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Efficacy of 3D Laparoscopy in Thoraco-Laparoscopic Esophagectomy for Caustic Esophageal Strictures

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Abstract: Ingesting caustic substances can cause severe esophageal strictures, particularly in young adults. Thoraco-laparoscopic esophagectomy (TLE) is a minimally invasive surgical treatment for complex strictures when conservative methods fail. However, dense fibrosis and altered anatomy pose challenges for conventional laparoscopic surgical systems. This prospective comparative study evaluated the effectiveness of three-dimensional (3D) laparoscopic visualization in TLE for post-burn esophageal strictures. Twenty-eight patients aged 18–40 years with caustic-induced strictures were divided into two groups: Full High-Definition (HD) laparoscopy (n = 14) and 3D laparoscopy (n = 14). Intraoperative and postoperative outcomes were compared between the two groups. The 3D group had significantly shorter operative times (200 ± 10 min vs. 230 ± 20 min; $p < 0.05$), reduced blood loss (40 ± 8 ml vs. 60 ± 10 ml; $p < 0.05$), and lower anastomotic failure rates (7.1% vs. 21.4%; $p < 0.05$) than the Full HD group. Postoperative complications and hospital stay were lower in the 3D group, although the difference was not statistically significant. Surgeon feedback indicated better depth perception and precision with 3D systems. Macroscopic examination of the resected specimens confirmed severe fibrotic strictures, whereas postoperative imaging showed patent anastomoses. The results suggest that 3D laparoscopy enhances surgical efficiency and safety in TLE for post-caustic strictures by improving visualization of the fibrotic planes. Incorporating 3D systems into surgical practice and training can potentially improve outcomes and expand minimally invasive techniques for complex esophageal surgeries, particularly in resource-limited settings.

Keywords: Caustic Injuries; Esophageal Injuries; Esophageal Strictures; Endoscopic Dilation; Thoraco-Laparoscopic Esophagectomy; Post-Burn Strictures

1. Introduction

Ingesting caustic agents can lead to severe esophageal injuries, especially in young adults, and requires swift medical intervention. Such ingestion can cause injuries ranging from minor erosions to severe necrosis and perforation of the esophagus and stomach. The severity of these injuries depends on the type and concentration of the ingested substance, quantity consumed, and duration of tissue exposure [1,2].

Managing caustic injuries begins with a swift evaluation of the extent of tissue damage through esophagogastroduodenoscopy within 24 hours of ingestion. This procedure is essential for classifying injuries, forecasting complications, and informing treatment choices [3]. In young adults, ingestion occurs due to accidental exposure or self-harm. In cases of self-harm, injuries tend to be more severe due to the intentional nature and larger quantity of substances ingested [4].

Clinical management is determined by the severity of the injury. Grade I injuries typically resolve independently and may require only symptomatic treatment. Grade II injuries can be managed conservatively but require observation for potential complications, such as strictures. Grade III injuries almost always require surgical intervention, either immediately or later, to address perforations or necrosis [2,5].

The management of complex injuries requires a multidisciplinary approach. This approach involves the stabilization of life-threatening conditions and surgical planning. Follow-up care manages complications such as esophageal strictures or cancer [1,6]. Models predicting outcomes from symptoms such as vomiting and stridor can indicate esophageal damage, although their reliability is limited and requires diagnostics [7].

Ingesting caustic substances causes severe esophageal injuries, mainly among young adults, through self-harm. These injuries occur more frequently in low- and middle-income nations, where cleaning agents are less regulated. The esophagus is vulnerable because of its fragile mucosal lining [8–10].

The treatment of esophageal strictures caused by caustic substances presents significant challenges. The primary approach involves endoscopic dilation using a balloon or bougie dilator. However, for many patients, particularly those with long, winding, or multiple strictures, repeated endoscopic dilation fails to maintain open lumens or results in complications, such as perforation [9,10]. Therefore, alternative treatment methods are required. Surgical reconstruction, such as esophageal replacement with colonic interposition, is an established treatment for severe strictures; however, it involves morbidity risks and requires careful patient selection [11]. Furthermore, new endoscopic techniques, such as electrocautery incisional therapy (EIT) and biodegradable stents, are emerging as alternatives to surgery, potentially reducing the need for esophagectomy in both pediatric and adult cases [10,12,13].

The effectiveness of corticosteroids in preventing strictures after caustic ingestion remains a matter of controversy. Research suggests that high-dose corticosteroids might reduce stricture risk in specific injury grades [14,15].

Thoraco-laparoscopic esophagectomy (TLE) is a definitive surgical solution for severe post-burn esophageal strictures when conservative treatments, such as endoscopic dilation or stenting, fail to maintain luminal openness. This minimally invasive procedure, which integrates thoracoscopic and laparoscopic methods, allows for the removal of the fibrotic esophageal section and reconstruction using gastric or colonic conduits. Clinical data from benign esophageal conditions and cancer show that thoraco-laparoscopic esophagectomy delivers favorable results with less postoperative pain, shorter hospitalization, and reduced pulmonary complications compared to open esophagectomy, improving perioperative morbidity and recovery outcomes [9,16–18].

Thoracoscopic visualization offers high-definition magnification but is limited by two-dimensional imaging and restricted depth perception, challenges intensified by confined operative spaces in the thoracic and upper abdominal areas. Compared to open surgery, limited instrument maneuverability makes precise dissections and complex reconstructive tasks more difficult, such as forming tension-free, well-vascularized anastomosis safely [19–21]. These difficulties often result in longer operative times and steeper learning curves, with increased risks of intraoperative complications, such as hemorrhage, conduit ischemia, and anastomotic failure, especially in less experienced centers [17,22].

Intraoperative adjuncts, such as three-dimensional thoracoscopic systems and indocyanine green (ICG) fluorescence imaging, improve the visualization of tissue planes and evaluation of conduit perfusion. While these technologies enhance surgical accuracy, they do not fully address the challenges of dense fibrosis and tissue adhesion [19,21]. Hybrid techniques integrating minimally invasive abdominal procedures with limited thoracotomy have been explored, showing reduced pulmonary complications and similar oncological effectiveness. Although direct evidence of benign strictures is limited, these approaches may offer solutions for managing complexity [23].

Despite progress in minimally invasive surgery, the optimal treatment for benign esophageal strictures due to burns remains unclear. TLE is the main surgical option when endoscopic dilation fails; however, Full High-Definition (HD) two-dimensional (2D) laparoscopy has poor depth perception. These limitations affect dense fibrotic mediastinal areas, requiring precise dissection [24,25]. Although robotic surgery provides 3D visualization, its cost limits its widespread use, particularly in low-income countries. Thus, alternatives such as 3D laparoscopy

require evaluation. Three-dimensional (3D) laparoscopy overcomes the limitations of 2D imaging by providing binocular vision and restoring depth perception and spatial awareness for precise dissection and safer handling of fibrotic adhesions [24,26]. In post-caustic esophageal strictures, where fibrosis disrupts tissue planes, these advantages may enhance safety [27]. Despite evidence supporting the use of 3D laparoscopy in oncological surgeries, its use in benign post-burn esophageal surgery remains unexplored.

Meta-analyses suggest that 3D laparoscopy reduces surgery time and is favored over 2D systems in gastrointestinal operations [28]. In colorectal surgeries, particularly rectal cancer removal, 3D laparoscopy has been shown to decrease surgery time, blood loss, and hospital stay [29]. Similar outcomes have been observed in right hemicolectomy, with faster anastomosis times and shorter surgery duration [30]. These findings support the notion that enhanced depth perception and spatial awareness from 3D systems may offer advantages in complex benign esophageal surgeries.

In esophageal surgery, 3D visualization benefits become more pronounced. Thoracoscopic and laparoscopic esophagectomy involve working within confined mediastinal spaces altered by fibrosis and scarring from caustic injury, which challenges 2D imaging for safe dissection and reconstruction. The depth perception of 3D laparoscopy allows a clearer distinction between the esophagus and mediastinal structures, improving precise dissection and anastomosis.

While several studies in simulated environments and laparoscopic procedures have shown that 3D laparoscopy improves task performance, reduces operative time, and enhances depth perception compared to Full HD 2D systems, these data are mainly derived from generalized laparoscopy or cancer surgery and lack critical appraisal within post-burn esophageal surgery [24,25,31].

When endoscopic treatments fail or are unsuitable owing to complex stricture shapes, surgery becomes necessary. TLE, a minimally invasive procedure, has become feasible for esophageal reconstruction in these cases. However, dense fibrosis and obliterated anatomical planes from chemical burns present unique challenges for minimally invasive surgery. The adoption of 3D laparoscopy provides better spatial awareness and depth perception, potentially enhancing the safety of esophagectomy. Nevertheless, its use in benign post-burn strictures remains under-researched, despite its increasing application in cancer-related esophageal surgeries.

This study assessed the practicality, technical difficulties, and perioperative outcomes of 3D TLE in patients with severe esophageal strictures due to caustic ingestion. It also aimed to determine whether 3D visualization provides benefits over traditional methods in this complex non-cancerous context.

2. Methods

A prospective comparative study was conducted at the Department of Thoracic and Abdominal Surgery, National Center of Oncology and Hematology, Bishkek, Kyrgyzstan, between January 2022 and March 2024. This study compared 3D laparoscopic visualization with conventional Full HD systems during thoraco-laparoscopic esophagectomy for cicatricial esophageal strictures caused by caustic ingestion.

Twenty-eight individuals aged 18–40 with post-burn cicatricial esophageal strictures participated in the study. Patients were divided into two groups based on the imaging techniques used during surgery: Group 1 (n = 14) underwent TLE using Full HD laparoscopy, while Group 2 (n = 14) underwent the procedure using stereoscopic 3D laparoscopy.

The inclusion criteria were as follows: (1) age 18–40 years, (2) esophageal stricture exceeding 3 cm in length verified by imaging or endoscopy, (3) unsuccessful outcomes from at least three endoscopic bougienage sessions, and (4) no malignancy. Participants were scheduled for surgery six months post-injury to allow fibrotic phase stabilization. Patients with active inflammation, infection, or contraindications for general anesthesia were excluded.

Patient history identified the causative substances. Among the 28 patients, 18 (64.3%) consumed vinegar essence and 10 (35.7%) ingested alkaline cleaning products. The presence and severity of stricture were verified using endoscopic procedures and radiological contrast imaging.

All surgeries were performed under general anesthesia with single-lumen intubation. The operation consisted of both thoracoscopic and laparoscopic phases. Thoracoscopic Phase: Performed in the right lateral decubitus position with carbon dioxide insufflation at 7 mmHg. The thoracic esophagus was freed using Full HD or 3D visualization systems based on the group assignment. Laparoscopic phase: The procedure was performed in the supine position with pneumoperitoneum at 12–14 mmHg. The stomach was mobilized and prepared for a gastric pull-up, followed

by cervical esophagogastrostomy in all patients. Standardized procedures were followed, including the identification and preservation of vital structures, meticulous dissection in areas with dense fibrosis, and intraoperative hemostasis. No robotic systems were used in this study.

Participants were divided into two equal groups by visualization type: Group 1 (n = 14) underwent TLE with Full HD laparoscopic systems, while Group 2 (n = 14) underwent the procedure using stereoscopic 3D laparoscopic systems. The same surgical team, all skilled in minimally invasive esophageal surgery, performed the operations.

The study compared intraoperative and postoperative factors, including surgery duration (in minutes), blood loss volume (in milliliters), anastomotic failure rate, and postoperative complications categorized using the Clavien–Dindo classification system (grade II or above). Anastomotic integrity was evaluated using a contrast esophagogram nine days after surgery. Complications were recorded during the hospital stay. Postoperative follow-up included a hospital stay, 30-day check-up, and 3-month outpatient visit to assess anastomotic integrity, complications, and functional recovery.

Statistical methods were used to analyze the data. Quantitative variables, including operative time and blood loss, were presented as mean ± standard deviation and assessed using Student's t-test. Categorical variables, such as complication rates and anastomotic failure, were evaluated using the chi-square test. A p-value < 0.05 was considered significant.

3. Results

Twenty-eight patients aged 18–40 years (mean age 24.6 ± 3.9 years) with cicatricial esophageal strictures were included in the study (**Table 1**). The patients were divided into two groups: Group 1 underwent Full HD laparoscopy (n = 14), while Group 2 underwent 3D laparoscopy (n = 14). The mean ages were similar between the groups (24.4 ± 4.1 vs. 24.8 ± 3.7 years, $p > 0.05$). Of all patients, 18 (64.3%) had injuries from acetic acid ingestion, and 10 (35.7%) had injuries from alkaline substance ingestion. Surgeries were performed six months post-injury to allow for fibrotic healing stabilization. The causes of injury were evenly distributed between the groups, with no significant differences in type or timing.

Table 1. Comparative results of TLE in full HD and 3D groups.

	Parameters	Full HD Group	3D Group	*p*-Value
1.	Mean age (years)	24.4 ± 4.1	24.8 ± 3.7	> 0.05
2.	Operation duration (min)	230 ± 20	200 ± 10	< 0.05
3.	Blood loss (ml)	60 ± 10	40 ± 8	< 0.05
4.	Anastomotic failure	3 (21.4%)	1 (7.1%)	< 0.05
5.	Postoperative complications (Clavien ≥ II)	2 (14.3%)	1 (7.1%)	> 0.05
6.	Duration of hospitalization (days)	10.1 ± 1.5	9.2 ± 1.2	> 0.05

Note: Data presented as Mean ± Standard Deviation; HD = Full High-Definition laparoscopy, 3D = three-dimensional laparoscopy; A p-value < 0.05 was considered significant.

The 3D group showed a notable decrease in the surgery duration. The surgery time for the Full HD group was 230 ± 20 min, while the 3D group completed surgeries in 200 ± 10 min ($p < 0.05$). This 13% reduction in operative time reflects the efficiency gained through enhanced spatial orientation and depth perception. Intraoperative blood loss was significantly lower in the 3D laparoscopy group, averaging 40 ± 8 mL, than in the Full HD group (60 ± 10 mL; $p < 0.05$) (**Table 1**). This 33% decrease in bleeding indicates that 3D visualization enables safer dissection in dense fibrotic tissue typical of post-burn esophageal strictures.

In the 3D group, anastomotic failure was lower, with 1 patient (7.1%) affected, compared to 3 patients (21.4%) in the Full HD group ($p < 0.05$). This disparity might be due to improved depth perception and hand-eye coordination when performing cervical esophagogastrostomies, which are technically demanding in scarred tissue. Although not statistically significant, the 3D group experienced fewer postoperative complications. Complications of grade II or higher occurred in 2 patients (14.3%) in the Full HD group, whereas 1 patient (7.1%) in the 3D group experienced such issues ($p > 0.05$). This suggests the potential advantage of 3D visualization in reducing complications that require intervention.

Patients who underwent 3D laparoscopy had a shorter average hospital stay of 9.2 ± 1.2 days versus 10.1 ± 1.5 days in the Full HD group. Although not statistically significant ($p > 0.05$), this suggests better perioperative

recovery and fewer minor complications in the 3D group. Although not directly quantified, surgeon feedback indicated enhanced comfort and precision with 3D visualization. Surgeons noted improved clarity of the fibrotic planes and safer dissection near critical structures, such as the aorta and trachea, where dense adhesions were common. These observations align with the reduced surgical time and blood loss.

All patients underwent complete mobilization of the thoracic esophagus and cervical esophagogastric anastomosis. In the Full HD group, 4 cases of challenging anatomical boundary identification resulted in extended dissection time and increased hemostasis. The 3D group experienced more assured resections, corresponding to reduced blood loss and shorter operation times. These findings support the effectiveness of 3D laparoscopy in enhancing critical intraoperative metrics during complex esophageal surgeries. Statistically significant decreases in operation time ($p < 0.05$), intraoperative blood loss ($p < 0.05$), and anastomotic leakage ($p < 0.05$) were observed, highlighting the improved visual guidance in achieving safer and more efficient outcomes in post-burn cicatricial stricture. Although the sample size limits the detection of differences in complications and hospital stay, trends indicate a favorable clinical trajectory with 3D systems.

Figure 1A illustrates a longitudinal section of the excised esophagus from a patient with a cicatricial stricture resulting from burns. The image revealed dense fibrotic constriction, with the lumen almost entirely closed, indicating severe stricture due to corrosive damage. **Figure 1B** shows the specimen, highlighting the length of the esophageal damage. Thickened walls and a stiff tubular shape are typical of remodeling in response to chronic chemical injury. These images show the pathological severity and validate the need for an esophagectomy.

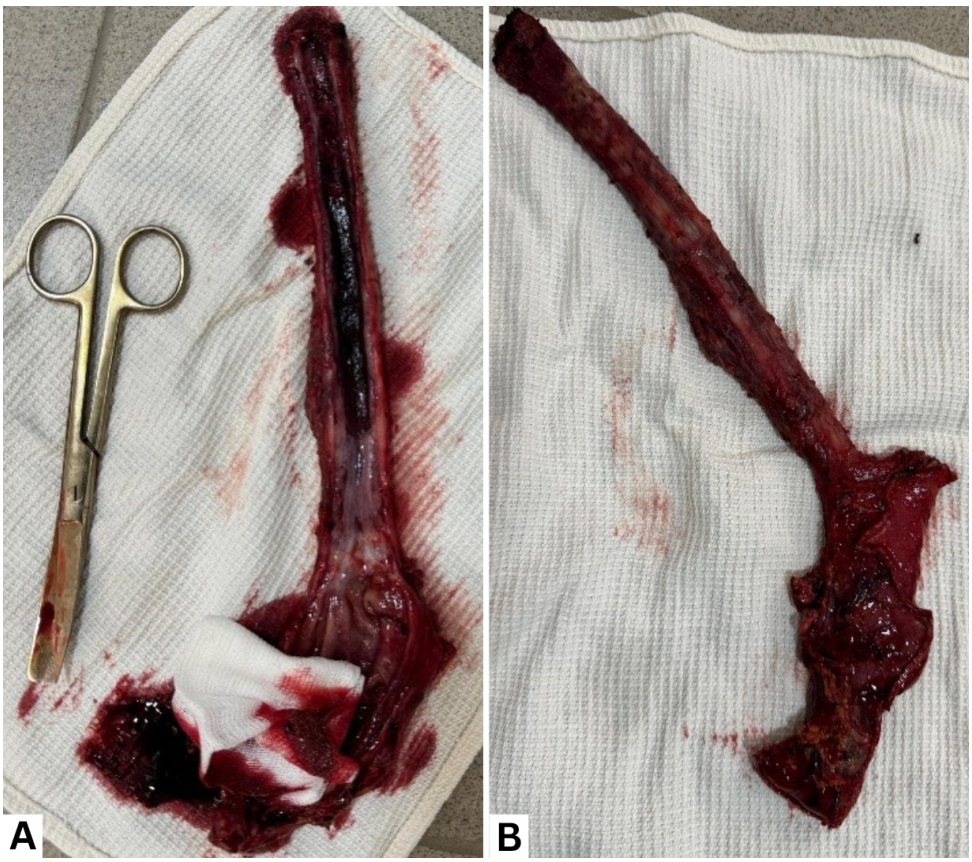

Figure 1. Macroscopic and sectional view of the resected esophagus in a case of postburn cicatricial stricture.

Figure 2 illustrates the X-ray conducted on the ninth day after surgery. The image shows the contrast flowing freely through the cervical esophagogastric anastomosis into the gastric conduit, with no leakage, narrowing, or pooling outside the lumen. The anastomosis was open and properly aligned, suggesting successful surgery. This radiographic assessment verifies anastomotic integrity before starting oral intake.

Figure 2. X-ray on the ninth day after surgery showing a patent esophagogastric anastomosis.

Incorporating stereoscopic 3D laparoscopy into TLE for caustic-induced strictures has shown intraoperative benefits without complications. The decrease in surgery time, blood loss, and anastomotic failure rates in the 3D group indicates that improved depth perception enables safer and more efficient procedures. While long-term data on stricture recurrence and functional outcomes are necessary, the current results support the use of 3D systems in benign esophageal surgeries with dense fibrosis. This study highlights the advantages of 3D visualization in low- and middle-income countries where robotic surgery is not readily available.

Preoperative contrast-enhanced esophagography revealed a constricted esophageal lumen with irregular edges and dilation above the narrowing, suggesting cicatricial strictures from caustic damage. The contrast material sometimes halted at the blockage and failed to enter the stomach. On the ninth postoperative day, imaging demonstrated smooth passage through the cervical esophagogastric anastomosis into the gastric conduit, with no leakage, narrowing, or pooling. This radiographic progress correlated with dysphagia relief and restored luminal continuity after thoracoscopic-laparoscopic esophagectomy. At the 3-month follow-up, imaging and clinical evaluations confirmed that the anastomosis remained patent without stricture recurrence and continued to show improvement in swallowing, indicating successful surgical reconstruction.

4. Discussion

The treatment of severe esophageal strictures after burns poses a surgical challenge, especially in the presence of extensive fibrosis and altered mediastinal structures. This prospective comparative study found that 3D TLE led to better perioperative results than conventional Full HD 2D systems, with shorter surgery times, less blood loss, and fewer anastomotic complications. These results align with those of studies emphasizing the benefits of

advanced visualization in complex gastrointestinal surgeries [32,33].

The shorter operative time in the 3D group (200 ± 10 min vs. 230 ± 20 min; $p < 0.05$) highlights the effectiveness of stereoscopic depth perception. Earlier studies have shown that 3D systems enhance task performance by improving depth cues and spatial orientation, particularly in fibrotic areas that require meticulous dissection and precise suturing [34,35]. These benefits are pronounced in caustic strictures, where obliterated anatomical planes and dense adhesions obscure vital structures such as the aorta, trachea, and pericardium [36,37].

The decrease in blood loss during surgery (40 ± 8 ml in the 3D group compared to 60 ± 10 ml in the 2D group; $p < 0.05$) aligns with research showing that enhanced visualization improves vascular control and minimizes damage to fibrotic vessels and attached tissues [38]. In difficult mediastinal dissections, improved visualization can reduce trauma and bleeding complications [39].

In the 3D group, anastomotic integrity was better maintained, with 7.1% leakage versus 21.4% in the Full HD group ($p < 0.05$). This indicates enhanced surgical accuracy during cervical esophagogastrostomy, a challenging procedure complicated by scarred and thickened tissue in cases of caustic strictures. Depth perception facilitates precise alignment of the conduit and esophagus, preventing tension or inadequate blood supply, which could lead to leakage [40]. These findings align with those of previous studies on minimally invasive colorectal and upper gastrointestinal surgeries, where 3D laparoscopy has shown better anastomotic outcomes [41].

Although the difference in postoperative complications (Clavien–Dindo grade ≥ II) was not statistically significant, the 3D group had fewer adverse events (7.1% vs. 14.3%), suggesting a clinical advantage. This pattern appears in studies comparing 3D and 2D laparoscopy in hepatobiliary and gynecological surgeries, where 3D imaging enables safer navigation in areas with scarring or anatomical changes [42].

These results align with previous research, which has shown that 3D laparoscopy offers greater operative efficiency than 2D laparoscopy in complex gastrointestinal surgeries [28,29]. In a meta-analysis, Amiri et al. [28] found that 3D visualization decreased operative time by 8% and was favored by 87% of the surgeons. Similarly, Zhan et al. [29] reported improvements in operative time, blood loss, and postoperative hospital stay in patients undergoing colorectal surgery with 3D systems. Portale et al. [30] noted reduced anastomosis times and better operative efficiency in right hemicolectomy. Furthermore, new technologies, such as autostereoscopic 3D systems, have shown surgical outcomes comparable to traditional glasses-based 3D platforms [43], suggesting ergonomic benefits.

The hospital stay duration was shorter for the 3D group (mean 9.2 ± 1.2 days versus 10.1 ± 1.5 days), possibly due to less surgical trauma and faster recovery; however, this difference was not statistically significant ($p > 0.05$). This aligns with multicenter studies indicating improved recovery in patients undergoing complex minimally invasive procedures using 3D systems [44].

Surgeons' feedback in this study reported that 3D systems provided better ergonomics and spatial awareness and reduced mental exhaustion. Enhanced visualization enabled safer resections in fibrotic areas and clearer identification of tissue planes. These findings align with simulation-based research showing that 3D laparoscopy reduces cognitive load and enhances performance across skill levels [45,46].

These findings must be considered in light of the current evidence limitations. Research on 3D laparoscopy has primarily focused on oncologic resections or intra-abdominal surgeries, with van Boeckel et al. [36] study addressing the anatomical and technical challenges of caustic-induced esophageal strictures. This highlights the innovation of the current study, which provides practical data on 3D-assisted esophagectomy in benign but anatomically challenging surgical settings.

Although robot-assisted esophagectomy offers improved articulation and 3D visualization, it remains unaffordable in many low-income areas, especially for non-cancerous conditions [47]. 3D laparoscopy is a more affordable alternative, offering visualization advantages without the high costs associated with robotic systems. This is crucial in Central and South Asia, where caustic injuries are common owing to inadequate chemical regulation and high self-harm rates among young adults [48]. 3D laparoscopic systems in TLE for post-caustic cicatricial strictures offer significant intraoperative and short-term postoperative benefits, including increased surgical efficiency, decreased blood loss, and improved anastomotic safety, particularly in patients with complex mediastinal fibrosis. 3D laparoscopy represents a notable advancement in minimally invasive surgery for complex benign esophageal conditions.

This study offers insights into the limited literature on 3D laparoscopic systems for treating benign, complex

esophageal conditions. The findings show that 3D visualization enhances surgical accuracy and safety, particularly in areas with scarring and anatomical distortion due to caustic injury.

5. Limitations

- In this study, the sample size (n = 28) limited the statistical power and generalizability of the results. Although improvements were observed in operative time, blood loss, and anastomotic failure with 3D laparoscopy, a larger group would provide more reliable data to confirm the findings and enable subgroup analyses (e.g., based on stricture severity or surgeon experience).
- This study was conducted at a single center with a specialized surgical team, which may not represent the outcomes in general surgical settings. The procedures were performed by surgeons skilled in minimally invasive esophageal surgery, which may have enhanced the benefits observed with 3D visualization.
- Long-term functional outcomes were not assessed. While the study focused on short-term perioperative metrics such as surgical duration, blood loss, and complications, data on long-term swallowing function, quality of life, nutritional status, and stricture recurrence are crucial for evaluating 3D TLE's clinical usefulness.
- Although surgeon feedback favored 3D systems, subjective aspects of ergonomic comfort and depth perception were not measured using validated tools, such as the NASA-TLX or SMEQ, which could have enhanced the analysis of operator experience.
- Technological and cost factors have not been thoroughly investigated. While 3D laparoscopy offers benefits over Full HD systems, its availability and cost-effectiveness, especially in low-resource settings, remain obstacles. A cost-benefit analysis would help determine whether improved metrics result in meaningful healthcare savings or better patient outcomes.

6. Clinical Implications

- This study has significant clinical implications for the surgical treatment of complex esophageal strictures caused by caustic ingestion, especially in settings where robotic surgery is unavailable. The improvements in operative duration, decreased blood loss, and reduced anastomotic failure rates in the 3D laparoscopy group demonstrate the advantages of enhanced spatial visualization when dealing with dense fibrosis and altered anatomical planes characteristic of caustic injuries.
- For surgeons in low- and middle-income countries, 3D laparoscopy offers a practical alternative to robotic systems, enhancing the accuracy of minimally invasive esophagectomy. This approach enables safe navigation of fibrotic mediastinal structures, minimizes surgical trauma, and preserves anastomotic integrity, potentially leading to better patient outcomes and fewer postoperative complications.
- These advantages could reduce the learning curve for novice surgeons, improve ergonomics, and lower the cognitive burden during prolonged, intricate operations. Implementing 3D systems in facilities treating benign esophageal conditions may standardize care and enhance surgical results for patients with post-burn cicatricial strictures.
- Incorporating 3D laparoscopy into thoraco-laparoscopic protocols could broaden the surgical indications for minimally invasive techniques in the treatment of benign esophageal conditions. This approach may promote earlier intervention when endoscopic methods fail, thereby decreasing the need for invasive open surgeries. These findings advocate for revising surgical training programs and equipment policies to integrate 3D systems into the modern esophageal surgery infrastructure.

7. Conclusion

This study demonstrates that stereoscopic 3D laparoscopy provides significant advantages over traditional Full HD 2D systems in treating TLE for cicatricial esophageal strictures resulting from caustic ingestion. The improved depth perception and spatial awareness of 3D imaging led to shorter surgery times, decreased blood loss, and reduced anastomotic failure rates in operations complicated by dense fibrosis and altered mediastinal anatomy. Despite the limitations of the small sample size and single-center design, the results indicate that 3D laparoscopy can enhance the safety and effectiveness of minimally invasive esophageal reconstruction in benign post-burn scenarios. This technology provides a practical, cost-efficient alternative to robotic surgery, especially in low- and

middle-income countries, where such injuries are prevalent and advanced resources are scarce. Integrating 3D visualization into surgical practice and training programs can improve outcomes, minimize complications, and promote the broader adoption of minimally invasive techniques in complex esophageal surgeries. Additional multicenter studies with long-term follow-up are needed to confirm these findings and broaden the evidence for 3D laparoscopy in non-malignant esophageal conditions.

8. Recommendations

Based on this prospective comparative study, several recommendations can be proposed to improve surgical results and enhance the management of post-caustic cicatricial esophageal strictures:

- For surgeons dealing with dense fibrotic strictures after caustic ingestion, 3D laparoscopic systems are advisable. The enhanced depth perception and spatial awareness from stereoscopic imaging decrease the surgery duration, blood loss, and anastomotic failure rates.
- Incorporating 3D laparoscopy into surgical training programs, particularly for thoracic and gastrointestinal surgery, is essential. This integration will reduce the time required for young surgeons to master skills, boost technical confidence, and ensure safer handling of fibrotic and complex surgical areas.
- Given the difficulties associated with cicatricial esophageal strictures, standardized surgical protocols utilizing advanced visualization techniques, such as 3D laparoscopy, are essential. These protocols should focus on safe mediastinal dissections and precise anastomotic techniques.
- Owing to its affordability compared to robotic systems, 3D laparoscopy should be prioritized in procurement strategies in low- and middle-income countries where caustic injuries are common. Investing in 3D platforms allows institutions to enhance care quality without the substantial costs associated with robotic infrastructure.
- Future studies should prioritize multicenter studies evaluating long-term results, including stricture recurrence, nutritional health, quality of life, and the cost-effectiveness of 3D-assisted TLE. This information will provide thorough evidence for shaping policies and clinical guidelines.
- Addressing esophageal injuries caused by caustic substances requires the involvement of surgeons, gastroenterologists, nutritionists, and psychologists, especially in cases of self-inflicted harm. Multidisciplinary care models are essential for managing both the surgical and psychological aspects of caustic injury treatment.

Author Contributions

Conceptualization, B.T. and R.O.; methodology, N.K.; software, T.B.; validation, A.K.; formal analysis, A.S.; investigation, B.T., R.O., and N.K.; data curation, T.B.; writing—original draft preparation, A.K., A.S., and Y.V.; writing—review and editing, Y.V. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki, and it was approved by the Bioethics Committee of the I.K. Akhunbaev Kyrgyz State Medical Academy (Protocol No. 24, dated February 20, 2025).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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