Endoscopic mitral valve repair—one hundred and one ways to use neochords: a narrative review

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Background and Objective: Mitral valve repair for mitral regurgitation remains technically demanding due to the complex anatomy of the mitral apparatus, including the annulus, left ventricle, papillary muscles, and chordae. Although Alain Carpentier's "French Correction" laid foundational principles, repair remains challenging, particularly for junior or low-volume surgeons. Neochordal implantation is a critical tool in mitral repair but lacks standardized technique selection, leading to variability in outcomes and surgical training. This narrative review aims to provide a comprehensive classification of neochordal repair techniques and a structured framework to guide clinical application.

Methods: A narrative review of published literature on neochordal implantation was conducted, emphasizing technique evolution, anatomical considerations, imaging guidance, and minimally invasive approaches. Over 100 techniques were identified and categorized by anchoring strategy, leaflet involvement, and integration with advanced technologies, including robotic and artificial intelligence (AI)-assisted planning. The review also considers educational tools, simulation methods, and credentialing practices relevant to neochordal repair.

Key Content and Findings: Endoscopic mitral valve repair offers patient benefits by avoiding sternotomy but increases technical complexity. Current surgical strategies largely depend on institutional habits, with limited structured guidance. Innovations highlighted include single- and multi-point anchoring, Y-shaped configurations, and techniques optimized using advanced imaging and simulation. These methods allow precise tension distribution, minimize leaflet manipulation, and enhance reproducibility. Despite these advancements, most techniques lack high-level evidence, with data primarily from single-center or retrospective studies. Emerging approaches show promise for biomechanically optimized repairs that simplify complex procedures, potentially reducing mid-term reoperation rates. Training limitations, absence of standardized checklists, and variability in credentialing remain barriers to widespread adoption.

Conclusions: Neochordal implantation represents a versatile and evolving component of mitral valve repair. While numerous innovative techniques exist, reproducible outcomes require multicenter validation, long-term follow-up, and standardized training frameworks. This review provides a structured classification of neochordal techniques, identifies emerging trends, and underscores the need for future research and educational standardization to improve surgical consistency and patient outcomes.

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Introduction

Mitral regurgitation (MR) repair is inherently complex, addressing a broad spectrum of valvular pathologies (1-4). The surgical toolkit for mitral repair is extensive, rooted in the foundational techniques and principles established by Alain Carpentier in his landmark "French Correction" of 1983, and further enriched by contributions from other surgeons over the years (5). The mitral valve apparatus itself is a sophisticated system composed of the annulus, left ventricle, papillary muscles, and chordae tendineae, with disease manifestations varying widely in form and severity. As a complex—rather than merely complicated—system, effective repair requires a structured, comprehensive, and teachable approach.

Among the available techniques, artificial chordal replacement has gained widespread acceptance as a cornerstone of contemporary repair. However, the diversity and sometimes non-intuitive nature of chordal insertion methods continue to pose significant challenges, especially for early-career or low-volume surgeons. The wide variability in both pathological presentation and repair strategies contributes to inconsistent decision-making, unpredictable outcomes, and significant barriers to effective teaching. In such multifactorially influenced systems, variability remains the greatest obstacle to reproducible success.

With the emergence of endoscopic cardiac surgery technologies, mitral valve repair quickly became one of the primary applications and has since remained a cornerstone of minimally invasive platforms. These approaches, which avoid median sternotomy, offer significant patient-centered benefits such as reduced trauma and faster recovery (3,6-9). However, they also introduce a steeper technical learning curve, potentially increasing the procedural complexity for the operating surgeon. In clinical practice, the selection of surgical techniques is often influenced by individual surgeon preference or institutional norms, leading to considerable variation in how similar pathologies are addressed (10-14).

Despite the widespread adoption of neochordal repair techniques, the current literature lacks a unified reference that systematically categorizes these methods based on anatomical targets, disease pathology, procedural approach, or imaging guidance. This review seeks to bridge that gap by identifying and analyzing one hundred and one distinct applications of neochordal repair in the context of endoscopic mitral valve surgery. It highlights the need for structured comparative evaluations and presents key concepts such as different anchoring configurations (e.g., single-point, multi-point, Y-shaped), as well as the integration of robotics and artificial intelligence (AI) into preoperative planning and surgical training (*Figure 1*). Unlike prior reviews, this manuscript categorizes new string repair techniques and summarizes early evidence to provide a structured overview. It also offers practical guidance for clinical application, highlighting the unique contributions and decision-making considerations for practicing surgeons. By consolidating these innovations alongside their respective evidence, the review aims to serve as a practical resource for both trainees and experienced surgeons seeking to refine their techniques in this evolving field. We present this article in accordance with the Narrative Review reporting checklist (available at https://jovs.amegroups.com/article/view/10.21037/jovs-25-27/rc).

Methods

A narrative review was conducted to provide a comprehensive overview of neochordal implantation in mitral valve repair (*Table 1*). The literature search was performed from January to July 2025, covering studies published between 2000 and 2025, using PubMed, Embase, Cochrane Library, and the Google Scholar. Search terms included "Mitral valve repair", "Neochords", "Endoscopic mitral valve surgery", "Surgical innovation", and "Minimally invasive cardiac surgery".

Inclusion criteria were studies describing neochordal techniques, endoscopic or minimally invasive approaches, clinical or experimental outcomes, and surgical innovations or educational frameworks. Exclusion criteria included case reports with fewer than five patients, non-English articles, and reviews not focused on neochordal repair. Titles and

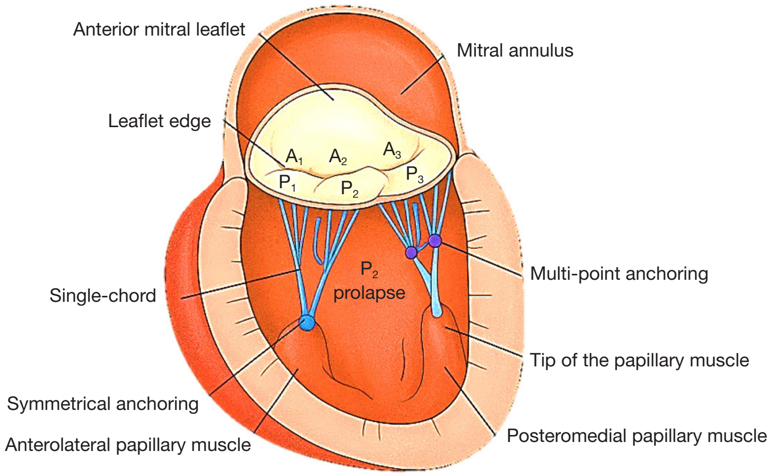

Figure 1 The diagram explains the connection among the mitral valve leaflets, the papillary muscles, and the points where the neochordae are fixed. Both types of anchoring—single-point and multi-point—are displayed, as well as where they can be positioned symmetrically or asymmetrically. These techniques repair typical degenerative issues, such as P_2 prolapse, leaflet prolapse, and displaced papillary muscle in cases of ischemic mitral regurgitation. A_1: anterior leaflet segment 1. A_2: anterior leaflet segment 2. A_3: anterior leaflet segment 3. P_1: posterior leaflet segment 1. P_2: posterior leaflet segment 2. P_3: posterior leaflet segment 3.

Table 1 The search strategy summary

Items	Specification
Date of search	January 1, 2025 to July 31, 2025
Databases searched	PubMed, Embase, Cochrane Library, Google Scholar
Search terms used	"Mitral valve repair", "Neochords", "Endoscopic mitral valve surgery", "Surgical innovation", "Minimally invasive cardiac surgery"; both MeSH and free-text terms were used; filters applied: English language, human studies
Timeframe	Studies published from 2000 to 2025
Inclusion and exclusion criteria	Inclusion: studies describing neochordal techniques, endoscopic/minimally invasive approaches, clinical or experimental outcomes, surgical innovations, and educational frameworks
	Exclusion: case reports with fewer than five patients, non-English articles, reviews not focused on neochordal repair, and studies with insufficient methodological detail
Selection process	Titles and abstracts screened independently by two reviewers; full-text articles reviewed for eligibility; disagreements resolved by discussion and consensus with a third reviewer if needed
Any additional considerations	Focus on classifying over neochordal repair techniques, integration with advanced technologies (robotic/AI-guided planning), training tools, and credentialing practices. Narrative review design; no formal meta-analysis performed

AI, artificial intelligence.

Table 2 Summary of neochord techniques by category and clinical use-case

Category	No. of techniques	Representative use-cases
Annular dilation (Type I)	15	Annular enlargement, functional MR, ring-less repair
Prolapse/flail (Type II)	35	P_2 prolapse, commissural support, bileaflet prolapse, Barlow's disease
Tethering/stiffening (Type III)	25	Ischemic MR, rheumatic valve, endocarditis, functional MR
Technical variations	8	Loop techniques, pledgeted sutures, Cor-Knot, figure-of-eight stitch
Single-suture innovations	12	Kofidis running-suture loops (12 distinct configurations)
Instrumental & technological	6	Robotic arms, 3D planning software, NeoChord DS1000 device

P_2: posterior leaflet segment 2. 3D, three-dimensional; MR, mitral regurgitation.

abstracts were screened, followed by full-text review to confirm eligibility. Over 100 techniques were classified by anchoring strategy, leaflet involvement, and integration with advanced technologies, with additional focus on clinical outcomes, simulation-based training, and credentialing practices.

As a narrative review, no formal meta-analysis was performed; instead, the goal was to synthesize current knowledge, highlight innovations, and provide a practical framework for surgeons and trainees, summarizing early evidence where available.

Historical aspects and evolution of neochordal implantation in mitral valve repair

The concept of artificial chordal replacement in mitral valve repair has evolved significantly over the past few decades. Initially, mitral valve repair relied heavily on leaflet resection techniques, particularly for degenerative MR. Early surgical efforts involved the use of synthetic materials such as Dacron and polyethylene for artificial chordae, but these had limited durability and biocompatibility. A major advancement came in the late 1990s with the introduction of expanded polytetrafluoroethylene (ePTFE) sutures and the development of the "loop technique", which provided a more reliable, physiologically adaptable substitute for native chordae (15-17). Biomechanical studies confirmed that ePTFE neochords could withstand dynamic stress and maintain effective leaflet coaptation over time (18-25).

As cardiac surgery shifted towards minimally invasive approaches in the early 2000s, the need to adapt neochordal techniques for smaller incisions became paramount (26-35). The refinement of video-assisted and endoscopic tools allowed surgeons to perform complex repairs without median sternotomy, preserving the advantages of reduced trauma and faster recovery (6,10,36-44). The subsequent introduction of robotic platforms enhanced visualization, enabling placement of neochords under challenging anatomical conditions (5,10,45). Alongside these developments, adjunctive tools such as Chord-X PTFE Loop System, RAM device, Cor-Knot devices, and transesophageal echocardiography (TEE) became standard, facilitating reproducibility and safety (2,3,7,11,40). More recently, computational modeling has been explored to optimize artificial chordal geometry and improve long-term outcomes (24).

Classification of neochordal approaches and repair techniques

Guided by Carpentier's functional classification of MR, we grouped 101 neochordal intervention techniques into three major pathological categories: Type I, characterized by normal leaflet motion with annular dilation; Type II, defined by excessive leaflet motion such as prolapse or billowing; and Type III, involving restricted leaflet motion due to tethering or stiffening. Within each category, these techniques were further organized based on the specific anatomical lesion being addressed, providing a structured framework for understanding the application of neochordal repairs across varying forms of mitral valve pathology (*Table 2*).

Type I: normal leaflet motion with annular dilation

Type I neochordal techniques target functional MR by using subannular neochords placed below the mitral annulus. These neochords act to reduce annular circumference, elevate the coaptation point, and improve valve competence—without involving the leaflets directly.

The primary aim is to restore normal valve function by correcting annular geometry rather than leaflet pathology. These techniques are frequently combined with ring annuloplasty, which helps re-establish physiological leaflet alignment. The neochords exert tension that reshapes the annulus into its native three-dimensional (3D) saddle shape, optimizing leaflet coaptation and enhancing the durability of the repair (12,16,27).

Type II: excessive leaflet motion (prolapse and flail)

In Type II, excessive leaflet mobility resulting from chordal rupture, segmental prolapse, or flail is treated. In isolated P_2 prolapse, the treatment of choice procedure is still insertion of artificial cords—single polytetrafluoroethylene (PTFE) neochord between the medial papillary head and the free edge of the P_2 scallop; this returns accurate leaflet support, eliminates billowing and reconstitutes a central and anteriorly directed jet into normal coaptation (4,9). In bileaflet prolapse, simultaneous capture of both leaflets is achieved using either multiple individual neochords or a paired neochord technique with dual-port access. In the latter, two PTFE loops are passed through A_2 and P_2, securing both prolapsing segments under 3D transesophageal echocardiographic guidance to optimize central coaptation height (3,18). Commissural prolapse is corrected using fine-caliber PTFE neochords anchored at the posteromedial or anterolateral commissures. These reestablish commissural integrity, preventing localized billowing that cannot be fully addressed by ring annuloplasty alone (4,9). When clefts or indentations compromise coaptation, horizontal ePTFE loops (e.g., between P_2 and P_3) are anchored to the opposing papillary muscle to support scallops and prevent regurgitation along the cleft line (4,17). A lattice of multiple neochords may also be interwoven between segments such as A_2 and P_2 to distribute mechanical stress across redundant tissue. This approach preserves leaflet integrity and eliminates the need for aggressive resections while preventing localized billowing (11,24,39,46-51). In cases of mitral annular disjunction, where the atrial wall detaches from the ventricular myocardium at the leaflet hinge point, tensioned neochords spanning from the displaced annulus to the papillary apparatus can restore leaflet-ventricular alignment, reversing atrialization and re-anchoring the leaflet base (11,39,51).

Type III: restricted leaflet motion (tethering and stiffening)

Type III neochordal techniques address restricted leaflet motion caused by ischemic tethering, rheumatic thickening, or tissue destruction following infective endocarditis. In cases of ischemic MR, neochords are anchored around the subannular region to reposition the papillary muscles centrally within the left ventricle. This reestablishes appropriate papillary-annular tension and helps alleviate leaflet tethering and regurgitant jets—achieved without the need for extensive leaflet resection or patch augmentation (12,16,27). For rheumatic mitral disease, where leaflets are thickened and shortened due to fibrosis, a reinforced chordal transfer technique is employed. Secondary native chordae are mobilized and strengthened with ePTFE loops, enhancing leaflet mobility and restoring coaptation—thus avoiding the use of large pericardial patches that may calcify over time (14,15). However, in cases of post-endocarditis damage, where leaflet segments are partially destroyed, reconstruction involves the use of bovine pericardial patches in combination with single or multiple neochords. This patch-chord construct restores both the structural integrity of the leaflet and effective coaptation (16,24,31). Finally, in patients with functional MR secondary to dilated cardiomyopathy, a hybrid approach is used. This involves multi-point neochords insertion to reposition tethered leaflets, combined with downsized annuloplasty rings. This strategy reshapes the annular-ventricular interface, improves leaflet coaptation, and reduces regurgitation—despite the absence of primary leaflet pathology (12,16,21,27).

Segmental and multi-segment mitral valve repair

Placing a single PTFE neochord on the P_2 scallop and fixing it to the medial edge of the papillary muscle is still a standard approach for isolated P_2 prolapse and allows excellent grip of the prolapsing leaflet (4,9). Using a pledgeted neochord and repairing the anterolateral papillary muscle allows the surgeon to fine-tune the coaptation height and duplicate the original tension during saline testing (9,17). In leaflet prolapse, the repair is centralized by placing both neochords by simultaneously operating through A_2 and P_2 on dual port access (3,18). When the chord is attached at the posteromedial commissure, it can restore the commissural function, while small-size PTFE chords, besides the anterolateral papillary muscle, assist buckling in para commissural zones (4,9). Sometimes, for multi-segment posterior leaflet prolapse, a neochord is needed on each P_1, P_2 and P_3 papillary head to hold and regulate the scallops (11,51). After P_2 resection, two artificial fold-like tissues are placed on the edges of the leaflets to prevent further prolapse (4,9). PTFE chords that go horizontally over a P_2–P_3 cleft and attach to a papillary muscle keep the leaflets steady (4,17). Supporting a P_3 flail is a brief neochord that links the flail scallop to the papillary muscle (4,9).

New chordae made of ePTFE are anchored to both the belly and papillary head of the mitral valve, replacing the broken native chordae (9,17) instead of having extensive reduction of valve tissue. A lack of fibroblastic tissue with stretched chords is addressed with preoperative 3D TEE imaging, which helps design and anchor loop neochords to the papillary muscles (3,18,21). Applying neochords to restricted leaflets in ischemic MR corrects regurgitation, avoiding the phenomenon of one jet in each leaflet (12,16,27). Besides rheumatic material, chordal transfer includes surgically moving and reinforcing additional chords (14,15). The chordal attachment to the papillary muscle (neochords) is extended to several leaflets, which stabilize the valve right away (5,22,25).

Systolic anterior motion (SAM) can be prevented by implanting new chords on the opposite (asymmetric) side (11,18,24). After removing the damaged parts, fibrotic valve leaflets get more flexible because new neochords are attached to the papillary muscle (16,17). When endocarditis leaves a leaflet damaged, surgeons attach patch-chord constructs to restore its integrity (16,24,31). Functional MR in cardiomyopathy uses neochords that support the valve to help reshape the left ventricle shape (12,16,21,27). In Barlow's disease, placing artificial chordae on the P_2 segment can eliminate the need for excessive leaflet resection (11,39,51). Using interlocking neochords on A_2–P_2, severe Barlow forms a sturdy yet slim lattice without cutting away much tissue (11,24,39,51).

As an extension of existing neochordal classifications, single-suture or running suture techniques have been introduced by Kofidis *et al.* (52-55). The continuous PTFE suture follows a defined pattern, reducing variability in chordal positioning. In the "Roman Arch" technique, the suture runs from the papillary muscle to the leaflet edge and back to the opposite papillary muscle, ideal for P_2 or A_2 prolapse but applicable to other segments. The "Minotaurus" technique starts at the commissures, descends to the papillary muscles while incorporating all prolapsing leaflet edges, then ascends to the opposite commissure, addressing Forme Fruste or Barlow's disease in a single pass. Collectively, Kofidis's 12 techniques (52,55) allow dynamic, uniform tension adjustment, streamline workflow, and make mitral valve repair accessible even to less experienced surgeons.

These techniques offer theoretical and practical advantages, including fewer fixation points, reduced leaflet manipulation, and potential durability improvements. Early data suggest lower mid-term reoperation rates for single- and multi-segment prolapse due to even chordal tension and efficient deployment (3,6,51). If validated in larger multicenter studies, these methods may represent a paradigm shift in minimally invasive mitral valve repair, offering a standardized and reproducible approach to neochordal implantation.

Technical variations

Using PTFE neochord, the free edge of the mitral leaflet is anchored to the papillary muscle with a single suture loop. This configuration distributes force evenly and reduces the risk of localized stress points. The method is analogous to techniques commonly employed in conventional mitral valve surgery (17,18,46). In an alternative approach, interrupted neochords implantation involves placing individual PTFE chords, each independently attached to the leaflet and papillary muscle. This technique allows for independent tension adjustment of each neochord, as demonstrated in several case studies (9,17,45). The loop technique employs pre-sized PTFE loops to ensure consistent neochords length and reduce procedural errors (9,46). The use of a loop sizer during neochords implantation enables intraoperative adjustment under saline pressurization, simulating ventricular filling and facilitating optimal knot placement (3,18,21). This technique offers advantages in terms of simplicity, speed, and consistency of neochords length, allowing for even distribution across multiple points along the leaflet margin as needed. However, a key limitation is that all loops are of identical length, which may not accommodate the natural variability in the distance between the leaflet edge and the tip of the papillary muscle. Double-armed PTFE sutures with pledgets help prevent leaflet tearing and improve ease of fixation during endoscopic procedures (17,18). Based on hemodynamic insights, neochords may be anchored closer to the flow axis or slightly distal to the papillary body to simplify implantation (9,17,23). In minimally invasive settings, Cor-

Knot fasteners are frequently used in place of manual tying to reduce cross-clamp time. Surgeons must remain vigilant for rare but potential leaflet perforations (7,40). Some prefer placing neochords after ring annuloplasty, using the ring as a reference to determine chord length, while others insert neochords first to stabilize the leaflet during ring sizing (3,4,9,44). Preoperative 3D TEE enables measurement of the leaflet-to-papillary distance, helping determine optimal chord length and reduce cross-clamp duration (3,6,38). Advanced instrumentation improves surgical access, i.e., articulating arms offer better angles and reduce suture tension for deep knots (5,10,43,45).

A MitraClip-like approach may be employed in complex cases, replicating transcatheter edge-to-edge repair using additional sutures or materials (2,3). A mini-thoracotomy incisions (3–4 cm) in such cases enhances visualization and instrument handling (1,6,44). Two-dimensional (2D) and 3D endoscopic cameras assist in accurate chordal placement and ensure proper leaflet coaptation (2,6,10). Off-pump chord insertion (NeoChord device)—performed under echocardiographic guidance without cardiopulmonary bypass—avoids crossing the chordal path behind the valve (*Figure 2*) (13,18,29). The "figure-of-eight" stitch, used to anchor neochords to the papillary muscle, enhances security by minimizing slippage (17,23). In some cases, the papillary muscle is split longitudinally to increase the area of attachment; after chord fixation, the muscle is reapproximated, improving access to deeper structures (17,27). Finally, surgeons select from two types of chordal guides: flexible silicone measuring guides that conform to curved pathways and rigid metal guides that improve maneuverability—choices often gained by experience in nonrobotic endoscopic bypass procedures (3,7,47).

Number and length optimization

Tightening a single neochord under saline pressure within a prolapsing segment typically yields the best anatomical fit (17,18,21). Balancing medial and lateral dual neochords on the P_2 segment during repair helps align the leaflet symmetrically and improve stability, a technique consistent with findings from Barlow's pioneering work (11,51). Surgeons may also use chords of unequal lengths (e.g., 12 mm medially and 14 mm laterally) to guide tissue tapering, thereby optimizing coaptation and curvature based on fluid-structure interaction analyses (9,24,32). During this adjustment phase, the neochord is initially tied loosely, followed by the placement of additional knots to incrementally adjust the chordal length until regurgitation is eliminated under saline testing, allowing real-time intraoperative fine-tuning (9,17,46). The use the Bigelow device (a manual valve tester machine) to simulate systolic pressure further facilitates dynamic chord length titration until the desired coaptation is achieved (3,8,18). Intraoperative 2D/3D TEE helps assess inter-papillary muscle distance and leaflet height, guiding appropriate chord length selection—a process referred to as chord tuning, which enhances procedural accuracy and outcomes (2,3,38).

Using pre-sized loop sets (such as Chord-X in 12, 14, and 16 mm sizes) ensures uniform loop lengths and streamlines workflow by eliminating the need for intraoperative measurement (9,17,41). Neochords can also be modified intraoperatively with sliding knots, allowing endoscopic adjustment similar to techniques used in transcatheter devices (3,17,50). Chord length selection is influenced by ventricular dimensions: larger ventricles require longer chords to prevent slack, while smaller ventricles benefit from shorter chords to avoid anterior systolic motion (11,12,24,26,27). For central leaflet prolapse, three neochords are typically ideal, distributing mechanical forces and reducing leaflet stress (11,51). Excess chordal length is trimmed after saline testing to prevent obstruction of leaflet mobility or flow interference (17,18). 3D organ modeling allows surgeons to rehearse procedures and accurately plan neochord placement preoperatively, reducing cross-clamp time during surgery (3,6,47). Additionally, preoperative computed tomography (CT) mapping of the papillary-annular complex enhances precision in chord length selection (3,18,34). During TEE-guided surgery, determining the leaflet-to-coaptation zone distance further aids in selecting the appropriate neochordal device (*Figure 3*) (3,14,38).

Pathology-specific use

A lattice of interlaced neochords extending from A_2 to P_2 is used in patients with myxomatous Barlow's disease to redistribute stress, prevent excessive billowing, and preserve vascularized leaflet tissue for effective and durable repair (11,24,39,51). Isolated chordal ruptures, often seen in fibroelastic deficiency, are typically repaired by implanting a single PTFE neochord at each affected segment, minimizing foreign material use and preserving native leaflet mobility (9,15,17). In cases where valve leaflets become fibrotic following commissurotomy for rheumatic disease, reinforced neochords anchored to the papillary muscles help restore leaflet mobility and reduce transvalvular

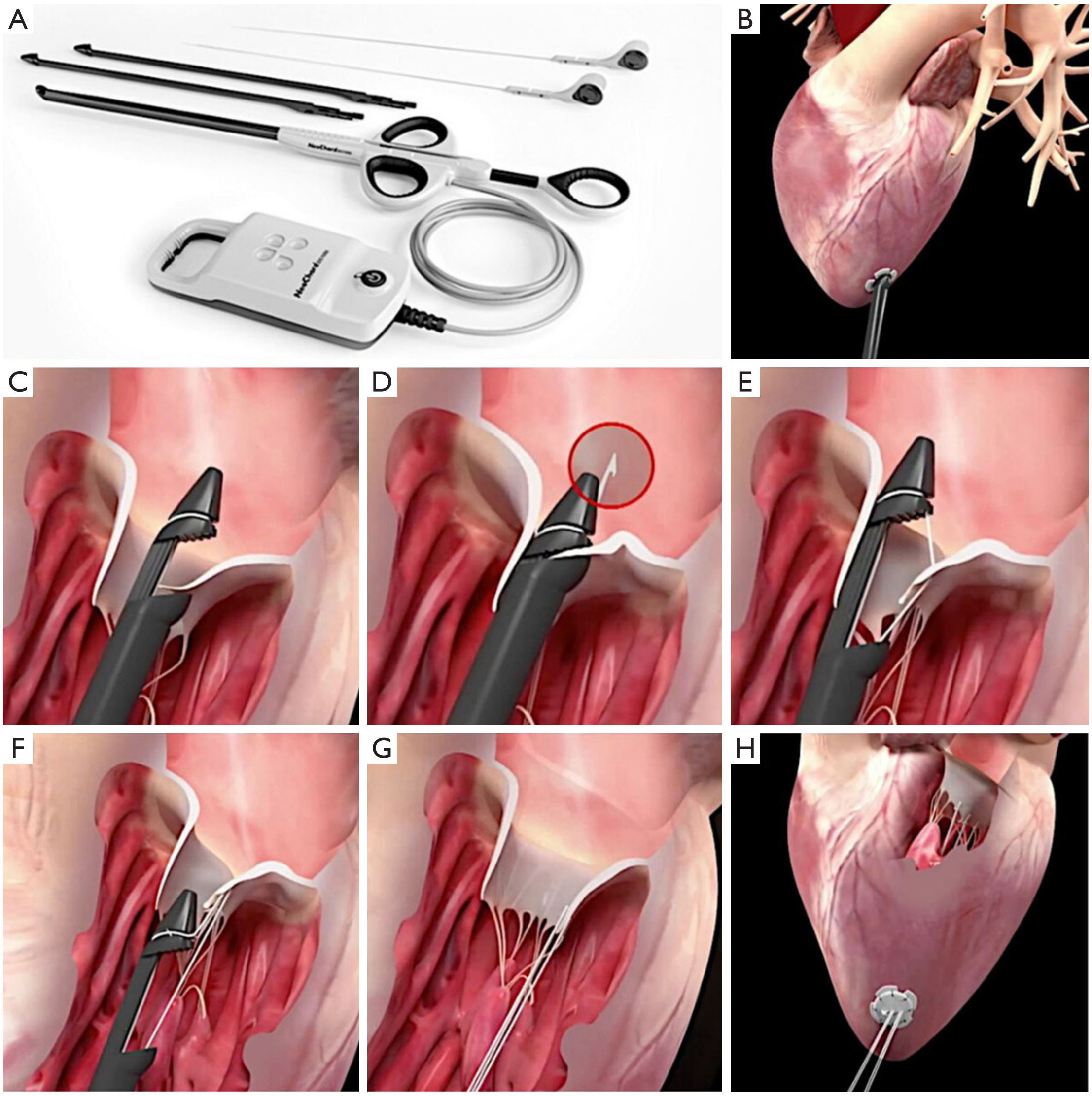

Figure 2 Off-pump neochord implantation schematics. (A) The NeoChord device. (B) The device is introduced into the left ventricle. (C) After crossing the mitral valve, the jaws of the device are opened, and the leaflet edge is grasped by gently retracting the device toward the left atrium. (D,E) A needle (red circle highlighted) pierces the leaflet, allowing deployment of a suture loop. (F,G) The device is withdrawn, bringing the neochordal loop out of the ventricle and forming a girth hitch knot. (H) Neochordal length is adjusted under real-time transesophageal echocardiographic guidance until satisfactory leaflet coaptation is achieved. Each neochord is then secured to the epicardial surface using a Teflon pledget. Reprint with permission under open access from D'Onofrio *et al.* (56).

pressure gradients (16,17,37). For post-endocarditis repairs, a bovine pericardial patch is placed over the damaged leaflet segment, and neochords are attached from the patch to the papillary muscle—similar in principle to transcatheter plug closures (16,24,31). When papillary muscle displacement leads to ischemic MR, neochords can be used to reposition the papillary muscles centrally, improving leaflet coaptation, as supported by computational modeling studies (12,16,21,27). In ventricular dilatation, commonly associated with functional MR (Type IIIb), a combination of multiple neochords and a downsized annuloplasty ring is often employed to address leaflet tethering and optimize coaptation (12,16,21,27).

In secondary MR, many surgeons realign the leaflets by attaching neochords to the central region of the papillary muscles, thereby reducing regurgitant flow (12,16,27). For

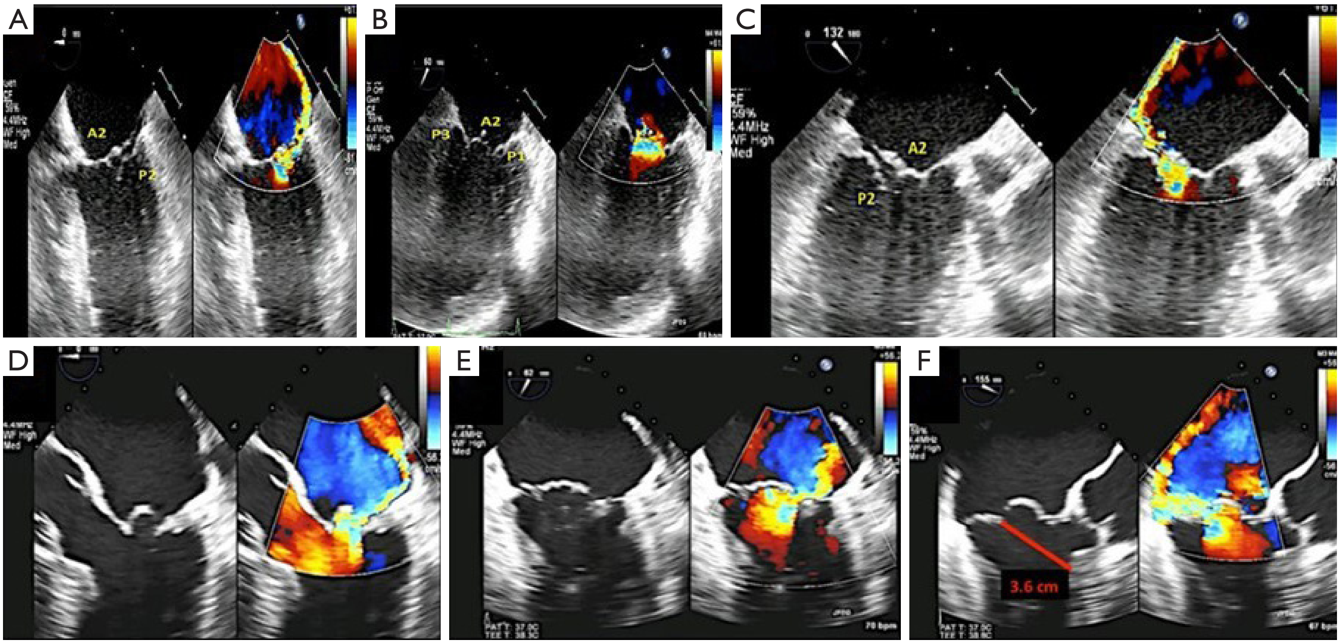

Figure 3 Intraoperative TEE-guided evaluation of mitral regurgitation showing panel. (A) Mid-esophageal view at 0 degrees demonstrates the baseline transesophageal echocardiographic image. (B) Color Doppler reveals mitral regurgitation originating near the A_2 scallop. (C) Long-axis view showing both A_2 and P_2 scallops. (D) 2D TEE at 0 degrees confirms severe posteriorly directed mitral regurgitation due to a flail A_2 segment. (E) Bicommissural TEE view further delineates the origin of the regurgitant jet. (F) The regurgitation is localized between the A_2 and P_2 scallops, with the coaptation-to-septum distance also visualized. Adopted with permission under open access from Quader *et al.* (57). A_2: anterior leaflet segment 2. P_1: posterior leaflet segment 1. P_2: posterior leaflet segment 2. P_3: posterior leaflet segment 3. 2D, two-dimensional; TEE, transesophageal echocardiography.

congenital double-orifice valves, a pair of chordal webs may be constructed to enable effective leaflet fusion and centralization (5,13,22). When MitraClip failure occurs, additional neochords are often placed adjacent to the clip to reinforce mitral closure (3,19,29). For residual prolapse, supplementary neochords can be implanted to strengthen and stabilize the remaining unsupported areas (3,11,49). In cardiomyopathy-related papillary displacement, neochords are utilized to redirect leaflet motion and restore effective coaptation (12,21,27,36). Some procedures also combine limited annular incisions with neochords implantation, guided by findings from cardiac magnetic resonance imaging (16,18,34). In cases of leaflet perforation due to trauma or infection, surgical repair includes patching the defect and reinforcing the area with neochords to restore valve competence (16,24,31).

Instrumental & technological innovations

3D measurement charts generated from preoperative CT or TEE scans allow surgeons to estimate neochord length prior to surgery, improving accuracy and reducing operative time (3,6,47). 3D TEE images analyzed by AI can suggest optimal chordal placement and length (3,18). Virtual reality (VR) planning environments enable surgeons to rehearse neochord placement and simulate balance testing preoperatively (3,6,47). Haptic-sensor-equipped instruments provide real-time feedback on suture tension during neochordal tying, reducing the risk of over-tightening and preventing leaflet distortion during endoscopic procedures (5,7,26). Using a customized chordal arm, neochords can be delivered directly from the papillary muscle to the leaflet edge, avoiding difficult suture angles (3,5,47). Robotic wrists offer 360° articulation, providing surgeons with greater maneuverability and replicating the precision of open-heart techniques in a minimally invasive setting. These systems have demonstrated excellent durability, with no mechanical degradation over 7 years of use (5,10,43,45). Pre-packaged neochord and ring kits streamline workflow by allowing sequential use, reducing instrument changes, and shortening operative time (3,11,41,42). The transcatheter NeoChord DS1000 device, guided by TEE and introduced through a left mini-thoracotomy, enables chordal implantation in high-risk patients (13,18,29). Intraoperative chord-mapping software, integrating TEE and 3D models, suggests optimal suture anchor points based on real-time heart geometry (2,3,24,32). Fibre-optic tension sensors embedded in neochords allow surgeons to monitor tension dynamically, particularly when adjusted with saline infusion (5,18,21). Microsuture drivers stabilize the chordal needle under endoscopic visualization, minimizing leaflet trauma and enhancing precision (42-47).

Training & learning curve applications

Silicone mitral valve models are used for *ex vivo* simulation, allowing trainees to practice neochord placement safely, similar to telesimulation (2,6). In VR-based simulation, surgeons can rehearse hemodynamic conditions and apply tension to xenografts, a growing component of modern surgical training (2,6,47). Dual-console robotic systems enable supervised neochordal implantation, allowing trainees to receive immediate expert feedback while performing each procedural step—from leaflet grasping to papillary anchoring and final chordal adjustment (5,10,41). This sequence mirrors the structured learning pathway of endoscopic mitral valve surgery (2,6,46). Providing 3D-printed anatomical models allows residents to study patient-specific mitral anatomy and better understand chordal architecture prior to actual surgery (3,6,47,48). Trainees typically begin with P_2 repairs, progress to A_2, and ultimately perform multi-chordal bileaflet repairs, a curriculum validated in cadaver-based biannual workshops (2,6,10). Robotic simulators with haptic feedback enhance manual dexterity and teach precise knot tensioning, reducing risks of over- or under-tightening during live procedures (5,10,41). Endoscopic cadaveric practice helps bridge the gap between simulation and real-life surgery, akin to how REBOA devices are validated in porcine models. In live animal labs, trainees observe the real-time effects of chord tension on leaflet function under physiological blood flow (2,6,25). Video libraries of all 101 techniques offer visual learning of global best practices in endoscopic neochordal surgery (2,6,49).

Kofidis techniques

A novel neochordal strategy has been proposed that involves symmetrical anchoring of papillary tissue under endoscopic visualization to improve biomechanical stress and render mitral valve repair easier and standardized across experience spectrum (3,6). At the core of this technique is a running PTFE neochord, which runs through leaflet margin and papillary muscles, or engages the commissures too, enabling even tension distribution (3,6). This configuration reduces guesswork as to where to place the individual artificial cords. This form of repair may be seen as a democratization and an improvement upon existing techniques, as it reduces variability and inconsistency or result (3,11,51).

The technique is performed via a sternotomy or minimally invasive lateral thoracotomy, often through the nipple line or submammary approach. Under endoscopic and 3D echocardiographic guidance, the papillary heads are measured externally (17); the neochord is then inserted into both muscle heads (7,40) and secured to the valve leaflet at the appropriate depth (2,3,38). Emerging data suggest that this Arch-shaped course (Roman Arch) or Horn-like suture pattern (Minotaurus) design distributes forces more evenly across the leaflet and widens the coaptation zone, potentially enhancing long-term durability compared to conventional neochordal techniques. It is also powerful in excessive tissue presence, such as Forme Fruste and Barlow's, as it also stabilizes the commissures and associated mitral annular disjunction (MAD) (3,18,24,39). The Kofidis techniques, though initially developed in a single institution, have since been published and are beginning to generate early evidence within the wider scientific community. While further external validation and long-term outcome data are warranted, their emerging adoption underscores the growing interest in these methods as part of contemporary surgical practice.

Comprehensive listing of 101 neochordal techniques

Numerous variations of neochordal implantation techniques exist, encompassing anatomical, technical, optimization-based, pathology-specific, instrument-driven, and training-related strategies.

Anatomically, surgeons may choose simple P_2 repair for isolated prolapse or perform complex web dissections for Barlow's disease. Techniques are also tailored to specific conditions such as ischemic, rheumatic, and infective pathologies (4,9,11,12,16,17,24-37,39,51).

Technically, various approaches are used for chordal placement, including continuous suturing, interrupted

Table 3 Technique summary by pathology, clinical role, and level of evidence

Pathology	Technique focus	Clinical role	Evidence type
Barlow's disease	Interlocking lattice neochords, web dissection	Tissue preservation, tension distribution	Multi-center observational studies (4,5,9,11,12,16,17,24,25,27,31,36,39,51)
Fibroelastic deficiency	Single PTFE neochord per rupture site	Minimally invasive correction	Early surgical case series (5,8,9,21,26,27,30,32-34)
Rheumatic disease	Reinforced neochords with fibrotic leaflets	Improve leaflet mobility	Biomechanical and histopathology studies (2,3,6,9,11,14,16,18,21,27,32,34,37,38)
Ischemic MR	Papillary realignment with sub-annular neochords	Restore coaptation, correct leaflet tethering	Computational modeling & clinical data (2,3,5-7,10-13,18,21,24,29,32,38,41-45,47,50)
Functional MR (Type IIIb)	Multi-neochord plus ring reduction	Leaflet realignment in dilated ventricles	Imaging-guided planning studies (2,5,6,10,16,21,25,47-49)
Endocarditis	Patch-chord constructs, leaflet segment reinforcement	Structural integrity restoration	Case reports and device trials (3,5,7-9,16,17,23,31,44)
Congenital double orifice	Dual chordal webs	Normalize leaflet fusion	Pediatric surgical innovation reports (5,22)
Post-MitraClip failure	Adjunct neochords beside clip	Reinforce closure	Edge-to-edge repair studies (3,29)

MR, mitral regurgitation; PTFE, polytetrafluoroethylene.

PTFE chords with pledgets, loop techniques with pre-measured loops, U-clips versus manual knot tying, and decisions on whether to perform annuloplasty before or after chordal implantation. Chords may be inserted directly through the endoscope, or with the aid of organ pins or robotically guided instruments (3,5,7-9,17,23,44).

Optimization strategies include tailoring the number and length of neochords using intraoperative saline testing, valve testers, intraoperative ultrasound, pre-sized loop systems, adjustable sliding-knot techniques, 3D simulators, and imaging the papillary muscle-to-leaflet distance for accurate fitting (2,6,9,11,14,18,21-27,38).

Pathology-specific adaptations range from using single neochords for fibroelastic deficiency to multi-point support for functional MR, bicuspid or double-orifice valve repairs, and patch/neochord reconstruction for endocarditis-related defects (*Table 3*) (8,21,26,27,30,32-34).

Technological innovations have introduced a broad set of tools and systems, including 3D templates, advanced echocardiographic imaging, VR-based surgical planning, precision robotic tools, individualized chordal arms, flexible robotic wrists, integrated NeoChord—annuloplasty systems, transcatheter neochord delivery devices, suture mapping software, optical tension-measuring sensors, and microsuture drivers—all contributing to enhanced precision, safety, and procedural efficiency (2,7,10,11,13,18,21-24,38,41-45,50).

Training and simulation tools further support proficiency development. These include dry-lab silicone valve models, VR simulation, robotic telesurgery with real-time feedback, stepwise procedural breakdowns, rehearsals based on preoperative 3D planning, staged skill acquisition (from basic to complex), cadaveric dissections, live animal laboratories, and video libraries illustrating the full spectrum of neochordal repair techniques (2,5,6,10,25,47-49).

Discussion

One hundred and one neochordal techniques demonstrate that ePTFE chords offer significant flexibility in minimally invasive mitral valve repair. Advances in imaging, suture materials, anchoring devices, and robotic platforms have refined these foundational methods, resulting in a wide array of strategies tailored to specific clinical scenarios (9,17,18,24). Constrictive annular constructs, such as Y-shaped or lattice neochords, help distribute tension evenly, thereby reinforcing the valve apparatus and enhancing long-term durability (3,6,11,24,39,51). Many surgical teams now rely on preoperative 3D TEE and CT imaging to estimate optimal chordal lengths, reducing intraoperative adjustment time and minimizing aortic cross-clamp duration (2,3,6,34,38). Robotic assistance enables precise chord placement in anatomically challenging locations, reducing surgeon fatigue and allowing for fine motor replication of open-surgery techniques (5,10,43,45). AI-assisted echocardiographic analysis and VR planning are increasingly used in preoperative preparation and surgical rehearsal. However, large-scale validation of these technologies is still pending (3,6,32,38). Pre-packaged neochord and annuloplasty kits, such as those used with NeoChord^{TM} systems, show promise in streamlining procedural steps and expanding access to minimally invasive options—though long-term outcome data are still under investigation (13,18,29,41,49).

Chordal strategies must be adapted to individual pathology. For example, fibroelastic deficiency may require only a single chordal replacement, whereas Barlow's disease, characterized by redundant tissue, often benefits from multi-chordal reconstruction to preserve leaflet integrity (9,11,15,17,21,24,37). In cases of ventricular dilation or ischemic MR, subannular chordal placement combined with annuloplasty is required to restore effective coaptation (12,16,21,27). Patch techniques, often involving chordal or pericardial tissue, are employed in rheumatic disease or endocarditis to reconstruct areas of missing or damaged leaflets (16,24,31). Although observational studies support many of these evolving techniques, the growing diversity of options presents a challenge in determining the most effective approaches. There remains a lack of standardized protocols across centers, contributing to outcome variability. Some patients may benefit significantly at one institution compared to another, purely due to technique selection and institutional preferences. Moreover, a stepwise integration of training modalities, ranging from high-fidelity technologies such as VR, simulation, and robotics to more scalable low-cost alternatives, may enhance the practicality and accessibility of surgical education. Such an approach could provide a flexible framework adaptable to diverse institutional settings, thereby supporting both high-volume academic centers and lower-volume programs in resource-limited environments.

This review is the first to comprehensively classify one hundred and one neochordal techniques based on underlying pathology, available evidence, and clinical applicability. It further introduces modern surgical paradigms—such as analyzing anchoring patterns (symmetrical *vs.* asymmetrical, single-point *vs.* lattice), integrating AI for neochord length estimation, and utilizing robotics for enhanced precision (3,6,11,18,24,38). These are not merely incremental modifications; they represent a fundamental shift in how mitral valve repair is conceptualized and performed. As more centers adopt endoscopic mitral repair, there is a clear need for standardized frameworks. This collection of techniques offers a basis for evidence-based decision-making, reduced variability, and future comparative studies aimed at establishing uniform protocols. The author's own techniques offer a facil and powerful new platform which may eliminate variability and guesswork during repair.

Critical evaluation

The one hundred and one neochordal approaches provide a wide array of options for minimally invasive mitral valve repair. However, each technique comes with limitations, gaps in supporting evidence, and elements of uncertainty.

Anatomical applications

Many procedures rely heavily on the surgeon's ability to assess leaflet thickness, morphology, and papillary muscle orientation. Patient-specific anatomical variation often complicates the use of standardized techniques. For example, there is limited long-term evidence supporting multi-point lattice neochord techniques for Barlow's disease when compared to traditional leaflet resection. Placing neochords on posterior scallops (P_1–P_3) can improve coaptation, but successful execution depends on accurately sizing the scallops intraoperatively—an especially challenging task via endoscopy (4,9). Moreover, the widespread use of nonchordal bands in Barlow's may lead to residual billowing if there is any tension imbalance, although no systematic studies have evaluated this risk (11). Many anatomical techniques remain segment-specific, and the supporting data are largely observational, raising questions about the long-term durability of complex anchoring patterns.

Technical variations

Techniques such as loop methods, figure-eight sutures, and Cor-Knot fasteners are used to facilitate implantation and reduce cross-clamp time. Each system, however, has limitations. For instance, while Cor-Knot fasteners save time, they have occasionally been associated with leaflet perforation (40). Preformed PTFE loops simplify chordal construction but lack adjustability and may not account for dynamic ventricular changes (9,17). Debate continues over the use of interrupted *vs.* continuous sutures—the former better distributes tension, while the latter can be challenging to control during endoscopic procedures (46). Though robotic platforms enhance precision, their high costs, steep learning curves, and resource requirements make them impractical for low-volume centers (5,10,43,45). Furthermore, many innovations are supported by single-center data, limiting generalizability.

Number and length optimization

Real-time length determination using valve testers or loop-sizer devices improves tension control, yet these tools rely heavily on saline testing, or optical rule-of-thumb assessments, which replicate physiological loading conditions poorly (18,21,24). No consensus exists on the optimal number of neochords; some studies advocate for three, while others report success with two or four (11,32). Preoperative 3D imaging (TEE or CT) aids planning, but its accuracy may be reduced in patients with leaflet asymmetry or calcification (3,38). Although fluid-structure interaction models suggest ideal chord lengths, these findings lack widespread clinical validation (24). Many optimization strategies still focus on surrogate measures, rather than long-term functional outcomes.

Pathology-specific use

Different disease mechanisms are managed with tailored approaches such as patch-chord combinations for endocarditis and papillary muscle realignment in ischemic MR. However, most of this evidence comes from small case series or observational reports. In ischemic MR, neochordal repair may initially reduce leaflet tethering, but long-term benefits may diminish as ventricular remodeling progresses (12). While replacing a single chord is relatively straightforward, concerns remain about the durability of neochords in cases with extensive leaflet destruction (9,15). In rheumatic disease, some studies question the sufficiency of chordal repair alone, recommending more aggressive leaflet debridement (16,37). Thus, although pathology-specific techniques offer targeted solutions, they remain under-investigated in large-scale, long-term studies.

Instrumental & technological innovations

Technologies such as 3D-printed models, AI-based chord measurement, VR simulations, and sensor-equipped neochords are being explored, but most remain experimental. AI algorithms for chord length prediction have not undergone large-scale validation, particularly in complex anatomical settings like calcified annuli (3,18,47). While robotic systems offer superior dexterity, their implementation introduces cost and training burdens (5,10,43,45). Transcatheter NeoChord devices provide an off-pump option for high-risk patients, yet their long-term outcomes are still under evaluation (13,29,49). The integration of these technologies into clinical practice depends largely on institutional resources, and high-tech solutions may not improve outcomes in low-volume centers.

Training & learning curve

Silicone valve models and VR platforms enhance skill acquisition but do not fully replicate tissue behavior under physiologic conditions (2,6,10). Cadaveric and animal dissection provides realistic anatomy but is constrained by ethical, logistical, and financial barriers (2,6,25). A standardized training curriculum for endoscopic neochordal surgery is lacking, leading to variability in surgeon proficiency. This ongoing variability fuels debate over credentialing requirements and case volume thresholds (2,6,47,48). Although trainees may perform well in simulation, translating that skill into real surgery requires validated intraoperative checklists—currently missing from most programs. In short, while surgical creativity continues to expand the field of neochordal mitral repair, the evidence base remains limited. There is a notable lack of randomized controlled trials, and much of the current literature relies on single-center, retrospective data. Establishing best practices, resolving controversies, and enabling broader adoption will require future multicenter registries and head-to-head comparative studies.

Conclusions

Mitral valve repair using endoscopic neochordal implantation has evolved from a handful of early techniques into a comprehensive repertoire of over one hundred approaches addressing a wide range of pathological conditions. The detailed classifications and references presented here provide valuable guidance for selecting the most appropriate technique for each patient, regardless of the surgeon's level of experience. Among these innovations, the development of running suture chordal anchoring

“Kofidis-techniques” reflects a shift toward intuitive tension-distribution strategies, supported by advancements in endoscopic imaging. As imaging modalities, surgical simulation, robotics, biomaterials, and computational modeling continue to progress, further refinement of neochordal techniques is anticipated. Perspectively, the advent of transcatheter mitral valve repair techniques continues chipping away on the surgical cake, leaving less opportunity for surgeons to train, and techniques to evolve. Hence, a more democratic, intuitive, standardized pattern of repair may serve the cohort well. These innovations underscore the need for rigorous studies to identify the most effective, reproducible, and durable repair strategies across diverse clinical settings.

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