삼첨판막질환에서 수술장 경식도심초음파의 적용

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Intraoperative Transesophageal Echocardiography in Tricuspid Valve Surgery

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Imaging the tricuspid valve (TV) using transesophageal echocardiography (TEE) seems more difficult than imaging other cardiac valves due to not only the complex valvular structure but also the anterior, far-field distance from the probe. The focus of the TEE during the surgery would not be much different from that of preoperative TEE. However, the anesthesia-induced changes of ventricular contractility, filling status, and vascular resistance should be considered when interpreting the images. Here, we thoroughly reviewed the major issues in the pre- and post-cardiopulmonary bypass intraoperative TEE in the TV surgery. Ultimately, a real-time intraoperative TEE monitoring should involve a simple or less time-consuming analysis which gives quick on-site information regarding the cardiac or hemodynamic status, communicating with the surgeon to lead to an optimal process.

Keywords: Intraoperative; Echocardiography, Transesophageal; Tricuspid valve

INTRODUCTION

Imaging the tricuspid valve (TV) using transesophageal echocardiography (TEE) seems more difficult than imaging other cardiac valves due to not only the complex valvular structure but also the anterior, far-field distance from the probe. Therefore, multimodal imaging for the TV is suggested, and intraoperative two-dimensional (2D) or three-dimensional

(3D) TEE plays a key role in the operating room [1].

Since most of the TV pathologies are tricuspid regurgitation (TR) rather than tricuspid stenosis, in this article TV surgery applies mostly to TR. About 80% of significant TR are functional TR related to tricuspid annular dilatation, right heart remodeling often secondary to left-sided heart disorder [2]. The only class I indication of TV surgery is for patients with severe TR undergoing left-sided valve surgery [2]. Therefore, intraoperative TEE

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(IOTEE) in the setting of TV surgery needs attention to left-side heart disorders as well.

The focus of the TEE during the surgery would not be much different from that of preoperative TEE. However, the anesthesia-induced changes of ventricular contractility, filling status, and vascular resistance should be considered when interpreting the images. In addition to evaluating the main valvular pathology, guiding the catheter tip (pulmonary artery catheter, superior vena cava catheter), and detecting air microbubbles or pleural effusions are also crucial, especially in the setting of on-pump beating TV surgery or one-lung ventilation for minimally invasive TV surgery. Pleural effusion can be aggravated even after weaning from the cardiopulmonary bypass. Here, we would like to present major issues in both pre- and post-IOTEE during the TV surgery.

PRE-CARDIOPULMONARY BYPASS IOTEE

The main goal of pre-bypass IOTEE in TV surgery is to determine the valvular etiology, TR severity, and hemodynamic consequences. More specifically, for etiology and hemodynamic consequences, to evaluate the TV leaflet/apparatus morphology, annulus size, right ventricular (RV) dimension and function, and pulmonary artery systolic pressure; for TR severity, the color Doppler jet area, vena contracta, flow convergence, and hepatic venous flow reversal.

Figure 1. Standard views of the tricuspid valve (TV) using intraoperative transesophageal echocardiography to appreciate the three leaflets. (A) Mid-esophageal four-chamber view, (B) mid-esophageal right ventricular (RV) inflow view, (C) transgastric RV inflow view, and (D) transgastric TV short axis view. AL, anterior leaflet; SL, septal leaflet; PL, posterior leaflet.

TV Morphology, RV size and function, and pulmonary artery pressure

TV Morphology

The TV comprises three leaflets (anterior, posterior, and septal), the chordae tendinae, the papillary muscles, and the annulus, with a normal orifice area between 7 and 9 cm² [3]. Based on the comprehensive preoperative transthoracic echocardiography (TTE) examination, the pre-bypass IOTEE exam would quickly double-check the TV morphology related to pathologic mechanisms with better image quality than TTE. There are four standard 2D TV views: mid-esophageal four-chamber (ME-4C), mid-esophageal RV inflow-outflow (ME-RV inflow-outflow), transgastric RV inflow (TG-RV inflow), and transgastric TV short axis (TG-TV short axis) views. In the ME-4C with 0–30°, the TV is seen with septal and anterior leaflets (Fig. 1A). Keeping the TV annulus in the center of the screen, rotate the multiplane angle between 50–70° until the RV outflow tract appears to obtain the ME-RV inflow-outflow

view (Fig. 1B). Further advancing the probe into the stomach at 100–120° makes the TG-RV inflow view with chordae tendinae (Fig. 1C), and withdrawing the probe slightly at about 30° provides the TG-TV short axis view (Fig. 1D) [1,4,5].

The normal TV is a complex 3D structure: the three leaflets are not equal in size, and the annulus shape is oval and non-planar with posterolateral annulus positions more apically. When it dilates, annulus becomes more round and planar, mostly stretching in the anteroposterior direction [6]. Therefore, 2D TEE is fundamentally limited, not visualizing all three leaflets simultaneously, off-angle views often not reliably representing the annulus size. In 2D TTE, the tricuspid annulus diameter is measured from the apical 4-chamber view, a diastolic diameter ≥ 40 mm or > 21 mm/m² indicating significant annular dilatation [2,7]. In 2D IOTEE, annulus diameter is measured from both the ME-4C view (septal-anterior diameter) and the ME-RV view (anterior-posterior diameter) (Figs. 1A and B), or biplane orthogonal view (Fig. 2) at end-diastole. At least two different cut planes with or without

Figure 2. Simultaneous biplane images of the tricuspid valve, measuring the tricuspid annulus diameter at the end-diastolic phase. RA, right atrium; RV, right ventricle; LA, left atrium; LV, left ventricle.

color Doppler imaging are required to evaluate TV morphology and regurgitation.

Real-time intraoperative 3D TEE saves time and effort when making multiple images with different angles via biplane or live 3D volumetric images (Fig. 3). The leaflet tethering or mode of coaptation is well appreciated in 3D TEE. The 3D TEE provides unique en face views of the TV that visualize all three leaflets simultaneously as well as the entire tricuspid annulus (Fig. 4). The inter-commissural distance can be measured using live 3D TEE, which is corresponding to the surgical tricuspid annular diameter measurement using a supple ruler [8] (Fig. 4). The surgeon's view of 3D en face images of the TV is most frequently used in the operating room, promoting communication between the surgeon

and cardiologist or anesthesiologist.

RV dimension and function

Hemodynamically significant chronic TR leads to enlargement of the RV, right atrium (RA), and inferior vena cava, and ultimately deteriorated RV performance. The interventricular septum has become flattened in diastole due to volume overload, or in both diastole and systole with pulmonary hypertension. The RV dilatation is indicated as a linear dimension > 42 mm at the base and > 35 mm at mid-level from the RV-focused view in 2D TTE [9], or the relative size of the RV is larger than that of the LV. Determination of RV performance is challenging in an intraoperative setting as these

Figure 3. An en face view of the tricuspid valve from atrial and ventricular perspectives. RA, right atrium; RV, right ventricle; TV, tricuspid valve; PV, pulmonary valve.

parameters are load dependent. The pre-bypass TEE for a RV exam begins with the ME-4C view, and TG mid-short-axis or TG-RV inflow views help visual assessment of RV size and function. Multiple parameters have demonstrated the clinical utility of using IOTEE, such as fractional area change (FAC), tricuspid annular plane systolic excursion (TAPSE), tissue motion annular displacement (TMAD), and RV strain. On the other hand, measuring the RV ejection fraction by 3D volume is

considered more accurate but clinically less applicable for a busy intraoperative monitoring.

RV FAC is measured by endocardial border tracing from the standard ME-4C view focused on the RV in end-diastole (ED) and end-systole (ES) phases, $RV\ FAC\ (\%) = 100 \times (ED\ area - ES\ area) / ED\ area$, a value $< 35\%$ indicating RV global systolic dysfunction [10] (Fig. 5A). For evaluation of the longitudinal RV systolic function, TAPSE is commonly measured by an M-mode

Figure 4. (A) Surgeon's view orientation with an en face live 3D tricuspid valve image. An arrow indicates the inter-commissural distance, from the anteroseptal commissure to the anteroposterior commissure. (B) An example of 3D measurement of an oval-shaped tricuspid annulus (dotted lines). AV, aortic valve; AL, anterior tricuspid leaflet; SL, septal tricuspid leaflet; PL, posterior tricuspid leaflet; AML, anterior mitral leaflet; PML, posterior mitral leaflet; LCC, left coronary cusp; RCC, right coronary cusp; NCC, non-coronary cusp.

cursor aligned the RV free wall as parallel as possible to the movement of the tricuspid annulus from the ME-4C view, and < 17 mm is considered abnormal in TTE [10]. However, TAPSE using IOTEE is a challenge to align with the lateral wall (Fig. 5B). Therefore, several modifications have been used to measure lateral tricuspid annular displacement using 2D (apical to lateral tricuspid annulus distance) or a speckle-tracking algorithm (TMAD). With the advantage of angle independency, TMAD is automatically quantified by identifying points on the lateral and septal tricuspid annuli and the RV apex (Cardiac Motion Quantification software, Philips Medical Systems, Andover, MA, USA) (Fig. 5C) [11]. Tricuspid TMAD is considered as a reasonable alternative to M-mode TAPSE on TTE [11]. Global longitudinal peak strain (GLPS) of the RV free wall (excluding the interventricular septum) is also considered a

reproducible and feasible index for RV function, with the advantages of angle independency and prognostic value (Fig. 5D). From the ME-4C view on the RV focus image, GLPS averaging over the three segments of the RV free wall, with $> -20\%$ considered abnormal [10].

Pulmonary artery pressure

Among the hemodynamic assessments of the RV, pulmonary artery systolic pressure (PASP) estimation using TR velocity is the most commonly performed and reported. PASP can be reliably determined from the peak TR jet velocity (V_{TR}) using the simplified Bernoulli equation, $PASP = 4 V_{TR}^2 + RA$ pressure (in the absence of any RV outflow obstruction, PASP is equal to RV systolic pressure) (Fig. 6). Under anesthesia with ventilator care in patients with significant TR, the RA pressure estimation strategy

Figure 5. Right ventricular (RV) performance evaluations from the RV focusing mid-esophageal four-chamber view. (A) Fractional area change, (B) tricuspid annular plane systolic excursion (TAPSE) measuring shows poor alignment with RV free wall, (C) tissue motion annular displacement (TMAD) on tricuspid annulus, and (D) global longitudinal peak strain of the RV free wall.

Figure 6. Biplane images using the 3D TEE probe reveal multiple tricuspid regurgitation (TR) jets (arrowheads). The vena contracta width (VCW) is measured from one of the TR jets (arrows). Continuous-wave Doppler peak velocity shows the TR maximum velocity as 2.0/s, suggesting no significant resting pulmonary hypertension.

Table 1. Severe tricuspid regurgitation

Publication	ESC/EACTS [7] (2017 Aug.)	ASE [12] (2017 Apr.)	AHA/ACC [2] (2014 Jun.)
Morphology	Abnormal/flail/large coaptation defect	Severe valve lesions (flail leaflet, no valve coaptation, severe retraction, large perforation), dilated annulus	Primary: flail or grossly distracted leaflets Secondary: severe annular dilation (> 40 mm or > 21 mm/m ²), marked leaflet tethering
Semi-quantitative			
Color flow jets	Very large central jet or eccentric wall impinging jet ^a	Large central jet (> 50% of RA; > 10 cm ²) or eccentric wall impinging jet ^b	Central jet area > 10 cm ²
VCW	≥ 7 mm ^a	> 7 mm ^b	> 7 mm
CWD jet	Dense, triangular with early peaking (peak < 2 m/s in massive TR ^c)		
Upstream	Hepatic vein systolic reversal		
Inflow	E-wave ≥ 1.0 m/s	E-wave > 1.0 m/s	
PISA radius ^d	> 0.9 cm	> 0.9 cm	
Quantitative			
EROA (cm ²)	≥ 0.40	> 0.40	
RegV (mL/beat)	≥ 45	≥ 45	
Hemodynamic consequences		RV, RA usually dilated (normal range in patients with acute severe TR), IVC dilated > 2.5 cm	RV, RA, IVC dilated with decreased IVC respirophasic variation; diastolic inter-ventricular septal flattening; reduced RV systolic function in late phase

ESC, European Society of Cardiology; EACTS, European Association for Cardio-Thoracic Surgery; ASE, American Society of Echocardiography; AHA, American Heart Association; ACC, American College of Cardiology; VCW, vena contracta width; CWD, continuous-wave Doppler; PISA, proximal isovelocity surface area; EROA, effective regurgitant orifice area; RegV, regurgitant volume; RV, right ventricle; RA, right atrium; IVC, inferior vena cava, TR, tricuspid regurgitation.

^aAt a Nyquist limit of 50-60 cm/s.

^bWith Nyquist limit > 50-70 cm/s.

^cDescription only in the ESC/EACTS.

^dBaseline Nyquist limit shift of 28 cm/s, limit shift of 28 cm/s.

from routine TTE is not applicable. Normal resting values are considered to imply a peak TR velocity of ≤ 2.8 m/s or PASP of 35–36 mmHg, assuming an RA pressure of 3–5 mmHg [9].

TR severity

Characterization of severe TR is presented in Table 1. Severe valvular lesions such as flail leaflets with no coaptation or severe annular dilatation with marked leaflet tethering in 2D might enough to indicate severe TR. For further hemodynamic flow information, qualitative or semi-quantitative imaging of color flow regurgitant jets, vena contracta width, proximal

isovelocity surface area (PISA) diameter, and upstream vein flow is recommended. Traditional TR severity quantification with the effective regurgitant orifice area (EROA) or regurgitant volume may not suitable for a busy intraoperative monitoring setting.

Color Doppler jets

Color flow Doppler is primarily applied for detection of valvular regurgitation, visualizing the origin and three jet components (jet area, vena contracta, and flow convergence). Optimization of the color gain (high, just below the clutter noise level) and Nyquist limit (50–70 cm/s) is required, and one

Figure 7. Multi-planar reformatting view of a 3D color full-volume image of the tricuspid valve. A tricuspid regurgitation jet with 3D vena contracta area measurement and multiple cross-sectional areas of vena contracta are presented by the semi-automatic slicing modality (right lower corner).

Figure 8. A hepatic vein (HV) systolic reversal flow is noted in red. The color scale should be lower than usual to visualize the low velocity reversal flow. A pulsed-wave Doppler image reveals systolic reversal flow (arrows), suggesting severe tricuspid regurgitation.

Figure 9. Post tricuspid annuloplasty (Carpentier-Edwards Classic Annuloplasty Ring 34 mm) intraoperative transesophageal echocardiography (IO-TEE). (A) A mid-esophageal four-chamber view from a 2D IOTEE demonstrating echogenic ring structure (arrows). (B) Real-time 3D image obtained using the 3D zoom mode reveals an oval ring in an en face view (arrows) and gap (asterisk) near the atrioventricular node.

could expect a slightly larger jet area with TEE due to the higher transducer frequency [12]. A large central jet ($> 50\%$ of RA) or any eccentric wall impinging jet would be considered severe TR [12]. In multi-origin TR, biplane imaging using a 3D TEE probe is helpful for individual TR flow evaluation (Fig. 6).

Vena contracta

The vena contracta is the narrowest portion of the regurgitant flow immediately downstream from the regurgitant orifice. Due to the cross-sectional area of the vena contracta being similar to the EROA, the vena contracta is an important parameter to determine TR severity. A vena contracta width ≥ 7 mm is defined as severe TR. As the shape of vena contracta is usually ellipsoid, it is necessary to have additional orthogonal image planes. Intraoperative 3D TEE could provide simultaneous biplane images, or 3D color volume-rendered multi-planar images to find the smallest cross sectional area of the vena contracta (Fig. 7). The lower spatial and temporal resolution of 3D color-flow still needs to be overcome.

Flow convergence

The flow convergence proximal to the regurgitant orifice provides a well-known semi-quantitative parameter of PISA, simply shifting the baseline of the color scale in the direction of the regurgitant jet at the Nyquist limit 30–40 cm/s. The PISA radius is measured from the point of Color Doppler aliasing to the vena contracta, a radius > 0.9 cm at the baseline Nyquist shift of 28 cm/s indicating severe TR [12].

Hepatic venous flow systolic reversal

The hepatic venous flow systolic reversal is an additional qualitative parameter suggesting severe TR (Fig. 8).

POST-CARDIOPULMONARY BYPASS IOTEE

Post-surgical IOTEE surveillance is critical to provide opportunities for fixing leftover lesions or unexpected complications immediately to avoid unnecessary future open heart surgery, a so-called “safety net”. During the transition off the cardiopulmonary pump, the post-surgical IOTEE should be

performed given the appropriate hemodynamic status, primarily focused on the TV surgical results followed by other basic surveillance including cardiac function and extra-cardiac fluid collections [13].

Depending on the surgical procedures, the morphology of prosthetic valve/ring and its function (regurgitation or stenosis) should be examined using IOTEE. The 3D TEE en face view offers a more intuitive prosthetic valve/ring structure from various perspectives than does 2D (Fig. 9). Color Doppler imaging is essential to detect residual leaks; if present, the origin (paravalvular or valvular) and regurgitant amount should be evaluated. A trans-tricuspid valvular mean pressure gradient < 5 mmHg seems acceptable [2] but this depends on the heart rate and volume status. Finally, based on the IOTEE information, either a continuous, successful weaning process or an unfortunate but necessary additional pump might be decided upon after on-site effective communication between surgeons, echocardiologists, or anesthesiologists.

CONCLUSION

We thoroughly reviewed the pre- and post-cardiopulmonary bypass IOTEE in the TV surgery. Ultimately, a real-time IOTEE monitoring should involve a simple or less time-consuming analysis which gives quick on-site information regarding the cardiac or hemodynamic status, communicating with the surgeon to lead to an optimal process.

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