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***Review** / Derleme*

# Surgical mitral valve repair technique considerations based on the available evidence

*Mevcut kanıtlara dayalı mitral kapak tamir tekniklerinin değerlendirilmesi*

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***ABSTRACT***

Mitral valve regurgitation is the second most common valve disease in the western world. Surgery is currently the best tool for generating a long-lasting elimination of mitral valve regurgitation. However, the mitral valve apparatus is a complex anatomical and functional structure, and repair results and durability show substantial heterogeneity. This is not only due to differences in the underlying mitral valve regurgitation pathophysiology but also due to differences in repair techniques. Repair philosophies differ substantially from one surgeon to the other, and consensus for the technically best repair strategy has not been reached yet. We had previously addressed this topic by suggesting that ring sizing is "voodoo". We now review the available evidence regarding the various repair techniques described for structural and functional mitral valve regurgitation. Herein, we illustrate that for structural mitral valve regurgitation, resuspension of prolapsing valve segments or torn chordae with polytetrafluoroethylene sutures and annuloplasty can generate the most durable results paired with the best achievable hemodynamics. For functional mitral valve regurgitation, the evidence suggests that annuloplasty alone is insufficient in most cases to generate durable results, and additional subvalvular strategies are associated with improved durability and possibly improved clinical outcomes. This review addresses current strategies but also implausibilities in mitral valve repair and informs the mitral valve surgeon about the current evidence. We believe that this information may help improve outcomes in mitral valve repair as the heterogeneity of mitral valve regurgitation pathophysiology does not allow a one-size-fits-all concept.

***Keywords:*** Degenerative mitral regurgitation, functional mitral regurgitation, mitral valve repair.

***ÖZ***

Mitral kapak yetmezliği, batı dünyasında en yaygın ikinci kapak hastalığıdır. Cerrahi, şu anda mitral kapak yetmezliğinin uzun süreli ortadan kaldırılmasını sağlamada en iyi tedavi seçeneğidir. Ancak mitral apparatus karmaşık anatomik ve fonksiyonel bir yapıya sahiptir ve onarım sonuçları ve dayanıklılığı önemli ölçüde heterojenite gösterir. Bu durum, sadece altta yatan mitral kapak yetmezliği patofizyolojisindeki farklılıklardan değil, aynı zamanda onarım tekniklerindeki farklılıklardan da kaynaklanmaktadır. Onarım felsefeleri de bir cerrahtan diğerine önemli ölçüde farklılık göstermektedir ve teknik olarak en iyi onarım stratejisi konusunda henüz bir fikir birliğine varılmamıştır. Biz bu konuyu daha önce mitral kapak tamirinde kullanılan anülüs boyutlandırma stratejilerinin "Voodoo" olduğunu öne sürerek ele almıştık. Şimdi ise yapısal ve fonksiyonel mitral kapak yetmezliği için tanımlanan çeşitli onarım tekniklerine ilişkin mevcut kanıtları gözden geçireceğiz. Bu yazımızda, yapısal mitral kapak yetmezliğinde prolabe yaprakçık segmentlerinin veya rüptüre kordaların politetrafloroetilen sütürler ve anüloplasti ile resüspansiyonunun, elde edilebilecek en dayanıklı sonuçları en iyi hemodinami ile birlikte üretebileceğini gösterdik. Fonksiyonel mitral kapak yetmezliği için kanıtlar, tek başına anüloplastinin çoğu durumda kalıcı sonuçlar elde etmek için yetersiz olduğunu ve ek subvalvüler stratejilerin daha iyi dayanıklılık ve muhtemelen daha iyi klinik sonuçlar ile ilişkili olduğunu göstermektedir. Yaptığımız bu derleme, mitral kapak onarımındaki güncel stratejilerin yanı sıra mitral kapak tamirindeki ikilemleri ele almakta ve cerrahı mevcut kanıtlar hakkında bilgilendirmektedir. Mitral kapak yetmezliği patofizyolojisinin heterojenliği her hastaya uyan tek bir konsepte izin vermediğinden bu bilginin mitral kapak onarımındaki sonuçları iyileştirmeye yardımcı olabileceğine inanıyoruz.

***Anahtar sözcükler:*** Dejeneratif mitral yetmezlik, fonksiyonel mitral yetmezlik, mitral kapak tamiri.

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The native mitral valve is a complex structure consisting of an anterior and a posterior leaflet, extending from the mitral annulus into the ventricle, sending off chordae tendineae to papillary muscles, which connect the mitral valve apparatus to the ventricular muscle.[1] Figure 1 shows intraoperative photographs of valvular and subvalvular (chordae tendineae and papillary muscles) units of the mitral valve. Dysfunction of this valve can result in stenosis or regurgitation, or both. Mitral valve regurgitation (MR) is the second most common valve disease in Europe.[2] Its prevalence increases with age,[3] and two major pathologies are distinguished.

Structural MR, also referred to as primary or organic mitral insufficiency, accounts for roughly one third of all cases with MR.[4] This pathology includes a wide spectrum of structural leaflet changes, ranging from severe myxomatous disease with excessive leaflet tissue (most prominent in bileaflet prolapse, surgically referred to as Barlow's disease)[5] to ruptures of single chordae from leaflets that appear otherwise normal (i.e., fibroelastic deficiency).[6] It is important to realize that, in addition to structural leaflet abnormalities, annular dilatation is almost always present in these cases, either as a result of longer standing severe mitral regurgitation ("flow induces growth") or as part of the causative pathology (specifically in Barlow's disease).[7] Current repair strategies, therefore, consist of annuloplasty plus either classic resection of the prolapsing segments[8,9] or respecting the available tissue and resuspending the prolapsing segments with Gore-Tex neochordae.[10-12] Patients with endocarditis also belong to the group of structural MR. However, they are comparably infrequent, and the ability to repair depends on both the severity and presentation of the endocarditis as well as the surgeon's mitral expertise.[13]

The remaining two-thirds of patients with MR present with functional or secondary MR, which is characterized by the presence of regurgitation without structural changes to the leaflets.[14] The guidelines distinguish two types of functional MR.[2] Atrial MR, where atrial dilatation also affects the annulus. Here, isolated ring annuloplasty addresses the pathomechanism and should generate lasting results.[15] As for the other, restrictive type, geometric changes in the ventricle cause lack of leaflet coaptation and MR (for details see below). Undersizing annuloplasty has been applied in these cases with mixed results.[16,17] That is not surprising since this type of MR is characterized by a ventricular pathomechanism (mostly associated with impaired ventricular function), which is not addressed by isolated annuloplasty. Surgically addressing left

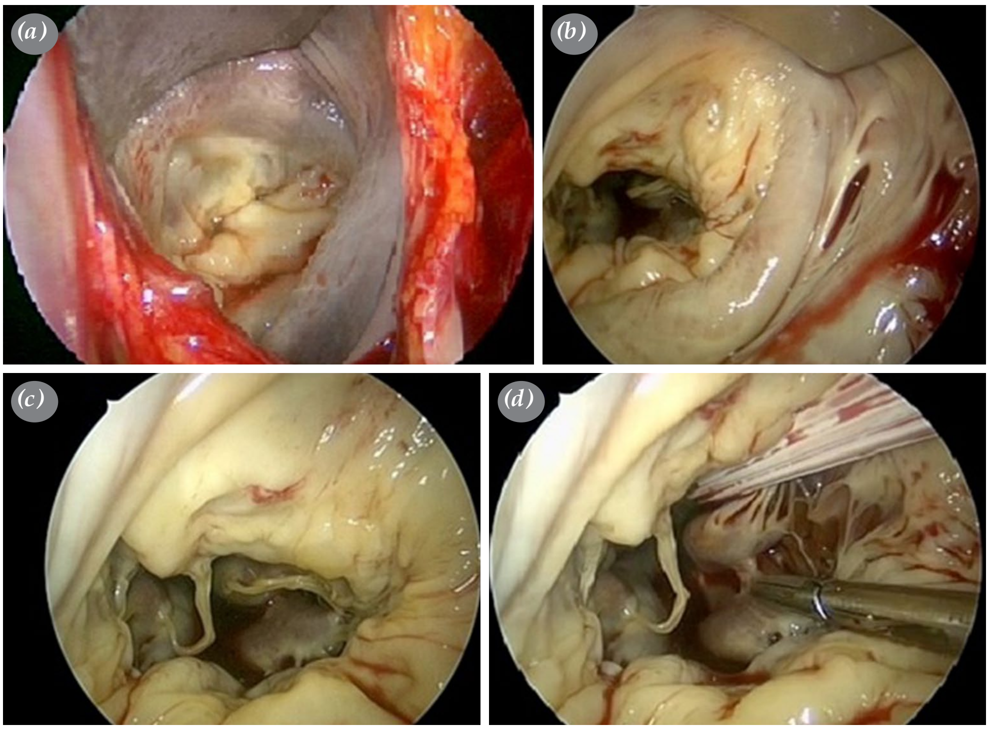


**Figure 1.** **(a)** Intraoperative images of the valvular and **(b-d)** subvalvular units of the mitral valve.

ventricular geometry by subvalvular strategies has only recently illustrated a potential improvement.[18,19] We will address the results in detail below. However, since the distinction between these two types of functional MR has only recently been introduced,[20] it is difficult to separate them in reports addressing patient populations from the past, which may explain part of the contradictory results in this field.

Given the above described pathophysiological and surgical repair principles, we will now illustrate which repair strategy for both structural and functional MR finds the best support with respect to repair success, durability, and clinical outcome.

### Evidence for structural MR

The presence of structural MR is associated with a gradual reduction in life expectancy. The more severe the MR, the lower the long-term survival.[3,4,21,22] There is ample evidence that suggests an improvement in survival after mitral valve repair compared to conservative therapy.[3,23-25] If the repair is performed early, normalization of life expectancy can be achieved.[26-30] Although prospective randomized evidence is missing in this field, the available evidence suggests that mitral valve repair is associated with significantly better survival compared to mitral valve replacement for structural MR.[24,31,32] Thus, mitral repair is the preferred strategy for patients with structural MR.[2,33]

The vast majority of patients with structural MR suffer from myxomatous disease, where the loss of elastic fibers is associated with different degrees of excessive tissue generation resulting in symmetric or asymmetric prolapse or chordal rupture.[2,33,34] For the resulting prolapses, two principles of repair have been described (summarized as “resect” *vs.* “respect”),[35-37] and both consist of an annuloplasty but differ in their ways of dealing with the diseased segments. The classic Carpentier[9] resection strategy cuts out the prolapsing segment and reconstructs most often the posterior leaflet either by direct suture (Figure 2a) or by liberating the entire leaflet and reconstructing the posterior annulus (sliding leaflet technique). Although Carpentier’s[9] so-called “French Correction” technique has favorable early results and low rates of mortality, its durability decreases over time.[38-40]

The respect approach consists of implanting polytetrafluoroethylene (PTFE) neochordae into the prolapsing segments (Figure 2b). Studies on chordal replacement (respect concept) show good long-term results with good survival,[31,35,40] low rates of MR recurrence,[11,41-43] and mitral valve reoperations.[37,44,45] Since the respect approach in principle leaves more valve tissue, larger rings may be selected for annuloplasty. A recent meta-analysis comparing these two techniques demonstrated an association of the respect (i.e., PTFE neochord) technique with larger annuloplasty rings (Figure 3a) and lower post-repair gradients (Figure 3b).[44] Interestingly, techniques avoiding resection also appeared to be associated with lower rates of reoperation, better postoperative ejection fractions, and better survival.[44,46] Table 1 shows a summary of studies addressing repair techniques for structural MR and reporting relevant outcomes.

It is important to note that all these studies always report the use of an annuloplasty ring or band, a currently key difference from the evolving interventional techniques.[47] Many different rings

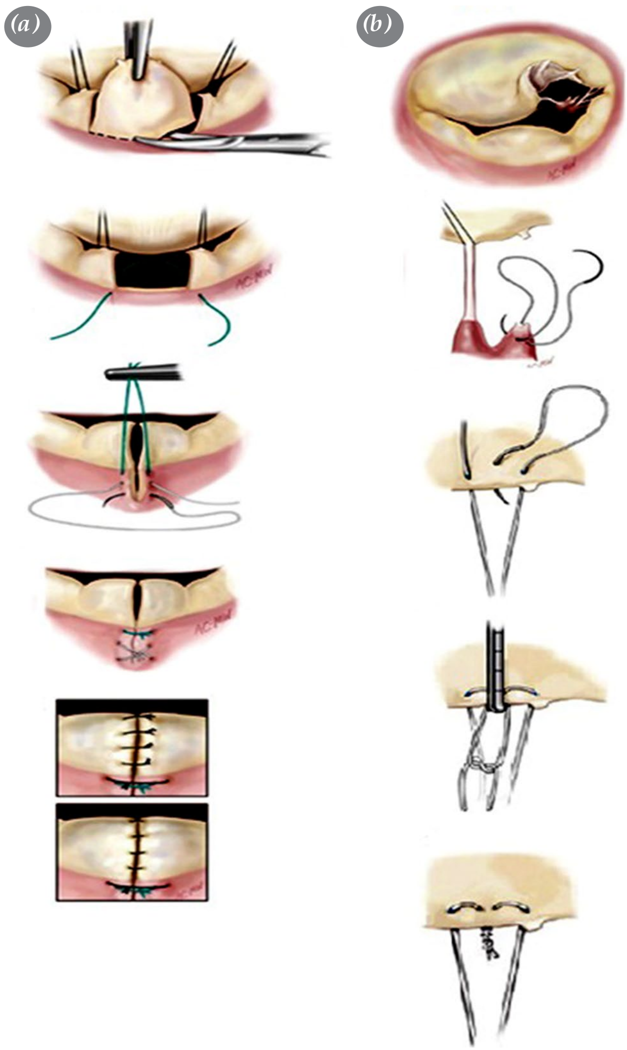


**Figure 2. (a)** Mitral valve repair with leaflet resection and **(b)** chordal replacement by Schubert et al.[35]

and bands have been described. However, evidence for a measurable or reproducible difference among them is missing. Thus, sizing appears almost like a religion.[48] There are different methods used in perioperative ring sizing (intercomissural distance, intertrigonal distance, anterior leaflet height and area), and companies sometimes provide the same sizer for different rings with different dimensions. Although surgeons often have a clear opinion on which ring or band they use, the true dimension of the ring is often

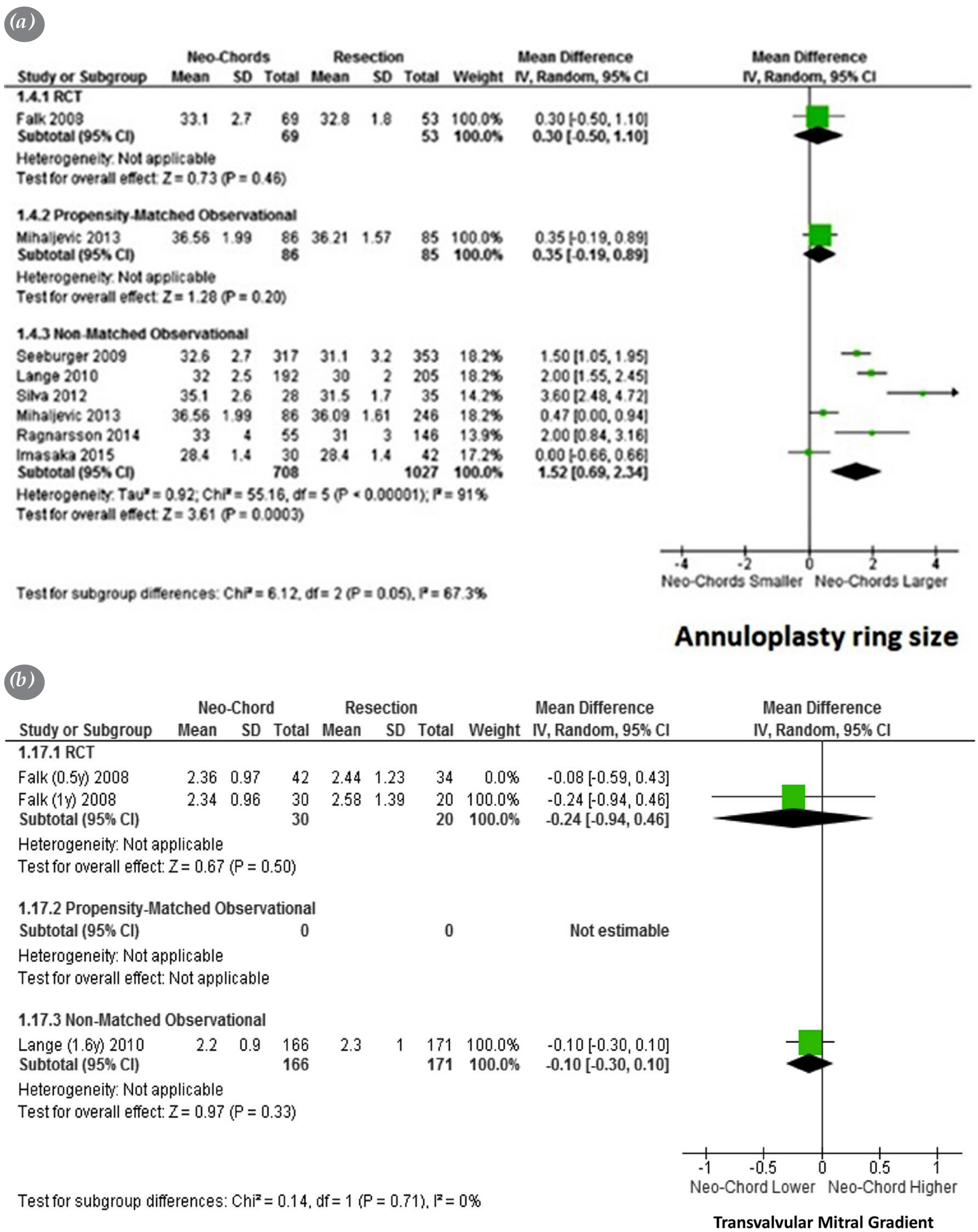


**Figure 3. (a)** Forest plot comparing implanted annuloplasty ring size diameter and **(b)** mean mitral gradients in mmHg at follow-up after chordal replacement or after leaflet resection techniques. Adapted from Mazine et al.[44]

**Table 1. Summary information for all current trials about resection and nonresection techniques in degenerative MR**

| Trial name (follow-up period, year of publication) | Primary end point | Principle of leaflet handling | Number of patients | Early mortality (%) | Freedom from reoperation caused by MR (%) | Freedom from recurrent MR III°/IV° (%) | Survival (%) |
|---|---|---|---|---|---|---|---|
| Chang et al.[39]<br>4 years<br>2007 | Early mortality, freedom from cardiac-related deaths, freedom from reoperation, freedom from recurrent MR, reverse LV remodeling | Resect | 363 | 1.4 | 98.2 | 92.7 | 94.2 |
| Flameng et al.[40]<br>10 years<br>2008 | Early mortality, Freedom from late cardiac-related deaths, cardiac-related events, freedom from reoperation, NYHA functional class | Resect | 348 | 1.6 | 94.4 | 64.9 | 80.1 |
| Gillinov et al.[98]<br>10 years<br>1998 | Early mortality, freedom from late cardiac-related deaths and cardiac-related events, NYHA functional class, and freedom from reoperation | Resect | 1072 | 0.3 | 93 | NA | 81 |
| Cetinkaya et al.[37]<br>10 years<br>2020 | Early mortality, recurrent MR, LV ejection fraction, NYHA functional class | Resect *vs.* Respect | 363/358 | 1.1/0.4 | NA | 99.6/100 | 88/89.3 |
| Pfannmueller et al.[46]<br>10 years<br>2021 | Early mortality, freedom from late cardiac-related deaths freedom from reoperation | Resect *vs.* Respect | 383/662 | 1.6/0.7 | 96/97 | NA/NA | 81/85.6 |
| Lazam et al.[31]<br>20 years<br>2017 | Early mortality, long-term survival, freedom from recurrent MR, freedom from reoperation, freedom from valve related complications | Respect | 1709 | 1.3 | 95.9 | 88 | 46 |
| Lawrie et al.[99]<br>10 years<br>2011 | Early mortality, freedom from recurrent MR, freedom from reoperation | Respect | 662 | 2.6 | 90.1 | 93.9 | NA |
| Shibata et al.[41]<br>5 years<br>2015 | Early mortality, long-term survival, freedom from recurrent MR, freedom from reoperation | Respect | 180 | 0.5 | 99.5 | 91.5 | 98.3 |
| Axtell et al.[42]<br>3 years<br>2020 | Early mortality, late cardiac-related deaths freedom from recurrent MR, freedom from reoperation, reverse LV remodeling | Respect | 101 | 0 | 100 | 100 | 100 |
| Lawrie et al.[43]<br>10 years<br>2021 | Early mortality, long-term survival, freedom from recurrent MR, freedom from reoperation | Respect | 1068 | 1.59 | 96.01 | 94 | 74.65 |

MR: Mitral regurgitation; LV: Left ventricle; NYHA: New York Heart Association; NA: Not available.

unknown.[48] The available evidence, as illustrated in Figure 3b, shows that larger rings lead to better hemodynamics.[44,49] Selecting smaller rings in the hope of obtaining a more competent valve appears to introduce a stenotic component, limit the left atrium reverse remodeling,[50] elevate postoperative transmitral gradients,[49,51-53] and presumably increase postoperative atrial fibrillation.[54] Many surgeons suggest using "true sizing" for this reason.[48] However, since we neither know the true size of an annulus for a severely regurgitant valve nor the true dimensions of our rings, this terminology can hardly be accurate and may hamper reproducibility. As it currently stands, the evidence suggests that in degenerative mitral regurgitation repair, choosing larger ring sizes (as long as durability is not compromised) may be beneficial for hemodynamics.

Despite plausible findings in the meta-analysis, the great heterogeneity of pathologies in structural MR makes drawing general conclusions difficult. In cases with fibroelastic deficiencies and only individual rupture of chords associated with MR and resulting annular dilatation, MR may be better treated by resecting the small prolapsing segment rather than resuspending a small section of paper-thin leaflet as the anchoring of the neochordae may be challenging. In contrast, in patients with excessive amounts of tissue in both leaflets (e.g., in Barlow's disease), resuspension of all segments or even massive "remodeling" of the valves[55-57] may be just as successful as a simple annuloplasty ring alone (if the disease pattern is symmetric).[34] In asymmetric cases, surgeons who prefer to resect may be faced with the need to combine resection with resuspension of remaining segments when resection alone cannot solve the entire problem. Finally, determination of the correct length of neochords is challenging. Some surgeons prefer isolated PTFE sutures that must be individually adjusted during the operation,[58] while others prefer to use sets of preformed PTFE loops.[12] Here, the base of the loop construct is anchored with felt pledgets at the papillary muscles, and the loops (up to four per set) are attached to the edge of the leaflets with an additional PTFE suture.[12,34,59] Again, properly randomized comparative evidence is missing.

Thus, a certain degree of experience is always required to generate competent and durable repairs.[60] For the beginner mitral valve surgeon, it may be good advice to know many different styles in conjunction with the results from the literature. The available evidence for surgical treatment of structural mitral valve regurgitation suggests that resuspension of prolapsing mitral valve segments with PTFE neochords combined with a rather generous annuloplasty ring sizing strategy appears to result in the best hemodynamics paired with comparable or even superior long-term durability and survival compared to the classic resection techniques.

### Evidence for functional MR

Similar to structural MR, the presence of functional MR is also associated with a gradual reduction in life expectancy, again being dependent on the severity of mitral regurgitation.[4] Since patients with functional MR often suffer from heart failure (which may be a cause or consequence), overall mortality is usually higher than with structural MR,[61] the evidence suggesting an improvement in survival is scarce,[62,63] and from a randomized-trial-perspective not existent. The available randomized evidence in this field suggests similar survival to not performing mitral repair (in patients with moderate MR undergoing coronary artery bypass grafts)[64] and no difference to mitral valve replacement in patients requiring surgery for functional MR.[65] However, the trials were performed with an annuloplasty-only approach, and two-thirds of the patients with repairs experienced the return of significant MR within two years after surgery.[17] The question arises if the potential clinical impact of a successful and durable repair can be properly assessed from studies that are affected by a high rate of MR recurrence. Thus, a detailed assessment of repair techniques, durability, and clinical outcomes seems in order. Table 2 shows a summary of studies addressing repair techniques for functional MR that also report relevant outcomes.

Functional MR, in which the fibers and chordae tendineae are structurally normal, develops due to the imbalance in tethering and closing forces as a result of geometric changes in the left ventricle or left atrium.[2] Thus far, mitral repair strategies for functional MR have focused on the annulus via restrictive mitral annuloplasty. However, although practically always present in the face of severe MR, annular dilatation is often not the cause of MR under these conditions. Restrictive mitral annuloplasty decreases the anteroposterior diameter of the mitral annulus and thereby "buys" coaptation surface. This strategy of approximating the leaflets has led to the suggestion of choosing 1 or 2 sizes smaller than the actual size that would be used for annuloplasty in SMR.[48] The concept of "the tighter, the better" for more durable repairs was proposed,[66-69] presumably with the idea that the "bought coaptation surface"

**Table 2. Summary information for all current trials about subvalvular mitral repair techniques in functional MR**

| Trial name (follow-up period, year of publication) | Study end point | Repair techniques (annuloplasty/annuloplasty + subvalvular techniques) | Number of patients | Early mortality (%) | Freedom from severe MR (%) | Survival (%) |
|---|---|---|---|---|---|---|
| Braun et al.[16] 7 years 2008 | Early and late mortality predictors, freedom from recurrent MR, NYHA functional class, reverse LV remodeling | Annuloplasty | 100 | 8 | 98.6 | 71 |
| Acker et al.[100] 1 year 2013 | LV reverse remodeling, mortality, MACCE, recurrent mitral regurgitation, rehospitalization | Annuloplasty | 126 | 1.6 | 95.8 | 84.1 |
| Goldstein et al.[17] 2 years 2015 | LV reverse remodeling, mortality, MACCE, recurrent mitral regurgitation, rehospitalization | Annuloplasty | 126 | NA | 86 | 81 |
| McGee et al.[101] 5 years 2004 | Early and late mortality, predictors of recurrent MR, recurrent MR rates | Annuloplasty | 585 | 6.3 | ≈30 | 60 |
| Hung et al.[102] 4 years 2004 | LV remodeling, recurrent mitral regurgitation | Annuloplasty | 30 | NA | 24 | NA |
| Harmel et al.[18] 42 months 2018 | Recurrence of MR ≥2 at the last echocardiographic follow-up (≥3 years) LVEF, LVEDD | Annuloplasty *vs.* annuloplasty + subvalvular techniques | 1093 | NA | 76 / 90.2 | NA |
| De Varennes et al.[81] 4 years 2009 | Early and late mortality, NYHA functional class, freedom from moderate or severe recurrent MR | Posterior leaflet extension | 44 | 11 | 93 at 3 years | 86 |
| Fattouch et al.[103] 5 years 2012 | Early mortality, Freedom from late cardiac-related deaths, cardiac-related events, NYHA functional class, reverse LV remodeling | Papillary muscle relocation | 55 | 3.6 | 96.4 | 91 |
| Fattouch et al.[104] 5 years 2014 | Early mortality, freedom from cardiac-related deaths and events, freedom from recurrent MR, NYHA functional class, reverse LV remodeling | Papillary muscle relocation | 115 | 3.4 | 97.3 | 90.9 |
| Fattouch et al.[105] 5 years 2012 | Early mortality, freedom from late cardiac-related deaths and cardiac-related events, and reverse LV remodeling | Papillary muscle relocation | 69 | 4.3 | 97.2 | NA |
| Roshanali et al.[80] 40 months 2017 | Early mortality, freedom from recurrent MR, NYHA functional class | Papillary muscle approximation | 100 | 6.5 | 96.6 | NA |
| Nappi et al.[66] 5 years 2016 | Early mortality, freedom from late cardiac-related deaths and cardiac-related events, and reverse LV remodeling | Papillary muscle approximation | 48 | 4.2 | 73 | 77.1 |
| Wakasa et al.[106] 3 years 2015 | Early mortality, late cardiac-related deaths freedom from recurrent MR, NYHA functional class | Papillary muscle approximation | 26 | 12 | 4.4 *vs.* 3.7 | 89 |

**Table 2. Continued**

| Trial name (follow-up period, year of publication) | Study end point | Repair techniques (annuloplasty/annuloplasty + subvalvular techniques) | Number of patients | Early mortality (%) | Freedom from severe MR (%) | Survival (%) |
|---|---|---|---|---|---|---|
| Hvass and Joudinaud[75]<br>5 years<br>2010 | Early mortality, late cardiac-related deaths, NYHA functional class | Papillary muscle approximation (sling) | 37 | 5.4 | NA | 80 |
| Nappi et al.[89]<br>5 years<br>2017 | Early mortality, freedom from late cardiac-related deaths and cardiac-related events, and reverse LV remodeling | Papillary muscle approximation | 48 | 4.2 | 73 | 83.3 |
| Langer et al.[76]<br>2 years<br>2009 | Early mortality, late cardiac-related deaths freedom from recurrent MR | Ring + String | 30 | 6.6 | 96 | 89 |
| Pingpoh et al.[107]<br>NA<br>2017 | Early mortality | Ring-Noose-String | 10 | 0 | NA | NA |
| Borger et al.[77]<br>4 years<br>2007 | Early mortality, late cardiac-related deaths and cardiac-related event, freedom from recurrent MR | Secondary chorda cutting | 43 | 9 | 85 | 79 |
| Murashita et al.[93]<br>5 years<br>2014 | Early mortality, late cardiac-related deaths and cardiac-related event, freedom from recurrent MR, NYHA functional class, reverse LV remodeling | Secondary chorda cutting | 15 | 0 | 80 | 80.8 |
| de Varennes et al.[81]<br>4 years<br>2009 | Early mortality, late cardiac-related deaths and cardiac-related event, freedom from recurrent MR, NYHA functional class, reverse LV remodeling | Patch enlargement | 44 | 11 | 90 | 73 |

MR: Mitral regurgitation; NYHA: New York Heart Association; LV: Left ventricle; MACCE: Major adverse cardiac and cerebrovascular events; LVEF: Left ventricle ejection fraction; LVEDD: Left ventricle end diastolic diameter; NA: Not available.

would last, but long-term results of these undersizing annuloplasty strategies have still been dismal (see Table 2).[16,17,70] It became clear that left ventricular dimensions played an important role in surgical repair of functional MR,[71-73] and different techniques addressing the subvalvular apparatus were developed (Figure 4 and Table 2).[19,74-80] Other techniques try to overcome the restrictive pattern of MR by implanting large patches into the posterior or anterior leaflet providing ample coaptation for a potentially durable result.[81] Again, other groups suggest replacing the valve if restriction is too strong.[73,82] This suggestion may be based on the rationale that replacement does not show worse survival in functional MR, and the goal of eliminating MR is better achieved with a good replacement than with a poor repair. However, since replacement has been associated with similar survival as a repair that has a 70% chance of MR recurrence in two years,[17] the question remains how this comparison would turn out if the repair showed excellent long-term durability. The current interventional techniques face the same challenge of subvalvular/ventricular changes in association with annular dilatation. Based on this view, it appears highly unlikely that clipping both leaflets together is able to generate a durable repair result. Alfieri et al.[83] already demonstrated that performing an edge-to-edge repair without annuloplasty delivers inferior results. Thus, the search for a durable repair should continue.

### Subvalvular techniques

Liel-Cohen et al.[84] suggested that the papillary muscle head shifted towards the apex after ischemia. Figure 4a shows displacement of the posterior papillary muscle as the main mechanism of functional

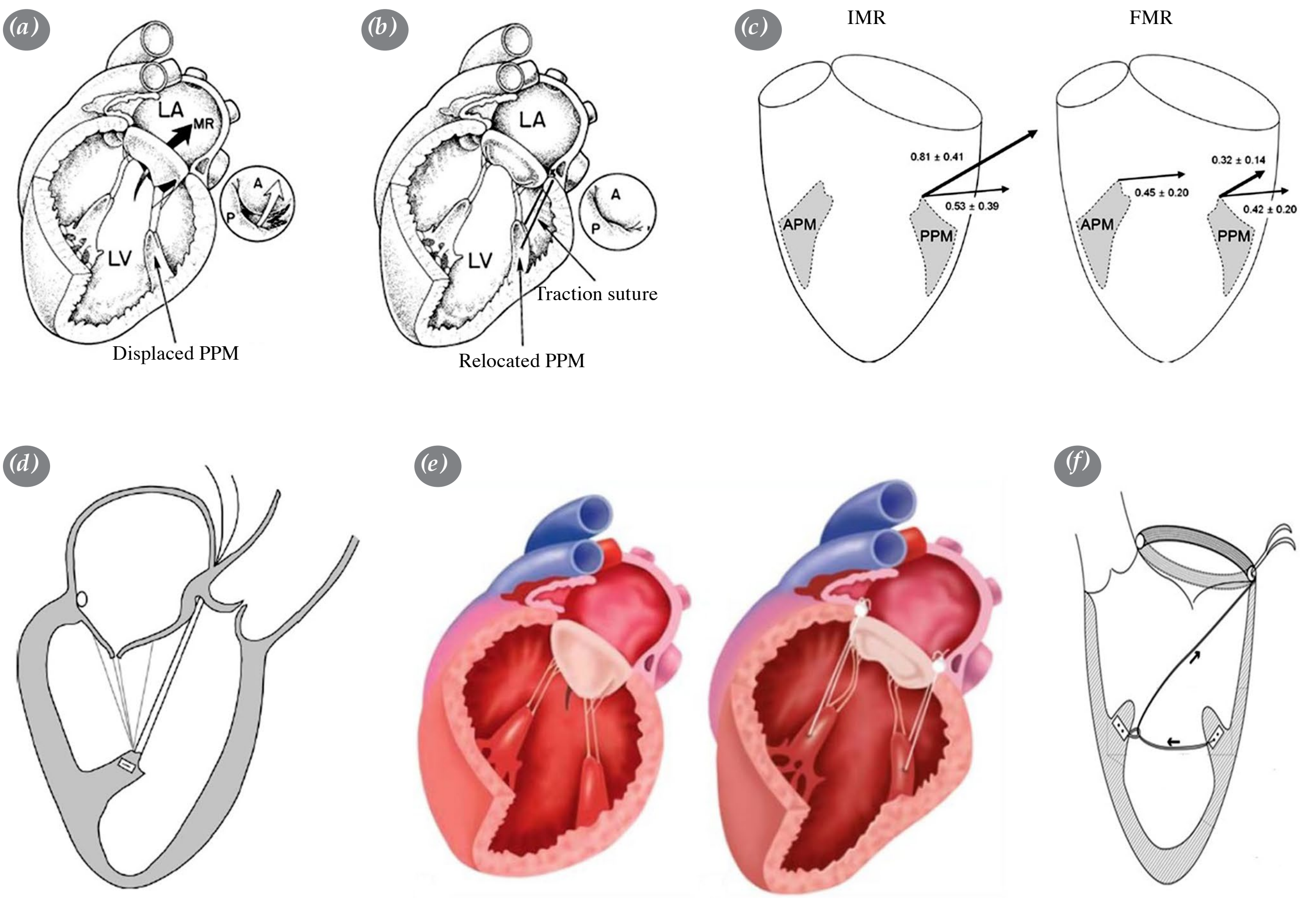


**Figure 4.** **(a)** Illustration of papillary muscle displacement by functional MR, and surgical strategies addressing the subvalvular apparatus; **(b)** relocation of the posterior papillary muscle;[74] **(c)** schematic illustrations depicting three-dimensional anterior and posterior papillary muscles displacement vectors in experimental ovine models of ischemic MR and functional MR;[86] **(d)** Ring and String technique;[76] **(e)** Girdauskas technique;[91] **(f)** Ring-Noose-String technique.[19]

MR: Mitral regurgitation; LA: Left atrium; LV: Left ventricle; APM: Anterior papillary muscle; PPM: Posterior papillary muscle; FMR: Functional mitral regurgitation.

MR. In light of this information, Kron et al.[74] defined the papillary relocation technique as bringing the posterior papillary muscle closer to the posterior annulus (Figure 4b). However, this relocation can cause a tilting effect on the posterior leaflet, leading to actual worsening of restriction of the mitral valve.[78,85] Bothe et al.[86] shed light on this phenomenon with their study on sheep hearts. In this model of ischemic MR, the anterior papillary muscle was displaced in the lateral direction and the posterior papillary muscle in the posterolateral direction, while no displacement was observed in the apical direction (Figure 4c). They also found support for their findings from other animal models, demonstrating that the direction of papillary muscle displacement is also not apical but instead lateral and basal.[87] Therefore, pulling the papillary muscle towards the annulus does not address the underlying pathology. Techniques that pull the laterally displaced papillary muscles together and fix the geometry of the entire mitral valve apparatus appear mechanistically more attractive. Various techniques have been proposed, which more or less contain these mechanistic considerations.[78,85,86,88-90] In any case, they have been associated with reverse left ventricle remodeling,[75,88-90] less mitral regurgitation recurrence,[75,89] fewer reoperations,[62,89] and higher survival rates,[62] although randomized evidence is missing. However, the individual techniques sometimes still raise mechanistic concerns.

For instance, Langer et al.[76] repositioned the posterior papillary muscle with the help of 4-0 expanded PTFE, which is passed through the aortomitral junction and exteriorized at the commissure between the noncoronary and left coronary cusp (Figure 4d). More durable mitral repair and better reverse remodeling were seen with this technique, possibly because in this technique, the posterior papillary muscle is pulled not only towards the annulus but also the anterior papillary muscle, therefore reducing the interpapillary distance and tethering forces. However, since only one papillary muscle is relocated, the subvalvular stability of the entire apparatus cannot be guaranteed. In addition, the technique requires a transverse aortotomy and a postbypass tying of the chord, which practically excludes a mini-thoracotomy approach.

Girdauskas et al.[91] described a technique that addresses both papillary muscles independently (Figure 4e), also providing more durable repair results and promising clinical outcomes. Nevertheless, the technique carries the risk of unequal resuspension of the two independently secured papillary muscles and does not connect the two papillary muscles so that the lateral displacement is still conceivable. However, this technique is the only one for which a signal for survival improvement of functional MR repair exists, although thus far nonrandomized.[62]

We devised our ring-noose-string method (Figure 4f) based on pathomechanistic considerations.[19] Since the posteromedial papillary muscle is the one with the greatest (basolateral) displacement, we guided a suture anchored at the base of this muscle through a 5 mm Gore-Tex noose that is anchored at the anterolateral papillary muscle. We then atrialized the suture at the level of P2 and secured it to the annuloplasty ring after the water test illustrated valve competence.

Irrespective of the pros and cons of any of the techniques, there is currently no randomized evidence available supporting the potential advantages described. The REFORM-MR (Operative Mitral Valve Reconstruction in Functional Mitral Valve Insufficiency With Reduced Systolic Ventricle Function) trial is currently ongoing to assess the impact of the Girdauskas technique (Figure 4e) on the durability of the valve repair at two years.

### Leaflet enlargement and chordal cutting

Before the subvalvular techniques were developed, the cutting of secondary chords had been proposed based on animal studies that demonstrated alleviation of restriction.[92] The first series of chordal cutting in patients was performed in Toronto with unclear results.[77] Despite signals for therapeutic potential, the technique was abandoned for concerns that cutting secondary chordae may adversely affect contractile function.[93]

In parallel to the efforts directed at alleviating chordal restrictions or securing the subvalvular apparatus through (re-)suspension of the papillary muscles, enlarging the anterior[94] or the posterior leaflet with a patch[81] and providing ample coaptation in conjunction with an annuloplasty was proposed. Again, promising initial results were published,[81] but a proper prospective randomized evaluation is also missing.

### Valve replacement as an alternative to repair

It is the general notion, that mitral valve replacement for functional MR is a valid alternative to repair in symptomatic patients with severe restriction. The evidence suggests that such a replacement requires full preservation of the chordae, which is considered to preserve the often already poor left ventricular function.[14,17,95,96] Suggestions to quantify the restriction by measuring tenting height or area[14,82] or determining it by assessing angles of mitral leaflet position[14,82] have been made to assist in decision making for replacement.[73,82] The results of an Italian collaborative effort suggesting a benefit for replacement in patients with severe restriction supports this suggestion.[97] However, it also supports the suggestion that treatment of MR must be successful and durable since repairs under these conditions do not fulfill these expectations and comparisons of replacement of durable repairs are not available yet.

In conclusion, the available evidence for surgical treatment of functional mitral valve regurgitation suggests that annuloplasty alone does not provide a reliable long-term repair result. Additional subvalvular or leaflet enlarging strategies appear to improve the durability of the repair, but the required randomized evidence is currently missing. The same pathomechanistic challenges apply to interventional techniques. It also remains to be determined whether the difference between repair and replacement for structural MR can then also be seen in functional MR. After all, there is still the potential that repair for functional MR improves survival.

**Data Sharing Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

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