

Neochords: How long, how many, too many?



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Video clip is available online.

Despite the ongoing discourse regarding the optimal approach to repairing myxomatous mitral regurgitation, both the *resect* and *respect* schools of thought have demonstrated merits and durability when patients are appropriately selected.¹⁻⁶ In our practice, we routinely employ both resectional and chordal replacement techniques depending on the culprit lesions. Reservations surrounding neochord repair techniques stem mainly from the precision required in sizing replacement artificial chordae, an aspect that certainly warrants thoughtful consideration. Additionally, important questions that have only recently begun to attract biomechanical investigations include the configuration of the neochordae (ie, running, interrupted, or looped) and location on the papillary muscles and leaflets, as well as the ideal number and caliber of chordae to optimize the force transferred to the mitral apparatus during systole. The purpose of this article is to describe our current approach to neochord repair as well as the biomechanical justifications upon which these techniques are based.

Although the long-term outcomes of neochord repair in the hands of experienced surgeons speak for themselves,^{1,2,6} there are scarce quantitative biomechanical data on this topic. Accordingly, the following techniques and recommendations are based on a single surgeon's experience of more than 1400 mitral valve repairs, as well as biomechanical engineering research from our laboratory, including ex vivo modeling and in vivo large animal translational experiments. We must add the caveat that much of this information is based on our approach of maximizing the

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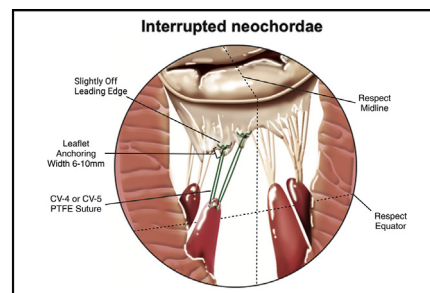
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Fundamental principles for surgical repair of degenerative mitral regurgitation.

CENTRAL MESSAGE

In this article, we describe our approach to neochordal repair of the myxomatous mitral valve based on biomechanical ex vivo and large animal translational research performed by our laboratory.

efficiency of each repair without sacrificing durability, and that the most appropriate repair strategy must be determined on a case-by-case basis. Using the framework described herein, we were able to perform 65% of more than 1400 mitral valve repairs via a minimally invasive approach with a mean crossclamp time of 58 minutes, 0 in-hospital deaths, and only 14 long-term reoperations for mitral regurgitation (unpublished data).

NEOCHORD CONFIGURATION

The 3 most commonly utilized neochordae configurations are the continuous running technique, popularized by Tirone David who has demonstrated outstanding long-term clinical outcomes using this technique,^{1,2,6} the Leipzig loop technique,^{7,8} and the simple interrupted technique (Figure 1).⁴ The running technique effectively distributes the forces across each segment of the neochord and results in the greatest rupture force threshold out of all 3 configurations when tested in a tensile force analysis machine.⁹ The argument against the running technique is that the integrity of the entire repair would be compromised by failure at any given point along the continuous running polytetrafluoroethylene (PTFE) suture. Therefore, if a surgeon favors the continuous running technique, it may be advisable to

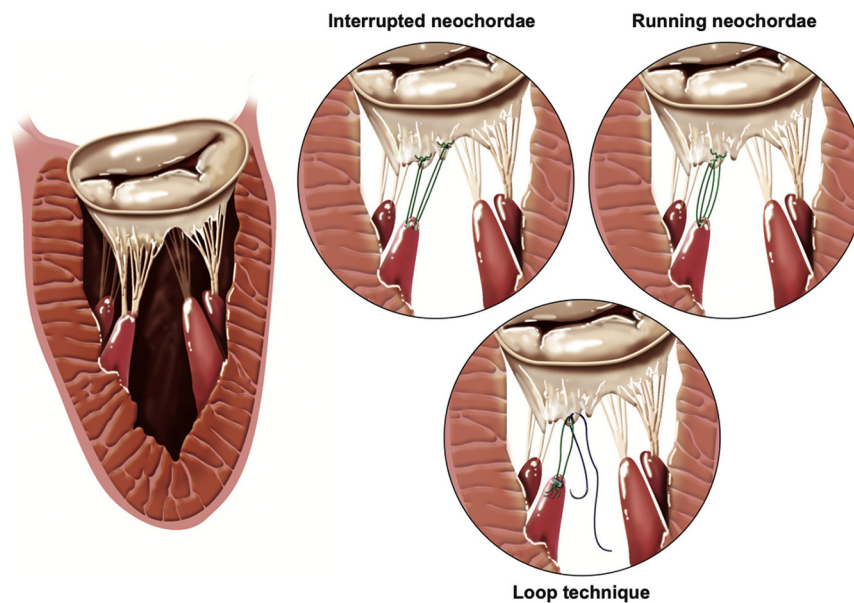


FIGURE 1. Schematic representation of the 3 most commonly utilized configurations of neochordae. Used with permission.⁹

implant 2 independent sets of running neochordae to avoid repair failure due to rupture of the lone suture.⁹

The Leipzig loop technique involves using up to 3 preformed loops per PTFE suture, presized with calipers against normal primary chordae of an adjacent nonprolapsed segment. The origin of the loops are anchored to a felt pledget and sewn to the fibrous tip of the appropriate papillary muscle, with the apex of the loop secured to the coaptation plane of the leaflet edge with polypropylene suture or PTFE suture.⁷ Although the Leipzig loop technique is an excellent strategy to ensure symmetry of the neochordae and has demonstrated 97% freedom from reoperation at 10 years, the point of contact between the polypropylene attachment sutures and the PTFE neochordae is susceptible to rupture—likely due to a sawing effect between the 2 different suture materials.⁹ Therefore PTFE attachment sutures may be advisable if utilizing the Leipzig loop technique.⁹ Additionally, surgeons should avoid the temptation to reach across the midline or equator with any of the 3 loops. In other words, all 3 loops should be fixed to the anatomically correct papillary muscle head corresponding to the prolapsing segment, as healthy native chordae would.

Finally, our preference is multiple simple interrupted sutures due to this configuration's efficiency, strength, and decreased risk of repair failure in the event of individual neochord rupture.⁹ There are many ways to do this, including looping the suture through the fibrous tip of the papillary muscle or through the leaflet; however, we prefer 1 pass of the needle through the papillary muscle and 1 pass through the leaflet. We do not believe that additional passes through the leaflet or the papillary muscle are needed, and

instead may result in microscopic damage to the tissue from excessive manipulation. Regardless of which neochord configuration is favored by a surgeon, the neochord must be anchored to the fibrous tip rather than the muscular body of the papillary muscle to avoid inadvertent tearing or tissue necrosis.

NEOCHORD LOCATION

A challenge of artificial chordae implantation is accurately ascertaining the optimal fixation point on the papillary muscles and the attachment point on the mitral leaflets. With the steady influx of minimally invasive, beating-heart mitral valve neochordoplasty devices designed to fix the neochordae near the left ventricular apex, our lab aimed to interrogate the biomechanical stress profile of various ventricular fixation points in an ex vivo model.¹⁰ Whereas both papillary and apical fixation eliminated mitral regurgitation and had similar hemodynamic profiles, apical fixation resulted not only in significantly greater neochordal forces, but also greater native chordal forces than in the case of fixing the neochordae to the papillary muscle.¹⁰ In this model, neochordal forces increase as the angle of fixation relative to the coaptation plane was increased from 0° to 45° (~papillary fixation) to 90° (~apical fixation). Additionally, the rate of change in forces was greater for apically fixed neochordae. Collectively, the biomechanical data from our group and others suggest that apically fixed neochordae experience a whiplash effect due to the increased length and suboptimal orientation relative to the coaptation plane, increasing the stress transferred to the mitral valve apparatus and potentially compromising long-term durability of the repair.¹⁰⁻¹⁴

Our group has also studied the optimal neochord implantation location on the posterior leaflet to mitigate the risk of the suture pulling out or tearing the leaflet. By varying both the location of the neochord with respect to the leaflet's leading edge and the suture anchoring width, we demonstrated that increasing the suture width up to 10 mm significantly increased the suture pullout force.¹⁵ It should be noted that the width of the leaflet anchoring suture is limited by the number of neochordae implanted, as well as the necessity of avoiding inadvertent plication of the leaflet. Increasing the distance of the leaflet anchoring suture from the leading edge also increases the pullout force threshold, although to a lesser degree than increasing the suture width.¹⁵ Although this study was isolated to the posterior leaflet, a surgeon should exercise caution when applying these findings to the anterior leaflet because increasing the distance from the leading edge may shift the coaptation line anteriorly, which can increase the risk of systolic anterior motion (SAM).

Our final comment on location relates to the concept of avoiding the implantation of neochordae that would cross the midline or equator of the mitral valve. If the en face mitral valve is divided into 4 quadrants, the midline is defined as a vertical line extending from the center of the A2 segment on the anterior annulus to the center of P2 on the posterior annulus, and the equator is a horizontal line extending from the nadir between the anterior and posterior heads of each papillary muscle (Figure 2). Although we

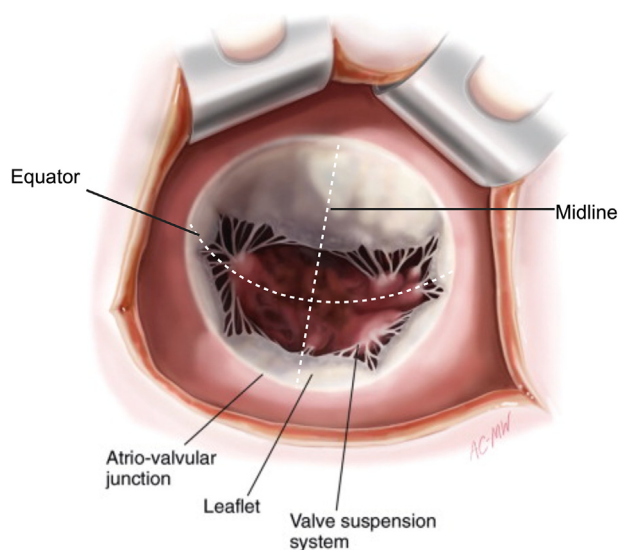


FIGURE 2. The midline of the mitral valve is defined by a vertical line extending between the anterior and posterior annulus in the center of A2 and P2. The equator is defined as a horizontal line extending between the nadir of the anterior and posterior heads of the anterolateral and posteromedial papillary muscles. Modified with permission from Carpentier A. *Carpentier's Reconstructive Valve Surgery*, Elsevier; 2010 [created with BioRender.com].

are actively studying the effect of neochordae crossing the midline and equator, our current practice is to use the posterior heads of each papillary muscle for neochordae to the posterior leaflet and the anterior papillary heads for anterior leaflet neochordae. Similarly, neochordae to A3 or P3 should be fixed to the posteromedial papillary muscle and A1 or P1 to the anterolateral papillary muscle.

NUMBER OF NEOCHORDS

Our group has previously demonstrated a significant force reduction on primary chordae with neochordal repair techniques compared with resectional repair techniques in the setting of P2 prolapse in an ex vivo model.¹⁶ We recently confirmed and expanded on these findings in an in vivo ovine model, which was presented at the 103rd Annual Meeting of the American Association for Thoracic Surgery and is currently under review for publication. Not only did neochordal repair techniques result in reduced forces on the native primary chordae, but also on the native secondary chordae. We also demonstrated a significant force reduction on the neochordae with an increasing number of artificial chordae. The force reduction was greatest when the number of simple interrupted neochordae was increased from 2 to 4. Although 6 neochordae significantly reduced the force profile compared with 2 chordae, the difference between 4 and 6 neochordae was not statistically significant. These findings suggest that in context of P2 prolapse, neochordal repair with 4 simple interrupted PTFE neochordae may be the most biomechanically efficient strategy. Although additional neochordae may modestly reduce the forces exerted on the artificial chordae, surgeons should be cautious when implanting more than 4. In addition to the limited spatial geography of the leaflets and papillary muscles, excessive neochordae may become entangled, increase the risk of tying error, increase the number of knots on the atrial surface of the leaflet, and have the potential to obfuscate the interpretation of subsequent echocardiography.

NEOCHORD LENGTH AND CALIBER

The seminal study by Perier and colleagues¹⁷ on nonresectional repair techniques for posterior leaflet prolapse clearly demonstrates why appropriate neochord length is critically important for the long-term durability of a repair. Excessively long neochordae put the patient at risk for residual posterior leaflet prolapse or SAM due to the increased coaptation height and will be exacerbated upon ventricular remodeling postrepair which, in general, reduces the end systolic diameter of the left ventricle. Even in the absence of posterior leaflet prolapse or SAM, based upon the principle that $\mathcal{F} = P \times A$ (where \mathcal{F} = force, P = pressure, and A = surface area), redundant neochordae may reduce the coaptation length, thereby increasing the surface area of the leaflet, resulting in a sail effect.¹⁸ The sail effect likely increases the forces exerted on the native

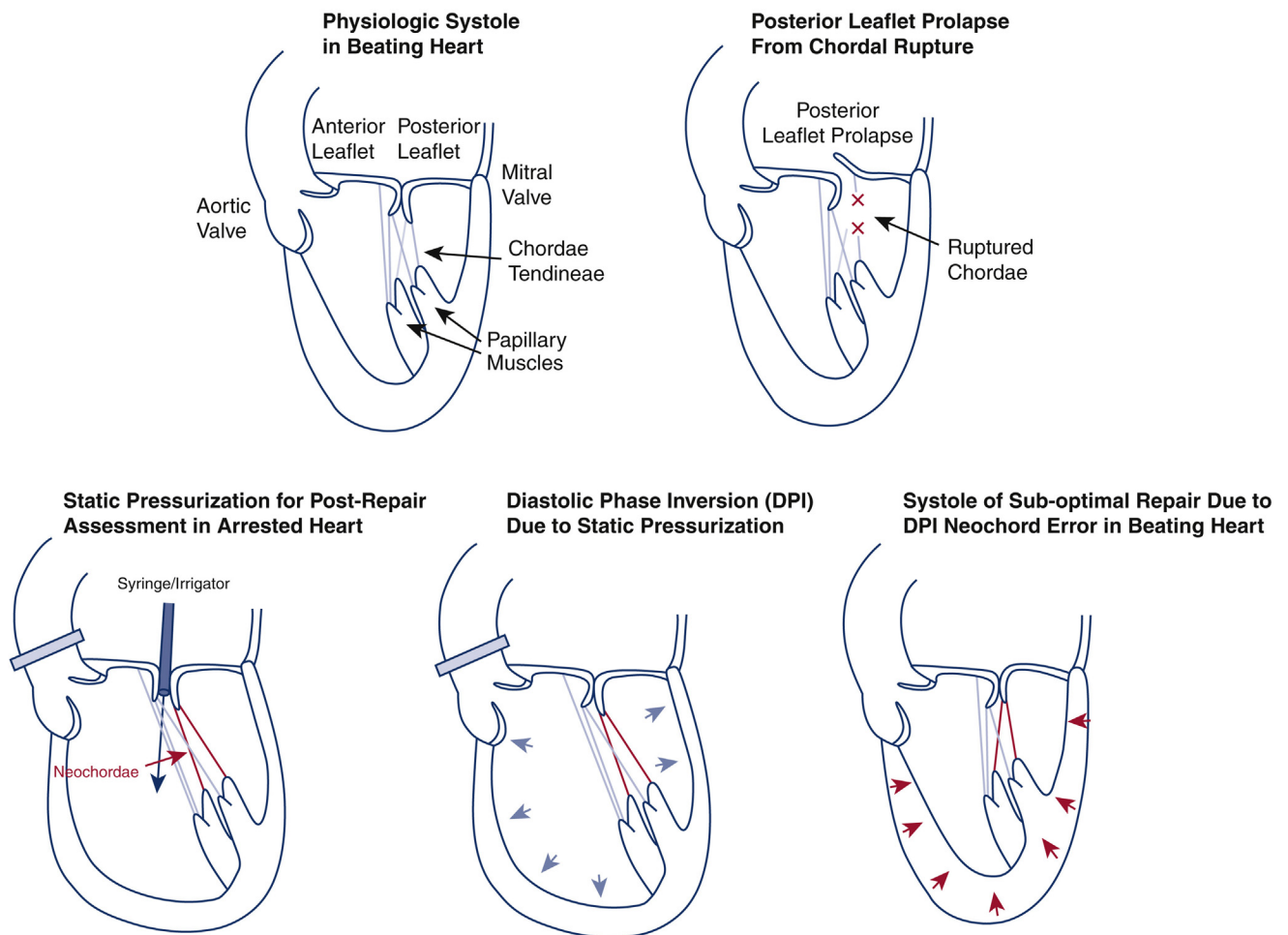
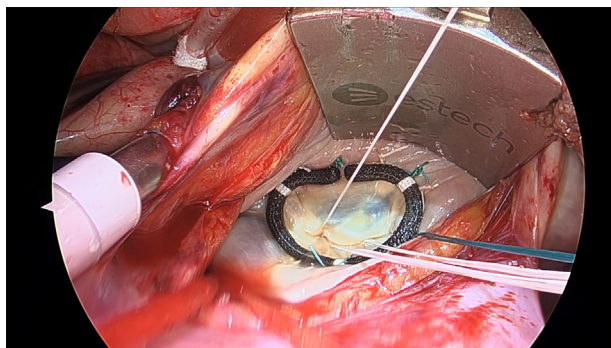


FIGURE 3. Labeled illustration of mitral valve neochordal repair with static pressurization for postrepair assessment and diastolic phase inversion (*DPI*). We hypothesize that *DPI* results in neochord length overestimation, which might lead to a suboptimal repair and reduced hemodynamic performance. Used with permission.¹⁹

and artificial chordae and could worsen the durability of the repair. Conversely, neochordae that are too short often result in restricted motion of the posterior leaflet and may lead to prolapse of the anterior leaflet because the coaptation height is inappropriately reduced.

Although a surgeon's judgment of appropriate neochord lengths will improve with experience, there are several maneuvers to increase the precision with which the knot (ie, suture length) is set. First, we deploy a technique called dynamic tying—where the location of the first knot can be fine-tuned by sliding the post or the opposite end of the suture to move the knot upward or downward (Video 1). Additionally, our preference is to interrogate the coaptation zone with the saline test after each individual neochord is secured. By placing all anticipated neochordae up front and temporarily anchoring each with a single knot, sequential and frequent saline testing provides immediate feedback, informs the desired location of the subsequent knot, and enhances the likelihood of a symmetric repair.

However, a surgeon must be keenly aware of the subtle differences between the static pressurization testing conditions and the physiologic biomechanics of the ventricle during systole. Specifically, when the ventricle is pressurized with saline during diastolic arrest, it is relatively distended compared with systole and the papillary muscles are farther away from the true plane of coaptation—a phenomenon called diastolic phase inversion (Figure 3).¹⁹ The surgical implications of this phenomenon are that the surgeon must avoid being misled by the slightly increased distance between the papillary muscles of a distended ventricle and the plane of coaptation. Keeping diastolic phase inversion in mind, the surgeon should secure the neochords at a slightly shorter length than suggested by the saline test when they are interrogating the coaptation of the repaired valve.¹⁹ In addition to achieving a repair without leakage and SAM, a surgeon must be facile with the interpretation of intraoperative echocardiography and capable of extrapolating the expected shift in the zone of coaptation to account



VIDEO 1. Dynamic tying allows the precise placement of the knot and is performed by sliding the post end of the suture to raise or lower the knot location. Video available at: [https://www.jtcvs.org/article/S2666-2507\(23\)00398-X/fulltext](https://www.jtcvs.org/article/S2666-2507(23)00398-X/fulltext).

for positive remodeling of the left ventricular geometry following repair. Specifically, an apparently acceptable zone of coaptation at the time of surgery may eventually result in SAM if positive remodeling is not duly considered when sizing neochordae.

Once the appropriate length is determined, several adjunctive maneuvers may be used to ensure the precise length of each neochord. One commonly utilized method is to use a Rumel tourniquet to adjust the length of the neochord and perform saline testing to evaluate coaptation before committing to that length. Another creative solution is to use an atraumatic neurosurgical aneurysm clip at the desired knot location and tying on top of the clip before removal.

We have also performed biomechanical tensile force analysis to determine the rupture force threshold of various caliber PTFE sutures used in neochord repairs.⁹ The rupture force of CV-3 to CV-6 PTFE sutures were tested in various configurations (discussed above). The most commonly utilized sutures, CV-4 and CV-5, had rupture forces of $113.7 \pm 9.2N$ and $92.9 \pm 5.4N$, respectively, in a configuration with four simple interrupted neochordae.⁹ While the rupture force of various sutures in this ex vivo model greatly exceed the force incurred by chordae under physiologic conditions (peak force $0.41 \pm 0.30N$ in artificial chordae and $<1N$ on native primary chordae), it is well documented that knots increase the local concentration of stress on a suture and create a nidus for friction that similarly reduces their resistance to rupture.^{11,20} Therefore, we recommend CV-4 suture for simple interrupted neochordal repair, whereas CV-5 is acceptable in running configurations that have lower neochordal force profiles, as discussed above.

POSTERIOR VENTRICULAR ANCHORING NEOCHORD REPAIR

Finally, we have developed a novel technique for addressing posterior leaflet prolapse or flail that simplifies the task of

precisely sizing neochordae and is easily accomplished through a minimally invasive approach.²¹ Posterior ventricular anchoring neochord repair (PVAN) is performed by first retracting the prolapsed segment into the atrium and fixing a CV-5 PTFE suture to the posterior ventricular wall at a depth of 3 to 4 mm, just beneath the leaflet. The suture is loosely tied to the posterior wall and then passed through the leading edge of the prolapsed segment, imbricating redundant tissue if present, and secured.²¹ The purpose of this technique is primarily to position the leaflet posteriorly to establish an ideal coaptation line and to prevent SAM, as opposed to being a force-bearing chord. Ex vivo composite force analysis demonstrates that after PVAN repair for posterior leaflet prolapse, forces on the native primary and secondary chordae returned to baseline, and peak forces on the PVAN repair suture itself were $0.08 \pm 0.04N$ with a pull-out force of $6.9 \pm 1.3N$.²² The minimal force exerted on the PVAN suture is likely due to both its short length and its orientation, which is nearly parallel to the plane of coaptation (ie, $\sim 0-15^\circ$), consistent with our findings on the force profiles of various anchoring neochord fixation points.¹⁰ Therefore, the risk of the posterior ventricular suture pulling out is quite low and has never been an issue in our experience.

CONCLUSIONS

Neochord repair is an effective and durable technique for correcting degenerative mitral regurgitation.^{1-6,16} In our practice, we routinely utilize both resectional and neochordal repair techniques. However, it bears mentioning that, when performed properly, neochordal repair techniques provide surgeons with an elegant solution to directly restore a sufficient coaptation zone, whereas resectional techniques in the absence of chordal replacement primarily address the issue of excessive leaflet tissue but do not necessarily resolve the issue of diseased or elongated chordae. Although the appropriate sizing and configuration of neochordae undoubtedly improves with experience and volume, in this article we have described a number of techniques, supported by biomechanical evidence, which may prove useful to mitral valve surgeons.

Our recommendation and general approach to neochord repair is to use simple interrupted CV-4 or CV-5 PTFE suture, with a leaflet anchoring width of 6 to 10 mm, positioned slightly farther from the leading edge of the posterior leaflet. Additionally, the midline and equator should be respected to avoid distortion of the coaptation zone. For P2 prolapse, we favor 4 simple interrupted neochordae. A surgeon should evaluate the repair with saline after each neochord is secured, bearing in mind the concept of diastolic phase inversion when tying, and shorten the length accordingly.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: mitral regurgitation, mitral valve repair, degenerative mitral valve, neochordae, systolic anterior motion, myxomatous mitral valve