

Simplifying Mitral Valve Repair: A Guide to Neochordae Reconstruction

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Innovations
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Abstract

Mitral valve reconstruction techniques using polytetrafluoroethylene sutures are associated with high repair rates and excellent durability but are dependent on accurate neochordae length estimates. Current strategies to determine the appropriate length of artificial neochordae commonly rely on nonphysiologic saline testing on the arrested heart, with erroneous lengths resulting in residual mitral regurgitation. We present a guide for reproducible and accurate neochordae reconstruction based upon transesophageal echocardiographic measurements, which simplifies mitral repair for most patients with degenerative mitral regurgitation and can be used in conventional or minimally invasive approaches.

Keywords

mitral valve repair, neochordae reconstruction, minimally invasive cardiac surgery, chordal replacement, mitral valve prolapse

Central Message

We present a guide for a reproducible and accurate neochordae reconstruction technique based upon transesophageal echocardiographic measurements.

Introduction

Degenerative mitral valve disease is the most common cause of severe mitral regurgitation (MR) in industrialized countries, often requiring surgical intervention.¹ Mitral valve repair is the procedure of choice, and it has been associated with lower rates of mortality, reoperation, and valve-related complications compared to mitral valve replacement.^{1–3}

Neochordae implantation has been increasingly adopted as the repair strategy for posterior, anterior, and bileaflet prolapse.^{4,5} When incorporating chordal replacement techniques into practice, repair success rates are directly related to the surgeon's ability to make proper neochordal length estimation and, therefore, to ensure adequate leaflet coaptation.

Several techniques have been described to determine the appropriate length of neochordae. However, most rely upon nonphysiologic saline tests on the arrested heart and a degree of “eyeballing.”⁶ Hence, to simplify mitral valve repair with artificial chordae, we present a guide for a reproducible and effective neochordae reconstruction technique based upon standardized echocardiographic derived length estimation.⁷

Surgical Technique

The following steps encompass preoperative measurement of the neochordae length using transesophageal echocardiography (TEE), preparation of the premeasured neochordae loops, neochordae

implantation, and neochordae adjustments. The complete step-by-step technique is described in the Supplemental Video that accompanies this article. All steps are also summarized in Figure 1.

TEE Measurement Technique

An outpatient transthoracic echocardiogram is performed to assess both the degree of MR and biventricular function under physiologic conditions and to determine indication for surgery, followed by a preoperative TEE used to plan for the primary operative repair strategy and backup techniques. We generally perform neochordae reconstruction in patients with mitral valve prolapse as the technique is broadly applicable to posterior, anterior, bileaflet, or commissural involvement, and can be easily adapted to single or multisegment disease. Patients with limited, narrow segment prolapse without much redundant leaflet tissue, most commonly fibroelastic disease, are often best treated with primary resection techniques.

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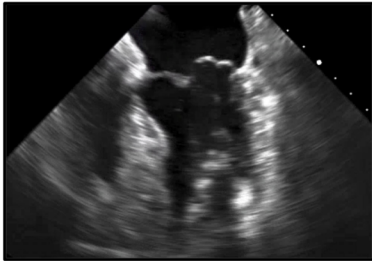
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GUIDE TO NEOCHORDAE RECONSTRUCTION

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1. TEE Measurement Technique

- TEE mid-esophageal; 0° or 120°; mid-systole;
- Visualize at the same time
 - prolapsing segment;
 - mitral annulus;
 - opposing leaflet and coaptation zone;
 - corresponding papillary muscle head;
- Measure 4 to 5 times and use the mean value.

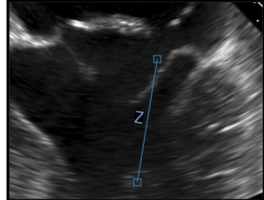


PL prolapse:

PL Length = X-Y

X : distance from papillary head to coaptation zone on AL;

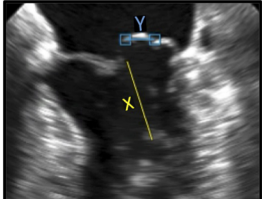
Y : length of flail segment on PL.



AL prolapse:

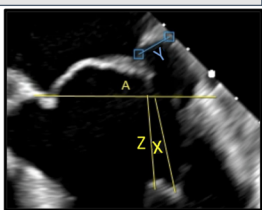
AL Length = Z

Z: distance from papillary head to coaptation zone on PL.



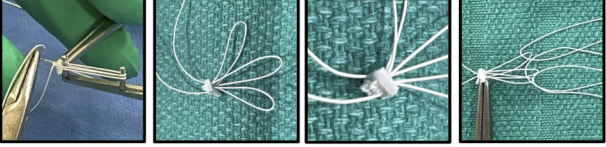
BL prolapse:

- Estimate a line for leaflet coaptation below the annulus (A);
- Combine PL and AL measurements.



2. Preparing the Neochordae Loops

- Set the caliper at the TEE-guided pre-measured length;
- Create the loops and flatten the knots;
- Pre-load 4-0 PTFE affixing sutures through each loop and secure with a hemostat;
- Organize the loops for implantation.

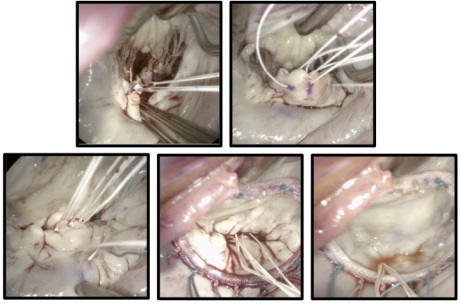


3. Implanting the Neochordae

- Assess the width of the prolapsing segment and identify the optimal affixing location on leaflet free margin;
- Identify the corresponding papillary head:
 - Do not cross the midline;
 - Keep posterior head to PL and anterior head to AL;
 - Do not interfere with native chords;

Implant the neochordae:

- Implant the base of the loops in the papillary head;
- Double check the orientation of loops;
- Implant each affixing suture into the leaflet free margin;
- Ring annuloplasty; saline test.

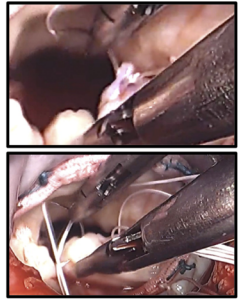


4. Minor Adjustments

Assess residual MR for location and mechanism: prolapse or restriction?
Is there room for optimization of neochord implantation?

Relocate the neochordae:

- Cut the affixing suture;
- Pass a new PTFE suture through the loop;
- Place the new affixing suture in the desired location.
- Reassess; saline test.



Repair Results

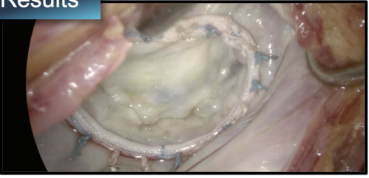


Fig. 1. Guide to neochordae reconstruction.

The decision to perform neochordae reconstruction is largely made upon the preoperative TEE, which shows reliable hemodynamic conditions. We believe that estimating the neochordae length preoperatively under light sedation best mimics

physiologic conditions, in contrast to the deep afterload reduction during general anesthesia. Also, direct intraoperative caliper measurements on the arrested heart may be associated with limited accuracy and therefore, compromise long-term repair durability.

An intraoperative TEE is used to confirm preoperative findings and to ensure no major strategic change is required secondary to new flail/prolapsing segments, infective endocarditis, or progression of ventricular dysfunction.

Neochordae length measurements are made from the preoperative 2-dimensional TEE midesophageal views, most commonly at 0° or 120°, at midsystole, when simultaneous and optimal visualization of the flail/prolapsing leaflet segments, mitral annulus, coaptation zone, and the corresponding papillary muscle head is achieved (Fig. 2a). Repeated measurements (4 to 5 times) and the use of a mean value are highly encouraged. Conversely, the use of suboptimal views that do not expose all abovementioned structures in the same frame may result in measurement errors and create the need for intraoperative adjustments. In addition, when 2-dimensional images are unclear about the extent of disease and its precise location, we find 3-dimensional TEE particularly useful to clarify if prolapsing segments are wide or narrow, and if the disease affects predominantly the medial or lateral aspects of the valve, or both.

Posterior Leaflet Prolapse

For posterior leaflet (PL) prolapse, the length of the neochordae loops is determined by the equation $PL = X - Y$, with X as the distance from the adjacent papillary muscle head to the intended

coaptation zone of the flail/prolapsing leaflet segment on the anterior leaflet and Y as the length of the redundant posterior flail segment that is rotated down into the ventricle (Fig. 2b). This calculation typically results in PL neochordae loops measuring 14 to 18 mm.⁷ We recognize that the Y segment is an estimation, often measured on the curve of the prolapsing leaflet and prone to interpretation bias. It is frequently estimated around 10 mm, but it can be longer in very redundant PL or shorter if PL is relatively normal (or short) in length, like in fibroelastic disease.

Anterior Leaflet Prolapse

For anterior leaflet (AL) prolapse, the flail/prolapsing segment is rarely that elongated (unlike the PL) such that it just needs to be rotated down into the coaptation zone. Hence, the length of AL neochordae loops equals the distance (Z) measured from the corresponding papillary head to the coaptation zone on PL (Fig. 2c). This measurement typically results in AL neochordae loops of 26 to 30 mm.⁷

Bileaflet Prolapse

Both techniques described above can be combined to treat bileaflet prolapse, including Barlow's disease. Due to the absence of a normal coaptation level, a line can be estimated below the

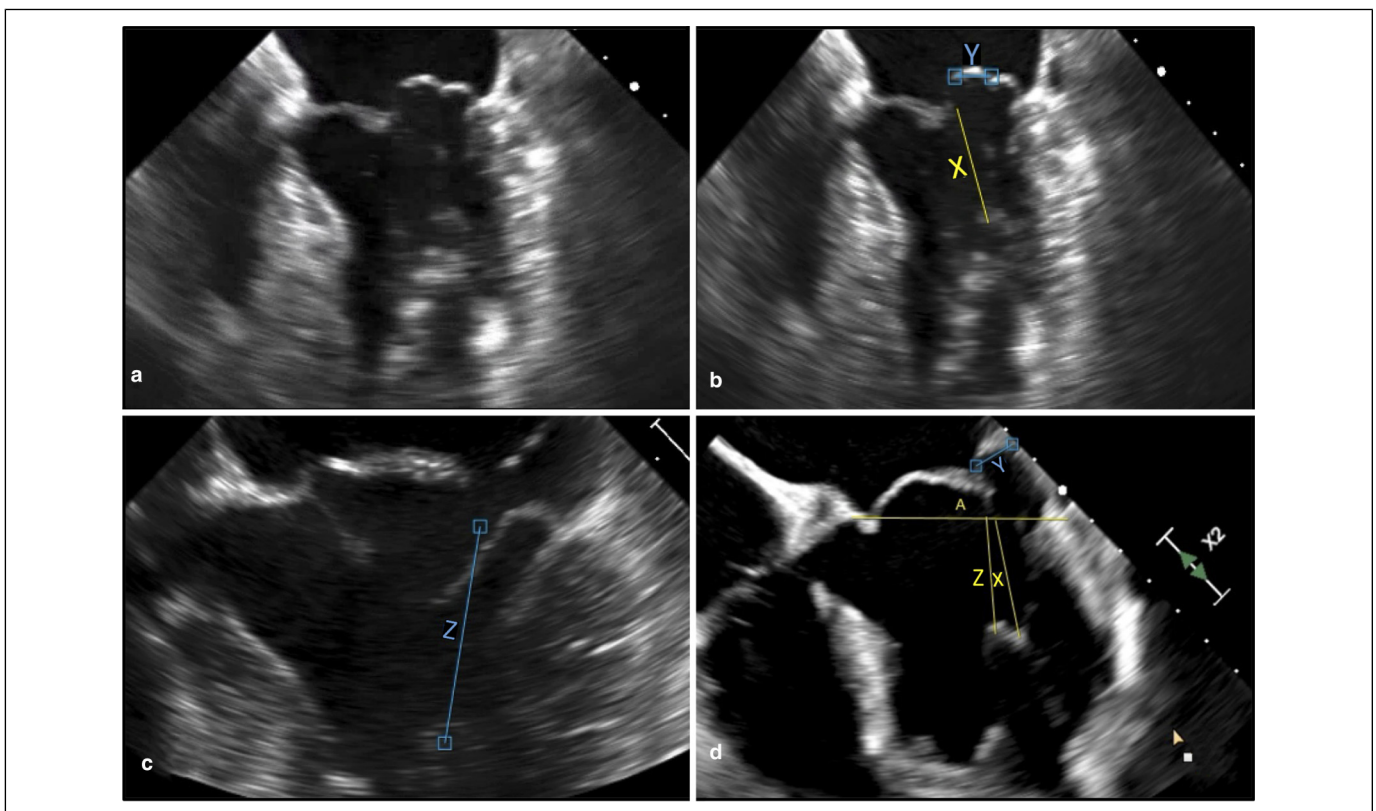


Fig. 2. Transesophageal echocardiography measurement technique. (a) Optimal view including the flail/prolapsing segment, mitral annulus, coaptation zone, and the corresponding papillary muscle head. (b) Length for posterior leaflet prolapse = $X - Y$. (c) Length for anterior leaflet prolapse = Z . (d) Length for bileaflet prolapse combines posterior and anterior leaflet measurements. A, mitral annulus.

annulus at the anticipated coaptation zone (Fig. 2d), preferably at 0° and 120° in the 4- or 5-chamber view, and in early midsystole, where the coaptation point is best seen. In general, PL neochordae are expected to be at least 10 mm shorter than AL neochordae in patients with bileaflet prolapse, as the PL is commonly much more redundant (i.e., AL neochordae loops 28 mm, with PL neochordae loops 18 mm).⁷

Of note, the coaptation zone is estimated to ensure a good coaptation height, and in most patients with bileaflet prolapse with such redundant tissue, especially in Barlow's valves, neochordae measurements are quite forgiving with acceptably wide margins. However, in patients with less leaflet redundancy, such as fibroelastic valves with limited PL prolapse, more accurate neochordae measurements are required - or it may be advisable to consider a simple triangular resection strategy.

Neochordae Loops Preparation

Although the TEE-derived length measurement can be used for any type of neochordae construction, we prefer using the Leipzig neochordae loop technique as we find it easy, reproducible, fast, and it provides multiple loops support for broad segments of prolapse. We believe that 3 loops generally provide adequate support for most prolapsing segments within each respective leaflet quadrant. Although more loops can be created, we standardized our technique to 3 loops per neochordae set to keep it simple and reproducible.

We advocate to prepare the neochordae loops before initiating cardiopulmonary bypass, ideally on a sterile back table at the beginning of the operation, to minimize any unnecessary added pump time and optimize intraoperative time efficiencies. The

following materials are required: 1 caliper, 4 polytetrafluoroethylene (PTFE) sutures (CV-4 GORE-TEX; WL Gore & Associates, Newark, DE, USA), 1 rectangular PTFE pledget (4 mm long), scissors, 4 hemostats, and elastic bands (Fig. 3).

First, set the caliper to the premeasured neochordae length. Then, secure the pledget in a longitudinal orientation on the hemostat. Subsequently, pass each end of a PTFE suture through the pledget forming the first loop around the caliper and tie at the base of the pledget with 3 knots (Fig. 4a). Ensure that both ends have the same length before tying. One end is then passed through the pledget and back forming the second loop superiorly to the first loop and tied at the base with 3 knots. The third loop is created passing the other end through the pledget and back, superiorly to the other 2 loops, and tied at the base with 7 to 8 knots (Fig. 4b). Remove the loops from the caliper but keep the pledget on the hemostat. Finally, to ensure the accuracy of the neochordae length, flatten the knots on the base of the pledget by passing both ends of the PTFE suture one last time up through the pledget and back, at the center of the pledget to remove the added height of the knot.

When the loops are ready, a 4-0 PTFE suture is preloaded on each loop and separately secured with a hemostat (Fig. 4c) to save time during implantation. Do not tie these preloaded sutures. Keeping the hemostats in the same order as the loops is recommended to avoid crossing and potential errors during implantation. The order can be secured with an elastic band or heavy suture tie around the hemostats. Finally, the sets of neochordae are saved inside a folded sterile field or towel to facilitate implantation (Fig. 4d). If more than 1 set is prepared, mark the corresponding lengths of the loops on the towels.

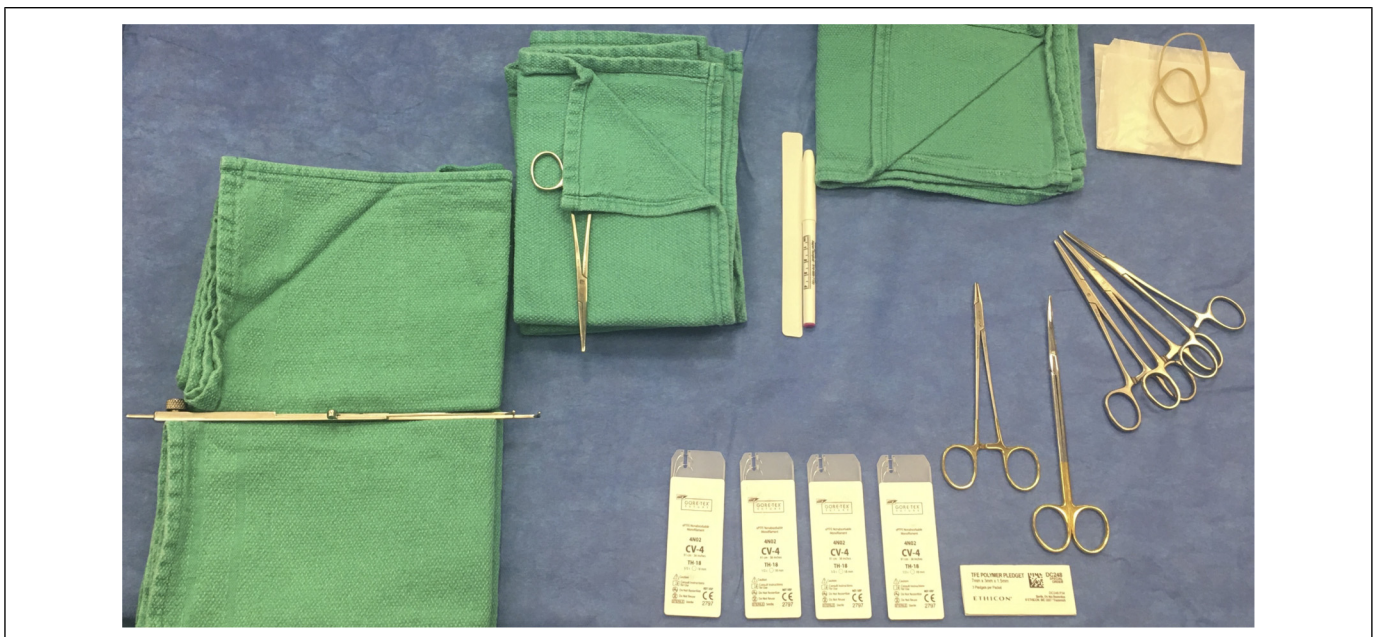


Fig. 3. Materials used for creating neochordae loops.

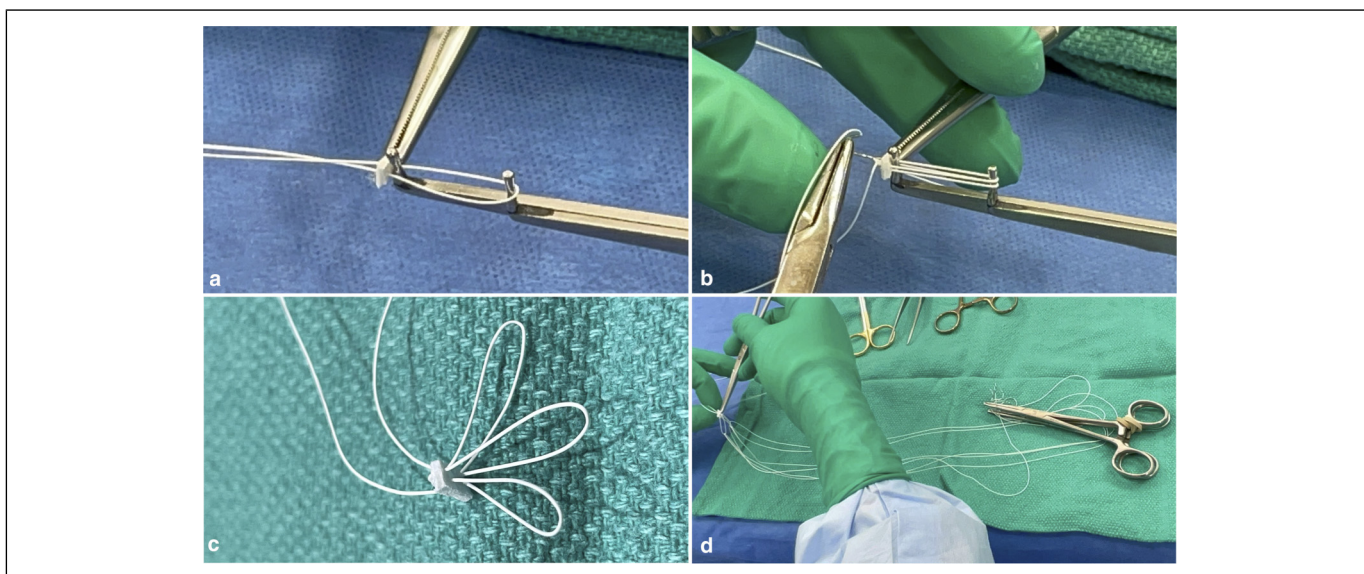


Fig. 4. Neochordae loops preparation. (a) The first loop is created in the longitudinal orientation of the pledget. (b) Subsequent loops are created, and the knots are flattened. (c) Final aspect of the loops. (d) A 4-0 polytetrafluoroethylene suture is passed through each loop and secured with a hemostat, ensuring the correct order for implantation.

Neochordae Implantation

Once the left atrium is opened and the mitral valve is exposed, the flail/prolapsing segments are evaluated to correlate anatomic and TEE findings. We do not spend an inordinate amount of time examining the valve, as we trust the TEE findings more than what we see with our eyes. The valve is briefly inspected to confirm previous imaging and we proceed with the preestablished surgical plan with neochordae measurements based upon the preoperative TEE.

We then divide the valve by quadrants and associate the prolapsing segment to its corresponding papillary muscle head quadrant (Fig. 5). Finding the base from where the ruptured chordae originated may be helpful at this point. Each papillary muscle often has an anterior and a posterior head quadrant. Thus, always keep the anterior head quadrants to the AL, the posterior head quadrants to the PL, and do not cross the annular midline (Fig. 5b). For example, when repairing a P2 to P3 prolapse (Fig. 5c), focus on the posteromedial papillary muscle with care not to cross the midline and specifically attach the base of the neochordae loops to the posterior head quadrant (Fig. 5d).

Similarly, for the lateral segment of the AL, attach a set of neochordae loops to the anterior head quadrant of the anterolateral papillary muscle, and implant the loops within A1 and A2 segments. When there is bileaflet prolapse (e.g., A2–A3 and P2–P3), 2 separate sets of neochordae loops are attached to both the anterior head and posterior head quadrants of the posteromedial papillary muscle, respectively. In addition, be aware that the midline of the mitral valve may not necessarily be the visual center of the valve but rather is defined by the midpoint where native chords converge in A2 or P2. Even when all the primary strut chordae are ruptured centrally, you can still

track secondary chordae back to the papillary muscles to determine the anatomic midline of the valve.

The following steps are crucial for success. The neochordae base is fixed to the corresponding head of the papillary muscle, ensuring that no surrounding chords are entrapped or restricted (Fig. 6a). The orientation of the base of the neochordae set must permit the neochordae loops to be properly fanned out across the width of the flail/prolapsing segment, left to right (from lateral to medial axis). Then, each loop is anchored on the leaflet free margin using the preloaded PTFE sutures at least 5 mm up the free margin (Fig. 6b).

As the loops must be spread out across the prolapsing free margin to provide adequate support, the distance between each loop may vary from 5 to 10 mm, depending on the width of the prolapsing segment (Fig. 6c). Neochordae loops attached too wide across the free margin may cause over-restriction at the most medial or lateral segments of the leaflet.

Similarly, leaflet restriction can occur if the loops are implanted too deep toward the annulus, especially at the most medial or lateral extent from the fulcrum of the papillary head attachment. We recommend a depth of 5 mm from the free edge, approximately at the coaptation line, and progressively shorter depths when moving to the most lateral segments when attached to the posteromedial papillary muscle or most medial segments when attached to the anterolateral papillary muscle.

Additional sets of neochordae loops can be implanted when required using the same principles described above. Most patients only require 1 set (3 loops). However, some patients with Barlow's disease, for example, can require up to 4 sets of neochordae loops (1 set in each quadrant, or a total of 12 loops).

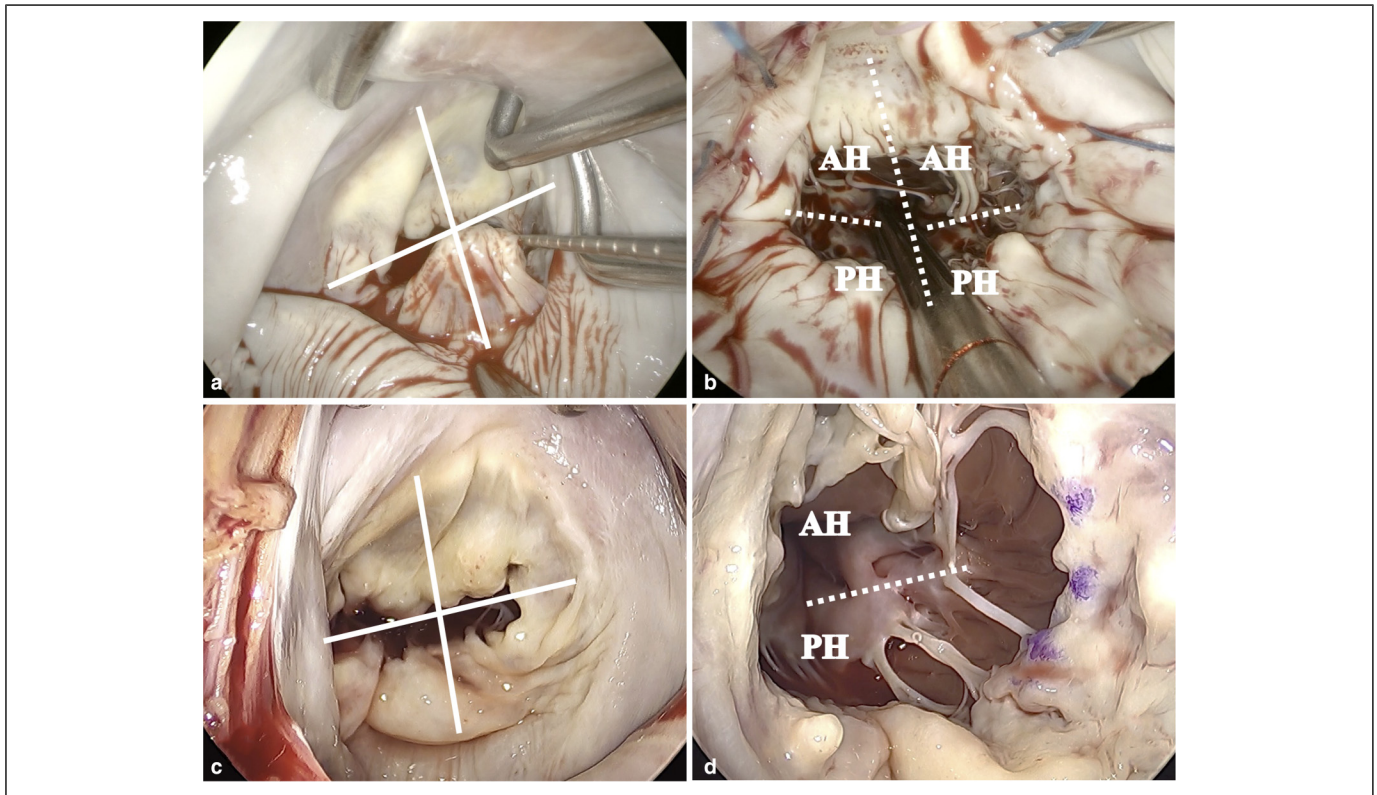


Fig. 5. On valve inspection, (a) divide the valve into 4 quadrants, and (b) localize the flail/prolapsing segment and the corresponding papillary muscle head. For neochordae reconstruction, keep the AH to the anterior leaflet and the PH to the posterior leaflet. The same applies to the anterolateral papillary muscle. (c) In this view, only the posteromedial aspect of the valve is visible. (d) The posteromedial papillary muscle divides into AH and PH. AH, anterior head; PH, posterior head.

After neochordae implantation, a ring annuloplasty is performed followed by saline test (Fig. 6d). To complement the repair, commissural advancement and cleft closure may be added to achieve optimal results.

Neochordal Adjustments

In most cases of residual regurgitation, minor adjustments to the neochordae are sufficient for optimizing repair results and can be easily performed. At saline test, assess the most lateral and medial neochordae loops to find out the mechanism of residual regurgitation.

If there is residual prolapse, take out the affixing suture from the prolapsing leaflet segment (without cutting the loop) and either move the loop deeper into the leaflet toward the annulus or move it further away from the fulcrum of the other loops to support a wider area of the leaflet free margin. On the other hand, if there is leaflet restriction, take out the affixing suture from the restricted segment and move the loop toward the fulcrum of the other loops or shallower toward the coaptation line.

To reimplant the loop, a new affixing suture must be passed through the loop and then through the leaflet using a single 4-0 PTFE suture. Sometimes, it is easier to pass another 4-0 PTFE

suture through the loop that needs adjustment prior to cutting the old affixing suture (Fig. 7). Moving only 1 loop (the most medial or lateral loop, depending on where the residual regurgitation is located) is frequently enough to achieve optimal results. However, it is possible that more than 1 loop requires repositioning, which can be done easily and quickly. At the end, a saline test will confirm the effectiveness of the adjustment.

Discussion

The concept of chordal replacement has gained popularity through the work of David et al,⁸ Von Oppell and Mohr,⁹ and Perier et al.¹⁰ In the “respect rather than resect” approach, the prolapsing mitral valve is preferably repaired with neochordae reconstruction and ring annuloplasty, focusing on restoration of the coaptation surface instead of leaflet resection. Additionally, PTFE sutures have been successfully adopted to create artificial chordae in simple and complex mitral valve prolapse with durable results.^{3-5,10}

Early and late results from the Leipzig experience comparing neochordae implantation to leaflet resection showed excellent freedom from reoperation in both groups and yet better survival with lower cardiac-related mortality in the chordal replacement group.^{11,12} Neochordae loops were custom-made using PTFE

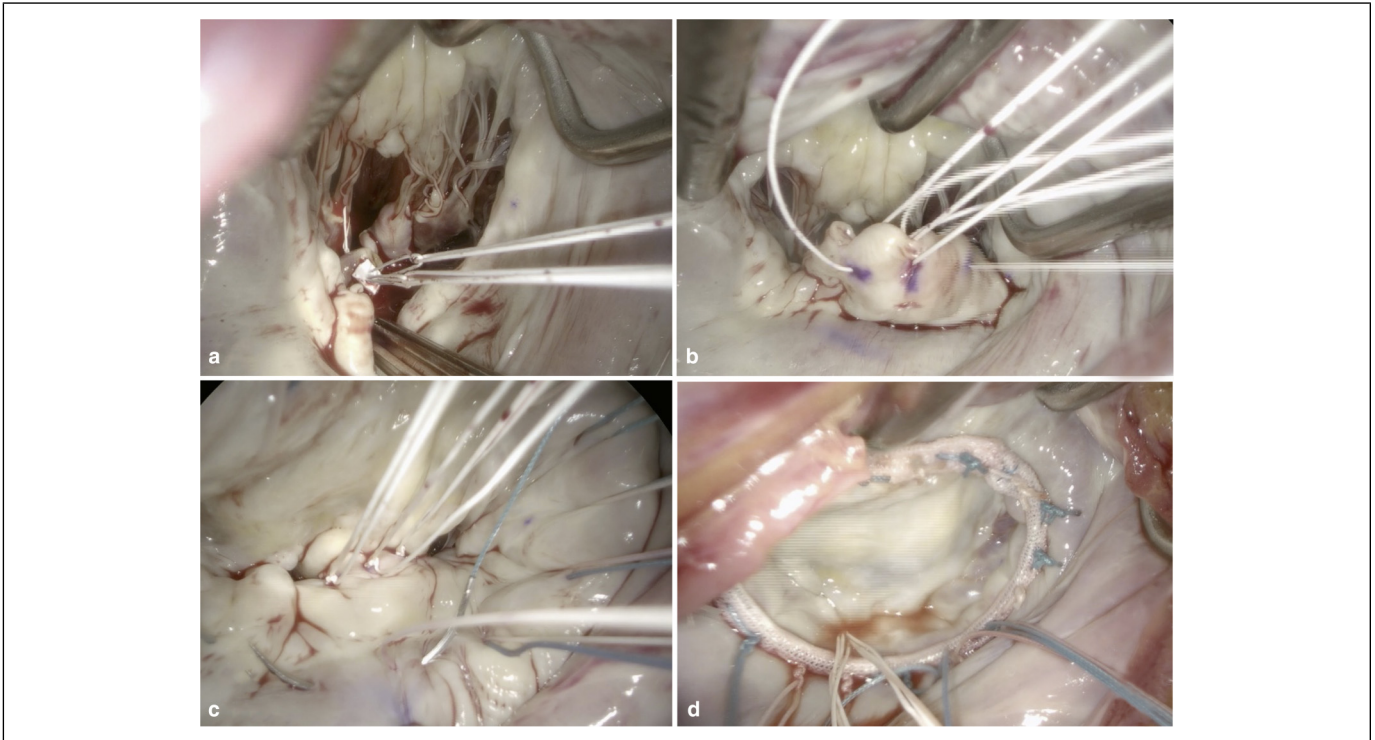


Fig. 6. Neochordae implantation. (a) Base fixation at the corresponding papillary muscle head. (b) Loops equally distributed across the flail segment are anchored on the leaflet edge with polytetrafluoroethylene sutures. (c) Ring annuloplasty. (d) Saline test showing good coaptation and no residual mitral regurgitation.

sutures after determining the required length by measuring the distance between the papillary muscle head and the line of leaflet coaptation with a caliper. In their experience, the loop technique was associated with longer lines of coaptation and larger rings, providing lower transvalvular gradients and favorable hemodynamics that may result in longer freedom from recurrent MR and therefore longer survival, with no difference between simple and complex repairs.^{5,12–14}

David and colleagues⁸ introduced PTFE sutures for replacement of chordae tendineae in their practice in 1985. They recently reported excellent long-term survival with 13.1% (95% confidence interval, 9.3% to 18.2%) recurrence of moderate or severe MR at 20-year follow-up. In their experience, a single PTFE suture was used to create multiple, interdependent neochordae by successively passing it through the papillary muscle and free margin of the prolapsing segment of the leaflet and tying the ends of the suture on the papillary muscle.

Recent studies showing higher repair rates and longer durability of neochordae reconstruction^{1,3,8,9,15} inspired new techniques, mostly based on premeasured PTFE loops or free-hand chordae implantation.^{1,6,8,9,15} In line with the current literature, our group demonstrated excellent midterm results with neochordae reconstruction for both simple and complex mitral valve disease.⁵ Furthermore, we showed that achieving adequate height of coaptation with premeasured neochordae is associated with excellent valve repair durability.¹⁶

Nevertheless, the greatest challenge with neochordae reconstruction remains determining the optimal neochordal length. Short neochordae can cause restriction, whereas long neochordae may lead to residual prolapse, both resulting in leaflet malcoaptation and residual MR. Current strategies for measurement are limited by “eyeballing” estimations and measurements performed on the arrested, open heart. Moreover, surgeons often rely upon saline testing, which may not reflect the normal dimensions or physiologic conditions of a beating heart. In addition, most existing techniques are prone to fore-shortening the neochordae with knot slippage or weakening the PTFE sutures while fixing the length of the neochordae, what may influence early results and long-term durability.

Consequently, we believe neochordal length estimation to be the cornerstone of neochordae reconstruction. We have demonstrated our initial experience with the TEE-guided premeasured loops for posterior, anterior, bileaflet, or commissural prolapse and in single-segment and multisegment disease.⁷ From 2008 to 2018, 264 consecutive patients underwent mitral repair with neochordae loop reconstruction with a repair success rate of 100%, and TEE-guided measurements were found to be accurate in 98% of cases. In 4 out of 5 cases showing more than trace residual post-pump MR, conversion to PL resection was performed with good results. The fifth patient had AL prolapse and required lengthening of the anterior neochordae loops from 23 to 27 mm. Generally, if the error involves the PL, we

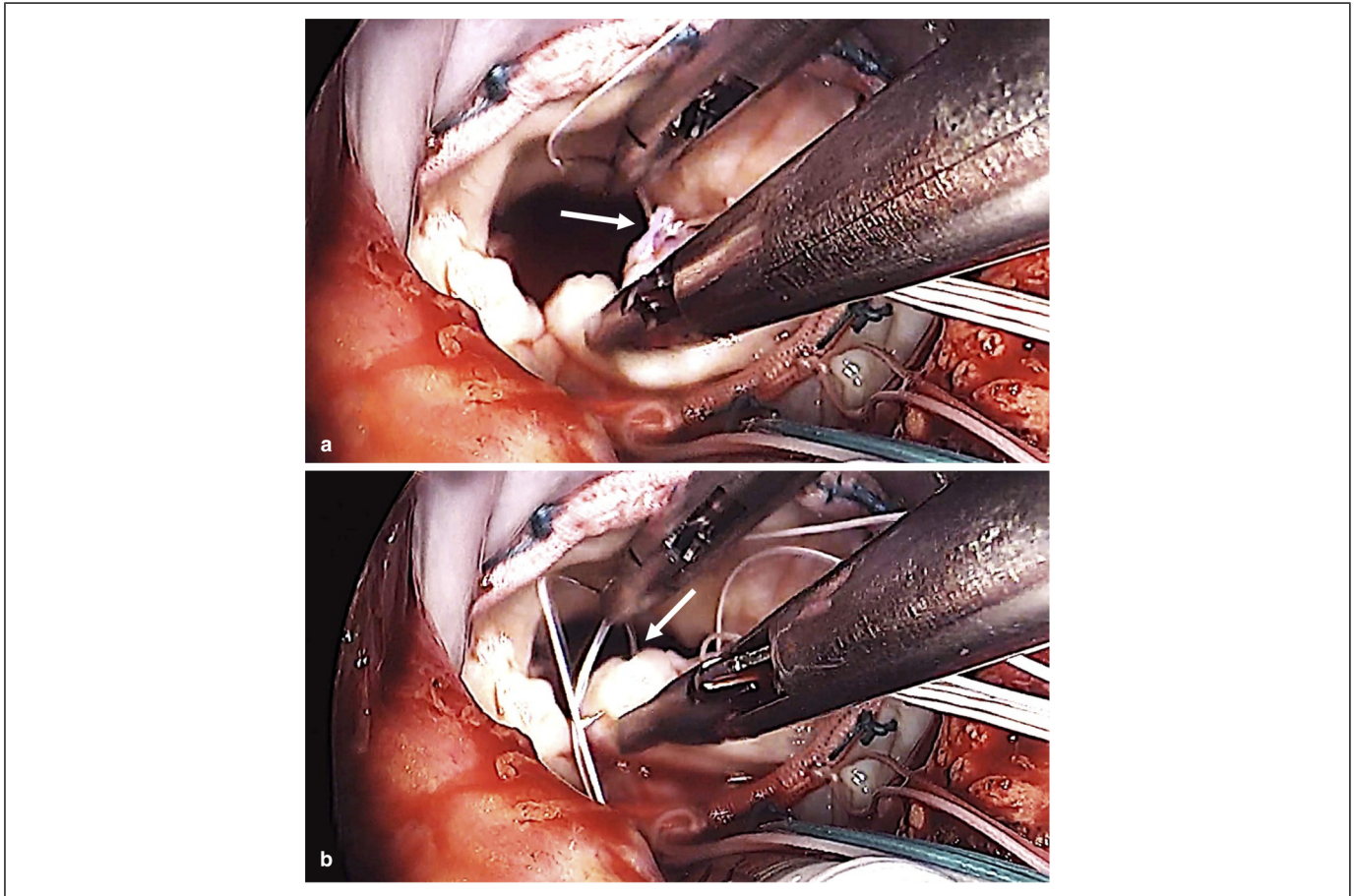


Fig. 7. Minor adjustments of the neochordae. (a) After removing the affixing suture from the leaflet, pass a new 4-0 polytetrafluoroethylene suture through the loop (b) and then through the leaflet edge on the new desired location.

recommend converting to a leaflet resection technique. Conversely, when the residual regurgitation involves the AL or commissures, we suggest remeasuring and reconstructing new neochordae loops.

In our series,⁷ 98.9% of patients remained free from at least moderate MR at a median follow-up of 12.6 months (interquartile range, 11.1), whereas freedom from reoperation was 100%. Actuarial survival at both 1 and 4 years was $96.9\% \pm 0.2\%$. These encouraging results support TEE-guided premeasured neochordae loops as a highly accurate and, most important, reproducible technique. TEE is a safe, cost-effective, and widely available diagnostic tool that enables reliable neochordae length measurements under normal physiologic conditions. We believe that a standardized measurement methodology is helpful to reduce error and improve mitral repair outcomes. This technique is broadly applicable for posterior, anterior, bileaflet, or commissural repair while easily allowing for additional minor adjustments in case of residual MR. It is particularly useful in valves with broad flail/prolapsing segments, multisegment disease, and especially when the prolapsing segment of the PL is very tall, wide, redundant, or asymmetrical (not at midline). Conversely, very narrow and midline

prolapsing segments of the PL, such as in fibroelastic disease, are best treated with traditional resection techniques.

This guide to neochordae reconstruction is designed to share a patient-centered, effective, and safe technique that may enhance results in mitral valve repair. Surgical teams earlier in their learning curve or those looking to expand neochordae repair techniques may particularly find this guide of use. Ultimately, TEE-guided measurements can accurately predict the length of neochordae loop reconstruction in simple or complex degenerative mitral valve repair and may be used in conventional or minimally invasive mitral valve surgery. Limitations of this technique include suboptimal TEE images that may lead to inaccurate measurements and inter-reader variation and reliability. Lastly, the measurement technique has not yet been validated with other imaging modalities.

Conclusions

TEE-guided premeasured neochordae loops are an accurate and reliable method to simplify mitral valve repair in patients with degenerative MR. The technique is broadly applicable for posterior, anterior, and bileaflet prolapse and for single or

multisegment disease. Finally, this guide to neochordae reconstruction can be used in both conventional and minimally invasive mitral valve repair.


Declaration of Conflicting Interests

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Supplemental Material

Supplemental material for this article is available online.

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