Review Article

Diaphragmatic plication: current evidence and techniques in the management of the elevated hemidiaphragm

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Abstract: Diaphragm plication is the preferred surgical intervention for elevation of the hemidiaphragm. This can be a consequence of trauma, damage to the phrenic nerve, or congenital eventration. There are numerous surgical approaches to diaphragmatic plication including open thoracic, open abdominal, minimally invasive transthoracic, minimally invasive transabdominal, and robotic assisted. All approaches are acceptable practices, but there has been a shift to more minimally invasive and video-assisted approaches. In this clinical practice review, we have assessed the current evidence and techniques used for hemidiaphragm elevation. Most evidence assessing the various techniques comes in the form of case studies, case series, and small institutional studies. Video-assisted thoracoscopic surgery is a commonly employed technique associated with positive outcomes as evidenced by improvement of pulmonary function test following the procedure, fewer chest tube days, decrease in self-reported dyspnea, and short hospital stays. Laparoscopic plication is also an acceptable technique. Multiple case studies showed overall positive outcomes with limited morbidity. Robotic assisted approaches were also reviewed. These interventions were shown to improve spirometry values and dyspnea scores. Minimal data exist on open abdominal approaches, and there are not currently enough data to assess their effectiveness. Open thoracic approaches were associated with improvements in spirometry as well as dyspnea scores. All surgical approaches discussed are acceptable strategies for the treatment of the elevated hemidiaphragm. No one intervention appears to be superior, but minimally invasive approaches have become more popular. The success of these procedures is largely believed to be based on surgeon preference and level of expertise.

Keywords: Minimally invasive thoracic surgery; robotic surgery; plication; elevated hemidiaphragm

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Introduction

Diaphragmatic plication is an operation to surgically treat congenital eventration, acquired eventration, and diaphragmatic paralysis (1). When the diaphragm is denervated it can undergo fibrosis, atrophy, and necrosis (2). With plication, the diaphragm is lowered to a more typical anatomical position, and it no longer moves paradoxically during inspiration (3). Many patients with diaphragmatic paralysis can be asymptomatic, and diagnosis is often made incidentally (4). The most common presenting complaint in symptomatic patients is dyspnea (4). Plication is indicated for patients experiencing severe dyspnea who have failed conservative measures (4).

Diaphragm paralysis is most commonly a consequence of trauma. This can be secondary to cardiothoracic surgery, damage to the phrenic nerve roots, and cervical nerve blocks (5-8). Thoracic tumors can have significant involvement of the phrenic nerve resulting in injury during *en bloc* resection (9,10). Demyelinating disorders, viral infections, and other inflammatory processes can also lead to diaphragm paralysis (10).

There are multiple plication techniques including transabdominal, transthoracic, minimally invasive, and robotic approaches. There is no consensus on which technique is superior; however, surgeon preference and expertise may play a pivotal role in outcomes (4). Case series and small single institutional studies have explored the various plication approaches. Longitudinal studies assessing the effectiveness, morbidity, and mortality of plication exist but are uncommon. Here we seek to provide a brief overview of the various plication methods reported in the literature, and comment on our preferred technique.

Anatomy

The diaphragm is the anatomic boundary between the abdomen and thorax with attachments to the sternum, xiphoid, ribs, arcuate ligaments, and the left and right crus (11). It contains multiple hiatuses allowing passage of the inferior vena cava, esophagus, and aorta. It is innervated by the phrenic nerve which has roots in C3,4, and 5 (11). The phrenic nerve courses inferiorly into the posterior triangle of the neck, through the scalene muscles, along the pericardium, and into the diaphragm (12). The diaphragm receives its main blood supply from the pericardiophrenic artery (12).

Denervation or idiopathic elevation of the hemidiaphragm leads to dyspnea by decreasing the contractile strength of the diaphragm. In the chronically relaxed position, the affected hemidiaphragm is displaced into the hemithorax causing compression of the ipsilateral lung during all phases of the breathing cycle. During inspiration, intraabdominal pressure increases due to caudal displacement of the healthy diaphragm (2,3). The increased pressure leads to further contralateral displacement of the diseased segment. Over time, the denervated diaphragm can become fibrotic, necrotic, dyspnea can worsen, and patients may experience respiratory failure (2).

Indications

Patients with an elevated diaphragm should trial conservative therapy prior to undergoing plication. If conservative methods fail, and the patient remains symptomatic, plication should be considered (4). Surgery is not indicated for patients with an incidental finding of hemidiaphragm elevation or paralysis (4). The decision to undergo plication is largely dependent on symptomatology. The most common presenting symptom is dyspnea, which can be evaluated with the medical research council (MRC) dyspnea scale. This tool is a subjective measure used to evaluate patient-perceived respiratory disability (13). In a two-person case series, functional respiratory imaging and dyspnea were used to determine treatment modality (14). One patient underwent plication, and the other received non-operative management. Both patients' conditions improved (14).

Diaphragm plication remains the mainstay treatment for symptomatic diaphragm paralysis. It has been shown to improve chest wall mechanics in diseased and healthy hemidiaphragms (15). However, there is no consensus regarding the optimal technique. Large, clinical studies that assess different surgical approaches and their effects on symptom improvement, morbidity, and mortality are scarce. Most studies are single case studies, case series, instructional videos, small retrospective institutional studies, and reviews. There is anecdotal evidence to support each approach, but the literature suggests that outcomes are largely dependent on surgeon preference and expertise.

Diagnostic evaluation

A thorough history and physical exam is indicated for all patients. The authors have noted that many patients with a paralyzed hemidiaphragm note significant dyspnea when bending over to tie shoes. Depending on their overall cardiorespiratory status, conditioning, and body habitus, patients can be completely asymptomatic, dyspneic with exertion, or even dyspneic at rest. For symptomatic patients where there is a high suspicion of diaphragm elevation, the initial imaging step should be a plain film radiograph of the chest in the posteroanterior view (16). If there are positive findings on initial imaging, follow-up computed tomography should be performed to rule out other causes of elevated hemidiaphragm (16). Diaphragmatic fluoroscopy is then used to determine if there is paradoxical movement of the affected diaphragm during inspiration (17). Paradoxical movement is indicative of true hemi-diaphragmatic paralysis and is used to confirm the diagnosis (17). Symptomatic patients without paradoxical movement but with an elevated hemidiaphragm may still benefit from diaphragmatic plication. This situation may be more indicative of either congenital eventration of the diaphragm or subtotal phrenic nerve injury. However, patients who exhibit paradoxical movement experience more meaningful improvements in pulmonary function test (PFT) compared to those with limited or no paradoxical movement following plication (18). Nerve conduction studies are generally not necessary during the evaluation, but can be ordered if fluoroscopy is equivocal for paradoxical motion and additional information about nerve status would be useful. It should be noted that the reliability of phrenic nerve conduction studies can be highly operator dependent. PFT should be done and include the forced expiratory volume in one second (FEV1), forced vital capacity (FVC), FEV1/FVC, total lung capacity (TLC), and diffusion capacity of the lungs for carbon monoxide (DLCO) (16). Although there are no strict criteria, a definitive diagnosis can usually be made when other diagnoses have been ruled out, there is radiographic evidence of an elevated hemidiaphragm, there is paradoxical diaphragm movement on inhalation seen during sniff testing, and FVC is decreased on spirometry.

Patient selection and initial management

Patients who are asymptomatic do not require intervention. For patients with symptoms, the degree to which they interfere with quality of life and their desired activities should be investigated. The time course of dyspnea should also be noted. Patients who have experienced a recent phrenic nerve injury or insult (<6 months to a year) may benefit from observation to see if they experience recovery of the nerve or if symptoms become less noticeable with time. Exercise therapy and/or cardiopulmonary rehabilitation can be offered as an initial alternative to surgical therapy. This strategy is often beneficial for mildly or minimally symptomatic patients. For patients with more severe symptoms, consideration of diaphragmatic plication is warranted. Choice of transthoracic or transabdominal plication is surgeon-dependent; both are effective. If a hostile chest is anticipated, a transabdominal approach may be useful, and vice versa. Heavier patients, especially those with significant central obesity, may be at risk of suboptimal outcomes. Increased intraabdominal pressure in these patients can limit the ability to achieve a "normal" diaphragm level. For patients with elevated right hemidiaphragms, achieving this can be especially difficult due to the presence and mass of the liver underneath the diaphragm. Patients who have tried and failed exercise therapy, or prefer the more immediate, surgical approach may go ahead with plication.

Technique

Our preferred technique is a robotic, transthoracic diaphragmatic plication using the DaVinci Xi system (Intuitive Surgical; Sunnyvale, CA, USA). The patient is intubated with a double-lumen endotracheal tube, and positioned in lateral decubitus. The camera port is placed in the 5th intercostal space in the mid-axillary line. Carbon dioxide insufflation to a pressure of 10 or 15 cmH_2O is initiated. An intercostal nerve block with local anesthetic is performed. The left and right arm ports are typically placed in the same transverse plane as the camera port, at least 9 cm away. Attention to being able to direct the instruments to both the medial and lateral aspects of the hemidiaphragm should be taken to guide placement. A fourth robotic arm is generally not necessary. An assistant port is placed anteriorly on the patient's body, usually 1–2 interspaces below the arm port, for suture exchange. The Xi system is targeted to the central tendon of the diaphragm. A suture-cut needle driver is used in the right arm, and a Cadiere forceps in the left arm; these are typically the only two instruments needed. We prefer placing 0 polyester suture with Teflon pledgets in a horizontal mattress fashion in a line running lateral to medial on the hemidiaphragm. Additional rows of plication sutures either adjacent to or encompassing the first row can be placed to achieve the desired result of eliminating laxity in the hemidiaphragm. Typically, 8–12 sutures are sufficient to complete the operation. After the plication is performed, carbon dioxide insufflation is turned off, and the pressure is vented from the chest to examine what the resting position of the hemidiaphragm will be. Ideally, the top of the diaphragm will be located at or beneath the 8th intercostal space; it can be helpful to place the camera in that location to get a true "horizontal" view of the chest cavity. Additional sutures can be placed if laxity is seen or more plication is desired. An angled chest tube is placed, the operative lung is ventilated, and the incisions are closed. An emphasis should be placed on ensuring the transition from sedation is not complicated by violent contractions of skeletal muscle during inspiration. Additionally, attention should be given to avoid retching or vomiting in the postoperative period. Multimodality pain control is employed. The chest tube can usually be removed and patient discharged by postoperative day 1.

Methods

A literature search was performed using PubMed as the primary resource. We used broad search terms in an attempt to yield the highest number of relevant articles. These included "diaphragm" and "plication". Publications were not excluded based on study design or sample size.

Discussion

Video-assisted thoracoscopic surgery (VATS) diaphragm plication

VATS is a commonly employed minimally invasive alternative to open diaphragmatic plication. Numerous informational video tutorials are available (19-21). Other minimally invasive approaches utilizing uniport VATS have been described (21). Another technique has been described that utilizes video guidance and insufflation to ensure the elevated diaphragm is not incised during entrance into the thorax (22). This method decreases the likelihood of violating the peritoneum, entering the abdomen, and puncturing hollow viscous organs. This is achieved by utilizing an endostitch suture technique and a moveable endo grasper (22). In a single institution observational study, when compared with open thoracotomy, VATS was shown to be a feasible and safe alternative (23). In patients receiving plication for elevated hemidiaphragm resulting in mediastinal shift and respiratory failure, VATS was associated with decreased hospital stay (23). However, fewer patients who underwent VATS had resolution of their dyspnea compared to those who underwent open thoracotomy (23). Patients who underwent VATS had higher rates of post-operative ICU admissions (23). VATS is also associated with significant improvements in spirometry values (24,25). In a single institution, retrospective analysis of 18 patients, utilization of a single, buttressed, double-layered, to-and-fro suture with additional plicating horizontal mattresses as needed showed an increase in FEV1 and FVC (24). Patients in this study also experienced decreases in perceived dyspnea and increases in DLCO (24). Patients from a case series published in 2017 who underwent VATS experienced an average increase of 540 and 776 mL in FEV1 and FVC, respectively (25). These patients also saw a mean hospital stay of 3.2 days and reduced post-operative pain (25). There were no differences in improvement when comparing left and right sided plication (25). In a retrospective study, undergoing VATS with mini-thoracotomy showed improvement of spirometry values that remained stable over the course of one year following the operation (26). A case series of patients undergoing single-port VATS following traumatic eventration had their chest tubes removed between 3 to 8 days post-operation; although one patient experienced a pleural effusion which resolved, all remained asymptomatic and free from dyspnea, and none experienced recurrence at thirteen months of follow-up (27). In another institutional study assessing dual port VATS in 12 patients, all experienced complete resolution of symptoms following plication, and there were no instances of recurrence (28). Patients in this study also experienced significant improvements in FEV1 and FVC following plication that continued up to 5 years after the operation (28). There was, however, no difference in blood gas values pre and post-operatively (28). In this dual port approach, there was no need for rib-spreading. While it can always be implemented if field visualization is suboptimal, it is often the reason for significant post-operative pain and should therefore be avoided if possible (28). Similar outcomes were observed in an additional single institution study assessing 41 patients who underwent plication (29). Patients who underwent plication with either three-port VATS or thoracotomy experienced a reduction in MRC dyspnea scores by 2, improvements in FVC (+19%), FEV1 (+23%), functional residual capacity (+21%), and TLC (+19%) (29). Ninety-one percent of those expressing an interest in returning to work were able to re-enter the workforce following plication (29). Patients who underwent plication had persistent symptom improvement and increased PFTs at follow-up 4 years after surgery, and no patients experienced breakdown or rupture of the plication (29). The utility of limiting the number of ports used in VATS has also been assessed. A retrospective analysis of 21 patients who underwent uniport or dual port VATS assessed for improvements in dyspnea, hospital length of stay, and operative time (30). Uniport VATS plication was shown to be similar to dual port VATS in all outcomes assessed (30). In institutional studies and small analyses, VATS has been shown to be both safe and effective and is a viable alternative to open plication procedures (*Table 1*).

Laparoscopic plication

Laparoscopic plication is another acceptable alternative to open surgical techniques. Similar to VATS, there are few large studies assessing the safety and efficacy of this procedure, and most of the evidence comes in the form of case series, case studies, and single institution analyses. Among patients undergoing laparoscopic plication, hospital stays have been reported to be 4 days or less with no complications (31). Patients in this case series also showed

Table 1 Results summary of studies assessing VATS plication

Authors	Year	Design	Technique	Outcome	Findings
Taberham *et al.*	2017	Single center observational (n=35)	VATS with insufflation (n=22); thoracotomy (n=13)	LOS	Mean LOS: 4.2; 5.1 days
				Dyspnea	% no dyspnea improvement: 18%; 8%
				ITU admissions	% ITU admission: 23%; 8%
Demos *et al.*	2017	Retrospective (n=18)	VATS with running suture	PFTs	PFTs (pre/post/P value)
					• FEV1: 73.5%/88.8%/0.002
					• FVC: 70.6%/72.3%/0.002
					• DLCO: 80.3/84.6/0.6
				Dyspnea (TDI)	Dyspnea (6 months/30 months/P value)
					• TDI: 7.1/7.2/0.38
Kocher *et al.*	2017	Case series (n=6)	VATS	LOS	Mean LOS: 3.2 days
				PFTs	Mean FEV1 increase: 540 mL
					Mean FVC increase: 776 mL
Rombola *et al.*	2016	Retrospective (n=18)	VATS mini-thoracotomy	Dyspnea	Dyspnea
					• Pre-op: 22% very serious
					• Post-op: 0% very serious
				Home O_2	O_2 at home
					• Pre-op: 33.3% yes
					• Post-op: 0% yes
				PFTs	FVC increase: 510.2 mL (P<0.001)
					FEV1 increase: 361.7 mL (P<0.001)
Zhang *et al.*	2020	Case series (n=3)	Uniport VATS	Chest tube days	Chest tube: 3–8 days
				Complications	Pleural effusion: n=1
				Symptoms	All asymptomatic at 13 months
Wu *et al.*	2013	Retrospective (n=21)	Uniport VATS (n=10)	Operative time	Time (2v1): 92.2; 82 min
			Dual port VATS (n=11)	LOS	LOS: 3; 2.85 days
				Dyspnea	Dyspnea
					• Dual: 8 improved; 3 not
					• Single: 8 improved; 3 not
Mouroux *et al.*	2005	Single center observational (n=12)	Dual port VATS	Operation time	Mean OR time: 77 min
				Drain output	Mean drain output: 0.8 L
				LOS	Mean LOS: 3.4 days
				PFTs	PFTs (pre/post/P value)
					1 year
					• FVC: 1.9 L/2.47 L/0.0001
					• FEV1: 1.4 L/1.72 L/0.0006
					5 years
					• FVC: 1.86 L/2.2 L/0.01
					• FEV1: 1.2 L/1.5 L/0.0003

Table 1 (*continued*)

Table 1 (*continued*)

Authors	Year	Design	Technique	Outcome	Findings
Freeman *et al.*	2009	Single center observational (n=41)	Three port VATS (n=30) Thoracotomy (n=11)	PFTs	PFTs (6 months/48 months/P value) • FVC: +19%/+17%/0.62 • FEV1: +23%/+21%/0.68 • FRC: 21%/+20%/0.82 • TLC: +19%/+20%/0.81
				Dyspnea (MRC)	Dyspnea (6 months/48 months/P value) • MRC: −2.0/−1.9/0.62
				LOS	Mean LOS: 3 days
				Mortality	Mortality: 0%
				Complications	Complications: pneumonia [2], a.fib [2], prolonged ileus [1], DVT [1]

VATS, video assisted thoracoscopic surgery; LOS, length of stay; ITU, intensive therapy unit; PFT, pulmonary function test; TDI, transitional dyspnea index; FEV1, forced expiratory volume in one second; FVC, forced vital capacity; DLCO, diffusion capacity for carbon monoxide; MRC, medical research council; FRC, functional residual capacity; TLC, total lung capacity; DVT, deep venous thrombosis.

a continued response to surgery with all three reporting complete symptom resolution at 6 months (31). Outcomes are often related to surgeon preference and level of expertise (32). A retrospective study assessing laparoscopic plication in 25 patients also found significant improvement in respiratory-related quality of life at 1 month and 1 year post-operatively (33). Patients from this study experienced significant decreases in dyspnea and improvements in PFTs (33). One quarter of patients did experience complications including prolonged chest tube days, pleural effusion, upper gastrointestinal (GI) hemorrhage, urinary tract infection, reintubation, stroke, and a-fib (33). One patient required conversion to open thoracotomy due to adhesive disease within the thorax. This rate of conversion to open approach is consistent with other plication techniques (33). However, median hospital stay was limited at 4 days, and chest tubes were removed at a median of 1 day (33). One year post-op, all diaphragms were lower than they initially were prior to undergoing plication (33). From the limited data and studies that exist, laparoscopic plication appears to be a safe and effective approach (*Table 2*).

Robotic assisted

Robotic approaches to plication have been postulated as a transitional procedure that may help to bridge the technical gap between open and minimally invasive plication. A modified laparoscopic approach with the Da Vinci robot, proponents argue, allows the physician to better visualize the surgical working are, and it ensures the abdominal organs are not inadvertently injured (34). Trans-diaphragm insufflation with carbon dioxide causes the lungs to "fall away" which also helps to attain a clear and more maneuverable operating field (34). However, this approach does require 4 total ports: 3 robotic and 1 assistant port (34). A case series assessing both transthoracic and transabdominal plication utilizing the robot found statistically significant improvement in spirometry values (35). There was no difference in spirometry outcomes when comparing transabdominal and transthoracic approaches (35). Mean FEV1 increased by 20% across both approaches, while FEV1/FVC did increase by 5.7%, but this was not a meaningful difference (35). There were complications in 28% of patients including pleural effusions, air leaks, paralytic ileus, and acute kidney injuries (35). This study showed that, while different in technique, robotic plication does not differ in outcomes as measured by PFT (35). When assessed by its effects on dyspnea, robotic assisted plication showed dramatic symptom improvement. Among 22 patients who underwent robot assisted transabdominal plication, 91% had an improvement in MRC score, while only 9% experienced no change (36). None of the patients experienced worsening of symptoms (36). Median hospital stay for these patients was 2 days, and their chest tubes were removed after 1 day (36). Data are limited, but robotic surgery for plication also serves as a safe option that increases pulmonary functionality, decreases dyspnea, and can be implemented

Table 2 Results summary of studies assessing laparoscopic plication

Authors	Year	Design	Technique	Outcome	Findings
Wang *et al.*	2018	Case series (n=3)	Laparoscopic	LOS	Mean LOS: 4 days
				Complications	Complications: none
				Symptoms	All asymptomatic at 6 months
Groth *et al.*	2010	Retrospective (n=25)	Laparoscopic	PFTs	PFTs (pre/1 month/1 year/P value)
					• FVC: 59.2/65.3/61/<0.05
					• FEV1: 55.4/62.5/60.9/<0.05
					• FIF-max: 93.2/113.9/111.5/P<0.05
				Dyspnea (SGRQ)	Dyspnea (pre/1 month/1 year/P value)
					SGRQ: 59.3/36.6/30.8/<0.05
				Chest tube days	Median chest tube: 1 day
				Hospital LOS	Median LOS: 4 days
				Complications	Complication rate: 25% of all patients

LOS, length of stay; PFT, pulmonary function test; SGRQ, Saint George's Respiratory Questionnaire; FVC, forced vital capacity; FEV1, forced expiratory volume in one second; FIF-max, % predicted maximum forced inspiratory flow.

with success either trans-thoracically or transabdominally (*Table 3*).

Open approaches—abdomen

Limited data or well-designed studies exist assessing open abdominal techniques. With minimally invasive approaches being the widely available standard of care, open approaches have largely fallen out of favor. A video tutorial published in 2022 displayed an open subcostal approach (37). Anecdotally, the authors suggested that this approach was as effective as an open thoracotomy (37). Furthermore, there was no need for drains when utilizing this approach (37). Although not mentioned in the study, this could theoretically decrease the likelihood of infections as well as decrease hospital stay. There are not enough recent data to formally assess the effectiveness of an open abdominal approach to diaphragmatic plication in an adult population.

Open approaches—thoracic

Open thoracotomy approaches have been described recently in the literature (*Table 4*). A recent analysis of 37 cases of video-assisted thoracotomy with a single camera port showed positive outcomes in pulmonary function (38). The mean increase in FEV1 was 13% with pre-op values 53% of expected and post-op values of 62% (38). Furthermore, post-op morbidity was low at 8.3% with no mortality, average operative time was 49 minutes, and average hospital stay was 3.1 days (38). This hybrid open procedure is both quick and effective at improving respiratory function with limited morbidity and mortality (38). A retrospective study of 17 patients showed improvements in dyspnea and PFTs following open thoracic plication (39). Patients experienced an average improvement in their dyspnea of 55% when measured on a visual, 10-point, analog scale (39). At 5–10 years of follow-up, patients were still experiencing significant symptom relief and improved PFTs (39). There was also a significant increase in the PaO_2 from 73.1 to 85.6 mmHg following the operation (39). Another institutional study assessing open thoracic plication yielded similar results with improvements in FEV1, FVC, and dyspnea (40). Three patients from this study died in hospital resulting in a 13% mortality (40). These deaths were attributed to acute myocardial infarction, pre-existing pulmonary hypertension and subsequent heart failure, and massive pulmonary embolism (40). All other patients experienced persistent resolution of symptoms at 1 year with no signs of recurrence or breakdown of the plication (40). All working age patients, save for 1, were able to return to work following plications (40). Another study assessed different methods of plication in patients undergoing open thoracotomy. Unopened, accordion plication was compared

Table 3 Results summary of studies assessing robotic assisted plication

Authors	Year	Study	Technique	Outcome	Findings
Zwischenberger *et al.*	2016	Case series (n=3)	Laparoscopic-robotic assisted	PFTs	Mean FEV1 increase: 17%
					Mean FVC increase: 17%
				LOS	LOS: 2 days
				Chest tube days	Chest tube days: 1
Bin Asaf *et al.*	2021	Retrospective (n=18)	Robotic assisted trans-abdominal (n=12)	PFTs	Mean FEV1 increase: 19.9% (P=0.002)
					Mean FEV1/FVC increase: 5.7% (P=0.225)
			Robotic assisted trans-thoracic (n=6)		PFT abdominal *vs.* thoracic: P=0.366
				Complications	Complication rate: 27.7% of all patients
Biswas *et al.*	2018	Retrospective (n=22)	Laparoscopic-robotic assisted	LOS	Median LOS: 2 days
				Chest tube days	Median tube: 1 day
				Dyspnea (MRC)	Dyspnea
					• Improved: 91%
					• No change: 9%
					MRC (pre/post): 4.0/2.0 (P<0.0001)

PFT, pulmonary function test; LOS, length of stay; FEV1, forced expiratory volume in one second; FVC, forced vital capacity; MRC, medical research council.

to opened, double breasted plication in 42 patients (41). There were no differences in operative duration, pre and post-operative spirometry, or length of hospital stay (41). The accordion group experienced less drain output (114 *vs.* 215 mL; P=0.0082), but both groups experienced improvements in dyspnea scores and spirometry (41). At 12 and 24 months, there were still no differences in FEV1 or FVC, and no difference in MRC dyspnea scores (41). The operations did differ slightly in diaphragmatic shift at 12 and 24 months. There was greater superior displacement of the diaphragm at 12 and 24 months in those who underwent open, double breasted plication (41). However, both operations are safe and durable and effective at improving symptoms as measured by perceived dyspnea and respiratory function as measured by spirometry (41).

Comparative studies

VATS and minimally invasive robotic assisted surgery have recently been assessed in a single center prospective study (*Table 5*). Both interventions utilize carbon dioxide insufflation; VATS implements 3 port sites. The robotic approach utilized 3 plus an assistant port (3). Forty-eight patients underwent 49 procedures. Differences in outcomes were not stratified by operative approach (3). The most common complication was pleural effusion experienced by 12.5% of patients. The mean reduction in MRC dyspnea score was 2.2 (3). Initial mean MRC score was 3.8 and post-operatively this decreased to 1.8 (P<0.05) (3). Ninety-seven percent of patients reported satisfaction with outcomes, and reported an overall dramatic improvement in quality of life (3). Minimally invasive approaches were therefore shown to be low-risk operations that can drastically improve patient well-being (3).

A review from 2016 found that transabdominal approaches are associated with lower pain scores when compared to thoracic approaches; this is possibly due to the lack of intercostal incisions made in transthoracic interventions (4). Another study assessed differences in outcomes between robotic assisted thoracoscopic plication and open transthoracic approaches (42). Robotic assisted thoracoscopic operations had shorter operative time (80 *vs.* 120 minutes; P=0.04), fewer days with chest tubes (1 *vs.* 3 days; P=0.01), less intraoperative blood loss (20 *vs.* 100 mL; P=0.01), and shorter hospital stay (3 *vs.* 7 days; P=0.04) (42). Each group showed the same improvement in MRC dyspnea scores (42). While both approaches yield improvement in dyspnea and respiratory function,

Table 4 Results summary of studies assessing open thoracic plication

Authors	Year	Study	Technique	Outcome	Findings
Yalcinkaya *et al.*	2017	Retrospective (n=37)	Open thoracic	Operative time	Mean operation: 48.8 min
				Morbidity	Morbidity: 8.3%
				LOS	Mean LOS: 3.1 days
				PFTs	Mean increase FEV1: 13% (P<0.001)
Evman *et al.*	2016	Retrospective (n=42)	Open thoracic (n=23) "accordion" plication, (n=19) "double-breasted" plication	Operative time, PFTs, LOS	No difference: time, PFTs, LOS
				Post-op drainage	Accordion *vs.* double-breasted plication: drainage 14 *vs.* 215 mL (P=0.0082)
Graham *et al.*	1990	Retrospective (n=17)	Open thoracic	PFTs	PFTs [liters] (pre/post/P value)
					• FVC (sitting): 2.7/3.2/<0.001
					• TLC (sitting): 4.1/4.5/<0.002
					• FRC: 2.5/2.9/<0.001
					• ERV: 0.6/0.9/<0.01
					• DLCO [%predicted]: 85/100/<0.05
				Dyspnea (visual scale 0–10)	Dyspnea (pre/post/P value) 7.4/3.3/<0.001
				PaO_2	PaO_2 (pre/post/P value) 73.1/85.6/<0.001
Versteegh *et al.*	2007	Single center observational (n=22)	Open thoracic	Dyspnea (TDI)	Dyspnea [mean TDI: −9 to +9]
					+5.69 improvement
				PFTs	PFTs [mean % predicted] (pre/post/P value)
					• FVC upright: 70/79/<0.03
					• FVC supine: 54/73/0.03
					• FEV1 upright: 64/71/<0.05
					• FEV1 supine: 45/63/<0.02
				Mortality	Mortality: 3 in hospital deaths (13.6%)
				LOS	Mean LOS: 5.5 days

LOS, length of stay; PFT, pulmonary function test; FEV1, forced vital capacity in one second; FVC, forced vital capacity; TLC, total lung capacity; FRC, functional residual capacity; ERV, expiratory reserve volume; DLCO, diffusion capacity for carbon monoxide; PaO_2, arterial oxygen tension; TDI, Transition dyspnea index.

minimally invasive robotic approaches have less healthcare utilization overall.

Another factor for consideration is healthcare costs. Although newer surgical techniques may improve patient outcomes, the overall cost of implementing these new approaches should be assessed. In thoracic surgery, the advent of VATS and robotic surgery has changed the way some procedures are performed. In a single institution study assessing the cost of different surgical approaches in lobectomy, implementation of robotic technology increased procedure price $3,880 above VATS alone (43). The disposable cost alone for robotic utilization in thoracic surgery can exceed $1,200 (44). Other factors contribute to the increased cost of robotic technology. Operative delays, equipment failures, and OR staff being unfamiliar with equipment all contribute to increased cost (45). This can represent as much as 10.6% of the overall cost of the case (45).

There have also been studies comparing phrenic nerve reconstruction to plication. In both instances, phrenic nerve reconstruction showed improvement in reported breathing and respiratory function (46,47). However, diaphragmatic plication remains the gold standard surgical intervention for

Table 5 Results summary of comparative studies assessing varying plication approaches

Authors	Year	Design	Technique	Outcomes	Findings
Nardini *et al.*	2021	Single center prospective (n=49)	Robotic (n=14)	Complications LOS	Pleural effusion: n=6
			VATS (n=35)		Tracheostomy: n=1
					Mean LOS: 5.9 days (range, 2–34)
				Drain removal	Median drain removal: 3 (range, 1–22)
				Post-op pain	Mean post-op pain score: 3.6/10
				MRC dyspnea	Mean MRC reduction: 2.2 (P<0.05)
Podgaetz *et al.*	2016	Review	Open thoracic	PFTs	Open thoracic
			VATS	Dyspnea	• FVC increase: 19–42%
			Robotic VATS	Pain	• Improved dyspnea
			Transabdominal		• Improved PFTs
			Laparoscopic		• Chronic post-op pain
					VATS/robotic VATS
					• FVC increase: 19%
					• FEV1 increase: 23%
					• FRC increase: 21%
					• TLC increase: 20%
					• Improved dyspnea
					Laparoscopic
					• Mean reduction in SGRQ >20 points
Lampridis *et al.*	2022	Retrospective study (n=20)	Robotic VATS (n=11); open thoracic (n=9)	Operative time	• Time: 80; 120 min (P=0.04)
				Chest tube days	• Chest tube: 1; 3 days (P=0.01)
				Blood loss	• Blood loss: 20; 100 mL (P=0.01)
				LOS	• LOS: 3; 7 days (P=0.04)
				MRC dyspnea	• MRC: no difference

VATS, video assisted thoracoscopic surgery; LOS, length of stay; MRC, medical research council; PFT, pulmonary function test; FVC, forced vital capacity; FEV1, forced expiratory volume in one second; FRC, functional residual capacity; TLC, total lung capacity; SGRQ, St. George's Respiratory Questionnaire.

the treatment of hemi-diaphragmatic paralysis; although, other methods, such as phrenic nerve reconstruction, have been shown to be effective at improving outcomes in carefully selected patients.

Conclusions

Plication is the definitive surgical intervention for diaphragmatic paralysis and eventration. It is a relatively low risk procedure that can be performed with much success. Symptomatic patients with diaphragm paralysis, who have failed other conservative measures, should be offered plication. It is effective at reducing dyspnea and improving symptoms.

Various surgical techniques can be used to achieve therapeutic diaphragm plication. Here we have discussed the outcomes associated with each of the major surgical approaches to plication: VATS, laparoscopic, robotic, open abdominal, and open thoracic. With the exception of open abdominal approaches, there are data to recommend each surgical technique. All techniques are associated with symptom improvement, lung functionality, as well as limited morbidity and mortality. Minimally invasive approaches have become readily accessible, and they are safe and effective alternatives to open approaches.

Cost should also be considered when determining which technique to utilize. Robotic thoracic surgery is significantly more expensive than other non-robotic approaches, but the safety and decreased technical difficulty of this approach may make it more desirable for surgeons. Surgeon preference therefore plays a large role in selection of technique.

Additionally, the implemented technique should be one in which the surgeon is familiar with and has a certain level of expertise. This would appear to be one of the main determinants of positive patient outcomes.

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Footnote

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