ORIGINAL ARTICLE

Temporal Trends in the Utilization and Survival Outcomes of Lobar, Segmental, and Wedge Resection for Early-Stage NSCLC, 2004 to 2020

Eden Z. Deng, BS,[a] Xiaofei Wang, PhD,[b,*] Jianrong Zhang, MD, MPH,[c,d] Thomas E. Stinchcombe, MD,[e] Chi-Fu (Jeffrey) Yang, MD,[f] Nasser Altorki, MD[g]

[a]*Department of Statistical Science, Duke University, Durham, North Carolina*
[b]*Department of Biostatistics & Bioinformatics, Duke University Medical Center, Durham, North Carolina*
[c]*Centre for Cancer Research & Department of General Practice and Primary Care, Faculty of Medicine, Dentistry and Health Sciences, University of Melbourne, Melbourne, Victoria, Australia*
[d]*Victorian Comprehensive Cancer Centre, Melbourne, Victoria, Australia*
[e]*Duke Cancer Institute, Duke University Medical Center, Durham, North Carolina*
[f]*Department of Surgery, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts*
[g]*Department of Cardiothoracic Surgery, Weill Cornell Medicine, New York-Presbyterian Hospital, New York, New York*

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ABSTRACT

Introduction: Although lobectomy has long been the standard of surgical treatment for early-stage NSCLC, segmental and wedge resections have become another option often used over the past two decades.

Methods: To examine the trends over time in the utilization, quality, and overall survival (OS) differences of lobectomy, segmentectomy, and wedge resection, we performed an observational, population-level study of 76,466 patients with T1 or T2 N0M0 NSCLC tumors 2 cm or less in size in the National Cancer Database, from 2004 to 2020. To compare the OS of the three treatments, we used inverse probability of treatment weighting to analyze a subgroup of cases with nodal examination and minimal comorbidity burden.

Results: From 2004 to 2020, the use of lobectomy decreased from 75.2% to 67.6% of resections, wedge remained relatively stable (20.5%–22.8%), and segmentectomy increased from 4.3% to 9.7%. The likelihood of nodal assessments and negative margins has increased for all treatments. Younger patients, patients with low comorbidity burden, and patients with smaller tumors have become increasingly likely to receive segmental and wedge resections. Five-year OS of segmentectomy (80.6%, 95% confidence interval [CI]: 78.1%–83.2%) remained non-inferior to lobectomy (83.6%, 95% CI: 83.1%–84.1%]), whereas wedge resection was inferior until 2016 to 2019 (five-y OS = 79.9%, 95% CI: 75.9%–83.8%).

Conclusions: Sublobar resections, particularly segmentectomies, have increased in frequency and quality. The growing use of sublobar resections for younger and healthier patients highlights the need for additional clinical evidence demonstrating whether these trends do indeed lead to better outcomes.

Keywords: Sublobar resection; Segmentectomy; Wedge resection; Temporal trends; National Cancer Database; Lung neoplasms

Introduction

Of the quarter million annual cases of lung cancer in the United States, NSCLC comprises roughly 84%.[1] For NSCLC diagnosed at stage T1 or T2, the first treatment is

*Corresponding author.

Address for correspondence: Xiaofei Wang, PhD, Department of Biostatistics & Bioinformatics, Duke University Medical Center, 2424 Erwin Road Suite 1102, 11080 Hock Plaza, Duke Box 272, Durham, North Carolina 27705. E-mail: xiaofei.wang@duke.edu

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often surgical removal of the tumor. Treatments differ by the amount of tissue removed: larger resections (e.g., lobectomy) reduce the likelihood of cancer recurrence but may lead to respiratory or cardiovascular complications that impact patients' quality of life and long-term mortality risk. Meanwhile, lesser resections (e.g., segmental or wedge resection) may spare cardiopulmonary function at the cost of higher local disease recurrence.[2,3]

In 1995, the Lung Cancer Study Group performed a randomized trial on patients with T1N0 NSCLC demonstrating a threefold increase in the cancer recurrence rate after sublobar resection (SLR) relative to lobectomy.[4] Since then, lobectomy has been recognized as the standard of surgical care for early-stage lung cancer, and SLR is an alternative, mostly for patients with reduced physiological fitness. Among the options of SLR, previous evidence from observational research shows that either wedge resection or segmentectomy were inferior to lobectomy in survival results for stage 1 NSCLC 2 cm or less in size.[5] Nevertheless, the same results were not found in subsequently published clinical trials. Between 2007 and 2017, the Cancer and Leukemia Group B (CALGB) conducted a multicenter, international, randomized, noninferiority phase 3 trial (CALGB 140503) in patients with NSCLC clinically staged as T1aN0 (tumor size $\leq$2 cm). SLR (both segmental and wedge resection) and lobectomy were randomly assigned to nearly 700 patients, and SLR was noninferior to lobectomy for both disease-free survival and overall survival (OS).[6] In another phase 3 randomized trial from the Japan Clinical Oncology Group (JCOG 0802), conducted between 2009 and 2014 with over 1000 patients meeting similar criteria, investigators found OS after segmentectomy to be superior to lobectomy.[7]

Throughout the past two decades, advancements in technology and surgical training and shifts in the treated patient population, have certainly impacted the utilization of the different lung cancer surgeries and their patient outcomes. The objective of this population-level study is to examine the trends over time in the utilization, quality, and survival differences of lobectomy, segmentectomy, and wedge resection. We used the National Cancer Database (NCDB) to analyze trends in demographic, clinical, and procedural measures of cases of early-stage NSCLC with a tumor size of 2 cm or less.

Materials and Methods

Study Population for Analysis of Temporal Trends

The NCDB collects data from over 1,500 centers across the United States and is estimated to capture 70% of all newly diagnosed cancers each year, beginning in 2004 and up to 2020.[8] From the NCDB's 2020 release, we selected a cohort of patients with NSCLC diagnosed with peripheral tumors of clinical size 2 cm or less in diameter, clinically and pathologically staged as T1N0M0 or T2N0M0, who received lobectomy, segmentectomy, or wedge resection at the reporting facility. Patients diagnosed before 2018 were staged using the seventh edition of the American Joint Committee on Cancer's staging system, and patients diagnosed after 2018 were staged according to the eighth edition. Patients had no history of cancer before the current diagnosis, did not receive any neoadjuvant therapy, and were at least 18 years of age. In total, 1173 unique centers across the United States were represented in the cohort, including 211 academic research centers, 272 integrated network programs, 219 community cancer programs, and 475 comprehensive community cancer programs as classified by the Commission on Cancer Accreditation program. Geographically, 26.8% of procedures were performed in the Northeast, 34.9% in the South, 25.1% in the Midwest, and 12.6% in the West.

Analysis of Temporal Trends in Surgical Approach, Quality, and Patient Demographics

Temporal trends in the prevalence of robotic-assisted thoracic surgery (RATS) and video-assisted thoracic surgery (VATS) and surgical quality were assessed using logistic regression models predicting whether a procedure utilized RATS/VATS, had at least one lymph node sampled and had negative surgical margins on the basis of the patient's surgery type (lobar, segmental, or wedge resection) and diagnosis year since 2004 (scaled by 0.2 for feature interpretability). To explore trends in treatment assignment over time, we used multinomial regression models to predict the probability of lobectomy, segmentectomy, or wedge resection given the patient's diagnosis year since 2004, stratified by age group ($\geq$70 y versus 18–69 y), tumor size (<1.5 versus 1.5–2.0 cm), comorbidity burden (Charlson-Deyo score $\geq$1 versus 0), tumor histological type (nonsquamous versus squamous), sex (male versus female), race group (non-White versus White), and the total volume of lung resections at the facility providing treatment (fourth quartile versus first to third quartiles of all lung resections recorded in the NCDB). Cut-offs were selected to yield similarly sized strata.

Analysis of Temporal Trends in OS in Noncompromised Patients

Across three time periods between 2004 and 2020, we also aimed to estimate the average treatment effect of segmental and wedge resection compared with lobectomy in non-compromised patients who may be candidates for both lobectomy and SLR. We filtered the original patient cohort for a subgroup of patients with minimal comorbidity burden, defined as having a Charlson-Deyo score of 0, and at least one lymph node examined to ensure the nodal stage was assessed.

To address treatment selection bias, we used a propensity score model to balance the baseline characteristics of each surgical group. McCaffrey et al.[9] have developed a robust method of estimating the propensity score for multiple treatment groups using Generalized Boosted Models (GBMs), a nonparametric, tree-based machine learning approach that is well-suited for estimating the propensity from many pretreatment covariates and capturing non-linear relationships between the baseline variables and treatment selection. We used the R package twang[10] to perform inverse probability of treatment weighting (IPTW) on the basis of the propensity score for multiple treatments.

We modeled the propensity score of lobectomy, segmentectomy, and wedge resection using 11 variables: patient age, race, sex, income level in area of residence, tumor size, histological type, year of diagnosis (scaled between 0 and 1), number of lymph nodes sampled, the surgical approach used, the volume of surgical resections at the treating facility, and the facility type. Although income levels were missing for up to 15% of cases in each surgical group, the GBM preserves incomplete observations using indicators for missing values. The GBM was trained to minimize the absolute standardized mean difference between treatment groups for each covariate, and we considered an absolute standardized mean difference of less than 0.10 to be small and indicative of sufficiently balanced covariates for our analysis. After weighting the data, we used the R package adjusted Curves[11] to plot IPTW-adjusted Kaplan-Meier curves[12,13] comparing the effects of segmental and wedge resection versus lobectomy.

Results

Study Population

The NCDB contained records from 76,466 patients diagnosed with T1 or T2 N0M0 NSCLC between 2004 and 2020, receiving surgical treatment for peripheral tumors 2 cm or less in diameter according to our selection criteria. 70.3% of patients were treated with lobectomy (N = 53,730), 6.3% were treated with segmentectomy (N = 4829), and 23.4% were treated with wedge resection (N = 17,907) (Table 1). Data were missing at less than 5% for histological type, margin status, facility type, and income. Any incomplete records were dropped from modeling analyses.

Trends in Surgical Utilization

Utilization of wedge resection remained relatively stable, comprising 20.5% of resections in 2004 and 22.8% in 2019. Segmentectomy reported a consistent increase from 4.3% to 9.7% of resections over the same period, whereas the use of lobectomy decreased steadily from 75.2% of resections in 2004 to 67.6% of resections in 2019 (Fig. 1).

Trends in Surgical Approach and Quality

For all three surgical treatments, the prevalence of VATS and RATS increased notably from 0% of procedures in 2004 to 70% in 2019. Both segmentectomy (OR = 2.05, 95% confidence interval [CI]: 1.63–2.56, $p < 0.001$) and wedge resection (OR = 1.50, 95% CI: 1.32–1.70, $p < 0.001$) were more likely to be accompanied by video or robotic assistance compared with lobectomy (Fig. 2*A*).

With respect to surgical quality, both segmentectomy and wedge resection were associated with significantly lower probability of nodal examination (segmental OR = 0.091, 95% CI: 0.069–0.120, $p < 0.001$; wedge OR = 0.025, 95% CI: 0.021–0.030, $p < 0.001$) and negative surgical margins (segmental OR = 0.48, 95% CI: 0.27–0.91, p = 0.018; wedge OR = 0.37, 95% CI: 0.27–0.49, $p < 0.001$) compared with lobectomy. The prevalence of nodal examination and negative surgical margins increased over time in all surgical groups, especially among segmental and wedge resections. By 2020, the predicted probabilities of nodal assessment and negative surgical margins were comparable for segmentectomy and lobectomy, but wedge resections were still less likely to include nodal assessment and achieve negative margins (Fig. 2*B* and *C*).

Trends in Clinical and Demographic Characteristics

Overall, patients aged over 70 years were more likely to receive segmentectomy (OR = 1.88, Z-test $p < 0.001$) and wedge resection (OR = 1.72, $p < 0.001$) compared with patients aged 18 to 69 years. Independent of age, the year of diagnosis was associated with increased odds of segmentectomy and wedge resection, but for patients older than 70 this effect was diminished (segmentectomy OR = 0.86, $p < 0.001$; wedge resection OR = 0.94, $p = 0.006$) (Fig. 3*A*; Supplementary Table 1). Compared with their counterparts diagnosed five years earlier, the odds of receiving segmentectomy increased by a factor of 1.55 for patients aged between 18 and 69 years old and 1.33 times for patients aged over 70 years.

Treatment probability for segmentectomy was comparable for smaller (<1.5 cm) and larger (1.5–2.0 cm) tumors, but smaller tumors were significantly more likely to receive wedge resection (OR = 1.60, $p < 0.001$). Among patients with smaller tumors, more recent diagnosis time was associated with higher odds of segmentectomy (OR = 1.09,

Table 1. Baseline Patient Demographics and Clinical Features

Characteristics	Lobar (n = 27,126)	Segmental (n = 2121)	Wedge (n = 5176)	Overall (N = 34,423)
Age (y)				
18-69	17,416 (64.2)	1228 (57.9)	2830 (54.7)	21,474 (62.4)
≥70	9710 (35.8)	893 (42.1)	2346 (45.3)	12,949 (37.6)
Race				
Black	2038 (7.5)	140 (6.6)	425 (8.2)	2603 (7.6)
White	23,568 (86.9)	1852 (87.3)	4475 (86.5)	29,895 (86.8)
Other	1520 (5.6)	129 (6.1)	276 (5.3)	1925 (5.6)
Sex				
Female	17,138 (63.2)	1445 (68.1)	3365 (65.0)	21,948 (63.8)
Male	9988 (36.8)	676 (31.9)	1811 (35.0)	12,475 (36.2)
Tumor size (cm)				
<1.0	2192 (8.1)	296 (14.0)	811 (15.7)	3299 (9.6)
1.0-1.5	12,821 (47.3)	1068 (50.4)	2765 (53.4)	16,654 (48.4)
1.5-2.0	12,113 (44.7)	757 (35.7)	1600 (30.9)	14,470 (42.0)
Clinical stage				
T1	25,765 (95.0)	2051 (96.7)	4958 (95.8)	32,774 (95.2)
T2	1361 (5.0)	70 (3.3)	218 (4.2)	1649 (4.8)
Histological type				
Adenocarcinoma	15,560 (57.4)	1210 (57.0)	2870 (55.4)	19,640 (57.1)
Squamous cell carcinoma	3759 (13.9)	271 (12.8)	814 (15.7)	4844 (14.1)
Other	7144 (26.3)	619 (29.2)	1374 (26.5)	9137 (26.5)
Missing	663 (2.4)	21 (1.0)	118 (2.3)	802 (2.3)
No. of lymph nodes examined				
1-5	6618 (24.4)	824 (38.8)	3109 (60.1)	10,551 (30.7)
6-10	8753 (32.3)	645 (30.4)	1081 (20.9)	10,479 (30.4)
11-15	5486 (20.2)	325 (15.3)	406 (7.8)	6217 (18.1)
>15	4937 (18.2)	223 (10.5)	304 (5.9)	5464 (15.9)
Other lymph node procedures	1332 (4.9)	104 (4.9)	276 (5.3)	1712 (5.0)
Surgical margin status				
Negative	26,790 (98.8)	2086 (98.3)	5057 (97.7)	33,933 (98.6)
Positive	261 (1.0)	27 (1.3)	80 (1.5)	368 (1.1)
Missing	75 (0.3)	8 (0.4)	39 (0.8)	122 (0.4)
Surgical approach				
Open or unspecified	15,499 (57.1)	831 (39.2)	2527 (48.8)	18,857 (54.8)
Video-assisted	7186 (26.5)	866 (40.8)	2004 (38.7)	10,056 (29.2)
Robotic-assisted	4441 (16.4)	424 (20.0)	645 (12.5)	5510 (16.0)
Diagnosis time period				
2004-2010	6361 (23.4)	266 (12.5)	924 (17.9)	7551 (21.9)
2011-2015	9324 (34.4)	627 (29.6)	1779 (34.4)	11,730 (34.1)
2016-2019	11,441 (42.2)	1228 (57.9)	2473 (47.8)	15,142 (44.0)
Facility type				
Academic/research program	10,727 (39.5)	1144 (53.9)	2513 (48.6)	14,384 (41.8)
Community cancer program	10,737 (39.6)	623 (29.4)	1807 (34.9)	13,167 (38.3)
Integrated network cancer program	5334 (19.7)	337 (15.9)	831 (16.1)	6502 (18.9)
Missing	328 (1.2)	17 (0.8)	25 (0.5)	370 (1.1)
Facility volume				
High	18,875 (69.6)	1709 (80.6)	3658 (70.7)	24,242 (70.4)
Low/moderate	8251 (30.4)	412 (19.4)	1518 (29.3)	10,181 (29.6)
Income				
<$46,227	3460 (12.8)	214 (10.1)	648 (12.5)	4322 (12.6)
$46,277-$57,856	4905 (18.1)	278 (13.1)	857 (16.6)	6040 (17.5)
$57,857-$74,062	5582 (20.6)	379 (17.9)	969 (18.7)	6930 (20.1)
≥$74,063	9697 (35.7)	962 (45.4)	2096 (40.5)	12,755 (37.1)
Missing	3482 (12.8)	288 (13.6)	606 (11.7)	4376 (12.7)

Baseline patient, surgical treatment, and facility characteristics for NCDB patients treated with lobectomy, segmentectomy, or wedge resection. Also, all values are indicated in n (%).
NCDB, National Cancer Database.

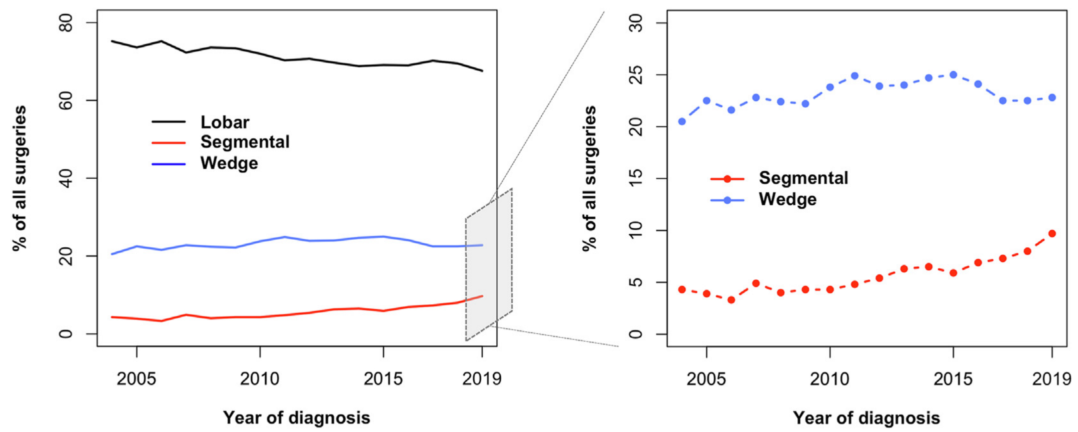

Figure 1. Utilization of lung resection procedures between 2004 and 2020. The proportions of lobectomy, segmentectomy, and wedge resections for patients with early-stage NSCLC with a tumor size of 2 cm or less, diagnosed between 2004 and 2020.

$p = 0.043$) and wedge resection (OR = 1.05, $p = 0.032$) (Fig. 3*B*; Supplementary Table 1).

Overall, patients with higher comorbidity burden (Charlson-Deyo score ≥ 1) were significantly more likely to be treated with segmentectomy (OR = 1.61, $p < 0.001$) and wedge resection (OR = 1.47, $p < 0.001$) compared with patients with minimal comorbidity burden (Charlson-Deyo score = 0). Nevertheless, over time, this difference in treatment odds decreased significantly, particularly for segmentectomy (segmental OR = 0.86, $p < 0.001$; wedge OR = 0.95, $p = 0.011$) (Fig. 3*C*; Supplementary Table 1).

Compared with male patients, female patients were more likely to be treated with segmentectomy (OR = 1.25, $p = 0.021$) but not wedge resection. Although not statistically significant, the sex difference for segmentectomy seems to have diminished over time (Fig. 3*D*; Supplementary Table 1).

No significant difference in the probability of segmentectomy was detected between non-squamous and squamous tumors. For wedge resection, a nonsquamous histological type was less likely to be treated compared with squamous cell carcinoma (OR = 0.74, $p < 0.001$). Nevertheless, more recent diagnosis time was associated with increased odds of wedge resection (OR = 1.07, $p = 0.011$) for patients with nonsquamous tumors (Fig. 3*E*; Supplementary Table 1).

Compared with White patients, non-White patients seem to be less likely to receive either SLR treatment, although overall the two groups did not differ

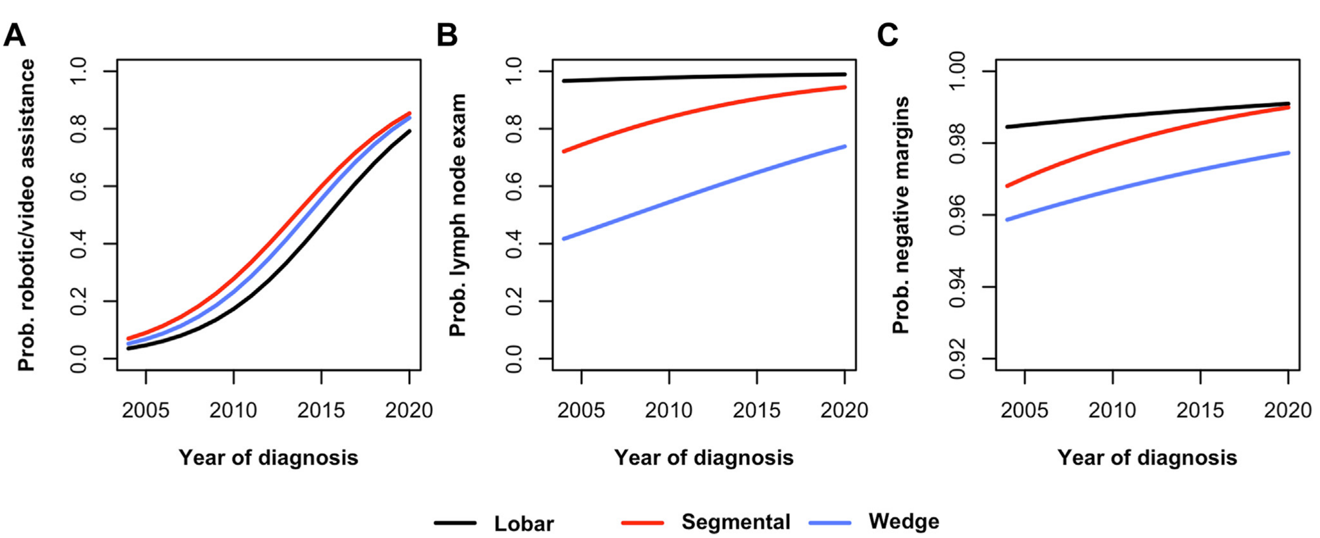

Figure 2. Probs. of surgical quality indicators between 2004 and 2020. Prob. of *(A)* robotic or video-assisted surgical approach, *(B)* at least one lymph node sampled, and *(C)* negative surgical margins, as modeled by logistic regression with interaction between patients' diagnosis year and type of surgical treatment (lobar, segmental, or wedge resection). Prob., probability.

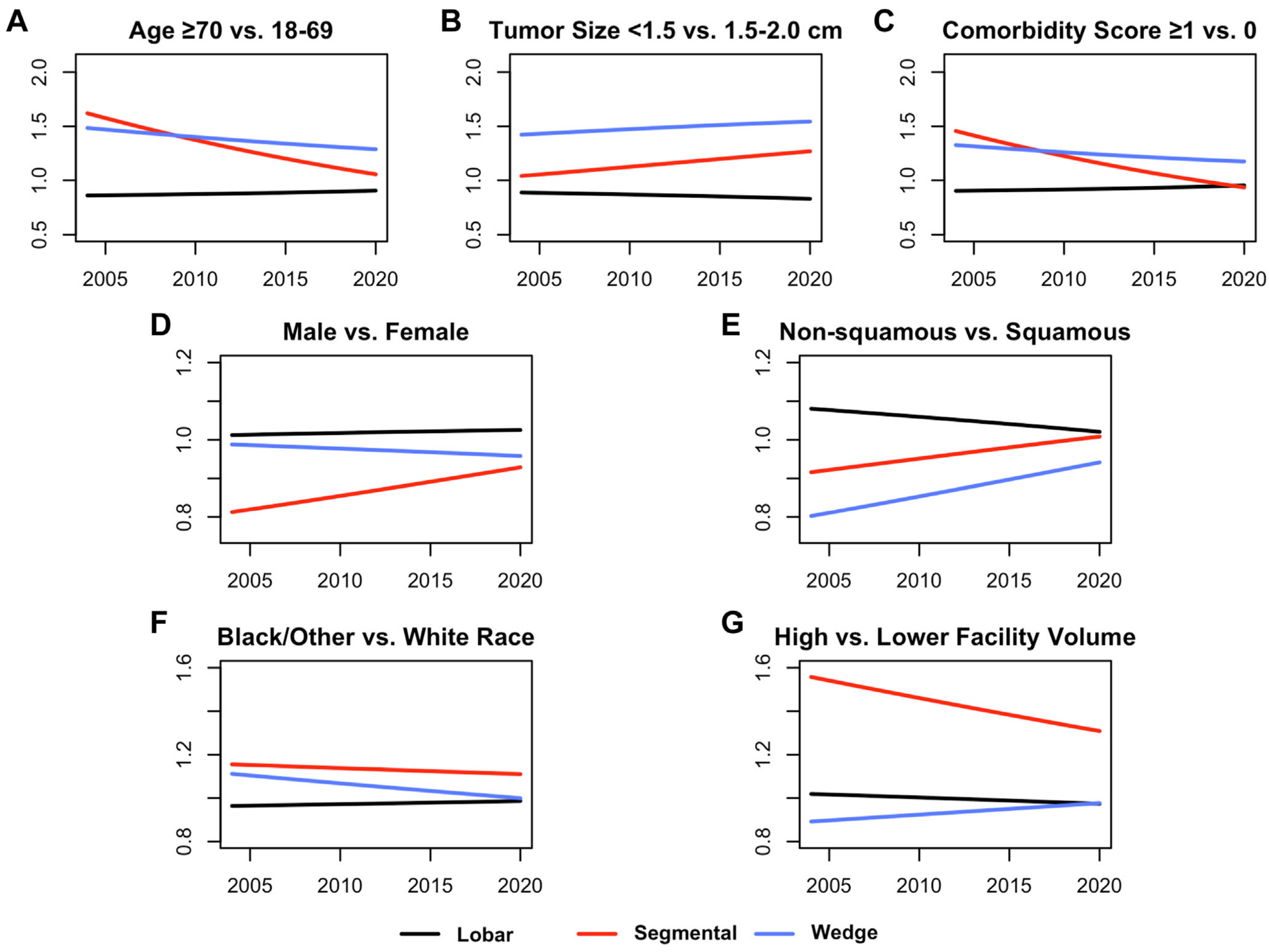

Figure 3. Treatment probability ratios by patient and facility characteristics, 2004 to 2020. Probabilities of lobectomy, segmentectomy, and wedge resection over time, as predicted by multinomial logistic regression models with interaction between patients' diagnosis year and pretreatment covariates. The ratios of predicted treatment probabilities are shown for *(A)* patients over age 70 compared with younger than 70, *(B)* tumors less than 1.5 cm compared with 1.5 to 2 cm in diameter, *(C)* patients with a Charlson-Deyo score of 1 or higher compared with 0, *(D)* male patients compared with female patients, *(E)* nonsquamous tumor histological type compared with squamous, *(F)* non-White compared with White patients, and *(G)* high versus low/moderate volume at the treating facility.

significantly in the likelihood of segmentectomy and wedge resection (Fig. 3*F*; Supplementary Table 1).

Facilities with high resection volumes were significantly more likely to perform segmentectomies (OR = 1.53, $p < 0.001$) and less likely to perform wedge resections (OR = 0.87, $p = 0.016$) compared with low/moderate-volume facilities, and differences persisted over time (Fig. 3*G*; Supplementary Table 1).

Trends in OS of Noncompromised Patients

To better understand the effect of treatment assignment on the survival of patients with NSCLC who are candidates for any surgical treatment, we compared OS between lobectomy, segmentectomy, and wedge resection for the subgroup of 34,423 patients with minimal comorbidity burden (Charlson-Deyo score = 0) and at least one lymph node sampled (Supplementary Table 2). Observations were weighted by IPTW to achieve balanced covariates between surgical groups (Supplementary Fig. 1). From the 2004 to 2010 period to the 2016 to 2019 period, the adjusted five-year OS rate increased from 81.3 % to 84.0% for lobectomy, 75.0% to 82.1% for segmentectomy, and 73.0% to 79.9% for wedge resection (Fig. 4). Kaplan-Meier curves of the IPTW-adjusted data reveal that, across all three time periods, segmentectomy (five-year OS = 80.6%, 95% CI: 78.1%–83.2%) had comparable five-year OS to lobectomy (five-year OS = 83.6%, 95% CI: 83.1%–84.1%). By contrast, the survival probability for wedge resection was lower than that for lobectomy in both the 2004 to 2010 and 2011 to 2015 periods. Nevertheless, in the 2016 to 2019 period, overlapping CIs

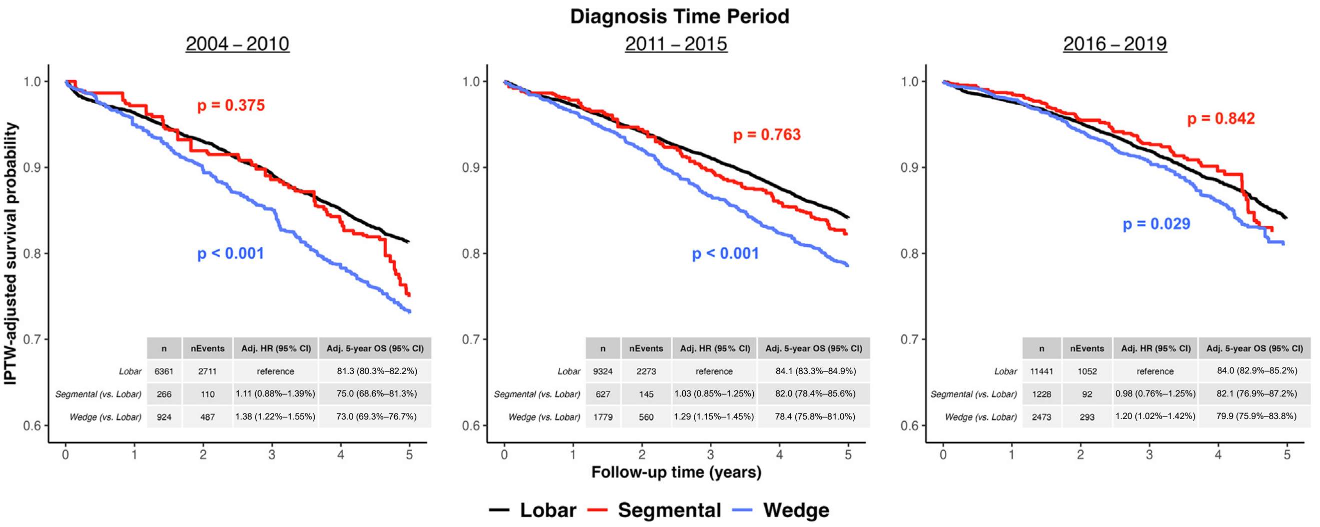

Figure 4. Adj. Kaplan-Meier curves by diagnosis time period. IPTW-adjusted Kaplan-Meier survival curves comparing OS after lobectomy, segmentectomy, and wedge resection for patients with minimal comorbidity burden and at least one lymph node sampled, diagnosed between 2004 and 2010, 2011 and 2015, and 2016 and 2019. Raw *p* values are reported for the hazard comparison between segmentectomy and lobectomy (red) and the comparison between wedge resection and lobectomy (blue). Note that in the third time period, the *p* value for wedge resection versus lobectomy does not survive Bonferroni correction for multiple comparisons. Adj., adjusted; CI, confidence interval; HR, hazard ratio; IPTW, inverse probability of treatment weighting; nEvents, number of events; OS, overall survival.

and no significant differences were observed between the five-year OS of lobectomy (five-year OS = 84.0%, 95% CI: 82.9%–85.2%), segmentectomy (five-year OS = 82.1%, 95% CI: 76.9%–87.2%), and wedge resection five-year OS = 79.9%, 95% CI: 75.9%–83.8%) (Fig. 4). Unadjusted survival curves and risk tables for each time period are reported in Supplementary Figure 2.

To explore whether these outcomes are consistent when considering all levels of nodal assessment, we repeated the survival analysis for the 3495 patients with zero or unknown lymph node sampling status. Across all time periods and surgical groups, the five-year OS rate was notably lower than the analysis of only patients with lymph node assessment. Comparison of survival curves suggests that, in all time periods, the five-year OS of both wedge resection and segmentectomy did not differ significantly from lobectomy for patients without node assessment (Supplementary Fig. 3). Finally, survival analysis on the entire cohort of 76,466 patients produced similar results to the noncompromised cohort for the first two time periods, where segmentectomy was noninferior to lobectomy whereas wedge resection reported worse OS (Supplementary Fig. 4). Nevertheless, without filtering for comorbidity burden and nodal assessment, wedge resection continued to reveal worse prognosis in the most recent 2016 to 2019 time period.

Discussion

In this population-level study, we investigated the temporal trends in the utilization, quality, and survival outcomes of lobectomy, segmentectomy, and wedge resection for early-stage NSCLC with a tumor size of 2 cm or less using NCDB data spanning from 2004 to 2020. Through the study of historical trends, our analysis offers a critical starting point for guiding future research efforts and implementation strategies to improve patient survival outcomes.

Increased Utilization and Quality of SLR

Among the cohort of 76,466 patients with NSCLC with T1 or T2 N0M0 peripheral tumors 2 cm or less in diameter, we observed a steady increase in the use of both segmentectomy and wedge resection between 2004 and 2020. In particular, the proportion of segmentectomies has doubled, and these trends are reflected in similar patient populations in other national databases.[14,15] Importantly, the quality of SLR (i.e., negative surgical margins and lymph node assessment) has also increased over time, reflecting greater surgical precision and attention to surgical staging, potentially leading to better patient survival.[16] The increased use and quality of SLR may be closely tied to the growing use of RATS/VATS, which is typically easier to perform with SLR and leads to better perioperative outcomes.[17] Advances in lung cancer screening and diagnostic technologies have detected a larger number of early cases treatable with SLR and minimally-invasive techniques, particularly cases of nonsquamous NSCLC that are also associated with lower mortality risk.[18]

Shifts in Treatment Selection

After the Lung Cancer Study Group trial in 1995, lobectomy was the standard surgical treatment for all early-stage NSCLC, and SLR was only reserved for patients with poor cardiopulmonary function (i.e., older age and higher comorbidity burden) who were not expected to be able to tolerate lobectomy. Although SLR remains the preferred treatment for older patients and patients with comorbidities, between 2004 and 2020, we observed that both segmental and wedge resections have become more likely treatments used for patients of younger age (<70 y) and minimal comorbidity burden (Charlson-Deyo score = 0). This likelihood has increased more rapidly for segmentectomy compared with wedge resection, which suggests a partiality toward selecting segmentectomy as the SLR alternative to lobectomy for cases involving younger, healthier patients. These changes may be a consequence of a growing body of evidence suggesting that segmentectomy and even wedge resection (with adequate lymph node sampling) have comparable mortality and disease recurrence risk to lobectomy for early-stage NSCLC with tumors 2 cm or less in diameter and a reduced risk of complication and better pulmonary preservation.[6,15,19–23]

With respect to tumor size, SLR continues to be the preferred treatment for smaller tumors less than 1.5 cm in size. Between 2004 and 2020, patients with tumors less than 1.5 cm in size were increasingly likely to receive SLR, which may reflect evolving beliefs among surgeons that smaller tumor size is associated with better outcomes for SLR, even among tumors 2 cm or less in size. A larger number of small tumors may also be treated with SLR owing to increased rates of lung cancer screening, with incidental findings of small tumors at an early stage.[24] Early evidence from the Surveillance, Epidemiology, and End Results (SEER) database suggests that smaller tumors (e.g., ≤1 cm) treated with SLR are more likely to lead to favorable postoperative outcomes,[25] although a subsequent, larger SEER study found lobectomy to still have better survival among tumors 1 cm or less in size.[5]

Trends in OS

Our findings of increased five-year survival probability after lobectomy, segmentectomy, and wedge resection for early-stage tumors in the NCDB are encouraging and consistent with earlier temporal trends observed in the SEER database.[15] Improved prognosis across all surgical treatments can be attributed to widespread advancements in lung cancer detection and care over the past 20 years, including improvements in postrecurrence treatments for NSCLC.[26,27] In addition, the adoption of positron emission tomography for more accurate preoperative staging could have contributed to improved outcomes in all groups.[28,29]

From 2004 through 2015, wedge resection was associated with higher mortality risk compared with lobectomy, despite requiring lymph node assessment in all cases and balancing treatment groups with IPTW adjustment. By contrast, the CALGB 140503 clinical trial, conducted from 2007 to 2017, did not find wedge resection to be inferior to lobectomy in terms of OS and disease-free survival in cT1a peripheral tumors among patients with good performance status.[6] This discrepancy may be explained by unobserved confounders; for instance, the wedge resection group may exhibit worse survival outcomes owing to higher rates of noncancer deaths[30] (e.g., death caused by comorbid conditions not counted in the Charlson-Deyo score) or poorer baseline cardiopulmonary function, which was not available in the NCDB.

From 2016 through 2019, nevertheless, for the first time, no difference in the five-year OS was observed between all three surgical procedures. Our results from this period corroborate evidence from the CALGB and JCOG clinical trials that both segmental and wedge resection have noninferior OS compared with lobectomy for patients with good performance status. We found that, in addition to having the largest improvement in five-year OS, segmentectomy was not associated with significantly higher mortality risk compared with lobectomy in any time period between 2004 and 2020, and we observed a trend of decreasing risk with more recent diagnosis time. These results are reflective of the positive impact that recent research and technology advancements and improvements in surgical training for SLRs have had on surgical quality and patient survival. In particular, advancements in diagnostic technologies, most notably the early identification of ground-glass nodules through low-dose computed tomography screening, may account for the improved prognosis seen in segmentectomies. Ground-glass nodules, the vast majority of which develop into adenocarcinomas,[31] are known to have better survival outcomes,[32,33] and we have observed a trend of increasing SLR utilization in the treatment of adenocarcinomas and other nonsquamous tumors.

Future Directions

The historical trends observed in this study cohort provide important insights for the future implementation of surgical treatments for NSCLC. First, the increasing use of segmentectomy and wedge resection in patients who are relatively healthy, aged less than 70 years, and have tumors less than 1.5 cm in size highlights the need for more robust evidence demonstrating whether either SLR approach does indeed lead to better outcomes in these cases. Although our analysis of noncompromised patients reveals improved survival outcomes in all surgical approaches and noninferiority for segmentectomy compared with lobectomy, we did not perform any survival comparisons across patient characteristics, and current evidence remains conflicting. In a recent JCOG 0802 investigation, Hattori et al.[34] found segmentectomy to have inferior five-year recurrence-free survival compared with lobectomy in female patients and patients aged 70 years and no benefit in OS owing to lower rates of non–cancer-related causes of death after surgery in these populations. Furthermore, the prognostic impact of tumor size, particularly tumors less than 1 cm or less than 1.5 cm in size, is unclear and may differ across histologic classifications and different surgical treatments.[5,25,35] To understand whether segmentectomy and wedge resection should be indicated for patients with certain features, future work should incorporate a wider scope of longitudinal evidence and investigate the impact of specific patient characteristics on survival and disease recurrence across the three surgical treatments.

In addition to patients' clinical and demographic features, we also observed that treatment availability varied significantly by facility volume; specifically, treatment using segmentectomy was heavily concentrated in high-volume facilities, suggesting disparate treatment access at different hospitals. Efforts should be made to understand the potential costs and patient benefits that would result from increasing access to segmentectomy at low-volume institutions or facilities with fewer resources.

Finally, our findings have important implications in relation to the recently published results of the JCOG and CALGB clinical trials. It remains unclear the extent to which the trials' results can be generalized to the larger population of patients with stage 1 NSCLC with tumors 2 cm or less in diameter in the United States. The baseline characteristics of the NCDB cohort in this study are closely aligned with the randomized cohort in the CALGB trial, so it may serve as a large, observational data set that can be jointly analyzed with the trial's results. Future studies may utilize a calibration weighting approach[36] to merge the data from the CALGB trial and the NCDB to estimate the average treatment effect of SLR versus lobectomy in the United States patient population.

Limitations

There are several limitations to this retrospective analysis. First, physiological performance status is known to be an important predictor of postoperative outcomes. Nevertheless, this information was not available in the NCDB, and thus patient selection bias may not be fully accounted for in our survival analysis. Instead, as lung function and comorbid disease are highly associated in many populations,[37] we utilize comorbidity status in an attempt to account for selection bias. Specifically, excluding patients with comorbidities helps reduce heterogeneity in performance status, respiratory function, and competing sources of mortality risk. Nonetheless, variable performance status may still be present as an unobserved confounder in this analysis. Second, we used patients' time of diagnosis as an indirect measure of treatment time, as lung cancer resections are generally performed shortly after initial diagnosis. Nevertheless, diagnosis time in the NCDB was recorded by year, which limited the resolution at which we were able to observe temporal trends. Furthermore, the scope of our prognostic analysis was limited to five-year OS and does not shed light on long-term survival, disease recurrence, or the effects of postoperative treatments. Third, the IPTW method is one of many approaches that are suitable for causal inference in observational studies, and it is sensitive to extreme weights, which may inflate the variance of the estimate. Although we chose to perform GBM-based IPTW to estimate the effects of multiple treatments and keep subjects with missing values, other approaches, such as empirical likelihood-based methods,[38] can be used to estimate the treatment effect without a propensity score model.

Conclusion

This population-level study reveals dynamic trends in surgical approaches for early-stage NSCLC, with a steady increase in RATS/VATS and widespread improvements in surgical quality indicators and OS over the past 15 years. Although the use of wedge resection remains relatively stable, segmentectomy has emerged as a popular alternative to lobectomy. Our prognostic analysis, in conjunction with recent findings from clinical trials, underscores the critical need for more evidence to understand whether segmentectomy or wedge resection may now be comparable to lobectomy in certain subgroups of patients.

Informed Consent

Exemption from informed consent was granted by the Duke University Health System Institutional Review Board due to the use of de-identified patient data.

CRediT Authorship Contribution Statement

Eden Z. Deng: Conceptualization, Methodology, Data collection, Data curation, Formal analysis, Interpretation, Writing - original draft, Final approval.

Xiaofei Wang: Conceptualization, Methodology, Project administration, Data collection, Data curation, Formal analysis, Interpretation, Writing - original draft, Final approval.

Jianrong Zhang: Formal analysis, Interpretation, Writing - original draft, Final approval.

Thomas E. Stinchcombe: Conceptualization, Methodology, Formal analysis, Interpretation, Writing - original draft, Final approval.

Chi-Fu (Jeffrey) Yang: Conceptualization, Methodology, Data collection, Data curation, Formal analysis, Interpretation, Writing - original draft, Final approval.

Nasser Altorki: Conceptualization, Methodology, Formal analysis, Interpretation, Writing - original draft, Final approval.

Data Availability

The de-identified patient-level NCDB data were available through an application process to the investigators at the Duke School of Medicine, an institute associated with CoC-accredited cancer programs. The request for data sharing should be addressed to the NCDB administrators.

Disclosure

The authors declare no conflict of interest.

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Supplementary Data

Note: To access the supplementary material accompanying this article, visit the online version of the *JTO Clinical and Research Reports* at www.jtocrr.org and at https://doi.org/10.1016/j.jtocrr.2025.100794.

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