Lessons learned during my 25 years as Dr. Carpentier's echocardiographer

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My collaboration with Professor Carpentier began in the early 1990s and was to continue for more than 25 years. Ours was a unique relationship based on mutual respect and unwavering trust: he liked to introduce me as "the justice of the peace", a symbol of the power of partnership. The lessons I learned during my 25 years with Professor Carpentier could be summarized in four key messages: understanding the surgeon's needs based upon the pathophysiological triad and functional approach, establishing a dedicated two-dimensional (2D)/three-dimensional (3D) intra-operative echo protocol in a common language, participating in evolution and evaluation of mitral valve reconstruction and transmitting knowledge to younger generations by education: "give to be given". I owe my entire professional career to him. Beyond that, we have forged an unbreakable bond, a relationship that is not only scientific but also deeply human. This filial bond will last forever.

Keywords: Heart team; intraoperative echo; mitral reconstruction; education

Submitted Sep 18, 2025. Accepted for publication Jan 12, 2026. Published online Jan 29, 2026.
doi: 10.21037/acs-2025-dmv-08
View this article at: https://dx.doi.org/10.21037/acs-2025-dmv-08

Introduction: my personal journey with Alain Carpentier

My collaboration with Professor Carpentier began in the early 1990s and was to continue for more than 25 years. Ours was a unique relationship built on mutual respect and unwavering trust, and he often liked to introduce me with a smile as "the justice of the peace".

At the time, integrating a clinical cardiologist as member of medical staff in a cardiac surgery department was one of Professor Carpentier's visionary and disruptive approaches. He was among the first surgeons in the late 1980s to recognize the critical role of intraoperative transesophageal echocardiography (TEE), especially with the advent of the first monoplane TEE probes. Echocardiography offered a more reliable assessment than intraoperative auscultation.

I was fortunate enough to be in the right place at the right time—when there was a pressing need to teach mitral valve reconstruction to surgeons who already believed in the superiority of reconstructive surgery over valve replacement. In Paris, during the renowned "Club Mitral" sessions and at conferences around the world, I had the honor of being introduced as "Professor Carpentier's echocardiographer". It was both a privilege and a commitment to uphold the highest standards of excellence. We had somehow inaugurated the concept of "team approach" ahead of its time, just like Monsieur Jourdain unknowingly writing prose in Molière's play.

The beginnings were not easy however: whenever I was satisfied enough to show the characteristics of a color jet or the existence of chordal ruptures, he would reply: "*Sorry Berrebi, please remove the color, I can't identify the leaflet motion and for chordal ruptures, I will see them by myself during surgical valve analysis.*" I was not sure I would stay in my position for long… This anecdote reflected the importance for me to be humble and never competing with surgeons for analysis of lesions, echo is more accurate for function in a beating heart: we are just complementary: the power of partnership

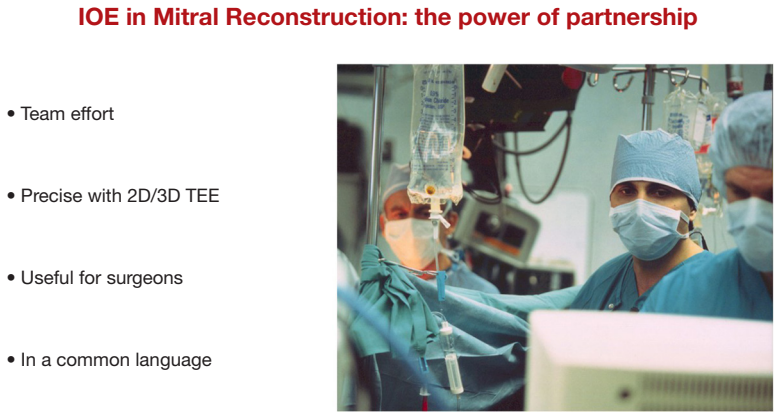

Figure 1 IOE in mitral valve reconstruction: the power of partnership. IOE, intra-operative echo; TEE, transesophageal echocardiography.

(*Figure 1*).

In seminal paper "The French Correction" published in 1983 (1), Alain Carpentier clearly mentioned that "*Surgeons are not concerned with lesions. We care more about function*."

I had to better understand surgeon's needs based upon the two key concepts of pathophysiological triad and functional approach. Furthermore, I tried to establish a specific intraoperative echo protocol, precise, useful and in a common language.

Thus, the lessons I learned during my 25 years with Professor Carpentier could be summarized in four key messages:

- ❖ Understanding the surgeon's needs: the pathophysiological triad and functional approach;
- ❖ Establishing a dedicated two-dimensional (2D)/three-dimensional (3D) intra-operative echo (IOE) protocol in a common language;
- ❖ Participating in evolution and evaluation of mitral valve reconstruction;
- ❖ Transmitting knowledge to younger generations by education: "give to be given".

Understanding the surgeon's needs: the pathophysiological triad and functional approach

To avoid a Babel syndrome and confuse flail, partial flail, billowing, myxomatous, mitral valve prolapse syndrome, Dr Carpentier proposed a clarification and a common language to improve communication between surgeon and echocardiography. This clarification is based upon a pathophysiological triad with a clear distinction between etiology (i.e., the cause of the disease), valve lesion (i.e., resulting from the disease) and valve dysfunction (i.e., resulting from the lesion).

This triad has clinical relevance for the individual patient because "long-term prognosis depends upon etiology, repair strategy and objective depend upon dysfunction, and surgical technics depends upon lesion". Echocardiographers and surgeons have complementary roles: lesions are well described by surgeons whereas dysfunction is well assessed by echocardiographers analyzing leaflet motion in a beating heart in agreement with the functional approach concept.

The aim of a valve reconstruction is to restore normal valve function rather than valve anatomy. Remodeling annuloplasty is almost systematic and a key factor in achieving durable results.

Three golden rules are critical to obtain a durable result:

- ❖ Restore a good surface of coaptation (6 to 8 mm);
- ❖ Preserve or restore full leaflet motion;
- ❖ Remodel the annulus with a ring annuloplasty.

The functional approach has led to the simplification of a complex field, based upon analysis of leaflet motion by echocardiography. It was thus essential to establish a dedicated echo protocol for mitral reconstruction using a common language (2).

Establishing a dedicated IOE protocol, in a common language

Dr. Carpentier often claimed that "*the very first step of a successful valve reconstruction is to look carefully at pre-pump echo with echocardiographer and discuss together valve analysis. These are foundations to provide a road map for valve reconstruction*".

The second step is the immediate post-pump control to detect any complications such as residual mitral regurgitation (MR), a safety net for surgeons and

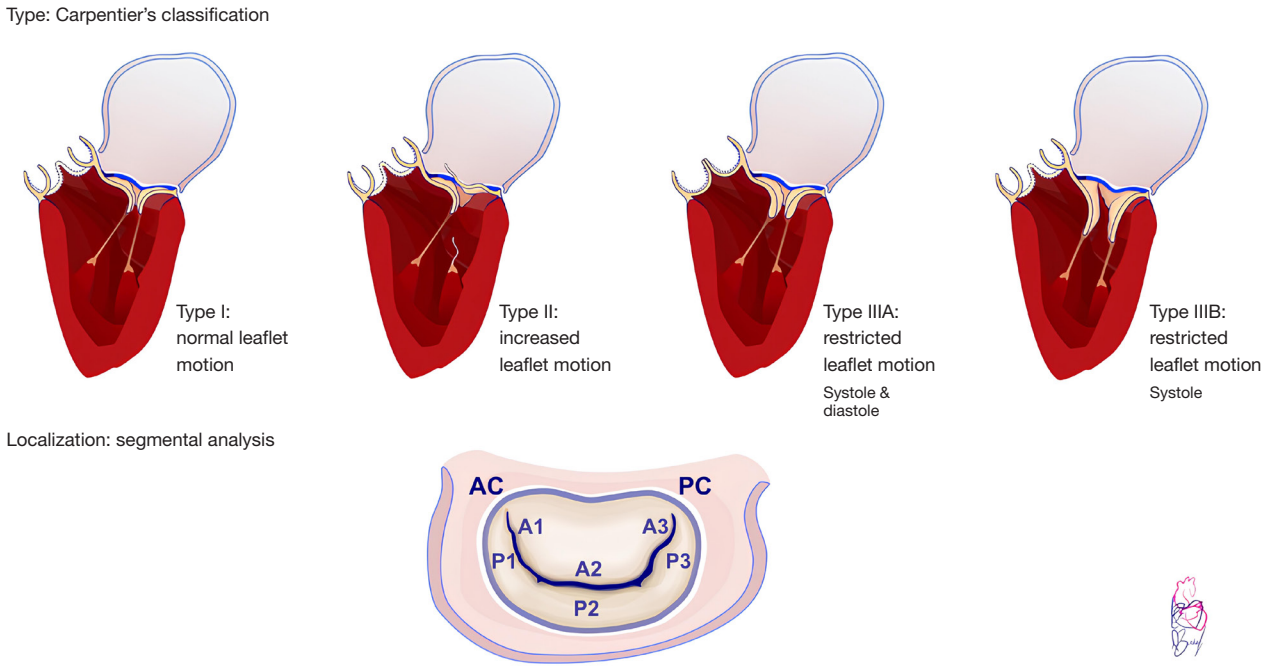

Figure 2 Dysfunction: to analyze type of dysfunction or Carpentier's classification (top) and to precise location of dysfunction or segmental analysis (bottom). AC, anterior commissure; PC, posterior commissure.

patients to avoid reoperation and achieve durable results: "echocardiographer is the justice of the peace" according to Dr. Carpentier.

First step: pre-pump 2D/3D IOE valve analysis

This report dedicated to surgeons includes a short checklist with five main chapters and other parameters to assess specifically valve analysis in a common language, precise and useful:

- Dysfunction;
- Lesion;
- Etiology;
- Risk of systolic anterior motion (SAM);
- Tricuspid assessment;
- Other parameters: aortic regurgitation (AR), circumflex.

Dysfunction (consequence of lesions)

Type of dysfunction or Carpentier's classification based upon leaflet motion (*Figure 2*):

- Type I: normal leaflet motion;
- Type II: excess leaflet motion or prolapse when the free edge of leaflet overrides the plane of the annulus in systole. By this surgical definition of prolapse, we consider prolapse is not a disease but a dysfunction. Furthermore prolapse (with MR) is not billowing defined by bulging of body redundant leaflets into the atrium but with still good coaptation of free edge (Barlow with click but no MR);
- Type IIIa: restricted leaflet motion (in systole and diastole);
- Type IIIb: restricted leaflet motion (only in systole).

Location of dysfunction or segmental analysis

Dr. Carpentier described height segments of the mitral valve: three real anatomical scallops of posterior leaflet (P1-P2-P3) separated by two indentations (P1-P2 and P2-P3) corresponding areas of anterior leaflet (A1-A2-A3), and two commissures, from left atrium (or surgical view) antero-lateral on the left and postero-medial on the right.

Lesions (consequence of disease and cause of dysfunction)

- For type I: isolated annular dilatation (rare except in atrial functional MR) or perforation (endocarditis).
- For type II: elongation or rupture or chordae and/or papillary muscle (PM). The term "flail" is often used as a combination of prolapse (dysfunction) due to chordal rupture (lesion) which is the source of confusion. "Partial flail" doesn't mean anything for surgeons and should be

Table 1 Etiology: main differences between fibro-elastic deficiency and Barlow's disease in degenerative MR

Criteria	Fibro-elastic deficiency	Barlow
Pathology	Thin leaflets (no prolapsed area)	Redundant leaflets (>5 mm)
	Disrupted elastin and rare collagen	Myxoid degeneration
Age	Old adult (>60 years)	Young adult (<60 years)
History of murmur	Recent	Long lasting—familial
Echocardiography	No excess of tissue (A2 ≤34 mm)	Excess of tissue (A2 ≥34 mm)
	Post-leaflet (P2) prolapse	Bileaflet prolapse
	Chordal rupture	Billowing—MAD
Surgery	Repair+++	Repair+++
	Replacement if fragile tissue	Single and large annuloplasty—risk of SAM+

MAD, mitral annular disjunction; MR, mitral regurgitation; SAM, systolic anterior motion.

abandoned in our echo reports. For type IIIa (diastole): commissural fusion/leaflet thickening and/or chordae thickening/fusion mainly seen in rheumatic disease.

- For type IIIb (systole): LV dilatation and/or dysfunction with PM displacement and chordal tethering mainly seen in ischemic/functional MR.

It is also important to detect and describe any:

- Calcifications:
  - Location: annulus or leaflet (body or free edge);
  - Extent: for annular calcification (localized or diffuse) and protrusion into the ventricle which is a high-risk lesion for surgeons. A diffuse and extensive calcification is considered as a limit for minimally invasive access.
- Leaflet retraction and/or stiffness: involving posterior and/or anterior leaflet, defining lack and of tissue available and unpliable leaflets, major criteria of unsuitable repair even for experimented surgeons. A2 length <26 mm is considered as a retraction of anterior leaflet.

Etiology (cause of lesions)

Degenerative MR includes a wide variety of disease (3) from fibro-elastic deficiency (FED) to Barlow disease with clear different clinical and echocardiographic characteristics (*Table 1*). We can't describe these two different diseases with the same confusing term anymore: "mitral valve prolapse syndrome". Prolapse is a dysfunction and not a disease. It seems that in many papers description of the term "mitral valve prolapse syndrome" corresponds to Barlow's disease.

Risk of SAM

SAM, or systolic anterior motion, is a potential complication after mitral valve repair with three main risk factors (4): excess of tissue, narrow mitral aortic angle <120° (C-septum distance <2.5 cm) and small ventricle. This risk is very frequent in Barlow's disease because of the intrinsic excess of tissue (large anterior leaflet >34 mm and excess of height of posterior leaflet >15–20 mm).

It is important for surgeons to know this risk before surgery and adapt surgical techniques accordingly: reduce the height of posterior leaflet and implant the largest annuloplasty ring size, if there is hesitation between the two sizes.

Tricuspid assessment

According to current international guidelines there is an indication to consider surgery (repair in most instances) in mild to moderate tricuspid regurgitation (TR) with a significant annular dilatation (≥40 mm or 21 mm/m^2 by 2D echocardiography). In borderline situations (for example, no or mild TR and annular diameter close to 40 mm), we propose in our team to add two other criteria: coaptation mode, particularly an edge-to-edge coaptation <3 mm) and right atrial enlargement (end-systolic area >18 cm^2 by 2D echo and visual surgical inspection) which are incentive for the decision to perform a tricuspid annuloplasty during mitral surgery (5).

Other parameters useful for surgeons

This includes the following:

- Presence and severity of AR with two roles:

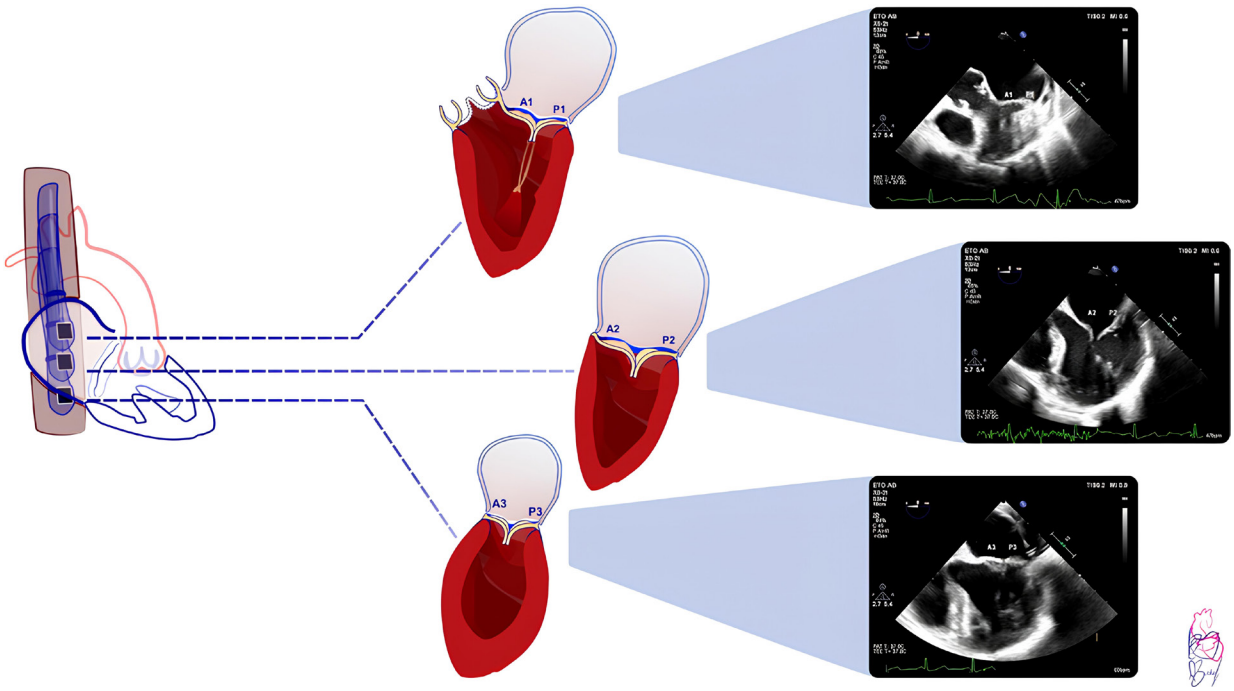

Figure 3 Four chamber views (0°): upper (A1P1), mid (A2P2), deep (A3P3).

- As a reference to compare with post-operative echo [potential injury of aortic valve, particularly left/non coronary cusp (L/N) commissure during annuloplasty].
- To predict mode of cardioplegia for perfusionists (left ventricular vent or retrograde cardioplegia through coronary sinus).

❖ Location of circumflex artery (particularly in left dominance) and distance with mitral annulus, potential injury during annuloplasty (kinking).

❖ Aorta: detection of mobile atheromatous debris in ascending aorta to the surgeon's attention for canulation.

Intraoperative TEE (IOTEE) is mandatory in all mitral valve repair (6). Echocardiographer (cardiologists or anesthesiologists upon local organization) is an essential player of Heart Valve Centre and must be experienced. To become proficient in intra-/peri-operative TEE, a minimum number of 125 comprehensive intraoperative TEE examinations is to be performed, interpreted, and reported unsupervised by the trainee: entrustable professional activities (EPA) level 5; level III (7).

IOE protocol

A standardized and systematic approach in a common language for surgeons allows for an accurate, reliable and reproducible 2D/3D echo protocol for any experienced echocardiographer in the operating room (OR), cardiologist or anesthesiologist.

We still start with a systematic 2D multiplane TEE (8), followed by 3D approach (9) in a complementary and combined approach.

2D approach: the basic "6 views-5 measurements" protocol

First, we assess 2D echo images with "color compare" or "dual view" modality, which allows us to see simultaneously:

❖ On the left 2D view alone (to evaluate the free edge motion regarding the plane of annulus in systole);

❖ On the right 2D with color view [to examine if there is a color jet at the origin with proximal isovelocity surface area (PISA) effect and vena contracta and jet direction].

The TEE probe can be manipulated by advance/withdraw; twist left/right, anteflex/retroflex and rotation of the transducer angulation. The three first views are obtained at 0° angulation in four chamber views with three different levels of depth in oesophagus (*Figure 3*):

(I) Upper oesophageal level (or five-chamber view) allows the visualization of A1P1 scallops which are small with two landmarks, aortic valve and root on

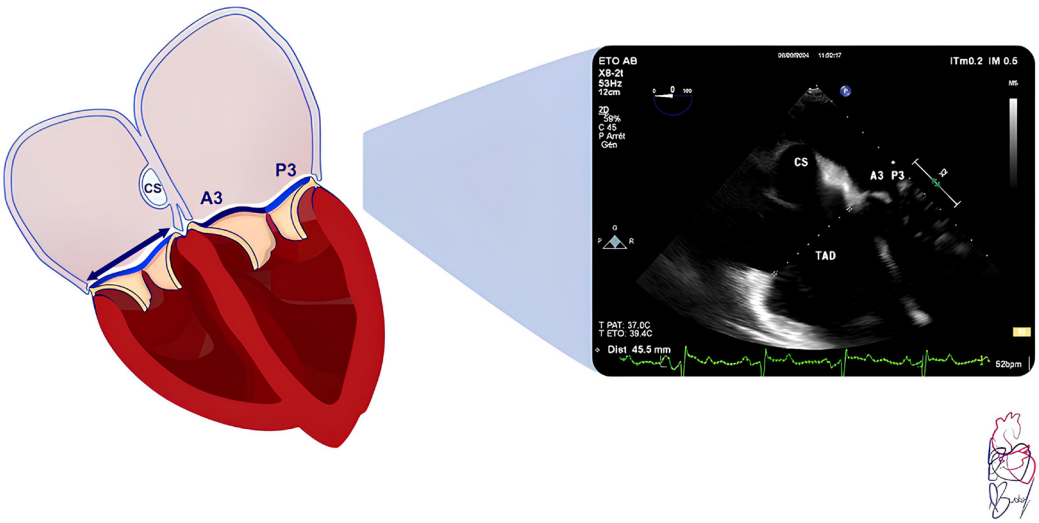

Figure 4 Assessment of tricuspid annulus diameter in deep 4 chamber view in mid-diastole with coronary sinus landmark. CS, coronary sinus; TAD, tricuspid annulus diameter.

the left and left atrial appendage on the right.

(II) Mid-oesophageal (ME) level (classical ME four-chamber view), by advancing the probe a few mm more or performing a slight retroflexion, allows the visualization of A2P2 scallops which are large. Usually, we lose aortic valve and root except if dilated.

(III) Lower oesophageal (deep four-chamber view) by advancing the probe a few millimeters more or by performing a slight retroflexion allows the visualization of A3P3 scallops: small scallops again with spherization of left ventricle, close to transgastric (TG) circular aspect. At this A3P3 level, we measure on right side cavities, the tricuspid annulus diameter (measurement 1) in four-chamber view in mid-diastole with two landmarks: coronary sinus and A3P3 (*Figure 4*).

(IV) The fourth view is the short axis TG views (*Figure 5*), still at 0° angulation, by advancing and flex the probe into the stomach. This is the unique 2D view to allow visualization of the height scallops in one view. We distinguish TG "valvular" view crossing the leaflets from the TG "annular" view crossing the annulus with a D shape aspect. The advantage of TG annular view is to depict the only scallops which are prolapsing because, by definition, in prolapse dysfunction, free edge reaches and overrides the plane of the annulus. It is particularly useful in localized commissural prolapse.

(V) The bi-commissural view (at 45°–60° angulation) that cuts the mitral valve in a horizontal plane crossing from right to left P1-A2-P3 scallops (*Figure 6*). In it, we can measure P1 and P3 length or height (measurement 2 and 3) and depict excess of posterior leaflet tissue (>15–20 mm) in diastole, which is the major risk factor of SAM.

(VI) Long axis view (at 120°–150° angulation), which cuts the mitral valve in a vertical plane crossing A2 and P2 scallops (*Figure 6*).

In long axis view, we can measure:

- ❖ In mid-diastole: the height of the middle part of anterior leaflet A2 (measurement 4). This A2 measurement has two roles:
  - To distinguish the two main etiologies regarding excess of tissue with a cut off limit of 34 mm (FED <34 mm versus Barlow ≥34 mm)
  - To predict annuloplasty ring size and avoid undersizing the ring, which is potential source of SAM in degenerative MR.
- ❖ In mid-systole: the measurement of mitral-aortic angle (measurement 5) which is associated with the risk of SAM if <120°. We will also measure C-septum (coaptation point–interventricular septum) distance also associated with risk of SAM if <2.5 cm.

The systematic 2D multiplane TEE approach (*Table 2*) is still mandatory and provides an overall diagnostic accuracy

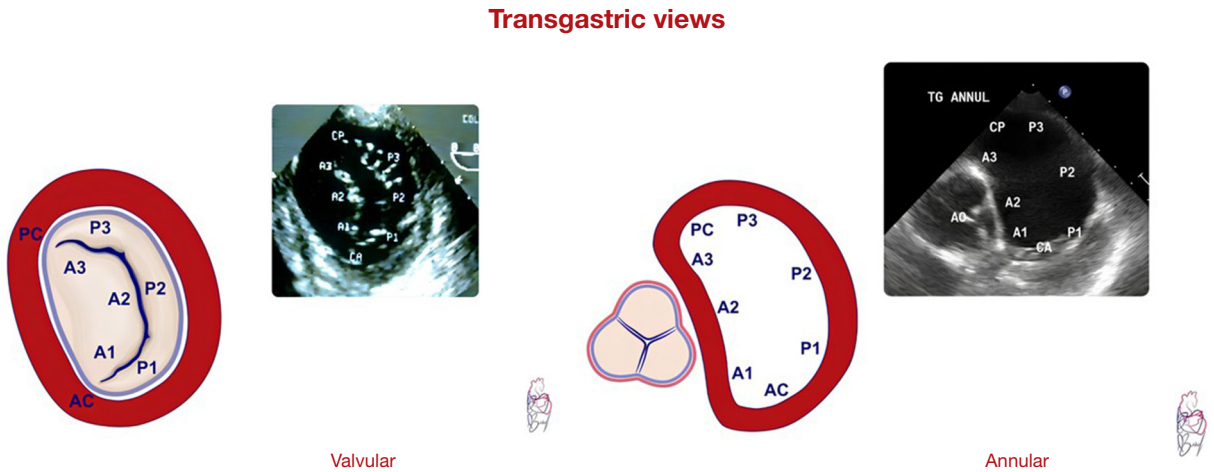

Figure 5 Transgastric view (on the left: valvular cut; on the right: annular cut). AC/CA, anterior commissure; AO, aortic valve; CP/PC, posterior commissure; TG, transgastric.

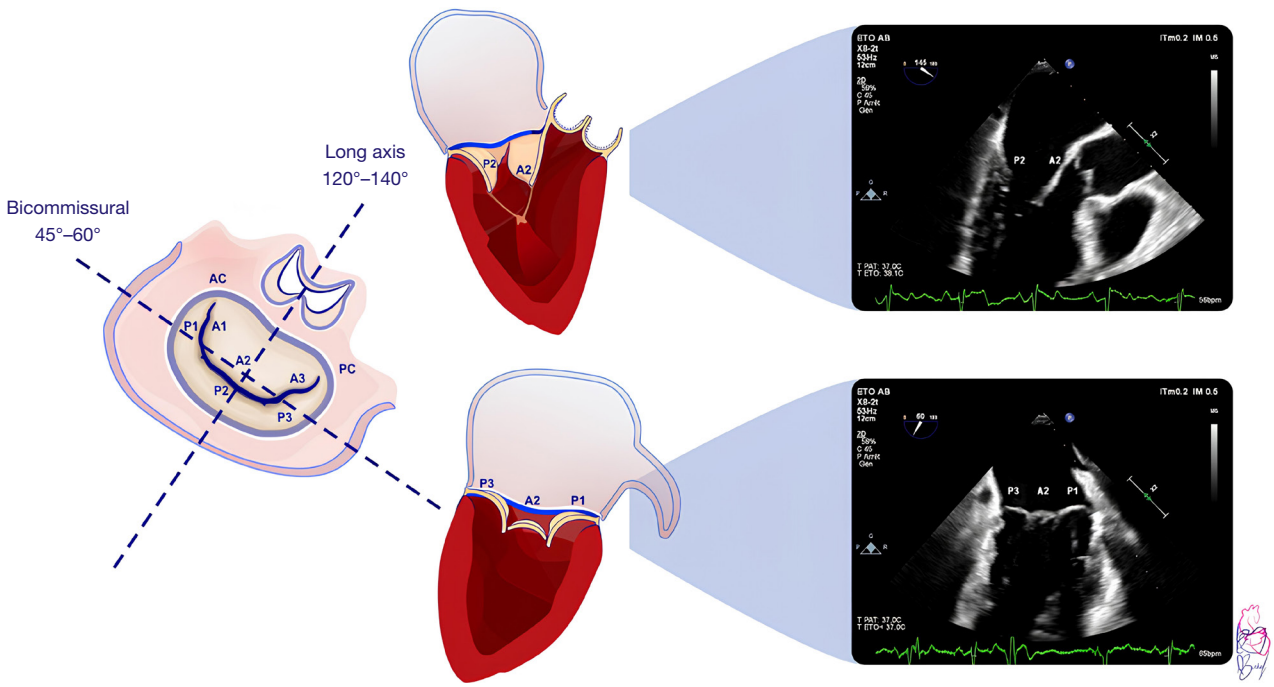

Figure 6 Bi-commissural (P1A2P3) and long axis (A2P2) views. AC, anterior commissure; PC, posterior commissure.

using individual scallops of 97.2% with a sensitivity of 96.6% and a specificity of 97.6% in comparison with surgical findings (10). However, surgeons need more intuitive images, surgical views that are easier to understand and interpret, while echocardiographers need more precisions in valve analysis. 3D protocol, complementary to the 2D protocol, is the optimal tool to achieve this goal.

3D approach: a more intuitive and precise valve analysis

The 3D approach allows us to improve precision in valve analysis and facilitate communication with surgeons with more intuitive surgical views. 3D approach includes in our protocol:

- 3D data set acquisition modalities: simultaneous 2D multiplane and zoom modality in single and multi-

Table 2 The "6 views-5 measurements protocol" in a nutshell

View	Measurement	Cycle	Cut-off	Goal
Deep 4-chamber	Tricuspid annulus	Diastole	≥40 mm	Tricuspid annuloplasty
Bi-commissural	PI and P3	Diastole	≥20 mm	Risk of SAM
Long axis	A2	Diastole	–	Etiology
				Risk of SAM
	Mitro-Ao angle	Systole	<120°	Risk of SAM

SAM, systolic anterior motion.

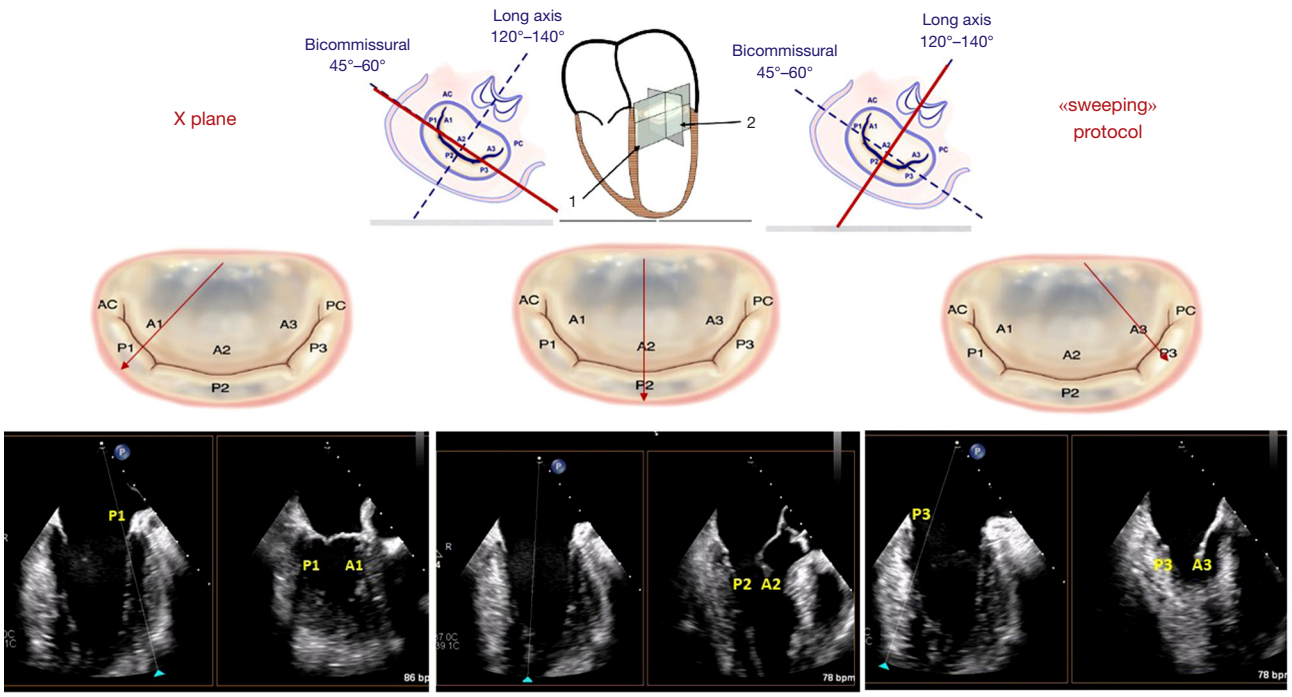

Figure 7 Sweeping protocol with X-0lane modality to assess segmental analysis. AC, anterior commissure; PC, posterior commissure.

beat.

- ❖ Image displays regardless of the acquisition modality will include volume rendering (adding photorealistic vision and glass view in some cases) and almost multiplanar reconstruction (MPR) improving our precision for valve analysis.
- ❖ Image optimization will include low compression to produce a high-contrast image, smoothing, an optimal gain to eliminate the static noises while preserving anatomic structures and manual cropping.
- ❖ Simultaneous 2D multiplane or X-plane. X-plane (or biplane) is the most commonly used, allowing us to obtain two simultaneous cross sections views of the same heartbeat. It allows us the "sweeping protocol" with bi-commissural view on the left (reference plane) and orthogonal (90°) long axis view on the right. We sweep the line of the matrix transducer on the left part on A2, P1 and P3 with simultaneous corresponding views on the right A2-P2, A1-P1 and A3-P3 (*Figure 7*).
- ❖ Zoom modality: real-time (single beat) and full volume ECG-gated (multi-beat) with volume rendering. This modality allows us to obtain a surgical view from the left atrium, which facilitates

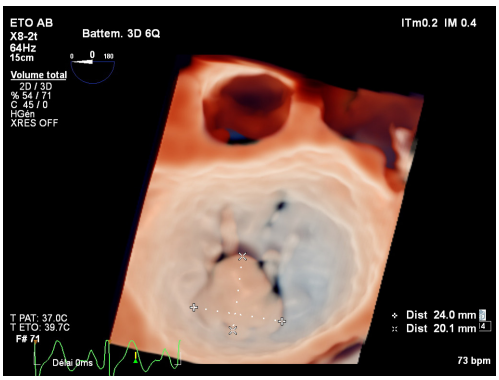

Figure 8 3D assessment of with and height of P2 prolapse.

communication with surgeons. The two landmarks are the aortic valve at twelve o'clock and left atrial appendage at nine o'clock. The 3D zoom acquisition is live in one beat but associated with low frame rate. The multi-beat ECG-gated acquisition (6 beats in sinus rhythm and 4 beats in atrial fibrillation) allows the highest temporal and spatial resolution. It will be acquired in the OR and, to avoid artefacts, the anesthesiologist will be asked to interrupt ventilation and the surgeon to stop electrocautery during a few seconds. Surgical view will be obtained in a post-processing cropping. This 3D "en face" surgical view from the left atrium has many advantages for surgeons: it is very intuitive and reproduces the surgical view in a dynamic and functional assessment. It allows a better communication between surgeons and echocardiographers and provides a road map for surgeons to predict techniques to be used. Surgical valve analysis with P1 scallop (rarely prolapsed) as reference point, is still mandatory but it has some limitations in an arrested heart.

3D approach allows an accurate assessment of segmental analysis particularly of the commissural prolapse, using key angled views (11). Correlation with surgical findings is excellent (12). 3D approach also allows us to measure the width and height of posterior leaflet in P2 prolapse, and thus to predict the extent of resection (width), and risk of SAM if the height is over 15–20 mm (*Figure 8*).

The identification of both indentations P1P2 and P2P3 in both atrial and ventricular views is important especially when the indentations are deep, wide and leaking with potential surgical consequences like their closure.

We must be aware of some 3D TEE pitfalls and limitations particularly artefacts or drop-out as hole aspects. It reflects the importance of having a complementary approach with 2D assessment, verified by 2D views if the "hole" is a real lesion as perforation or not.

MPR

MPR allows live or post-processing rotation of perpendicular planes on either 2D or 3D image to display any desired 2D imaging plane. It provides extreme precision in segmental analysis in three simultaneous planes (transverse, longitudinal and coronal) in one view and visible on 3D surgical view (*Figure 9*).

Surgical implications: valve analysis and likelihood of repair

Pre-pump valve analysis by 2D/3D IOTEE provides a road map to predict techniques to be used and complexity of repair (*Table 3*). However, the surgeon's experience is still the major factor of the likelihood of repair. We will also discuss a new paradigm in repair for patients with Barlow's disease with a specific echo pattern.

Second step: post-pump IOE

This is a critical moment where team effort is essential. The aim is to evaluate the immediate result of repair in a beating heart, in order to achieve durable result and avoid reoperation. The result must be perfect, particularly so in early surgical management of asymptomatic patients.

Surgically, two rules are essential: achieving a harmonious closure line and restoring a good coaptation height.

The post-pump echo protocol requires several steps:

- Obtaining similar hemodynamic condition than pre-pump with a mean of arterial pressure above 80 mmHg to achieve optimal closing forces. Optimal filling is needed. No inotrope infusion without prior echo-assessment to avoid dynamic SAM. Evaluation is performed after weaning from the cardiopulmonary bypass, with the cannula still in place.
- Assessing the coaptation height at the level of A2P2 which should be at least 6 to 8 mm in degenerative MR and at least 8 mm for ischemic/functional MR. This measurement demands to analyze accurately the distance between the proximal point of coaptation and the free edge of both leaflets. A common mistake is to overestimate true coaptation by measuring the distance between proximal point coaptation and the sole free edge of posterior leaflet without taking into consideration the free edge of anterior leaflet which

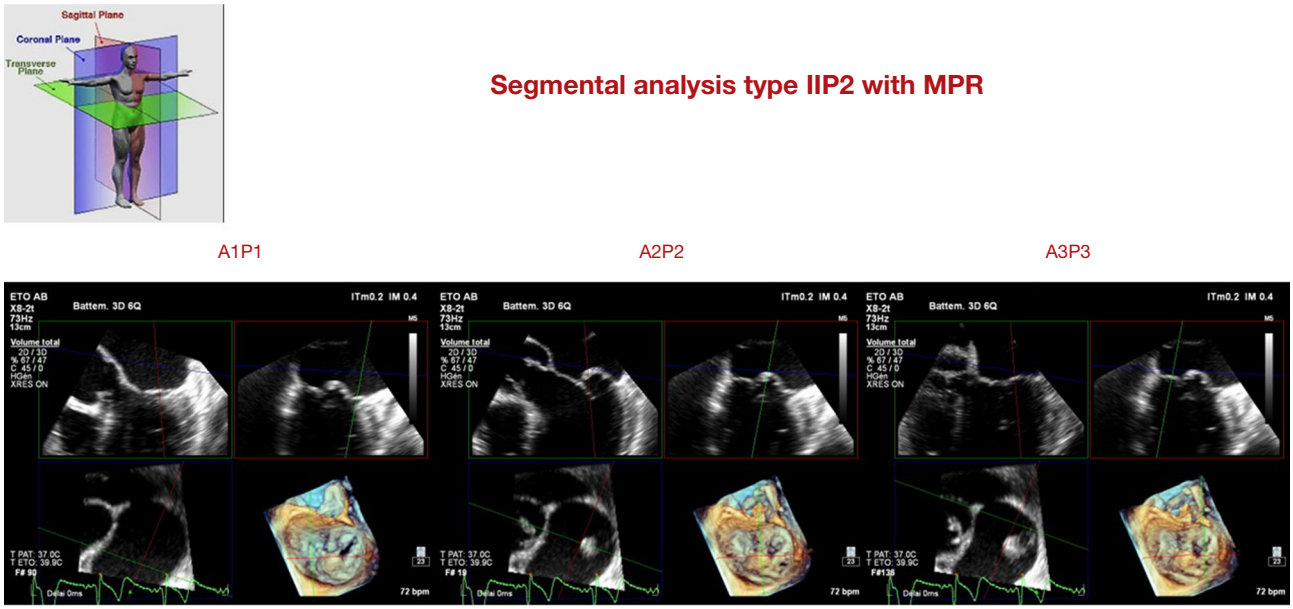

Figure 9 Segmental analysis of P2 prolapse with 3D MPR. 2D, two-dimensional; 3D, three-dimensional; MPR, multiplanar reconstruction.

is sometimes close to the plane of the annulus.

- ❖ Detecting the presence of residual MR with a bi-commissural view (45°–60°) to analyze the entire coaptation line with an X-plane sweeping protocol.
- ❖ Assessment of the severity of residual MR using multiparametric criteria in an integrated approach. Regularly, we accept trivial or less than mild residual MR (≤1/4). It is essential not to hurry in making the decision to reclamp, and carefully assess the evolution of residual MR and distinguish transient and reversible MR with permanent residual MR.
- ❖ Understanding the mechanism of residual MR with a complete valve analysis: beyond severity, the most important task of the echocardiographer is to help the surgeon to make the right decision to correct or neglect (see *Table 4*). We must assess the type of dysfunction and location of residual jet using 2D TG annular view and 3D color flow. It is crucial to identify the jet origin location and distinguish the leaflet from the coaptation jet.
- ❖ The only condition under which we could neglect a residual MR is different according to transient or permanent MR:
  - Transient MR: due to temporary LV dysfunction (type IIIb dysfunction) or dynamic SAM due to hypovolemia and/or inotrope infusion;
  - Permanent MR: with a central jet, less than mild, with a good coaptation due to irregularities of leaflets.

In permanent MR, under all following conditions, the common decision is to correct and reclamp to fix most often procedure-related failures, based upon type of dysfunction by 2D echo and jet location by 2D TG annular view and 3D color "en face" view:

- ❖ Type I:
  - Leaflet jet in the suture line or close to post annulus or indentation, mimics a jet perforation;
  - Central jet ≥2/4 due to oversized annulus;
  - Peri-annular jet due to ring dehiscence.
- ❖ Type II or residual prolapse due to:
  - Undiagnosed pre-pump prolapse (rewatch recorded pre-pump videos);
  - Excess length of neochords.
- ❖ Type IIIa due to too short length of neochords.

In presence of a permanent MR with SAM with left ventricular outflow tract (LVOT) obstruction due to surgical causes: excess of length and motion of posterior leaflet (sliding plasty or artificial chords on posterior leaflet) and/or too small ring (implant a larger ring).

Residual stenosis is rare—usually seen in rheumatic mitral repair or after undersized annuloplasty in ischemic functional MR.

Other complications concerning surrounding structures must be identified:

Table 3 Likelihood of repair and surgical implications according to valve analysis in a heart valve centre with an experienced surgeon

Etiology	Dysfunction	Lesion	Suitability of repair/surgical implications
Organic			Suitability of repair & surgical implications
Degenerative			
All phenotypes	Type II (prolapse): any leaflet (posterior and/or anterior) and any scallops involved (P1/P2/P3–A1/A2/A3) including commissures and/or indentations	Chordal rupture and/or elongation No or localized calcification Favorable amount and quality of tissue Annular dilatation	Optimal repair: with all surgical techniques available (resection and/or Gore-Tex) but with systematic ring annuloplasty
FED	Type II (prolapse)	Fragility of tissue +++ Calcifications: leaflet and/or annulus	Challenging repair: valve replacement if leaflet too fragile and/or extensive annular calcification and protrusion into LV
Barlow	Specific pattern: dynamic functional prolapse involving all scallops with a central color jet	Mitral annular disjunction with rocking/curling motion of posterior annulus and PM stretching Excess of posterior leaflet (>20 mm)	Optimal repair: sole and large annuloplasty ring (usually size 40 mm) with or without reduction of height of posterior leaflet to avoid SAM
Endocarditis	Type I	Perforation	Optimal repair: patch
	Type II	Numerous chordal ruptures with extensive infected leaflet tissue and/or annular abscess	Challenging repair: if early phase: repair possible. If late surgery and lack of non-infected tissue after resection of infected lesions: prefer valve replacement
Rheumatic	Type III posterior ± type II anterior	Retraction and/or stiff anterior leaflet Retracted, fused & short chordae Calcification involving leaflet and/or sub valvular apparatus	Challenging repair: repair possible with patch leaflet extension and/or "shaving" of the anterior leaflet. If stiff and calcified anterior leaflet and/or severe sub-valvular apparatus retraction and fused: prefer valve replacement
Functional			Surgical implications
Ventricular	Type IIIb (chronic)	Moderate LV dilation (EDD <65 mm and/or ESD <41 mm) and tenting area (<2.5 cm^2)	Optimal repair with undersized annuloplasty (2 sizes) with no MR and coaptation ≥8 mm Note: if posterior PM displacement only (IIIbP3) favor ischemic ring annuloplasty (undersized on P3)
		Severe LV dilation (EDD >65 mm and/or ESD >41 mm) and tenting area (>2.5 cm^2)	Challenging repair: high risk of recurrent MR, prefer valve replacement
	Type II (acute)	PM rupture	Challenging repair: unstable patients in cardiogenic shock: prefer valve replacement
	Type II (chronic)	PM elongation, particularly posterior PM	Optimal repair (PM repositioning)
Atrial	Type I	Annular dilatation	Optimal repair (isolated ring annuloplasty)

EDD, end-diastolic diameter; ESD, end-systolic diameter; LV, left ventricle; MR, mitral regurgitation; PM, papillary muscle; SAM, systolic anterior motion.

Table 4 Management of residual MR: correct or neglect?

Mechanism	Type	Inotropes effect	3D color	Decision
Transient and/or dynamic MR				
Severe LV dysfunction with reduced closing force	I or IIIb	Positive	NA	Neglect: LV support (on bypass)
SAM with hypovolemia	NA	Negative	NA	Neglect: filling and stop inotropes
Permanent MR				
Irregularities of leaflet coaptation with trivial or mild central jet (≤1/4)	I	NA	+++	Neglect
Leaflet jet in suture lines or closed to the ring	I	NA	+++	Correct
Leaflet jet at indentation	I	NA	+++	Correct
Residual prolapse or excess traction of Goretex	II or IIIa	NA	++	Correct
SAM with excess of post-leaflet and/or too small ring	NA	NA	+	Correct
Too large ring with central jet or ring dehiscence with periannular jet	I	NA	+++	Correct

3D, three-dimensional; LV, left ventricular; MR, mitral regurgitation; NA, not available; SAM, systolic anterior motion.

- AR due to anterior annular stitch, leading to restricted motion (type IIIa) of L/N commissure with severe leak. Reclamping to remove the culprit stitch is mandatory.
- Circumflex compression or "kinking" assessed by an X-plane protocol often associated with electrocardiogram (EKG) disturbances and segmental lateral wall hypokinesia. This complication is particularly severe when the left main distribution is dominant.
- Dissection of the ascending aorta secondary to cross-clamp injury.

Participating in evolution and evaluation of mitral valve reconstruction

Evolution of mitral valve reconstruction techniques

In two situations, the mechanism of dysfunction was elucidated by echocardiography:

- SAM mechanism (4) due to a discrepancy between an excess of tissue (particularly the posterior leaflet) and a small orifice area due to a too small ring. This led to the proposal of sliding leaflet technique (13) to reduce the height of posterior leaflet and prevent SAM. Thus, SAM was not due to the ring rigidity (14) but to the implantation of an undersized annuloplasty ring, a major step in the understanding of SAM mechanism. Never undersize in mitral valve reconstruction of patients with degenerative MR.

Barlow disease with symmetric bileaflet prolapse: a new paradigm?

Considered, even recently, as a difficult and unlikely repair we must discuss a new and simple approach with a single and large annuloplasty providing good mid-term results (15) based upon specific pattern identified by pre-pump echocardiography (16).

This pattern is defined by a peculiar valve analysis (*Figure 10*):

- Dysfunction is a bileaflet symmetric functional prolapse with central jet direction, along the line of coaptation (multiple jets in the bi-commissural view).
- Lesion is dynamic (no chordal rupture and/or elongation) with a systolic curling or rocking motion of native posterior annulus with consequently a significant mitral annular disjunction (MAD) >7 mm and upward motion and stretching of PM a potential source of fibrosis see on cardiac magnetic resonance and arrhythmogenic syndrome.

Based upon this specific and unique pathophysiology, the new and simple surgical option is to implant a single and large annuloplasty to avoid SAM which allows to block rocking motion of posterior native annulus and upward motion of PM leading and finally to correct functional

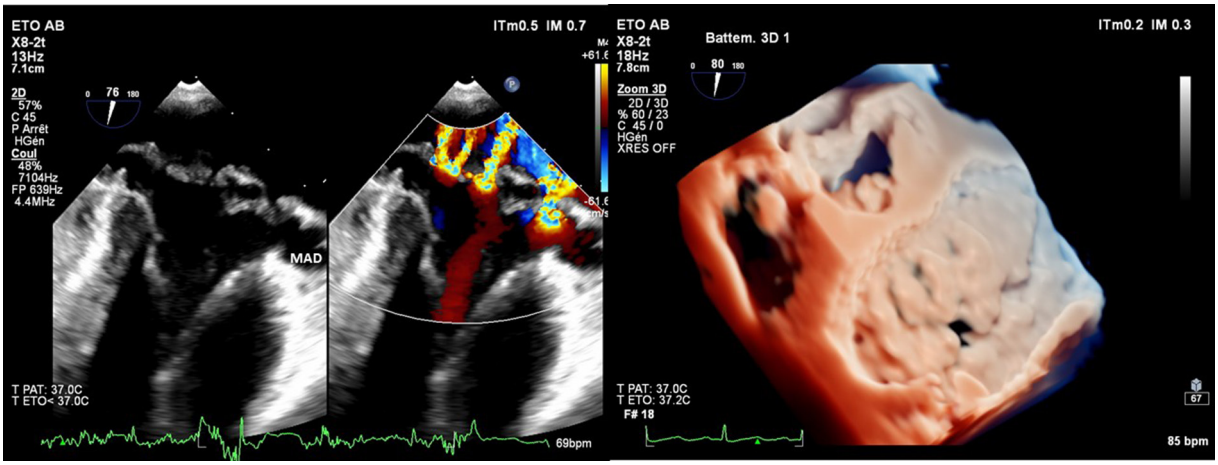

Figure 10 Symmetric bileaflet prolapse in Barlow's disease (left: central jets along coaptation line; right: 3D surgical view). 2D, two-dimensional; 3D, three-dimensional.

prolapse and restore a large surface of coaptation.

However, in patients with excess of tissue of posterior leaflet (>20 mm) and a coaptation line in the middle of the orifice (ratio anterior/posterior 0.5/0.5 and not ideally 3/4–1/4) a sliding plasty to reduce the height of the posterior leaflet may be necessary. Neochords on posterior leaflet are also proposed to achieve this goal. A syringe bulb test in the OR is systematic before implanting the ring to assess the excess of posterior leaflet tissue, the coaptation line position (middle or posterior), and presence or not of regurgitation (no regurgitation is in favor of single annuloplasty). Sizing of annuloplasty with obturator is critical to avoid SAM and if the surgeon hesitates between two sizes, the largest one will be chosen (often 38 or 40 ring size).

Evaluation of mitral valve reconstruction: durability is key

The objective of Alain Carpentier was "not only to treat a MR but for the first time in the history of valvular disease, patients could be cured for the rest of their lives". Echocardiography is critical for the evaluation of long-term results and accurate assessment of recurrence of MR (17), which is a better criterion than reoperation rates alone. We still need very long-term echo evaluation of alternative techniques like non resection approaches with only neochords in posterior leaflet prolapse. We have seen in our department some cases of patients with residual MR due to the late rupture of neochords (*Figure 11*) with "respect" techniques without resection despite excess of tissue, a complication that hasn't been tackled yet by current publications.

Recent data have shown excellent results with anterior leaflet repair without neochords (18): "*the newer the better is not always true in mitral valve repair*" (19). We still continue to evaluate new surgical techniques (20) as far as golden rules of valve reconstruction are respected.

Mitral valve reconstruction is the gold standard for surgical treatment of degenerative MR: new 2025 European guidelines (21) recommend (class IIa level B) a surgical mitral repair in severe primary MR even in low-risk asymptomatic patients without LV dysfunction in the presence of significant left atrial dilatation, when performed in a Heart Valve Centre and a durable repair is likely. Durability is a key factor of management of MR, mainly due to the presence of an annuloplasty ring: it may explain the superiority of surgical repair over transcatheter edge to edge techniques in terms of MR recurrence (22) in patients with degenerative MR.

However, in a recent real-world international registry (23) early intervention was observed only in 3% of patients and a repair rate of 62% overall (80% in myxomatous). We must improve these results when we know that almost 100% of patients with degenerative MR can be repaired in a Heart Valve Centre (24). For all these reasons, there is still a need of transmission of knowledge to younger generations.

To transmit knowledge to younger generations: "give to be given"

Transmitting knowledge was one of Alain Carpentier's most important missions. I was fortunate enough to work

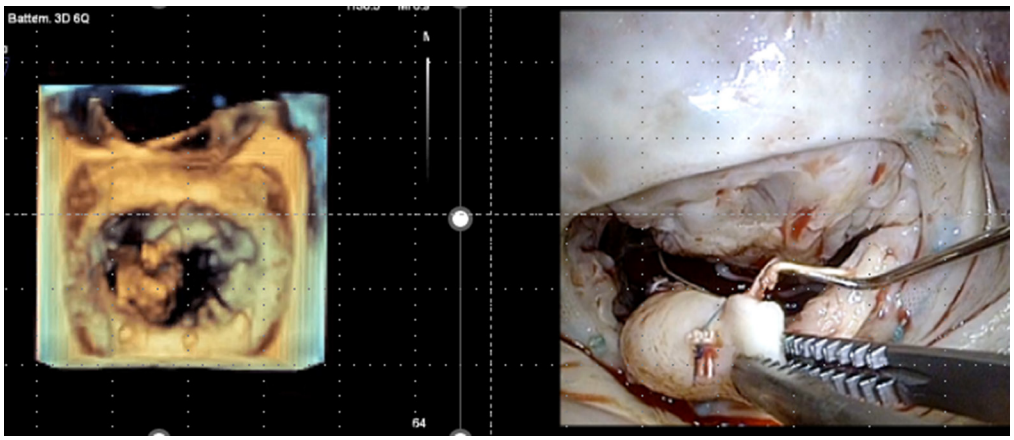

Figure 11 Late residual MR due to neochord rupture on P2. MR, mitral regurgitation.

as his echocardiographer in many settings, including the renowned "Club Mitrale" in a small amphitheater at Broussais Hospital in Paris, which attracted surgeons from around the world. I was also involved in the "Heart Valve Club" with Alain Carpentier around the United States. After the discontinuation of the "Club Mitrale", I was one of the course directors with surgeons of the European "Master of Valve Repair" educational program.

One of my most memorable experiences was being part of the medical team involved in the creation and medical development of the Ho Chi Minh City Heart Institute, a project made possible through the Carpentier Foundation.

Teaching is both a joy and a duty: I currently devote most of my time to teaching the younger generation and inspiring my passion for working as an imager within a surgical team dedicated to treating patients with valvular heart disease in a heart team approach. To implement guidelines and promote a higher rate of mitral valve reconstruction, it is essential to encourage the use of TEE simulation among the young generation of echocardiographers (25). This enables transmission of our standardized "6 views-5 measurements" protocol, reliable and reproducible. We will have future developments in virtual reality and artificial intelligence to improve precision and reproducibility in valve analysis and to provide a better prediction of suitability for repair based on surgeon's experience. Simulation is also an effective tool to improve surgical skills in minimally invasive mitral valve reconstruction (26).

I owe my entire professional career to him. Beyond that, we have forged an unbreakable bond, a relationship that is not only scientific but also deeply human. This filial bond will last forever.

Acknowledgments

The author would like to thank Raoul Biondi, MD, for the original illustrations.

Footnote

Funding: None.

Conflicts of Interest: The author has no conflicts of interest to declare.

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Cite this article as: Berrebi A. Lessons learned during my 25 years as Dr. Carpentier's echocardiographer. Ann Cardiothorac Surg 2026;15(1):2. doi: 10.21037/acs-2025-dmv-08