MITRAL VALVE REPAIR

Tanıl Özer • Adnan Ak

EVALUATION OF THE MITRAL VALVE (SEGMENTAL ANALYSIS)

Successful repair of the mitral valve requires accurate identification of pathology. This should be done through preoperative echocardiographic assessment, followed by intraoperative confirmation of all segments of the mitral valve. Pathologies in each segment can be identified using the Carpentier Classification.

The primary goal in mitral valve repair (MVR) is to ensure coaptation of both leaflets at the same level and achieve a coaptation depth of at least 1 cm. During evaluation of the mitral leaflets, it is important to note that both the anterior and posterior leaflets have three scallops, and each scallop's degree of degeneration may vary. Therefore, each scallop should be evaluated separately. Evaluation can start from the anterolateral or posteromedial commissures. Each scallop, along with its anterior and posterior counterparts (A1-P1, A2-P2, A3-P3), is assessed using a hook. Excessive traction should be avoided during this assessment, as it can lead to incorrect evaluation. Previously identified degenerations such as restriction, prolapse, or defect should be noted. Additionally, filling the ventricle with saline can help identify the location of any leakage. However, this method may be inadequate, when there are multiple leaks or leaks are too significant to fully fill the ventricle.

In some cases, even in the absence of significant degeneration, there can be a coaptation defect. This can occur due to annular dilation and/or stretching of chords due to ventricular dilation, resulting in secondary (functional) mitral insufficiency.

IMPLANTATION OF ANNULOPLASTY RINGS

1. Annuloplasty Ring Models

Mitral valve repair, whether focusing on leaflets or not, is typically completed with annuloplasty. Stabilizing the annulus post-successful mitral repair enhances the durability of the repair. Complete rings that encircle the entire annulus as well as incomplete rings (bands) are used. Rings are classified based on their flexibility: rigid, semi-rigid, and flexible.

Since the mitral annulus assumes different shapes during systole and diastole, support should be provided without compromising its mobility. While flexible rings allow for some degree of movement, rigid rings immobilize the annulus to maintain a single shape. Semi-rigid rings are flexible at the anterior annulus and rigid at the posterior, allowing partial flexibility.

Although the posterior annulus, particularly P2 and P3, is prone to dilation, the anterior annulus, neighboring the aortomitral curtain, is considered not to accompany this dilation.

There are rigid rings with shaped (saddle-shaped) and "D"-shaped designs. Shaped rings are designed to accommodate the different heights of the annulus in both commissures and anteroposterior directions during systole. In functional mitral insufficiency, where there is annular dilation and loss of elliptical shape during systole, rigid rings might be preferred. In such cases, a ring that reduces the annulus size is typically selected (undersizing).

Semi-rigid and flexible rings are preferred in cases where the annulus is relatively preserved, particularly in pathologies directly associated with the leaflets, and a ring of the measured size is used.

Incomplete rings, also known as bands, are preferred in cases where the anterior annulus is intact and does not need support due to its fibrotic structure and to avoid unnecessary anteroposterior narrowing.

2. Measurement, Suturing, and Testing

Regardless of the ring type, measurements are primarily based on the "anterior leaflet." After identifying both commissures, the intercommissural distance on the anterior leaflet side and the leaflet itself are measured using a ring sizer specific to the chosen ring. Accurate identification of the commissures is crucial at this stage.

While passing the ring sutures through the commissures, the anterior leaflet can be pulled toward the posterior annulus using a hook for measurement and planning. In particular, in degenerative diseases, measurement can also be done after leakage repair and ventricular filling to achieve complete ventricular filling. Then, measurements can be taken considering both anterior and posterior leaflets.

Before placing the ring sutures, it is important to clearly identify the atriovalvular junction. For this, the leaflets are gently tractioned in the transverse plane, and if necessary, the junction can be identified with the help of a right-angle clamp.

In general, 2-0 mattress sutures encircle the entire annulus if a ring is used, while if a band is used, only the posterior annulus is passed between each trigone, leaving the anterior leaflet part empty. The needle enters about 1 to 2 mm outside the atriovalvular junction and is advanced toward the annulus just beneath the leaflets, exiting approximately 1 to 2 mm away from the atrial side. The distance traversed on the annular plane should be approximately 10 mm. The angle of needle advancement should not be wide or deep. The spacing between each suture should be 1 to 2 mm (Figure 15.1).

Identifying sutures that align with the midline of the commissures and leaflets can facilitate passing them through the ring first, aiding in determining the positions of other sutures on the ring. Improper passage of sutures through the ring can disrupt its structure (Figure 15.2).

3. Tricks (Avoiding Ring Displacement, Preventing Systolic Anterior Motion)

Identifying fan-shaped chords and creating a pleat in the commissure with slight traction on the anterior leaflet can help identify the commissures.

During passage of sutures through the annulus, it is of utmost importance to be aware of the circumflex artery near the P1 segment, the coronary sinus near the P3 segment, and the atrioventricular (AV) node near the PM trigone. Aggressive deep tissue penetration should be avoided, particularly near these levels.

To avoid ring displacement, ensure that sutures pass through the intact fibrotic tissue of the annulus. Rigid or semi-rigid rings with a rigid posterior portion may resist myocardial contractions, leading to tearing and displacement of the ring.

Applying aggressive force while tying knots on flexible rings may cause asymmetric contractions and distortion of the annular structure. Knots should be adjusted to neither too loose nor too tight to avoid either slackness or constriction of the ring.

In particular, in degenerative pathologies, avoiding undersizing of the annulus is critical to reduce the risk of postoperative systolic anterior motion (SAM). Although successful in saline testing, postoperative echocardiographic evaluation may reveal significant regurgitation due to SAM.

Considering the length of the anterior and posterior leaflets and the coaptation distance, as well as the anteroposterior length of the ring can reduce the likelihood of SAM.

RESECTION TECHNIQUES

1. Triangular Resection

Triangular resection can be preferred, when the prolapsed segment is small. It can be applied to both leaflets. It can be performed, when the prolapsed segment on the anterior leaflet is less than 10% of the leaflet surface area and less than one fifth of the free edge length, and on the posterior leaflet, when the free edge length is less than one third of the annulus length.

The segment to be resected should be triangular, with the base at the free edge and the height greater than the base length. Particularly on the posterior leaflet, the free edge length of the prolapsed segment

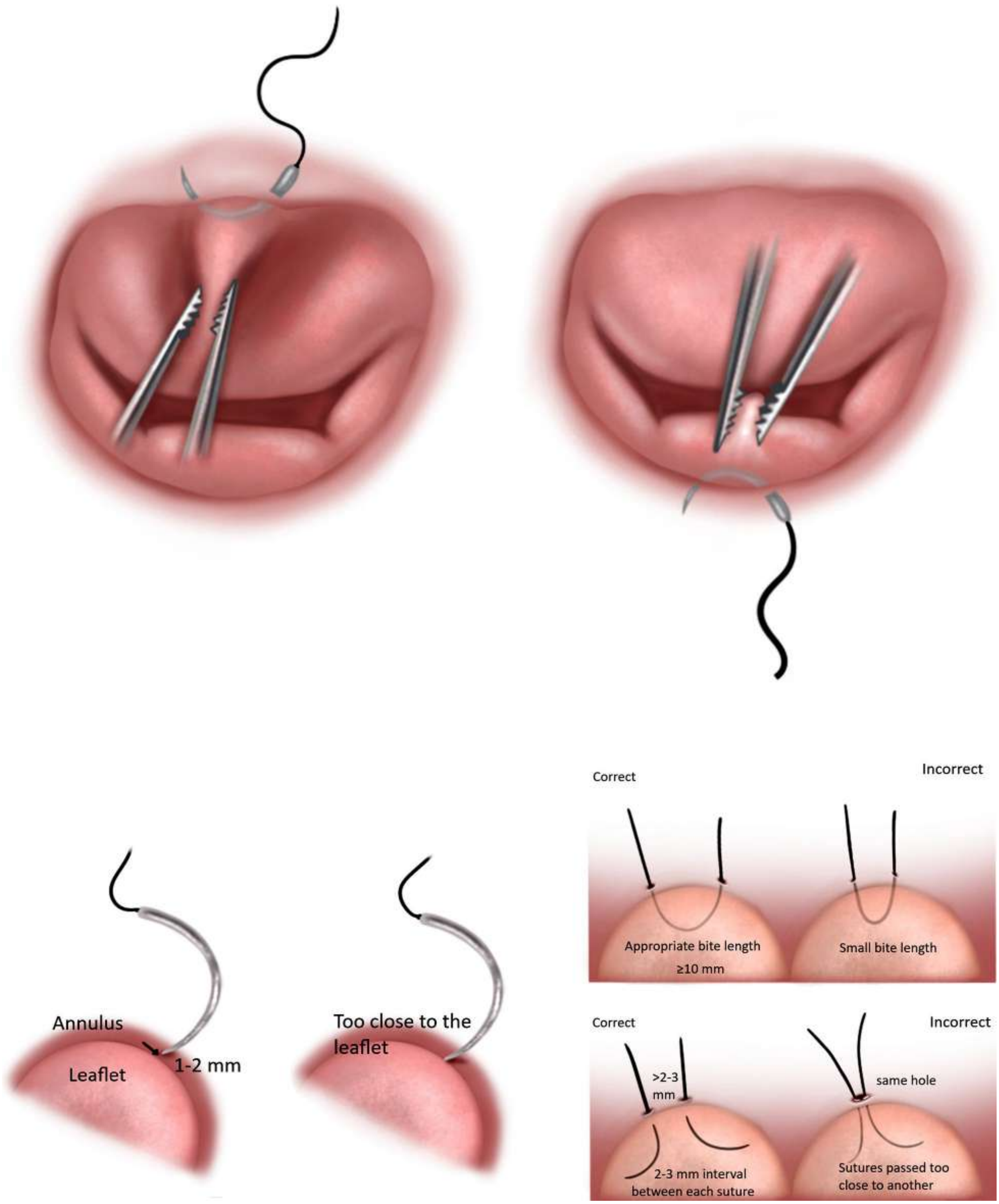

Figure 15.1. The needle enters about 1-2 mm outside the atriovalvular junction and is advanced toward the annulus just beneath the leaflets, exiting approximately 1-2 mm away from the atrial side. The distance traversed on the annular plane should be approximately 10 mm. The angle of needle advancement should not be wide or deep. The spacing between each suture should be 1-2 mm.

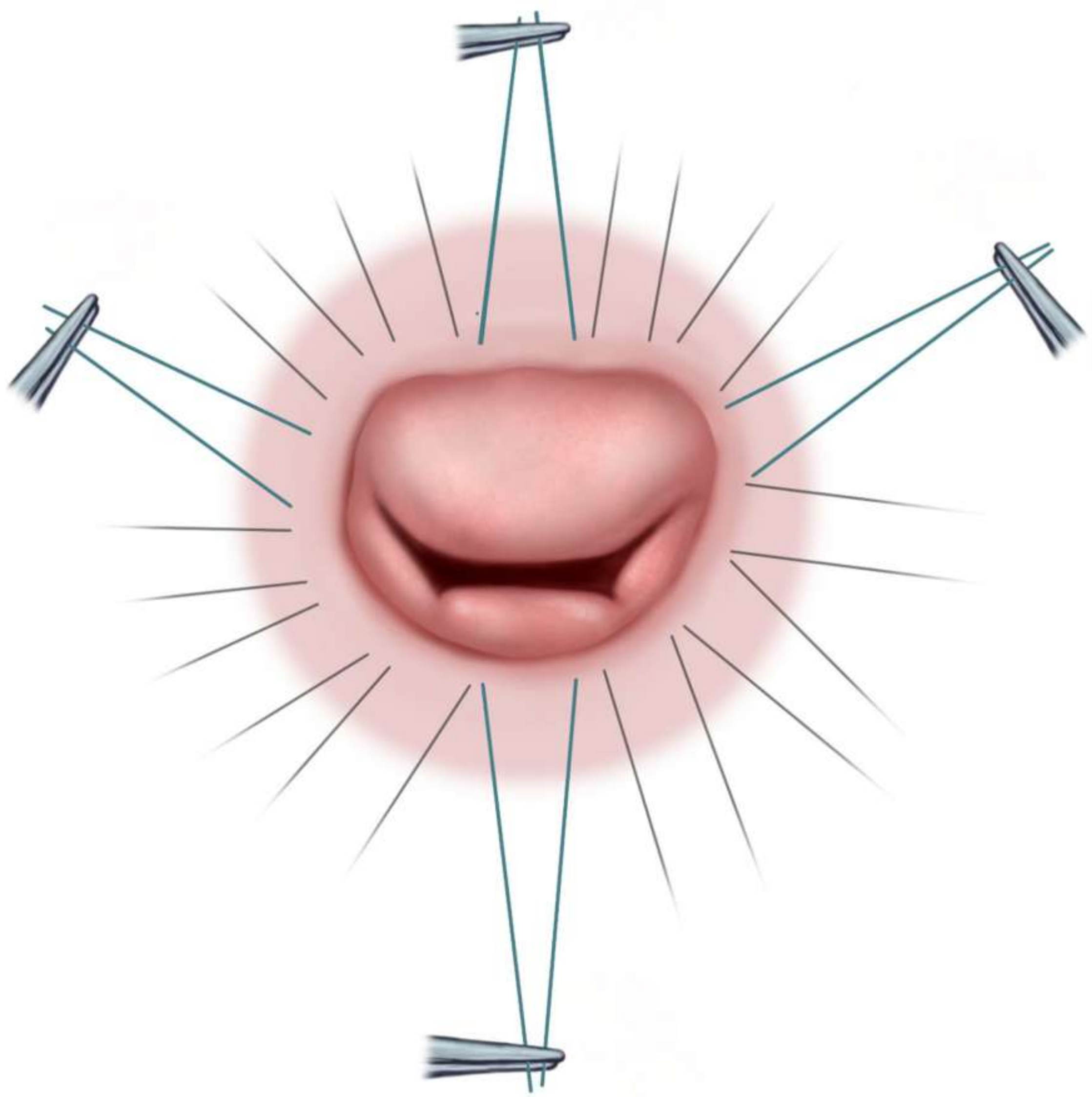

Figure 15.2. Identifying sutures that align with the midline of the commissures and leaflets can facilitate passing them through the ring first, aiding in determining the positions of other sutures on the ring.

should be less than one third of the annulus length (Figure 15.3).

Two healthy chordal structures adjacent to the prolapsed segment are identified, and with some leaflet tissue left for suturing, resection is performed by descending from the free edge to the atriovalvular junction. It is, then, repaired preferably with individual primary sutures using 5-0 sutures. If continuous repair is to be performed, intermittent locking can be used to avoid creating a purse-string effect.

2. Quadrangular Resection

This resection technique is used for the posterior leaflet. It is applied, when the prolapsed segment is large, with the expectation that it will be closer to the normal geometry. After resection, the remaining leaflet tissue can be approximated by equally plicating the annulus.

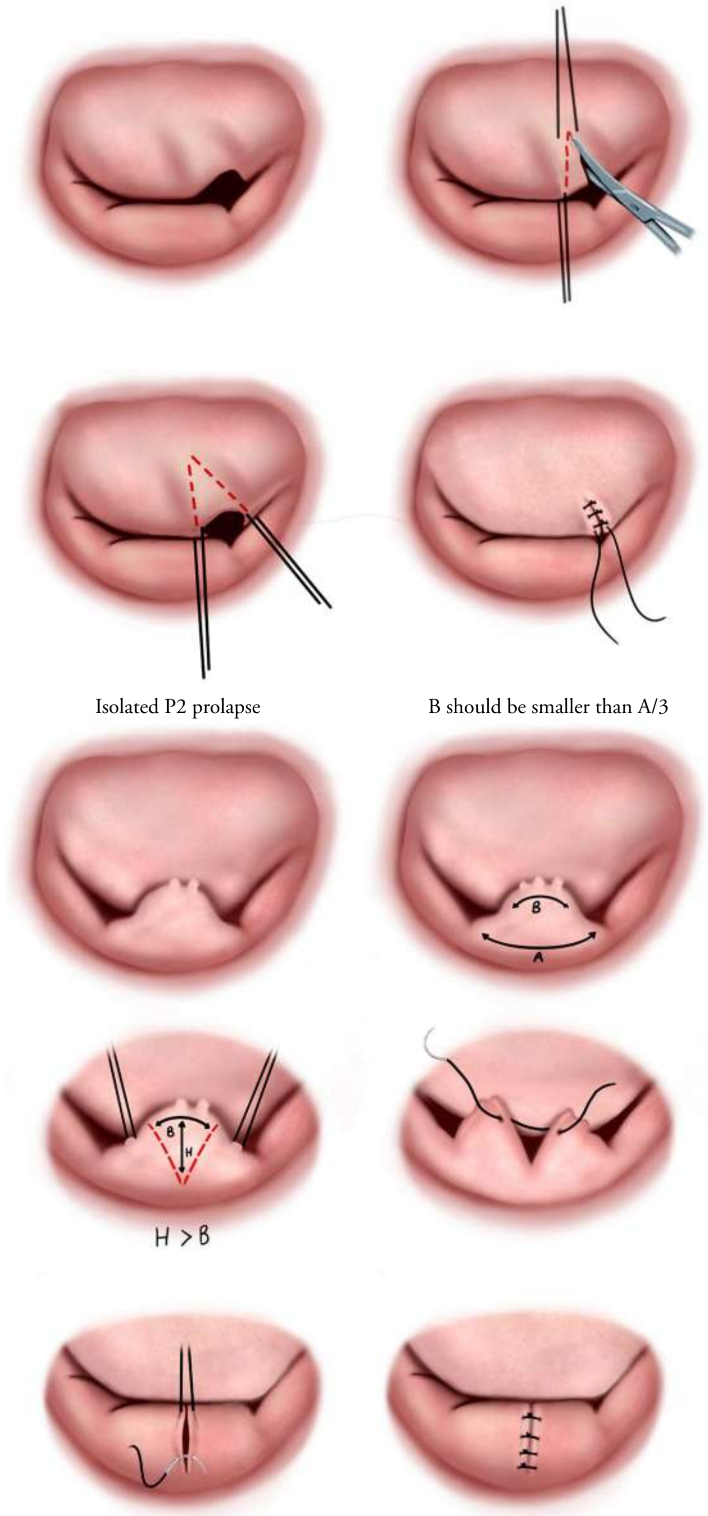

Figure 15.3. The segment to be resected should be triangular, with the base at the free edge and the height greater than the base length. In particular, on the posterior leaflet, the free edge length of the prolapsed segment should be less than one third of the annulus length.

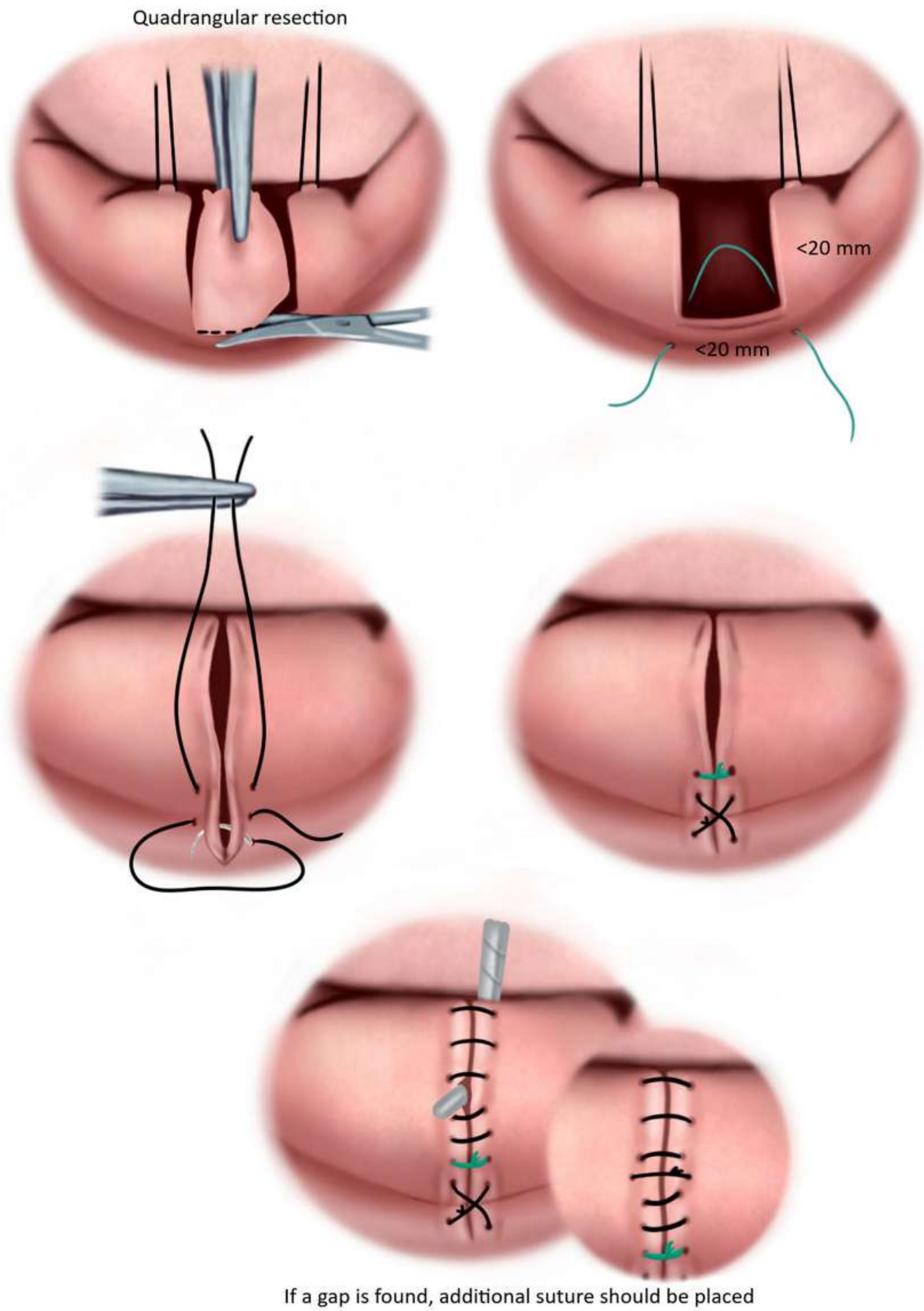

Figure 15.4. Healthy chordal structures are identified on both sides of the prolapsed segment, and enough tissue is left for suturing, then a quadrangular tissue resection is performed by descending from the free edge to the atriovalvular junction. The resected tissue width is plicated with 4-0 sutures. The remaining leaflet tissues, brought together, are sutured with 5-0 sutures. If the height of the remaining leaflet tissue is >20 mm after resection, to reduce the height, a horizontal triangular tissue resection at the atriovalvular junction is performed.

Healthy chordal structures are identified on both sides of the prolapsed segment, and enough tissue is left for suturing, and then a quadrangular tissue resection is performed by descending from the free edge to the atriovalvular junction (Figure 15.4). The resected tissue width is plicated with 4-0 sutures. The remaining leaflet tissues, brought together, are sutured with 5-0 sutures.

If the height of the remaining leaflet tissue is >20 mm after resection, to reduce the height, a horizontal triangular tissue resection at the atriovalvular junction is performed. If the space between two healthy tissues after resection is >20 mm, sliding annuloplasty is preferred over isolated annular plication.

3. Sliding Annuloplasty

Sliding annuloplasty is preferred, when the prolapsed segment is excessively large, or if too much annular plication would be necessary after quadrangular resection.

Half of the distance between the two healthy tissues is incised on both the anterolateral and posteromedial sides at the atriovalvular junction, and the leaflets are detached from the annulus. Then, the leaflet tissues on the healthy sides are approximated toward the midline and repaired with 5-0 sutures. The annulus side of the leaflet is repaired with 4-0 sutures to reduce the annulus length (Figure 15.5).

4. Butterfly Resection

Butterfly resection is applied, when the prolapsed segment is long to avoid excessive annular plication as in quadrangular resection. The procedure does not involve separating the leaflets from the atriovalvular part, as in sliding annuloplasty.

Two triangular resections are made in opposite directions. The triangle sitting on the annulus side has a wider base and shorter height, while the triangle with its based on the free edge of the leaflet has a longer height and narrower base.

After resection, the tops of the triangles are brought together at the midline of the annulus and sutured with 5-0 sutures. The free edges are also sutured together with 5-0 sutures, which both remove the excess segment from the posterior leaflet and reduce its height (Figure 15.6).

In cases where the prolapsed segment is wider, a similar resection shape can be used by widening the waistline to resemble an "hourglass" shape.

5. Other Resection Techniques

Although various resection shapes have been described for excess tissue in mitral leaflets, they are fundamentally combinations or modifications of triangular and quadrangular techniques.

RESPECT APPROACH/ ARTIFICIAL CHORD REPLACEMENT

With Frater and David first introducing the technique of chord replacement with artificial neochords in 1989, the concept of "respect instead of resection" has been widely adopted by surgeons. The main goal of MVR is to restore a satisfactory coaptation surface to ensure proper valve function. Since leaflet tissue is the primary component defining the coaptation surface, preserving a significant portion of the leaflet rather than resecting it forms the fundamental principle of this approach. It is also considered safe, as it allows transition to another technique if tissue is not resected or irreversibly altered.

Using 4-0 or 5-0 expanded polytetrafluoroethylene (e-PTFE) sutures, the leaflet is re-suspended to correct the prolapse, thereby preserving leaflet anatomy and mobility. Artificial chords not only correct leaflet prolapses, but also help prevent SAM by holding the posterior leaflet and coaptation surface at the left ventricular inlet. This method, particularly useful for mitral prolapse caused by chordal elongation or rupture, can be applied to almost all types of degenerative insufficiency, including fibroelastic deficiency, single and bileaflet prolapse, and advanced Barlow's disease, offering equivalent excellent long-term durability to quadrangular resection.

Isolated posterior leaflet prolapse can be equally effectively repaired by creating artificial chords or leaflet resection. While triangular resection is sufficient for limited prolapse areas, creating artificial chords is preferred for extensive and multifocal posterior prolapse. Anterior leaflet prolapse should be treated by creating artificial chords. Resection of the anterior leaflet is almost never a favorable option. Although chordal transfer is effective, creating artificial chords is simpler and faster.

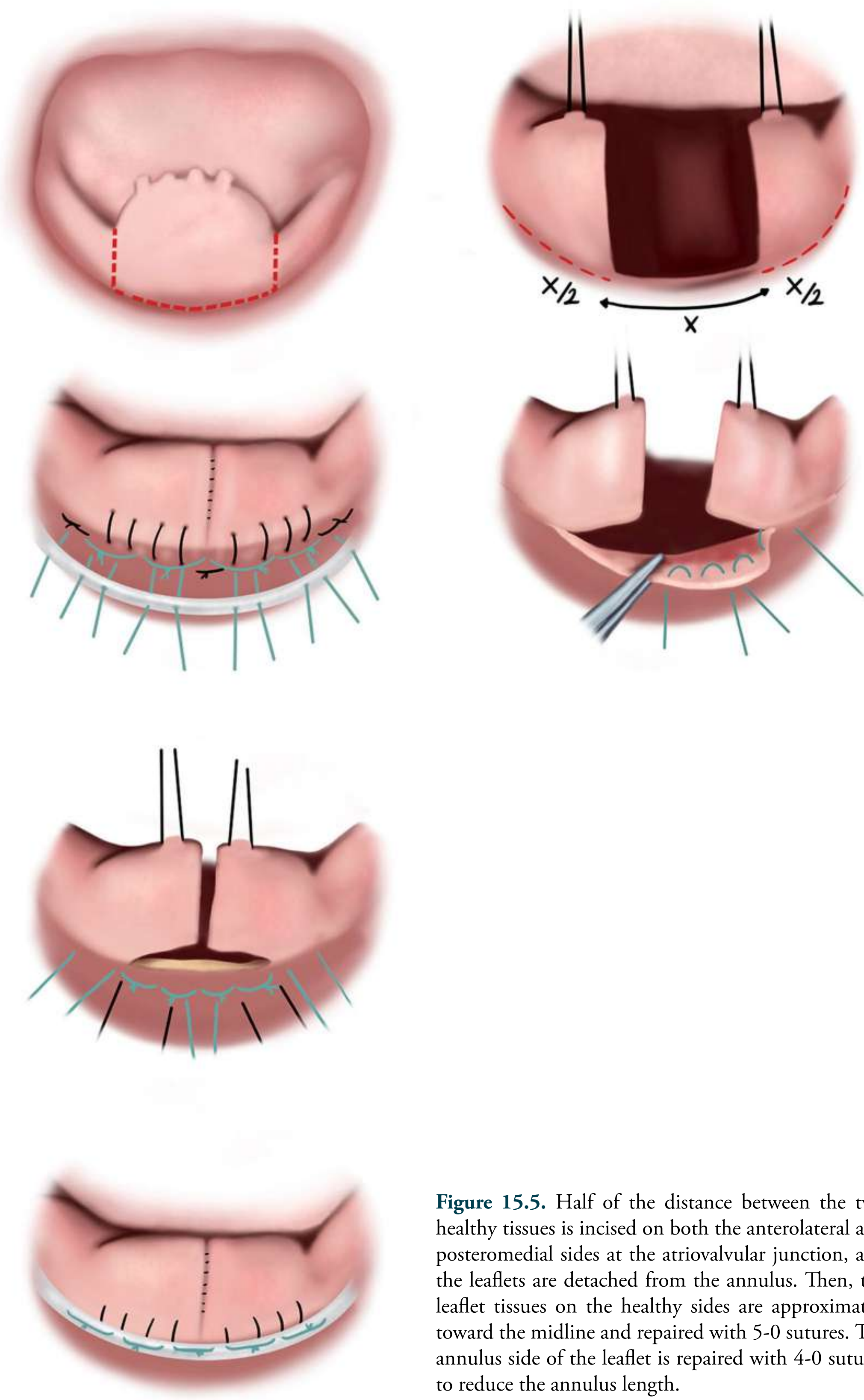

Figure 15.5. Half of the distance between the two healthy tissues is incised on both the anterolateral and posteromedial sides at the atriovalvular junction, and the leaflets are detached from the annulus. Then, the leaflet tissues on the healthy sides are approximated toward the midline and repaired with 5-0 sutures. The annulus side of the leaflet is repaired with 4-0 sutures to reduce the annulus length.

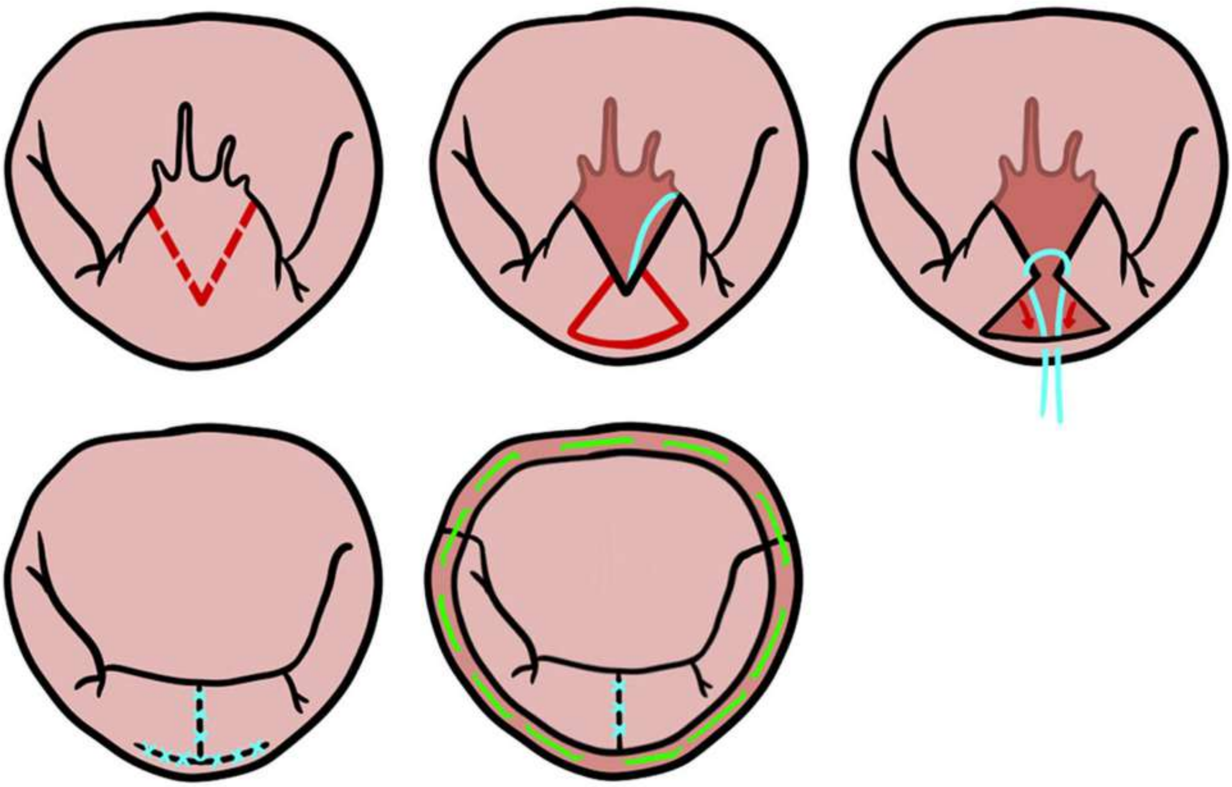

Figure 15.6. After resection, the tops of the triangles are brought together at the midline of the annulus and sutured with 5-0 sutures. The free edges are also sutured together with 5-0 sutures, which both remove the excess segment from the posterior leaflet and reduce its height.

Planning and Basic Techniques

The main challenge in chord replacement is to create chords of ideal length postoperatively. To achieve this, it is of utmost importance to accurately determine the length preoperatively and/or during surgery and carefully tie the knots without altering the set length.

It should be noted that very short sutures restrict leaflet motion, while very long ones lead to residual leaflet prolapse, and ultimately, both are associated with residual mitral insufficiency.

Apart from the now standard "free-hand" or "loop chord" techniques, surgeons continue to develop various methods to overcome the challenge of ideal length adjustment. These include the "Dubai stitch" or "Perier-Snail technique".

The ideal neochord length can be estimated either by preoperative transesophageal echocardiography (TEE) measurements or by using a graduated caliper during surgery, referencing the height of a normal healthy chord adjacent to the prolapse area. Alternatively, methylene blue can be used to mark the appropriate length neochord based on reference points such as the anterior mitral annular plane, P1 region of the posterior leaflet, or the level of the posterior leaflet's commissures on the coaptation line.

It should be kept in mind that preoperative TEE imaging under light sedation best mimics physiological conditions; thus, determining neochord length through sequential measurements from the placement point on the papillary muscles to the free edge of the prolapsed segment at the annular level will always be more accurate than other measurements taken in a fully distended, non-relaxed heart during surgery. Similarly, while taking intraoperative measurements, attention should be paid to ensure that subvalvular structures are tense by filling the ventricle with saline.

Before chord replacement, the boundaries of the prolapsed segment of the leaflet, the required number of artificial chords, and the placement point of the artificial chord should be clearly defined by direct inspection. Then, with mechanical retraction of the leaflets, access to the papillary muscles is achieved, and the placement of the artificial chord on each papillary muscle head is selected. Subsequently, surgeons typically choose one of two standard chord replacement methods:

1) Free-Hand Technique

After identifying the segment causing prolapse, a CV-4 Gore-Tex neochord is passed through a papillary muscle head corresponding to the prolapse area. Both arms of the neochord can be passed

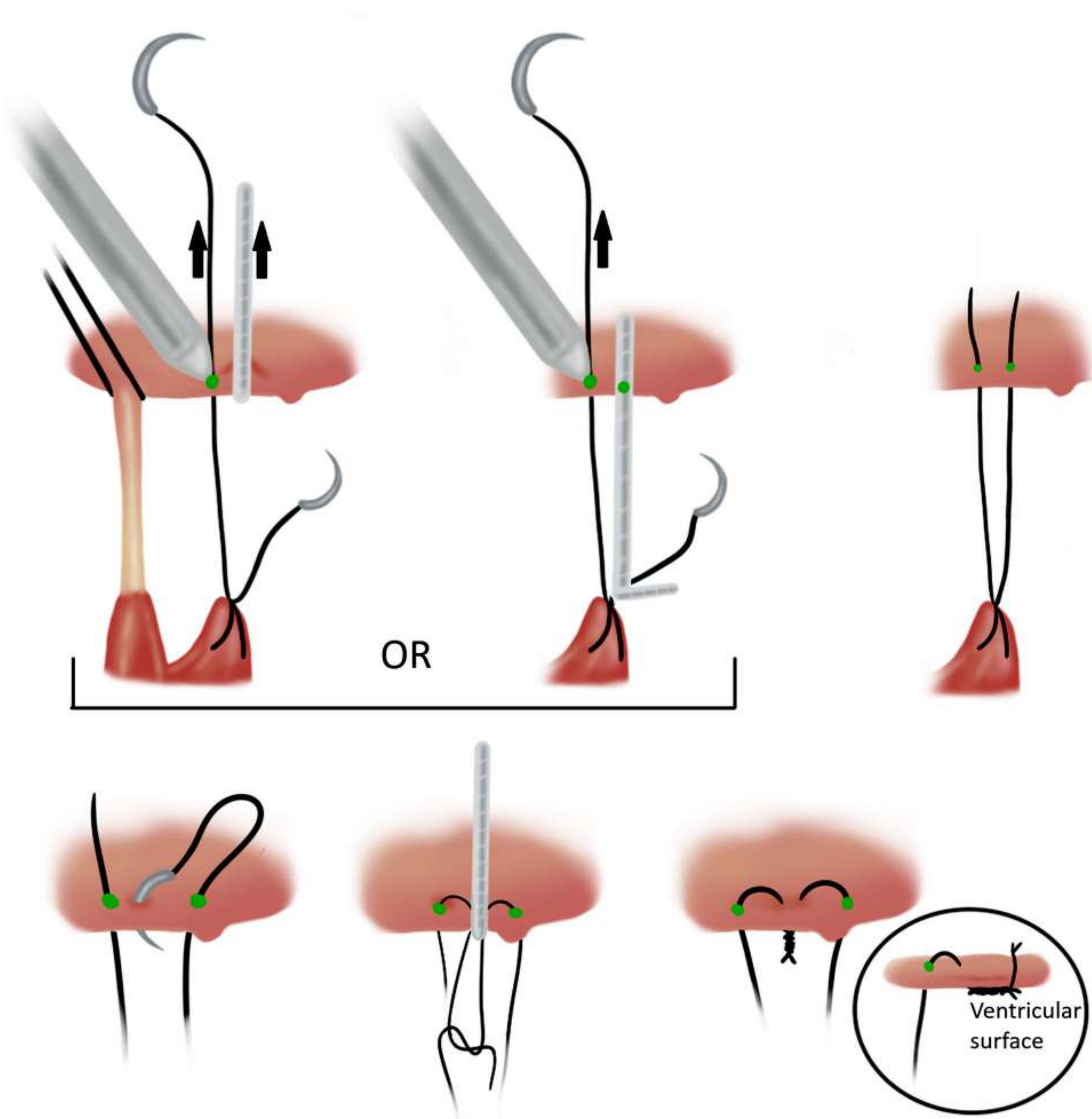

Figure 15.7. Free-hand technique; tying the suture after adjusting the length of the neochord. Tying the knot on the ventricular side ensures a smooth coaptation line and prevents the leaflet from sliding back and forth on the suture.

through the fibrous part of the papillary muscle head in a reciprocal "figure-of-eight" shape or with a simple U stitch, supported by a Teflon pledget or a small pericardial patch. Subsequently, each end of the neochord is passed twice from the ventricular to the atrial side of the leaflet edge, approximately 5 mm from the prolapse area and 2 to 3 mm away from the normal leaflet border. The neochord height is, then, adjusted to the measured length using a caliper or based on a reference point, and tied according to the surgeon's technique, either on the atrial or ventricular side of the leaflet. Tying the knot on the ventricular side ensures a smooth coaptation line and prevents the leaflet from sliding back and forth on the suture (Figure 15.7). Additionally, it eliminates any potential image on the atrial surface of the leaflet that may cause suspicion during echocardiographic evaluation. During the creation of artificial chords using the free-hand technique, care should be taken to adjust the final lengths of the chords after anchoring the annuloplasty ring to the annulus.

Some surgeons prefer to insert a split tube stent or a plastic tube around the Gore-Tex® suture on the ventricular side or temporarily secure it with a Hemoclip® on the atrial side to maintain the set length and prevent slippage during tying.

2) Loop Chord Technique (Pre-Measured Rings)

Developed by von Oppell and Mohr,[10] this method allows the use of pre-measured rings corresponding to the normal chord length, as evidenced by either preoperatively with TEE or intraoperatively with a caliper. These pre-measured loops, which simplify the repair process and save time, can be prepared by the surgeon during the case to the desired length or purchased commercially. The loops are first secured to the relevant papillary muscle with a pledget support using an anchoring suture underneath. Then, each loop is spread across the leaflet edge in prolapse area through separate stitches, spaced 5 to 10 mm apart depending on the width of the prolapsed segment (Figure 15.8). It should be noted that in cases where multiple chords are placed into scallops, the loops should not cross the midline of the leaflet or loop around the native chords. Therefore, the leaflets should be divided into four quadrants, with those on the right side of the midline attached to the posteromedial papillary muscle and those on the left side attached to the anterolateral papillary muscle.

3) Dubai Stitch

Developed by Safadi et al.[11] to overcome the difficulty in obtaining the ideal length of

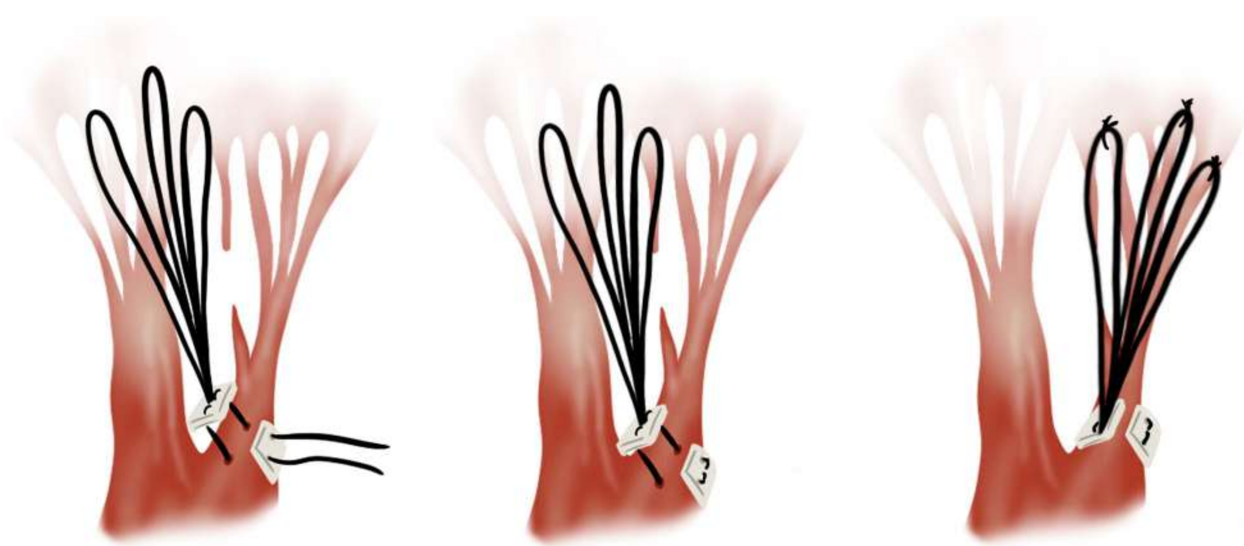

Figure 15.8. The loops are first secured to the relevant papillary muscle with a pledget support using an anchoring suture underneath. Then, each loop is spread across the leaflet edge in prolapse area through separate stitches, spaced 5 to 10 mm apart depending on the width of the prolapsed segment.

artificial chords, this method consists of a special sliding suture mechanism based on an adjustable PTFE/simple loop. Similar to a standard slip knot, this sliding suture allows unlimited fine adjustment of the loop length, providing the appropriate length for artificial chords. Initially, one end of a single 4-0 ePTFE suture is passed through the free edge of the prolapsed leaflet and then through the relevant papillary muscle. The first arm emerging from the leaflet edge corresponds to the narrow end of the loop, while the second arm emerging from the papillary muscle corresponds to the wider end. Subsequently, the second arm is passed in front of the first arm and a single knot is tied to create the first large loop. Then, the second arm is passed behind the loop in the segment of the papillary muscle and a second simple knot is tied. Pulling both arms together, two knots are gently brought close, completing the artificial chord. By pulling up the first arm and pushing down the sliding suture, the loop size is shortened, dragging the loop toward the leaflet coaptation area. If the chord is shortened excessively and the free edge of the leaflet remains below the coaptation level, the sliding suture is pulled up again to readjust the length and achieve the ideal coaptation.

4) Perier-Snail Technique

The "Snail" technique developed by Dr. Patrick Perier[12] is specifically used to treat posterior leaflet prolapse caused by tissue redundancy and/or myxomatous degeneration. Unlike many other techniques, it offers advantages such as not requiring resection, not requiring measurement for chord length, and not restricting the movement of the suspended segment, making it more standardized and providing predictable and highly successful outcomes for most posterior prolapse cases. Often, a single set consisting of two chords is sufficient. In this method, chords are first anchored to the posterior papillary muscles. Then, these chords are passed through the free edge of the posterior leaflet in the prolapsed area, removing excess slack while ensuring they are not overly tense. Next, the sutures are brought intermittently along the length of the leaflet through several passes, toward the mitral annulus. Finally, they emerge superficially from the left atrial endocardium 1.5 cm behind the annulus, avoiding damage to the circumflex artery and aligning just outside the annuloplasty ring. Once the annuloplasty ring is positioned, these external sutures are tied with attention to tension, ensuring optimal coaptation of the posterior leaflet within the inflow and eliminating the risk of SAM.

Possible Disadvantages, Complications, and Limitations of Artificial Chords

The main reasons for the failure of chordal replacement are technical failure, progression of existing degenerative disease, or the development of new disease (e.g., endocarditis). Failure to adjust chord length correctly or leaving out part of the repair technique are the primary causes of technical failure. In addition, artificial chord rupture, as described in isolated cases, is another reason. Chords can break due to hyalinization or calcification of the ePTFE pores. Therefore, surgeons should avoid compressing the ePTFE with surgical instruments such as forceps or clamps during surgery, and thin sutures should be avoided. Reports in the literature indicate the presence of hemolytic anemia as another presentation of mitral repair failure; it is believed to be associated with the failure of artificial chords to endothelialize. Finally, it should be noted that postoperative positive remodeling of the left ventricle can lead to a mismatch between artificial and natural chords, reducing the success of repair. Therefore, while dealing with patients with significantly dilated left ventricles, the lengths of artificial chords should be adjusted with the understanding that left ventricular volumes may decrease over time.

The use of ePTFE neo-chords in mitral repair procedures provides excellent long-term outcomes in terms of repair durability and survival. However, it should be remembered that chordal replacement is not a one-size-fits-all approach for every patient. Neochordal techniques may be the best choice for focal disease of both leaflets or cases consisting solely of leaflet prolapse. However, respectful resection approaches should also be added to chordal replacement in cases of widespread bileaflet disease or excessive posterior leaflet width accompanying P2 height, particularly if echocardiographic determinants of SAM are present. Therefore, all surgeons should adopt a patient-specific complementary approach from respect to resection, using these techniques according to the type of mitral disease they encounter.

SUBVALVULAR REPAIR TECHNIQUES

A. Papillary Muscle Procedures

1) Repositioning of the Posterior Papillary Muscle:

- In chronic ischemic mitral regurgitation, the posterior papillary muscle displaces apically, resulting in mitral insufficiency. Repositioning of the muscle restores mitral competence.
- In this procedure, a 3-0 polypropylene or CV4 Gore-Tex® suture is passed twice through the fibrous part of the posterior papillary muscle and then through the annulus just posterior to the fibrous trigone via a transventricular approach.
- Following placement of the annuloplasty ring, the papillary muscle is pulled upward to maximize leaflet coaptation, and the suture is tied.

2) Papillary Muscle Sling:

- This technique involves placing a 4-mm Gore-Tex® tube graft around the base of both papillary muscles to reduce the displacement of the posterior papillary muscle in ischemic insufficiency.
- The sling is, then, tightened between both papillary muscles to reduce the distance, realign the papillary muscles, and decrease tension on the chordae tendineae.

3) Papillary Muscle Approximation:

- Alternatively, papillary muscles can be approximated by suturing their heads together to reduce displacement and tethering (Figure 15.9).
- Another method is the sandwich-plasty, where a 3-0 TiCron™ suture, coated with Teflon, is passed from the posterior papillary muscle head to the anterior leaflet and supported with another Teflon patch.

4) Papillary Muscle Sliding Plasty:

- This method is suitable for anterior leaflet prolapse due to elongation of chordae extending from a single papillary muscle to both the anterior and posterior leaflets.
- The extended portion of the papillary muscle supporting the elongated chordae is longitudinally split, and one portion is reattached at a lower level with a Teflon-supported prolene suture (Figure 15.10).

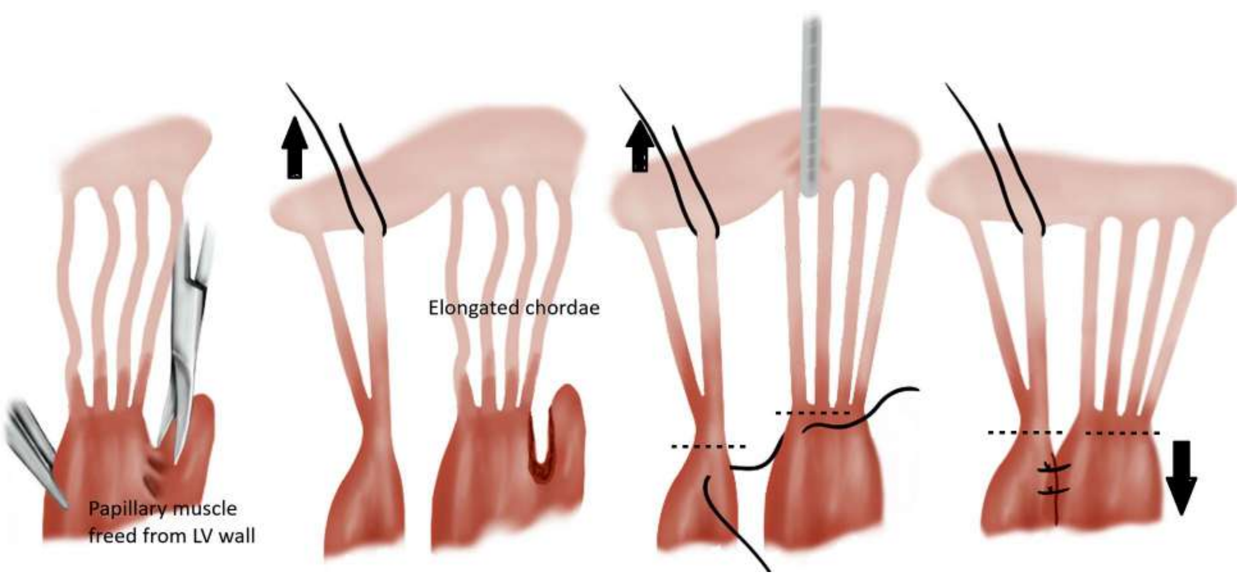

Figure 15.9. Papillary muscles can be approximated by suturing their heads together to reduce displacement and tethering.

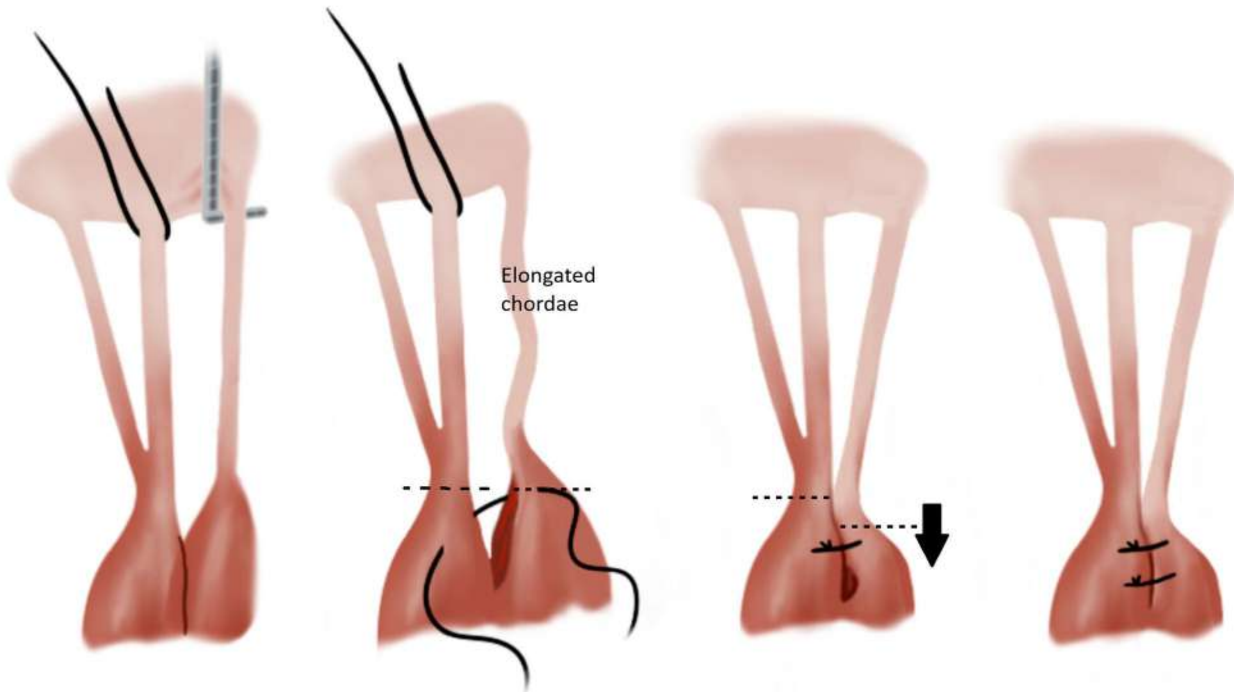

Figure 15.10. The extended portion of the papillary muscle supporting the elongated chordae is longitudinally split, and one portion is reattached at a lower level with a Teflon-supported prolene suture.

5) Papillary Muscle Shortening:

- This technique addresses papillary muscle elongation due to ischemia by shortening its length with a suture supported by a Teflon felt. There are two other techniques to reduce the length of the papillary muscle either with or without resection of the muscle (Figure 15.11).

6) Papillary Muscle Head Repositioning:

- This technique, a form of papillary muscle shortening, is useful for patients with commissural prolapse due to elongated chordae from the same papillary muscle head.
- A small wedge-shaped excision is made at the base of the papillary head equal to the prolapse distance, and the gap is closed with 4/0 prolene suture (Figure 15.12).

7) Papillary Muscle Splitting:

- In patients with rheumatic mitral valve disease, where commissures are immobilized post-fusion, splitting the papillary muscles and chordae can increase their mobility and flexibility.

B. Chordal Procedures

1) Chordal Shortening:

- This technique allows reducing chordal height by repositioning a group of long chords into the papillary muscle.
- A longitudinal incision is made from the exit point of elongated chords toward the base of the papillary muscle. Then, the elongated chords are folded at the deepest point of the incision to match the length of adjacent normal chords and sutured into the muscle.
- However, it should be noted that putting additional stress on an already thin and weak chord can lead to negative outcomes such as chordal rupture and recurrent leaflet prolapse.
- An alternative technique to this is the "chordal plication and free edge reshaping" technique described by Fundaró et al.[23] Elongated chords are captured at their tips and plicated along the free edge of the leaflet using a continuous suture technique.

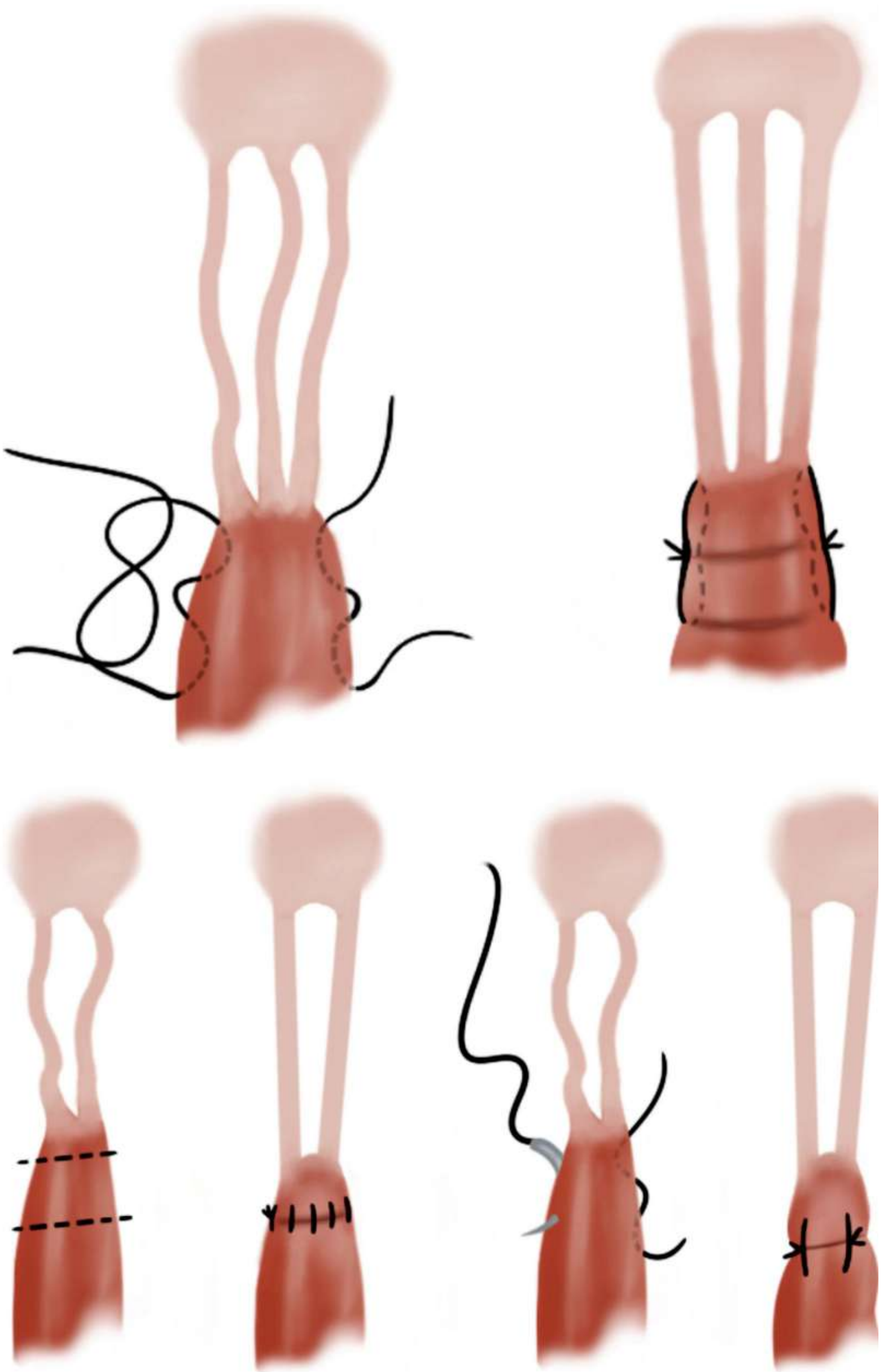

Figure 15.11. Length of the papillary muscle is reduced either with or without resection of the muscle.

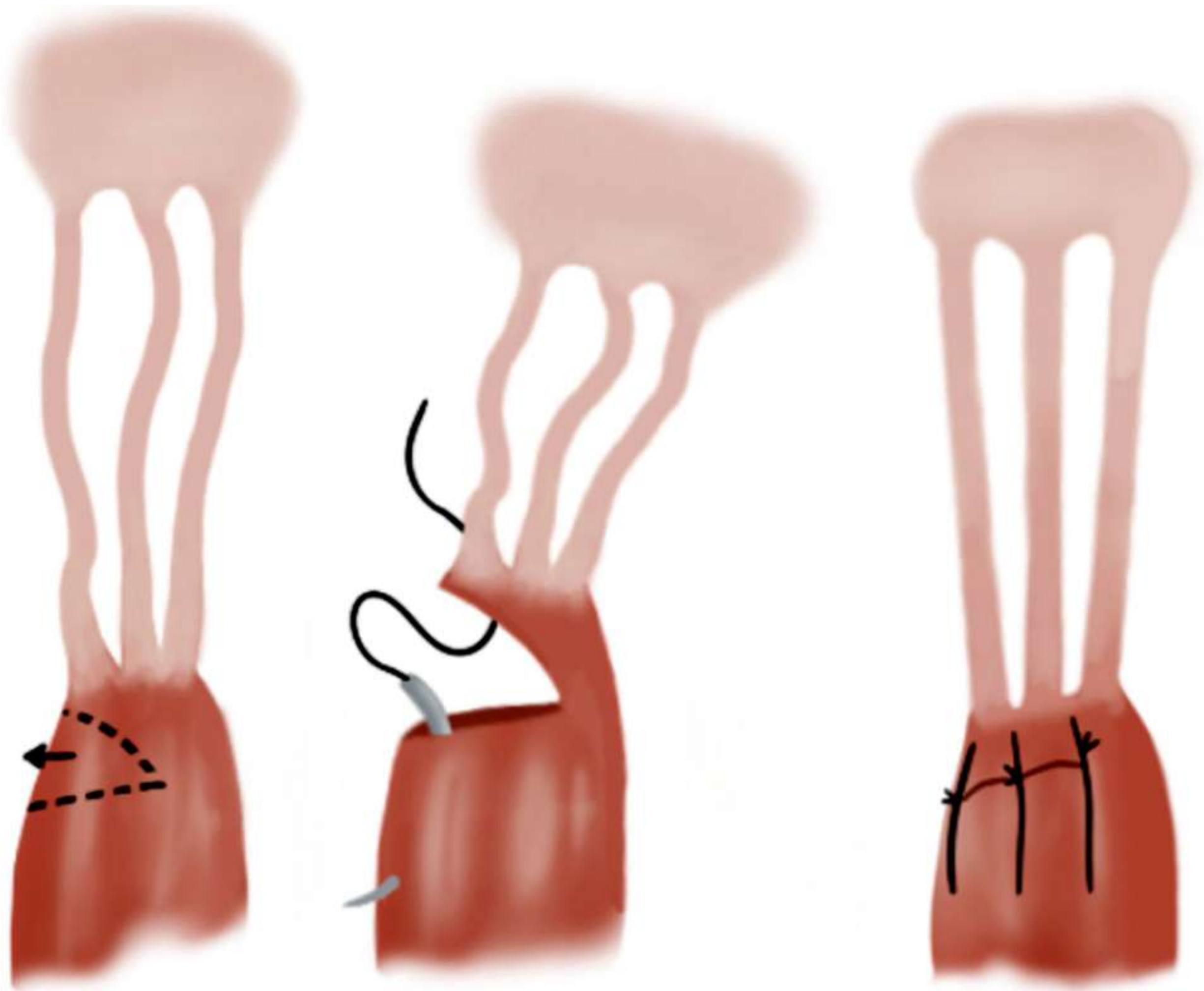

Figure 15.12. A small wedge-shaped excision is made at the base of the papillary head equal to the prolapse distance, and the gap is closed with 4/0 prolene suture.

- Another method is "papillary muscle repositioning," which is based on the fact that papillary muscles have multiple heads. Essentially, it is similar to the techniques of "papillary muscle sliding plasty" and "papillary muscle head repositioning." The principle of the technique is to reattach the higher-positioned head, which supports the elongated chord, to a lower-level adjacent head.

2) Chordal Cutting:

- Secondary chords carry three times the load compared to primary chords and remain tense during the cardiac cycle, maintaining the papillary-annular distance.
- In ischemic mitral insufficiency, displacement of papillary muscles can result in tethering of secondary chords on the leaflet.
- Cutting these affected secondary chords improves leaflet motion and increases coaptation depth. However, cutting the chords can disrupt the valve-ventricle continuity, leading to regional left ventricular dysfunction, particularly in patients with pre-existing ventricular dysfunction. Thus, instead of cutting secondary chords, they can be transposed to the free edge of the leaflet using a 5/0 prolene suture, while preserving primary and tertiary chords.

3) Chordal Transposition or Transfer:

- Two types of chordal transposition have been described: transposition of primary posterior leaflet chords to the anterior leaflet edge and transposition of secondary anterior leaflet chords to the leaflet edge.
- The first method, also known as the "flip-over technique," is performed in patients with isolated anterior leaflet prolapse and a normal posterior leaflet. It involves resecting a portion of the healthy posterior leaflet and transposing it to support the flail segment of the anterior leaflet.
- In the second method, a secondary chord from the base of the leaflet is cut and transferred to the free edge of the leaflet using a 5/0 prolene suture. Another variant involves folding the free edge of the leaflet over the torn primary chord and securing it to a secondary chord.

EVALUATION OF REPAIRED VALVE

The indispensable final step of mitral repair is the intraoperative evaluation of repair quality, based on visual examination, saline test, ink test, and finally, TEE In an optimally repaired valve:

- There should be no leakage in the saline test;
- Adequate coaptation surface should be present;
- A symmetric closing line covering 80% or more of the valve area of the anterior leaflet should be present;
- Residual prolapse or bulging should not be observed;
- There should be no inclination toward SAM.

Alongside visual examination, the simplest and most reliable method, the saline test, is used first. Using a 20-Fr rubber catheter attached to a syringe, the left ventricle and aortic root are filled. Sufficient ventricular distention must be achieved to pull the leaflets below the annular plane, which may require multiple injections. It should be noted that an inadequately filled ventricle may not allow sufficient valve coaptation, causing even a well-repaired valve to leak.

Although saline injection is invaluable in evaluating valve competence, it is a limited test as it does not fully confirm the coaptation surface. For instance, a valve with no leakage on saline test may actually have a minimal coaptation surface or excessive anterior leaflet tissue below the closing line. Although TEE can detect such defects, there is a need for a technique that allows the surgeon to confirm the coaptation surface and the amount of anterior leaflet tissue below the closing line before separation from cardiopulmonary bypass; this is the role of the ink test.

The ink test is performed after the ventricle is completely filled with saline, by drawing a line on the closing line. The coaptation area beyond the ink line should be at least 6 mm long; when part of the ink is within the coaptation area, this will correspond to approximately 10 mm on echocardiography. Additionally, the amount of anterior leaflet beyond the ink line should not exceed 10 mm.

After the saline and ink tests, when the heart is beating and cardiopulmonary bypass is terminated, the valve should be visualized for leaks or SAM using TEE. Any trace or 1+ leak should be closely evaluated on intraoperative TEE, as long-term failure rates are significantly higher with 2+ or higher insufficiency. In the presence of trace or 1+ leak, the systolic blood pressure should be raised to 150 to 160 mmHg to confirm that the degree has not changed.

POSSIBLE RESIDUAL LEAKAGE SCENARIOS

Central Residual Leakage:

When residual leakage is detected centrally after valve reconstruction, the direction of the regurgitant jet is determined, and the region with functional impairment is identified by comparing the free edges of A2 and P2. The leakage is corrected by applying either artificial chordae replacement or secondary chordal transposition to the relevant free edge.

Commissural Residual Leakage:

Commissural leakage can occur, when the commissural edges do not coapt properly or when the commissurotomy is extended excessively toward the annulus during mitral stenosis repair. By using the "magic suture technique" with 5-0 prolene, where sutures are placed through both free edges of the leaflet from the atrial to ventricular side, the coaptation surface is increased, and the leakage is corrected.

Mitral Scallop Residual Leakage:

An excessively wide or retracted scallop can be another cause of residual leakage. If retraction is significant, after freeing the chordae attached to the edges of the notch, primary approximation is done with 5-0 suture to close the gap. In particular, in patients with mitral stenosis, if the notch is very large, after resection of thickened tissues, a triangular pericardial patch can be used.

If no cause is found for residual insufficiency after careful analysis, or if the surgeon believes that the insufficiency cannot be predictably or durably corrected, valve replacement should be considered.

SAM

Systolic anterior motion is the movement of the anterior leaflet toward the septum during systole, instead of moving toward the posterior leaflet and closing. This condition leads to left ventricular outflow obstruction and mitral insufficiency. Of note, SAM occurs in nearly 4 to 10% of cases after mitral repair surgeries, particularly in the presence of excessive leaflet tissue as in Barlow's disease and after excessively corrective annuloplasty.

Causes of SAM include excessive leaflet tissue, particularly leaving too much of the posterior leaflet, and choosing a small annuloplasty ring. Factors such as small left ventricular diameter, accompanying left ventricular or septal hypertrophy, and hyperdynamic conditions such as tachycardia increase the severity of SAM.

To prevent SAM during MVR, attention should be paid to ensure that the height of the posterior leaflet does not exceed 15 mm, adequate posterior leaflet resection should be performed, and additional sliding plasty should be applied to correct the leaflet-annulus ratio, and a larger size ring should be preferred.

Postoperative monitoring with TEE reveals SAM, when there is a gradient toward the outflow tract and systolic mitral regurgitation characterized by a posterior jet along with excessive posterior leaflet. If SAM is detected, it is often resolved by correcting underlying factors such as suboptimal ventricular filling, AV conduction abnormalities, and tachycardia. To illustrate, increasing preload and afterload, correcting conduction abnormalities with AV pacing, and starting beta-blockers will often be beneficial. The most practical way to test this intraoperatively is to fill the heart and temporarily compress the ascending aorta with a clamp or finger.

If despite these manipulations, there is still a gradient and leakage on TEE, or if a structural cause causing SAM can be clearly demonstrated, such as excessive leaflet tissue, then a second surgical intervention should be considered. Alfieri edge-to-edge repair, once considered life-saving, is now highly controversial, as it may adversely affect a repaired valve or cause stenosis, particularly in cases where the annulus has been significantly reduced. Instead, it is more appropriate to intervene for the cause. For instance, if excessive posterior leaflet tissue is identified, it is appropriate to reduce the leaflet size by making a parallel oval incision to the annulus and then using a continuous suture technique. Another method described by Calafiore et al.[25] is to shorten the posterior leaflet by making a longitudinal plication with sutures placed on the annulus side of the posterior leaflet. If the problem is the use of a too small annuloplasty ring, the existing ring should be removed and replaced with a larger one. In cases with a small and hypertrophic ventricle, anterior leaflet reduction can be performed with a half-moon-shaped excision parallel to the annulus.

However, whether these additional interventions will be successful in correcting SAM or whether the adequacy of the repaired valve will be adversely affected after these interventions is another matter of debate. Therefore, after a time-consuming primary complex mitral repair, rapid mitral replacement may be the safest alternative compared to an uncertain additional intervention. If there is a failure in the additional intervention, it may require further intervention and ultimately replacement due to repeated cross-clamping and long perfusion times, which should be considered.

REFERENCES

1. Frater RW, Vetter HO, Zussa C, Dahm M. Chordal replacement in mitral valve repair. Circulation 1990;82(5 Suppl):IV125-30.
2. David TE. Replacement of chordae tendineae with expanded polytetrafluoroethylene sutures. J Card Surg 1989;4:286-90. doi: 10.1111/j.1540-8191.1989.tb00291.x.

3. David TE, Armstrong S, Ivanov J. Chordal replacement with polytetrafluoroethylene sutures for mitral valve repair: a 25-year experience. J Thorac Cardiovasc Surg 2013;145:1563-9. doi: 10.1016/j.jtcvs.2012.05.030.
4. Gillinov M, Burns DJP, Wierup P. The 10 Commandments for Mitral Valve Repair. Innovations (Phila) 2020;15:4-10. doi: 10.1177/1556984519883875.
5. Di Bacco L, Miceli A, Glauber M. Mitral valve repair techniques with neochords: When sizing matters. Innovations (Phila) 2020;15:22-25. doi: 10.1177/1556984520901487.
6. Montanhesi PK, Ghoneim A, Gelinas J, Chu MWA. Simplifying Mitral Valve Repair: A Guide to Neochordae Reconstruction. Innovations (Phila) 2022;17:343-351. doi: 10.1177/15569845221115186.
7. Perier P, Hohenberger W, Lakew F, Batz G, Diegeler A. Minimally invasive repair of posterior leaflet mitral valve prolapse with the "respect" approach. Ann Cardiothorac Surg 2013;2:833-8. doi: 10.3978/j.issn.2225-319X.2013.10.11.
8. Chang JP, Kao CL. Slit stent technique for ensuring the correct length of artificial chordae in mitral repair. J Card Surg 2011;26:259-60. doi: 10.1111/j.1540-8191.2011.01237.x.
9. Chan DT, Chiu CS, Cheng LC, Au TW. Artificial chordae: a simple clip and tie technique. J Thorac Cardiovasc Surg 2008;136:1597-9. doi: 10.1016/j.jtcvs.2007.12.080.
10. von Oppell UO, Mohr FW. Chordal replacement for both minimally invasive and conventional mitral valve surgery using premeasured Gore-Tex loops. Ann Thorac Surg 2000;70:2166-8. doi: 10.1016/s0003-4975(00)02047-6.
11. Safadi F, Yilmaz A, Glauber M. New adjustable "DUBAI" artificial chord for mitral repair: innovative method to ensure accurate length. Innovations 2018;13(3 Suppl):S64-S65.
12. Perier P. A case of mitral annulus disjunction repaired with the "snail" technique. JTCVS Tech 2023;22:92-93. doi: 10.1016/j.xjtc.2023.09.009.
13. Vendramin I, Milano AD, Pucci A, Lechiancole A, Sponga S, Bortolotti U, et al. Artificial chordae for mitral valve repair. J Card Surg 2022;37:3722-3728. doi: 10.1111/jocs.16937.
14. Nakaoka Y, Kubokawa SI, Yamashina S, Yamamoto S, Teshima H, Irie H, et al. Late rupture of artificial neochordae associated with hemolytic anemia. J Cardiol Cases 2017;16:123-125. doi: 10.1016/j.jccase.2017.06.007.
15. Mutsuga M, Narita Y, Tokuda Y, Uchida W, Ito H, Terazawa S, et al. Predictors of Failure of Mitral Valve Repair Using Artificial Chordae. Ann Thorac Surg 2022;113:1136-1143. doi: 10.1016/j.athoracsur.2021.04.084.
16. Kron IL, Green GR, Cope JT. Surgical relocation of the posterior papillary muscle in chronic ischemic mitral regurgitation. Ann Thorac Surg 2002;74:600-1. doi: 10.1016/s0003-4975(02)03749-9.
17. Hvass U, Tapia M, Baron F, Pouzet B, Shafy A. Papillary muscle sling: a new functional approach to mitral repair in patients with ischemic left ventricular dysfunction and functional mitral regurgitation. Ann Thorac Surg 2003;75:809-11. doi: 10.1016/s0003-4975(02)04678-7.
18. Wakasa S, Kubota S, Shingu Y, Ooka T, Tachibana T, Matsui Y. The extent of papillary muscle approximation affects mortality and durability of mitral valve repair for ischemic mitral regurgitation. J Cardiothorac Surg 2014;9:98. doi: 10.1186/1749-8090-9-98.
19. Ishikawa S, Ueda K, Kawasaki A, Neya K, Suzuki H. Papillary muscle sandwich plasty for ischemic mitral regurgitation: a new simple technique. J Thorac Cardiovasc Surg 2008;135:1384-6. doi: 10.1016/j.jtcvs.2007.12.034.
20. Fasol R, Lakew F, Pfannmüller B, Slepian MJ, Joubert-Hubner E. Papillary muscle repair surgery in ischemic mitral valve patients. Ann Thorac Surg 2000;70:771-6; doi: 10.1016/s0003-4975(00)01727-6.
21. Duran CM. Surgical techniques for the repair of anterior mitral leaflet prolapse. J Card Surg 1999;14:471-81.
22. Carpentier A. Cardiac valve surgery--the "French correction". J Thorac Cardiovasc Surg 1983;86:323-37.
23. Fundaró P, Lemma M, Di Mattia DG, Santoli C. Repair of anterior leaflet prolapse: chordal transfer versus chordal shortening. Which is better? J Thorac Cardiovasc Surg 1997;114:1125-7. doi: 10.1016/S0022-5223(97)70033-3.
24. Dreyfus GD, Bahrami T, Alayle N, Mihealainu S, Dubois C, De Lentdecker P. Repair of anterior leaflet prolapse by papillary muscle repositioning: a new surgical option. Ann Thorac Surg 2001;71:1464-70. doi: 10.1016/s0003-4975(00)02677-1.
25. Calafiore AM, Refaie R, Iacò AL, Asif M, Al Shurafa HS, Al-Amri H, et al. Chordal cutting in ischemic mitral regurgitation: a propensity-matched study. J Thorac Cardiovasc Surg 2014;148:41-6. doi: 10.1016/j.jtcvs.2013.07.036.
26. Duran CG. Repair of anterior mitral leaflet chordal rupture or elongation (the flip-over technique). J Card Surg 1986;1:161-6. doi: 10.1111/j.1540-8191.1986.tb00705.x.
27. Smedira NG, Selman R, Cosgrove DM, McCarthy PM, Lytle BW, Taylor PC, et al. Repair of anterior leaflet prolapse: chordal transfer is superior to chordal shortening. J Thorac Cardiovasc Surg 1996;112:287-91; doi: 10.1016/S0022-5223(96)70251-9-.
28. Hetzer R, Rankin J S, Yankah CA. Mitral valve repair. Berlin: Springer-Verlag; 2011.
29. Anyanwu AC, Adams DH. The intraoperative "ink test": a novel assessment tool in mitral valve repair. J Thorac Cardiovasc Surg 2007;133:1635-6. doi: 10.1016/j.jtcvs.2007.01.035.
30. Carpentier A, Adams DH, Filsoufi F. Carpentier's reconstructive valve surgery. Philadelphia: Elsevier Saunders; 2010.