half-time of PI jet <100 msec • Short deceleration time PI spectral Doppler <260 msec			

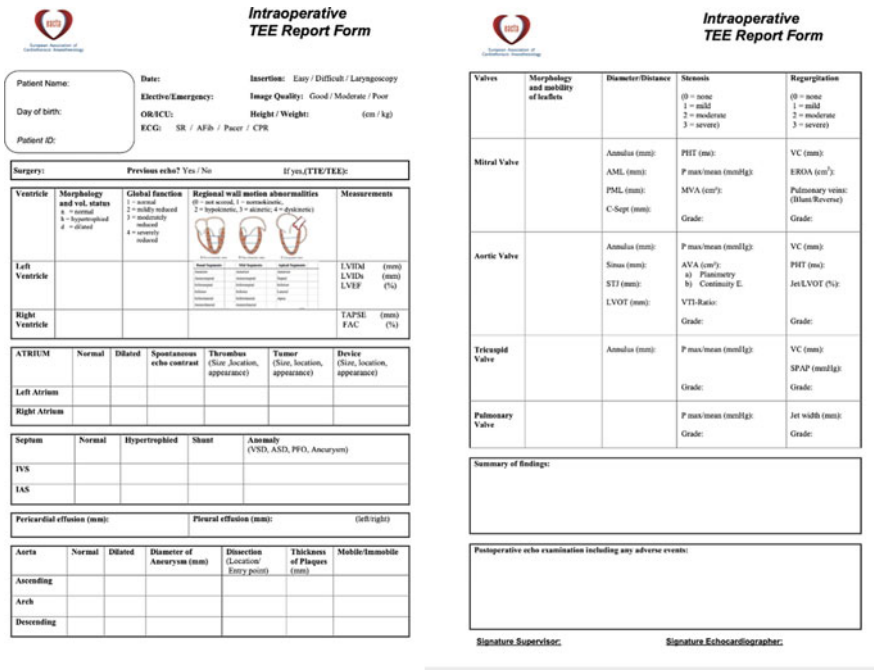
◂**Fig. 12** Assessment of the Pulmonic Valve. ME: Mid Esophageal; 4C: Four Chambers; RVIO: Right Ventricular Inflow-outflow; AV: Aortic Valve; MV: Mitral Valve; TV: tricuspid Valve; Ao Arch: Aortic Arch; TG: Trans gastric; SAX: Short Axis; mod: modified; CS: Coronary Sinus; IVC: Inferior Vena Cava, A: Anterior; R: Right; L: Left; CFD: Color Flow Doppler; TV: Tricuspid Valve; TR: Tricuspid Regurgitation; PA: Pulmonary Artery; PV: Pulmonic Valve; RV: Right Ventricle; PWD: Pulsed Wave Doppler; CWD: Continuous Wave Doppler; PS: Pulmonary Stenosis; PI: Pulmonary Insufficiency; PHT: Pressure Half Time; PISA: Proximal Isovelocity Surface Area; RA: Right Atrium; PG: Peak Gradient; TVA: Tricuspid Valve Area; NSR: Normal Sinus Rhythm; JW: Jet Width; RVOT: Right Ventricular Outflow Tract; Reg: Regurgitant; VTI: Velocity Time Integral; PHTN: Pulmonary Hypertension; EDD: End Diastolic Diameter; ESD: End Systolic Diameter; RSVP: Right Ventricular Systolic Pressure; Abn: Abnormal

Thoracic Aorta and Pleura

The Esophagus is located right next to the Thoracic aorta (TA). From the ME 4C, rotation of the probe would display the short axis of the TA. The TA can be scanned from the stomach to the arch by advancing and withdrawing the probe. A TA dissection would be easily identified with this view. Next to the TA the left pleural space can be clearly displayed at zero degrees as a crescent opening to the left. Rotation of the probe to the Right allows display of the right pleural space. These can only be clearly displayed in presence of pleural effusion.

Reporting and Storage

Digital storage of TEE examination is mandated by most guidelines [1, 2, 8]. TEE views are usually saved as two beat loops in the echo machine as DICOM files. They can be copied to a DVD, a memory medium or stored in a cloud or network server. Server storage allows retrieval and review of studies, off-line measurements and electronic reporting. Given the high cost this remains in many centers a limiting factor specially for non-cardiac surgical examinations. The availability of cloud storage may allow storage at lower costs and may be available for more centers. Reporting of TEE examination is recommended, and it is required in many countries for billing and medico-legal purposes. The European Association of Cardiothoracic anesthesiologists has recommended a standard template with the purpose of allowing standardization and quality control (Fig. 13).



Intraoperative TEE Report Form

Patient Name:
Day of birth:
Patient ID:

Date:
Elective/Emergency:
OR/ICU:
ECG: SR / AFib / Pacer / CPR

Insertion: Easy / Difficult / Laryngoscopy
Image Quality: Good / Moderate / Poor
Height / Weight: (cm / kg)

Surgery: Previous echo? Yes / No If yes,(TTE/TEE):

Ventricle	Morphology and vol. status	Global function	Regional wall motion abnormalities	Measurements
Left Ventricle				LVIDd (mm) LVIDs (mm) LVEF (%)
Right Ventricle				TAPSE (mm) FAC (%)

ATRIUM	Normal	Dilated	Spontaneous echo contrast	Thrombus (Size ,location, appearance)	Tumor (Size, location, appearance)	Device (Size, location, appearance)
Left Atrium						
Right Atrium						

Septum	Normal	Hypertrophied	Shunt	Anomaly (VSD, ASD, PFO, Aneurysm)
IVS				
IAS				

Pericardial effusion (mm): Pleural effusion (mm): (left/right)

Aorta	Normal	Dilated	Diameter of Aneurysm (mm)	Dissection (Location/ Entry point)	Thickness of Plaques (mm)	Mobile/Immobile
Ascending						
Arch						
Descending						

Intraoperative TEE Report Form

Valves	Morphology and mobility of leaflets	Diameter/Distance	Stenosis (0 = none 1 = mild 2 = moderate 3 = severe)	Regurgitation (0 = none 1 = mild 2 = moderate 3 = severe)
Mitral Valve		Annulus (mm): AML (mm): PML (mm): C-Sept (mm):	PHT (ms): P max/mean (mmHg): MVA (cm^2): Grade:	VC (mm): EROA (cm^2): Pulmonary veins: (Blunt/Reverse) Grade:
Aortic Valve		Annulus (mm): Sinus (mm): STJ (mm): LVOT (mm):	P max/mean (mmHg): AVA (cm^2): a) Planimetry b) Continuity E. VTI-Ratio: Grade:	VC (mm): PHT (ms): Jet/LVOT (%): Grade:
Tricuspid Valve		Annulus (mm):	P max/mean (mmHg): Grade:	VC (mm): SPAP (mmHg): Grade:
Pulmonary Valve			P max/mean (mmHg): Grade:	Jet width (mm): Grade:

Summary of findings:

Postoperative echo examination including any adverse events:

Signature Supervisor: Signature Echocardiographer:

Fig. 13 European Association of Cardiothoracic Anesthesiologists' intraoperative TEE reporting Template

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