European Journal of Cardio-Thoracic Surgery 2025, 67(3), ezaf026
https://doi.org/10.1093/ejcts/ezaf026 Advance Access publication 6 February 2025

**ORIGINAL ARTICLE**



Cite this article as: Cho JM, Carpenter SL, Mathew F, Heidel JS, Kent M, Gangadharan SP *et al.* The first comparative analysis of open and robotic tracheobronchoplasty for excessive central airway collapse[†]. Eur J Cardiothorac Surg 2025; doi:10.1093/ejcts/ezaf026.

# The first comparative analysis of open and robotic tracheobronchoplasty for excessive central airway collapse[†]

**Jae M. Cho, Sandra L. Carpenter, Fleming Mathew, Justin S. Heidel, Michael Kent, Sidhu P. Gangadharan and Jennifer L. Wilson***

Division of Thoracic Surgery and Interventional Pulmonology, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA

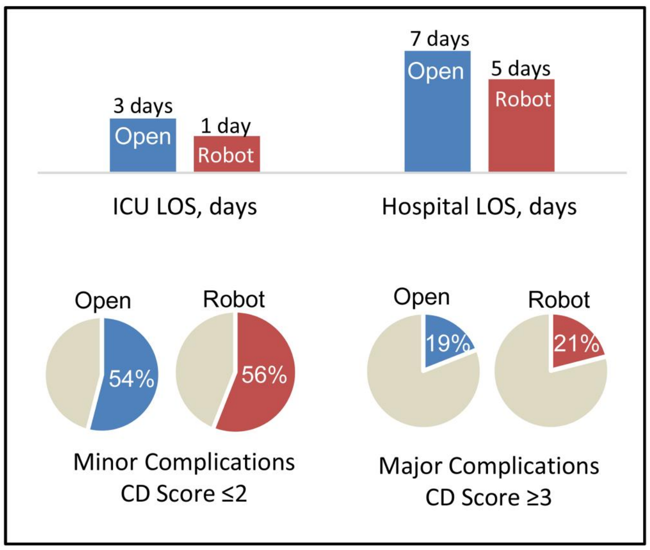
* Corresponding author. Division of Thoracic Surgery and Interventional Pulmonology, Beth Israel Deaconess Medical Center, Harvard Medical School, 185 Pilgrim Road, W/DC 201, Boston, MA 02215, USA. Tel: +617-632-8252; e-mail: jwilso10@bidmc.harvard.edu (J.L. Wilson).

Received 26 August 2024; received in revised form 19 December 2024; accepted 3 February 2025

**The First Comparative Analysis of Open and Robotic Tracheobronchoplasty for Excessive Central Airway Collapse**

**Summary**

Patients with Excessive Central Airway collapse who underwent robotic TBP, compared to patients who underwent the traditional open TBP, had shorter ICU stays, shorter total hospital stays, with equivalent complication rates and quality of life improvements at 3 months. In highly selected patients, robotic TBP is a safe and feasible alternative to the traditional open approach.




TBP: Tracheobronchoplasty; ICU: Intensive Care Unit; LOS: Length of Stay; CD: Clavien-Dindo

## Abstract

**OBJECTIVES:** Tracheobronchoplasty is an operation to treat excessive central airway collapse by stabilizing the posterior tracheal membrane. In 2020, our institution transitioned from the traditional open approach to the robotic-assisted tracheobronchoplasty in select patients. This retrospective cohort study compares postoperative complications and short-term outcomes for patients undergoing open versus robotic tracheobronchoplasty at a high-volume complex airway centre.

†Presented at ESTS 2024, Barcelona, 27 May 2024.

**METHODS:** A retrospective review of all patients who underwent open tracheobronchoplasty (2018–2020) and robotic tracheobronchoplasty (2020–2023) was conducted.

**RESULTS:** During the study period, 43 and 69 patients underwent robotic and open tracheobronchoplasty, respectively. Robotic tracheobronchoplasty had longer median operative times than open (8.4 vs 6.2 h; $P \leq 0.01$). Both median intensive care unit (ICU) length of stay (1.0 vs 3.0 days, $P \leq 0.01$) and hospital length of stay (5.0 vs 7.0 days, $P \leq 0.01$) were shorter after robotic tracheobronchoplasty. There were no significant differences in major or minor complications, total Clavien–Dindo Score, estimated blood loss, discharge to home, and 30-day readmission. The robotic group had two reoperations during the index hospitalization and three conversions to open. There were no mortalities in either group. Short-term (3-month) functional and quality-of-life outcomes were equivalent between groups.

**CONCLUSIONS:** In selected patients with severe and symptomatic excessive central airway collapse, robotic tracheobronchoplasty is a safe and feasible alternative to the traditional open approach. Patients undergoing robotic tracheobronchoplasty have shorter ICU and total hospital stays with equivalent complication rates. As the robotic approach becomes more prevalent, further comparative outcomes are necessary with longer follow-up to ensure durability of the robotic-assisted repair.

**Keywords:** Robotic-assisted thoracoscopic surgery • Airway surgery • Tracheobronchoplasty • Excessive central airway collapse • Tracheobronchomalacia • Excessive dynamic airway collapse



**ABBREVIATIONS**

| | |
|---|---|
| 6MWT | 6-minute walk test |
| BMI | Body mass index |
| CD | Clavien–Dindo score |
| COPD | Chronic obstructive pulmonary disease |
| CQLQ | Cough-Specific Quality-of-Life Questionnaire |
| CT | Computed tomography |
| EBL | Estimated blood loss |
| ECAC | Excessive central airway collapse |
| EDAC | Excessive dynamic airway collapse |
| FEV1 | Forced expiratory volume in 1 second |
| GERD | Gastroesophageal reflux disease |
| ICU | Intensive care unit |
| LMSB | Left mainstem bronchus |
| LOS | Length of stay |
| mMRC | Modified Medical Research Council Dyspnoea scale |
| OSA | Obstructive sleep apnoea |
| oTBP | Open tracheobronchoplasty |
| PFT | Pulmonary function testing |
| rTBP | Robotic tracheobronchoplasty |
| SGRQ | St George Respiratory Questionnaire |
| TBM | Tracheobronchomalacia |
| TBP | Tracheobronchoplasty |

## INTRODUCTION

Excessive central airway collapse (ECAC) encompasses a spectrum of central airway pathology, including tracheobronchomalacia (TBM) and excessive dynamic airway collapse (EDAC). Both TBM and EDAC are characterized by excessive collapse of the central airways during expiration. While TBM exhibits weakening and subsequent loss of curvature of the anterior airway cartilage, EDAC primarily involves increased laxity of the posterior tracheal membrane [1]. Patients with ECAC can experience significant respiratory symptoms affecting quality of life (QOL), such as barking cough, dyspnoea, recurrent respiratory infections, and/or inability to clear secretions [2]. The epidemiology of ECAC remains incompletely understood and is believed to be an underrecognized driver of breathing symptoms, which are often attributed to other more recognized diagnoses such as asthma and chronic obstructive pulmonary disease (COPD) [3]. The prevalence may be as high as 3.1% in the general population [4]. The aetiology of ECAC is likely multifactorial. It can present secondary to underlying congenital conditions or acquired due to an acute injury as seen in prolonged tracheostomy or chronic damage to the central airways seen in COPD [5–7]. Diagnosis is established using dynamic CT and dynamic bronchoscopy. The degree of collapse determines the severity: collapse of 70–80% is considered mild, 81–90% is moderate, and >90% is severe [8]. At our institution, we only consider further workup for operative repair with severe disease.

Tracheobronchoplasty (TBP) is the only definitive surgical treatment for severe diffuse ECAC (>90% collapse of central airways). Traditionally performed open via right thoracotomy, TBP involves remodelling the airway using a permanent polypropylene mesh. The mesh is affixed to the posterior aspect of the airway using partial-thickness permanent sutures [9]. There is increasing evidence that minimally invasive thoracic surgery, including robotic-assisted techniques, decreased mortality, length of stay (LOS), and overall complication rates [10]. In 2015, Lazar *et al.* described the technique for the first robotically assisted bilateral bronchoplasty [11]. In 2019, Lazzaro *et al.* published the first series of patients undergoing robotic TBP (rTBP) and found the approach to be both safe and effective [12]. Our institution implemented rTBP in 2020 in select patients, and a review of the first 43 patients demonstrated safety of the robotic repair with no 90-day mortalities and an acceptable rate of respiratory complications. This study aims to compare the postoperative complications and short-term outcomes between open and robotic TBP in patients with severe ECAC.

## PATIENTS AND METHODS

### Ethical statement

This study was approved by the Beth Israel Deaconess Medical Center Institutional Review Board (Protocol 2023P000957, approval 11/14/2023).

### Patients and selection

A retrospective review was conducted of a prospectively maintained database to identify all patients who underwent open

TBP (oTBP) from 2018 to 2020 and rTBP from 2020 to 2023 for severe ECAC. In selecting our two groups, we examined patients undergoing open TBP before the introduction of the robotic approach at our institution (pre-2020) to reduce surgeon-specific selection bias. Inclusion criteria included all patients who underwent open (2018–2020) and robotic TBP (2020–2023) during the study period. Exclusion criteria included patients undergoing reoperation after a previous TBP and cases of cervical tracheoplasty, an operation involving resection and reconstruction of only the cervical trachea.

Severe ECAC is defined as complete or near-complete collapse (>90%) of the trachea and bilateral bronchi. Patients underwent an extensive workup after their diagnosis to determine their eligibility for operative repair [13–15]. Our clinical flowsheet outlining our algorithm for selection of patients for TBP can be seen in Fig. 1. After optimization of comorbid conditions, patients undergo a short-term airway stent trial to assess improvement in their symptoms after endoscopic stabilization. Patients who have subjective and objective improvement with the stent trial are considered for definitive repair with TBP.

## Outcomes of interest

The primary outcomes were postoperative complications stratified into major and minor by the Clavien–Dindo (CD) score. Secondary outcomes included operative time, estimated blood loss (EBL), hospital and intensive care unit (ICU) LOS, reoperation rate, discharge disposition, 30-day readmission, and change in subjective QOL scores and 6-minute walk test (6MWT) at 3 months.

## Considerations for approach

The surgical approach, robotic or open, was determined independently by the two experienced airway surgeons. The criteria currently employed to determine candidacy for a robotic approach are evolving. Currently, both surgeons offer the rTBP only to patients with EDAC because this pathology requires less posterior airway tension and downsizing to remodel the airway. The TBM pathology, in contrast, requires additional tension to plicate the cartilage edge to the mesh during suturing because of the weakened tracheobronchial cartilage. This is achieved by placing the rows of suture closer together and under greater tension. For these reasons, for our initial patient cohort, we favoured the open approach for patients with TBM and the robotic approach for patients with EDAC.

## Functional and quality-of-life testing

Patients were evaluated with both physiologic assessment and scored with standardized QOL questionnaires before the procedure, during the stent trial, and at follow-up outpatient clinic visits. Physiologic assessments included pulmonary function tests (PFTs) and the 6MWT [16]. Standardized validated questionnaires were used to evaluate functional impairment due to dyspnoea from respiratory disease [Modified Medical Research Council (mMRC) Dyspnoea Scale], respiratory-impacted QOL [St George Respiratory Questionnaire (SGRQ)], and cough-specific QOL [Cough Quality-of-Life Questionnaire (CQLQ)] [17–19]. For the study, preoperative and 3-month postoperative assessments were examined.

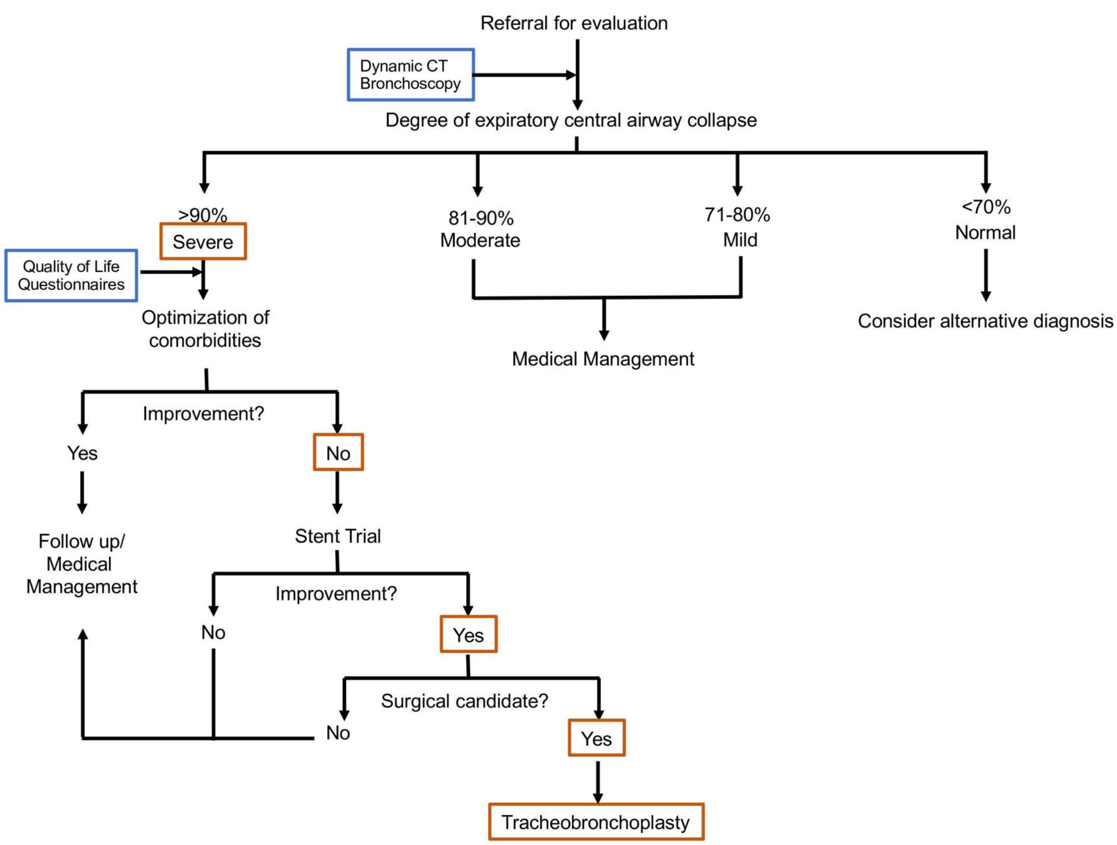



**Figure 1:** Clinical flowsheet outlining our algorithm for selection of patients for tracheobronchoplasty.

## Surgical techniques

The goal of TBP is to stabilize the posterior trachea and bronchi by affixing a polypropylene mesh to the posterior membrane and cartilage edges at the tracheobronchial angle. By reducing the posterior width of the airway, the mesh can plicate the redundant membrane for EDAC and splint open the weak, collapsible cartilage for TBM. The mesh is secured with interrupted partial thickness 4-0 permanent sutures (Prolene®, Ethicon, Raritan, NJ, USA) for oTBP and Ethibon® (Ethicon, Raritan, NJ) for rTBP. These sutures are placed in rows of four across the trachea and three in the bronchi in increments of 5–7 mm. The rows are continued proximally to the thoracic inlet and distally to the distal bronchus intermedius and distal left mainstem bronchus (LMSB). The goal is to cover the entire intrathoracic airway up to the inlet and down to the secondary carina on each side.

While the robotic approach is generally similar to the open approach, there are several fundamental differences. The technique for the traditional oTBP approach via right thoracotomy has been previously described [9]. The Intuitive Surgical Da Vinci Xi™ (Intuitive Surgical Inc., Sunnyvale, CA, USA) system was used for all cases. In contrast to the open approach where one 'Y'-shaped piece of mesh is cut from direct measurement after exposure, three pieces of polypropylene mesh are cut based on transverse dimension measured on coronal CT for the robotic. The surgeon decides if any downsizing is needed, and the mesh is cut 4 mm wider to provide a small buffer during suture placement. Four 8-ml robotic ports and one 12 mm AirSeal® (ConMed, Utica, NY, USA) assistant port are used (Fig. 2). Overview and operative key points are available in Video 1.

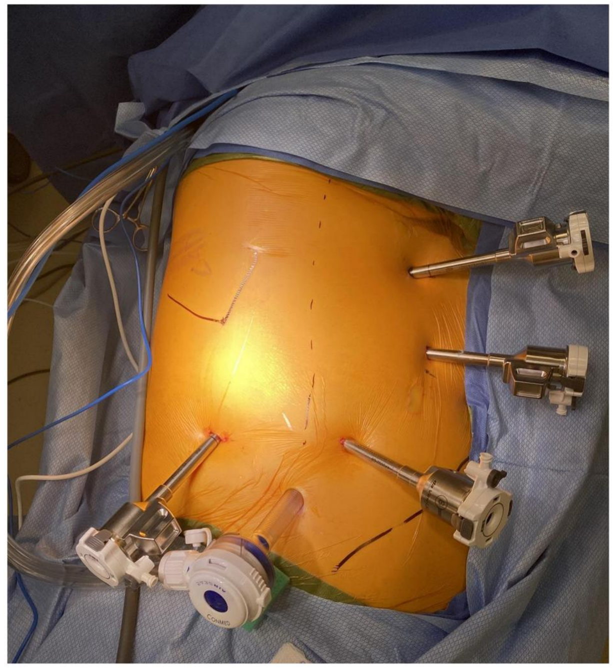
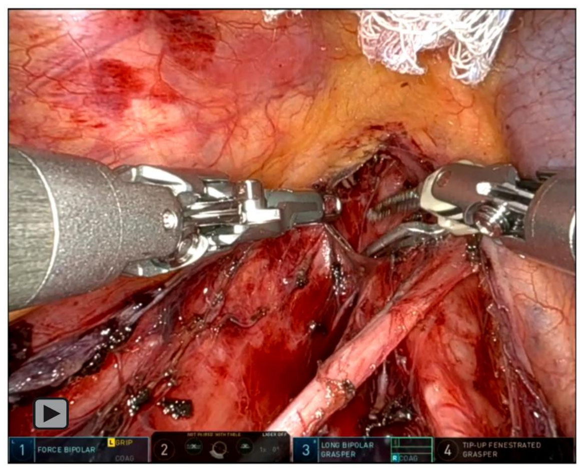


**Figure 2:** Port site schematic for robotic tracheobronchoplasty. Four 8-mm robotic ports and one 12-mm assistant port are placed in a 'J'-shaped configuration.




**Video 1:** Video overview of operative techniques and key points during robotic tracheobronchoplasty.

## Statistics

Continuous data are presented as median and interquartile range. Nonparametric continuous data were compared using the Wilcoxon signed-rank test. Categorical data are presented as *n* (%). Categorical data were compared using Fischer's exact test. Threshold for statistical significance was set at <0.05. All analyses were conducted, and graphs were created in R (R version 4.4.3, http://www.r-project.org). The ggplot package was used for creation of figures [20].

## RESULTS

All patients who underwent open TBP (2018–2020) and robotic TBP (2020–2023) were reviewed. During the study period, 70 and 43 patients underwent open TBP and rTBP, respectively. Of these, one patient in the open TBP group was a reoperation and excluded from the study. There were no reoperations in the robotic group.

Baseline demographics were compared between the open TBP and robotic TBP groups. The median age (58 vs 61 years), female sex (74% vs 60%), white race (91% vs 98%), and BMI (32.0 vs 32.5 kg/m$^2$) were similar between the two groups. All patient demographics and selected comorbidities appear in Table 1. Notably, there were fewer patients in the open group with ASA ≥4 (3% open vs 16% robotic, $P = 0.03$), although there was no statistical difference in the Charlson Comorbidities Index (3.0 open vs 4.0 robotic, $P = 0.34$). The most common comorbidities in both groups were gastroesophageal reflux disease, obstructive sleep apnoea, and asthma.

Patients undergoing robotic TBP had approximately 2 h longer median operative times than open TBP (6.2 vs 8.4 h; $P \leq 0.01$). ICU LOS was 2 days shorter (3.0 vs 1.0 days, $P \leq 0.01$), and hospital LOS was 2 days shorter (7.0 vs 5.0 days, $P < 0.01$) after rTBP compared to open. There were no significant differences in EBL (150 vs 150 ml, $P = 0.4$), discharge to home (84% vs 88%, $P = 0.59$), and 30-day readmission (19% vs 19%, $P = 1.0$). There were two reoperations during the index hospitalization in the robotic group: one for haemothorax requiring washout and the

**Table 1:** Demographic profile and procedure-specific outcomes

| Variable | Open group ($n=69$) | Robotic group ($n=43$) | *P*-value |
|---|---|---|---|
| Age, years | 58 (15) | 61 (19) | 0.47 |
| Female sex, *n* (%) | 51 (74%) | 26 (60%) | 0.15 |
| White race, *n* (%) | 63 (91%) | 42 (98%) | 0.25 |
| BMI, kg/m$^2$ | 32 (9) | 32.5 (7.8) | 0.98 |
| ASA ≥4, *n* (%) | 2 (3%) | 7 (16%) | 0.03* |
| Comorbidities | | | |
| Smoking history, *n* (%) | 26 (38%) | 22 (51%) | 0.24 |
| COPD, *n* (%) | 15 (22%) | 14 (33%) | 0.27 |
| Asthma, *n* (%) | 46 (67%) | 33 (77%) | 0.29 |
| OSA, *n* (%) | 43 (62%) | 33 (77%) | 0.15 |
| GERD, *n* (%) | 56 (81%) | 41 (95%) | 0.04* |
| Steroids at time of surgery, *n* (%) | 16 (23%) | 12 (28%) | 0.66 |
| Charlson Comorbidities Index | 3 (2) | 4 (3) | 0.34 |
| Intraoperative | | | |
| Operative time, hours | 6.2 (1.2) | 8.4 (2.4) | $<$0.01* |
| EBL, ml | 150 (150) | 150 (225) | 0.40 |
| IVF, ml | 2200 (800) | 2800 (1450) | 0.02* |
| Conversion to open, *n* (%) | | 3 (7%) | |
| ICU LOS, days | 3 (2) | 1 (2.5) | $<$0.01* |
| Hospital LOS, days | 7 (3) | 5 (4) | $<$0.01* |
| Discharge disposition, home, *n* (%) | 58 (84%) | 38 (88%) | 0.59 |
| 30-day readmission, *n* (%) | 13 (19%) | 8 (19%) | 1 |

Presented as median (IQR) or *n* (%).

*$P < 0.05$

ASA: American Society of Anesthesiologists Score; BMI: body mass index; COPD: chronic obstructive pulmonary disease; EBL: estimated blood loss; GERD: gastroesophageal reflux disease; ICU: intensive care unit; IVF: intravenous fluid; IQR: interquartile range; LOS: length of stay; OSA: obstructive sleep apnoea.

second for severe subcutaneous emphysema requiring blowhole. There were no mortalities in either group.

Four patients (9%) in the robotic group had significant intraoperative events, with three (7%) requiring conversion to open. All patients requiring conversion to open were analysed in the robotic group. One patient had a cardiac arrest intraoperatively requiring cardiopulmonary resuscitation with return of spontaneous circulation. The operation was completed successfully without conversion to open. The reasons for the three conversions are as follows:

1. There was an iatrogenic injury to the LMSB. Conversion was necessary due to the location on the posterior wall of the distal LMSB.
2. There was a witnessed iatrogenic LMSB airway perforation caused by overinflation of the bronchial cuff after readvancement of the endotracheal tube. The bronchial cuff perforated the LMSB, causing separation of the membrane along the entire length of the LMSB.
3. Patient had persistent hypercarbia despite multiple periods of bilateral lung ventilation requiring conversion to open to proceed with the operation safely.

Amongst the 21 examined postoperative complications, there was no statistical difference in any (Table 2). Specifically, there were no differences between the incidences of respiratory complications such as respiratory infection (pneumonia/bronchitis), need for postoperative bronchoscopy, intubation >48 h, or need for reintubation postoperatively. There were no differences in the overall CD score (12.0 open vs 8.7 robotic, $P=0.74$) and after stratification of complications into minor (CD ≤2) (54% vs 56%, $P=0.85$) and major (CD ≥3) (19% vs 21%, $P=0.81$) complications between the two groups.

At follow-up in 3 months, both patients who underwent open and rTBP had improvements in their 6MWT and all three QOL scores (Fig. 3). Decreased score of SGRQ, CQLQ, and mMRC, as denoted by a negative change, indicates improvement in symptoms, while improved distance on 6MWT suggests improved physiologic reserve. PFTs have previously not been shown to be well correlated with symptomatic improvement, with over one-fifth of patients displaying normal spirometry testing despite severe symptoms on diagnosis [21]. Again, we see an equivocal change in forced expiratory volume in 1 second at the 3-month follow-up. The two groups did not have statistically different outcomes to each other in terms of improvements in their QOL scores or 6MWT (Table 3).

## DISCUSSION

This study shows that in highly selected patients with severe and symptomatic EDAC, robotic TBP is a safe and feasible alternative to the traditional open approach. Patients undergoing rTBP have shorter ICU and hospital stays, with equivalent complication rates and reported short-term QOL improvements as the traditional open approach.

Currently, we see that the first series of robotic cases require longer operative times than the open approach, an already long and complex surgery. However, as we have become more adept at the rTBP approach, our efficiency has improved, and operative time continues to improve (unpublished data).

The technical benefits of robotic platforms are multifold. Appropriate retraction and magnified views provide the surgeon with improved visualization and exposure critical for this operation. The enhanced range of motion with the robotic instruments can facilitate precise suture placement with scaled motion. Furthermore, the ergonomic benefit of robotic approach for the surgeon during multi-hour cases such as TBP cannot be understated [22].

The shorter ICU and hospital stay seen in the robotic group is an important factor to examine when exploring the surgical outcomes of the financial burden on both the patient and the facility [23]. In our study, we see that patients are able to leave the ICU 2 days and the hospital 2 days earlier than the open group. With the implementation of enhanced recovery pathways after TBP, we anticipate that ICU and hospital stays will further shorten.

During the hospital stay, our study found that patients undergoing rTBP have equivalent rates of complications as the open group. There were no differences in the overall CD score or after stratification of complications into minor and major complications between the two groups. However, we do expect that with experience, we will see a lower rate of complications in the robotic group.

One other institution has completed a case series exploring early robotic TBP outcomes. Lazzaro *et al.* published a case series of the first 42 patients undergoing rTBP, in which they

**Table 2:** All complications and aggregate and stratified CD score

| All complications | Open group ($n = 69$) | Robotic group ($n = 43$) | *P*-value |
|---|---|---|---|
| Delirium, *n* (%) | 5 (7%) | 4 (9%) | 0.73 |
| Mechanical ventilation >24 h, *n* (%) | 7 (10%) | 4 (9%) | 1 |
| Bronchoscopy postoperative, *n* (%) | 10 (14%) | 5 (12%) | 0.78 |
| Reintubation, *n* (%) | 2 (3%) | 2 (5%) | 0.64 |
| Pneumonia/bronchitis, *n* (%) | 4 (6%) | 6 (14%) | 0.18 |
| Recurrent laryngeal nerve injury, *n* (%) | 2 (3%) | 4 (9%) | 0.2 |
| Air leak >2 days, *n* (%) | 1 (1%) | 1 (2%) | 1 |
| Chylothorax, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| Postoperative bleeding requiring takeback, *n* (%) | 0 (0%) | 1 (2%) | 0.38 |
| Empyema, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| Airway abscess, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| Exposed mesh, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| UTI, *n* (%) | 7 (10%) | 1 (2%) | 0.15 |
| AKI, *n* (%) | 5 (7%) | 4 (9%) | 0.73 |
| Atrial fibrillation, *n* (%) | 11 (16%) | 6 (14%) | 1 |
| Cardiac arrest, *n* (%) | 0 (0%) | 1 (2%) | 0.38 |
| Effusion requiring drainage, *n* (%) | 1 (1%) | 2 (5%) | 0.56 |
| VTE/PE, *n* (%) | 1 (1%) | 1 (2%) | 1 |
| Sepsis, *n* (%) | 0 (0%) | 1 (2%) | 0.38 |
| C. Diff, *n* (%) | 1 (1%) | 1 (2%) | 1 |
| Brachial plexus injury, *n* (%) | 0 (0%) | 1 (2%) | 0.38 |
| In-hospital mortality, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| Mortality at 30 days, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| Mortality at 90 days, *n* (%) | 0 (0%) | 0 (0%) | 1 |
| Reoperation within 30 days, *n* (%) | 0 (0%) | 2 (5%) | 0.15 |
| Minor complication (CD ≤2), *n* (%) | 37 (54%) | 24 (56%) | 0.85 |
| Major complication (CD ≥3), *n* (%) | 13 (19%) | 9 (21%) | 0.81 |
| CD score | 12.0 (26.0) | 8.7 (29.6) | 0.74 |

Presented as median (IQR) or *n* (%).

AKI: acute kidney injury; C. Diff: Clostridium difficile; CD: Clavien–Dindo score; IQR: interquartile range; PE: pulmonary embolism; UTI: urinary tract infection; VTE: venous thromboembolism.



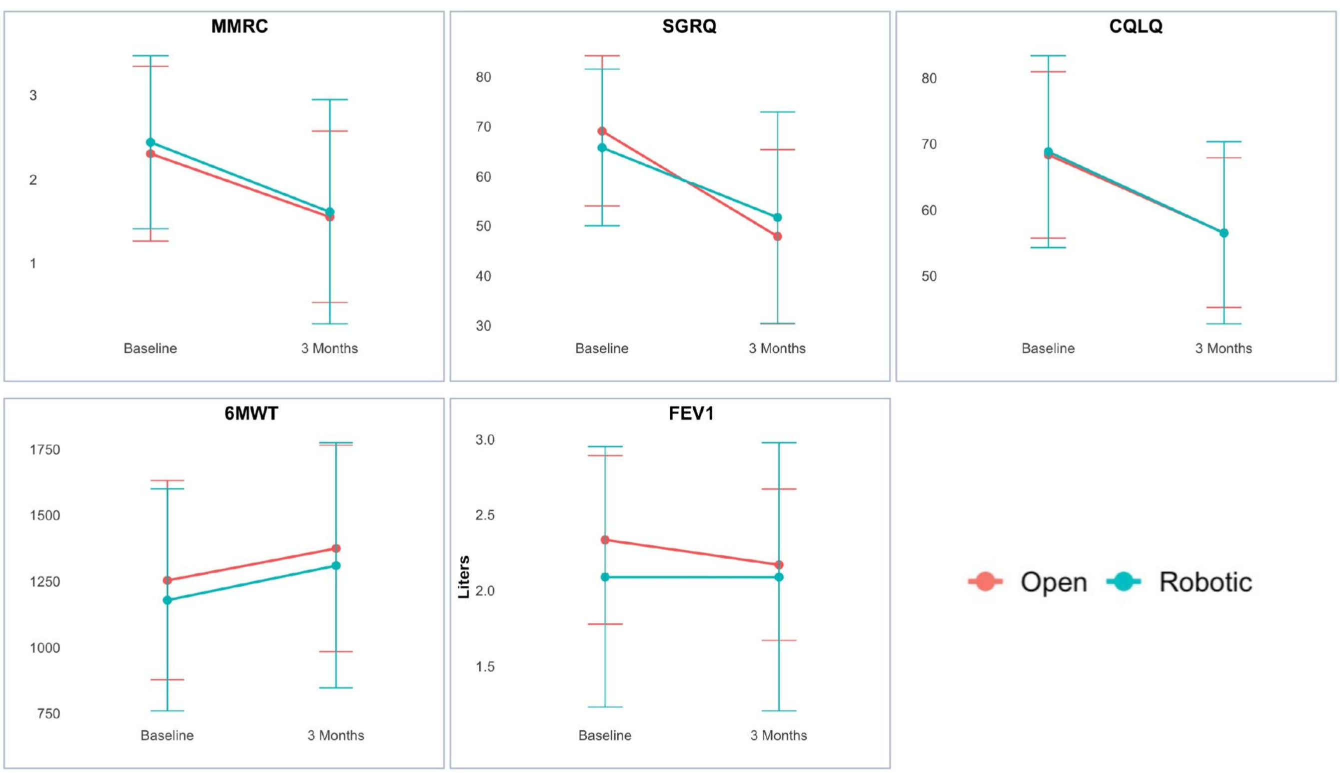



**Figure 3:** Patient outcome measures at baseline and 3 months. Decreased score of SGRQ, CQLQ, and mMRC denotes improvement in symptoms, while improved distance on 6MWT denotes improved physiologic reserve. CQLQ: Cough-Specific Quality-of-Life Questionnaire; FEV1: forced expiratory volume; L/min: litres per minute; mMRC: modified Medical Research Council; SGRQ: St George Respiratory Questionnaire; 6MWT: 6-minute walk test.

**Table 3:** Patient outcome measures at baseline and 3 months

| Outcomes (*n* = baseline, 3 months) | Baseline (SD) | 3-month change (SD) | *P*-value |
|---|---|---|---|
| SGRQ | | | |
| Open ($n = 56, 23$) | 69 (15.1) | −18.6 (24.8) | 0.33 |
| Robotic ($n = 38, 15$) | 65.7 (15.8) | −11.6 (16.9) | |
| CQLQ | | | |
| Open ($n = 55, 22$) | 68 (12.6) | −9.7 (14.3) | 0.59 |
| Robotic ($n = 38, 15$) | 68.8 (14.5) | −7.9 (13.3) | |
| mMRC | | | |
| Open ($n = 66, 29$) | 2 (1.0) | −0.54 (1.1) | 0.63 |
| Robotic ($n = 41, 18$) | 2.4 (1.0) | −0.78 (1.0) | |
| 6MWT, feet | | | |
| Open ($n = 67, 38$) | 1253 (377.9) | +148.6 (259.0) | 0.30 |
| Robotic ($n = 38, 16$) | 1178 (420) | +119.3 (404.1) | |
| FEV1, L/min | | | |
| Open ($n = 69, 38$) | 2 (0.56) | −0.09 (0.29) | 0.18 |
| Robotic ($n = 41, 16$) | 2.1 (0.86) | −0.01 (0.51) | |

Decreased score of SGRQ, CQLQ, and mMRC denotes improvement in symptoms, while improved distance on 6MWT denotes improved physiologic reserve.

CQLQ: Cough-Specific Quality-of-Life Questionnaire; FEV1: forced expiratory volume; L/min: litres per minute; mMRC: modified Medical Research Council; SD: standard deviation; SGRQ: St George Respiratory Questionnaire; 6MWT: 6-minute walk test.

reported a minor complication rate of 26% and a major complication rate of 19%, as compared to our reported minor complication rate of 56% and major complication rate of 21% [12]. It is unclear what accounts for this difference, but certainly, selection criteria and the evaluation process for TBP differ across institutions, which makes direct comparisons and a multi-institutional study challenging. Additionally, the relatively high rate of major complications of this complex procedure at our institutions serves as a reminder that the procedures should be completed by experienced surgeons in specialized centres. Similarly, to our study, they found improvements in the SGRQ from baseline at 3 months, although other QOL measures such as mMRC and CQLQ were not used.

This study has important limitations to consider. First is the retrospective nature of the study. Currently, we enrol patients undergoing TBP for ECAC prospectively, and no randomization is applied as all qualified patients undergo operative fixation. In addition, patients who underwent rTBP were highly selected by the surgeons, which can introduce selection bias. To mitigate this bias in the open group after 2020, we only included open TBPs occurring before the introduction of rTBPs. However, one selection criterion for undergoing robotic TBPs was diagnosis of EDAC, rather than TBM. Currently, there are no data that explore the impact of the anatomic differences between these pathologies on surgical outcomes. Furthermore, the small sample size limited conducting analyses adjusted for potential confounders, and there are likely clinically relevant differences that were not statistically significant. As we continue patient recruitment, the next steps include an analysis of the larger patient cohort with longer follow-up.

## CONCLUSION

As diagnostic technology improves, ECAC is an increasingly identified pathology causing severe functional impairment for patients. The true prevalence of ECAC is unknown but is currently likely underdiagnosed and undertreated [4]. There are many challenges remaining in the treatment of ECAC. Patient selection is a key part of identifying patients who may benefit from TBP and determining the appropriate operative approach. Additionally, the minimally invasive robotic approach may further provide an option for patients who were previously ineligible for oTBP. As the robotic approach becomes more prevalent, further studies on comparative outcomes are critical at longer-term follow-up to ensure the fidelity of the repair is durable. Looking forward, robotic TBP appears to be a promising technical improvement in the management of ECAC.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the tremendous contributions from our interventional pulmonary colleagues (Adnan Majid, MD; Mihir Parikh, MD; Jason Beattie, MD; Kai Swenson, MD), and the BIDMC Complex Airway Program nurse coordinator Adam Rojek, RN.

## FUNDING

No external funding sources were acquired.

**Conflict of interest:** Sandra L. Carpenter has received compensation from Intuitive Surgical Inc. for participating in a research study designed to evaluate their surgical products. Michael Kent has worked with Intuitive Surgical Inc. as a speaker and received honoraria. The other authors have declared no conflict of interest.

## DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

## Author contributions

**Jae M. Cho, MD:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing. **Sandra L. Carpenter:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing—original draft; Writing—review & editing. **Fleming Mathew:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Writing—original draft; Writing—review & editing. **Justin S. Heidel:** Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Writing—review & editing. **Michael Kent:** Conceptualization; Data curation; Methodology; Project administration; Writing—review & editing. **Sidhu P. Gangadharan:** Conceptualization; Data curation; Methodology; Project administration; Supervision; Validation; Writing—review & editing. **Jennifer L. Wilson:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing

## Reviewer information

European Journal of Cardio-Thoracic Surgery thanks Gunda Leschber, Israel Hernandez Ramirez and the other anonymous reviewers for their contribution to the peer review process of this article.

## REFERENCES

[1] Murgu SD, Colt HG. Tracheobronchomalacia and excessive dynamic airway collapse. Respirology 2006;11:388–406. doi:10.1111/j.1440-1843.2006.00862.x
[2] Gangadharan SP. Tracheobronchomalacia in adults. Semin Thorac Cardiovasc Surg 2010;22:165–73. doi:10.1053/j.semtcvs.2010.07.001
[3] Sverzellati N, Rastelli A, Chetta A *et al.* Airway malacia in chronic obstructive pulmonary disease: prevalence, morphology and relationship with emphysema, bronchiectasis and bronchial wall thickening. Eur Radiol 2009;19:1669–78. doi:10.1007/s00330-009-1306-9
[4] Ikeda S, Hanawa T, Konishi T *et al.* Diagnosis, incidence, clinicopathology and surgical treatment of acquired tracheobronchomalacia. Nihon Kyobu Shikkan Gakkai Zasshi 1992;30:1028–35.
[5] Chetambath R. Tracheobronchomalacia in obstructive airway diseases. Lung India 2016;33:451–2. doi:10.4103/0970-2113.184929
[6] Sams VG, Lawson CM, Shibli AB *et al.* Severe tracheobronchomalacia after prolonged intubation of multitrauma patient. Case Rep Surg 2011; 2011:627012. doi:10.1155/2011/627012
[7] Oryoji D, Ono N, Himeji D *et al.* Sudden respiratory failure due to tracheobronchomalacia by relapsing polychondritis, successfully rescued by multiple metallic stenting and tracheostomy. Intern Med 2017;56: 3369–72. doi:10.2169/internalmedicine.8778-16
[8] Buitrago DH, Wilson JL, Parikh M *et al.* Current concepts in severe adult tracheobronchomalacia: evaluation and treatment. J Thorac Dis 2017;9: E57–E66. doi:10.21037/jtd.2017.01.13
[9] Gangadharan SP, Bakhos CT, Majid A *et al.* Technical aspects and outcomes of tracheobronchoplasty for severe tracheobronchomalacia. Ann Thorac Surg 2011;91:1574–80; discussion 1580-1581. doi:10.1016/j.athoracsur.2011.01.009
[10] Kent M, Wang T, Whyte R *et al.* Open, video-assisted thoracic surgery, and robotic lobectomy: review of a national database. Ann Thorac Surg 2014; 97:236–42; discussion 242-244. doi:10.1016/j.athoracsur.2013.07.117
[11] Lazar JF, Posner DH, Palka W *et al.* Robotically assisted bilateral bronchoplasty for tracheobronchomalacia. Innovations (Phila) 2015;10: 428–30. doi:10.1097/IMI.0000000000000215
[12] Lazzaro R, Patton B, Lee P *et al.* First series of minimally invasive, robot-assisted tracheobronchoplasty with mesh for severe tracheobronchomalacia. J Thorac Cardiovasc Surg 2019;157:791–800. doi:10.1016/j.jtcvs.2018.07.118
[13] Majid A, Guerrero J, Gangadharan S *et al.* Tracheobronchoplasty for severe tracheobronchomalacia: a prospective outcome analysis. Chest 2008;134:801–7. doi:10.1378/chest.08-0728
[14] Ernst A, Majid A, Feller-Kopman D *et al.* Airway stabilization with silicone stents for treating adult tracheobronchomalacia: a prospective observational study. Chest 2007;132:609–16. doi:10.1378/chest.06-2708
[15] Loring SH, O'Donnell CR, Feller-Kopman DJ *et al.* Central airway mechanics and flow limitation in acquired tracheobronchomalacia. Chest 2007;131:1118–24. doi:10.1378/chest.06-2556
[16] ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories. ATS statement: guidelines for the six-minute walk test. Am J Respir Crit Care Med 2002;166:111–7. doi:10.1164/ajrccm.166.1.at1102
[17] Mahler DA, Wells CK. Evaluation of clinical methods for rating dyspnea. Chest 1988;93:580–6. doi:10.1378/chest.93.3.580
[18] Jones PW, Quirk FH, Baveystock CM. The St George's Respiratory Questionnaire. Respir Med 1991;85 Suppl B:25–31; discussion 33-37. doi:10.1016/s0954-6111(06)80166-6
[19] French CT, Irwin RS, Fletcher KE *et al.* Evaluation of a cough-specific quality-of-life questionnaire. Chest 2002;121:1123–31. doi:10.1378/chest.121.4.1123
[20] Wickham H. ggplot2: Elegant Graphics for Data Analysis. 2nd edn. Springer International Publishing, 2016. doi:10.1007/978-3-319-24277-4
[21] Seastedt KP, Wilson JL, Gangadharan SP. Robotic surgery for tracheobronchomalacia. Thorac Surg Clin 2023;33:61–9. doi:10.1016/j.thorsurg.2022.09.003
[22] Wee IJY, Kuo LJ, Ngu JCY. A systematic review of the true benefit of robotic surgery: ergonomics. Int J Med Robot 2020;16:e2113. doi:10.1002/rcs.2113
[23] Polverejan E, Gardiner JC, Bradley CJ *et al.* Estimating mean hospital cost as a function of length of stay and patient characteristics. Health Econ 2003;12:935–47. doi:10.1002/hec.774




European Journal of Cardio-Thoracic Surgery, 2025, 67, 1–8
https://doi.org/10.1093/ejcts/ezaf026
Original article