

Factors associated with cardiopulmonary exercise capacity changes after anatomical and non-anatomical lung resection: a retrospective cohort study

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Abstract

Background

Postoperative cardiopulmonary exercise testing (CPET) parameter shifts following lung resection remain incompletely understood. We investigated which clinical and physiological factors are associated with CPET changes after wedge resection, segmentectomy, and lobectomy.

Methods

A retrospective cohort of 149 patients (wedge resection, $n = 47$; segmentectomy, $n = 53$; lobectomy, $n = 49$) underwent preoperative and postoperative CPET at a single center. Within-group paired testing quantified postoperative shifts. Analysis of covariance (ANCOVA), adjusting for preoperative baseline, age, sex, body mass index (BMI), and follow-up duration, compared postoperative CPET parameters across groups. Dose-response trend tests employed ordinal coding of resection extent. Multivariable linear regression identified variables independently associated with CPET parameter changes (Δ CPET). Sensitivity analysis was limited to patients followed up 6–18 months.

Results

All three groups showed significant shortening of time to anaerobic threshold (all $P \leq 0.005$). Segmentectomy affected the widest range of parameters (five significantly altered), followed by wedge resection (two) and lobectomy (two). ANCOVA revealed no significant inter-group differences for any adjusted postoperative CPET parameter (all $P > 0.05$). The dose-response trend for Δ time to peak was borderline significant ($P = 0.045$) but lost significance in the sensitivity subset ($P = 0.071$). Preoperative baseline value was the strongest correlate of Δ CPET across all models (standardized β from -0.23 to -0.68 , all $P \leq 0.008$). Age independently predicted Δ peak heart rate (HR) (standardized $\beta = -0.20$, $P = 0.017$). BMI trended toward predicting Δ peak HR (standardized $\beta = -0.12$, $P = 0.102$) without reaching significance. Resection extent did not independently predict any Δ CPET parameter (all $P > 0.05$).

Conclusions

Lung resection was associated with meaningful changes in exercise timing and heart rate indices, yet resection extent did not independently determine CPET parameter change magnitude. Preoperative baseline values and age were the most consistent predictors of postoperative CPET variation, with BMI showing a marginal trend. Individual patient characteristics—rather than tissue volume removed—drive most variability in postoperative cardiopulmonary adaptation.

Background

Anatomical resections (lobectomy, segmentectomy) and non-anatomical approaches (wedge resection) constitute the cornerstone of surgical management for early-stage lung cancer and suspicious pulmonary nodules [1–3, 16]. The expanding uptake of low-dose CT screening has increased resection volumes and drawn greater attention to how these procedures affect postoperative functional status. Striking the right balance between oncological thoroughness and cardiopulmonary preservation remains a daily clinical dilemma, making it essential to understand which factors shape functional recovery after surgery.

As the reference standard for measuring functional exercise capacity, CPET reflects the combined performance of the cardiovascular, respiratory, and metabolic systems under physical load [4, 5]. Parameters derived from the test—including peak heart rate, oxygen pulse, ventilatory efficiency (EqCO_2 at anaerobic threshold), and temporal exercise indices—provide a window into multi-organ coordination. Within thoracic surgery, CPET has been applied primarily for preoperative risk stratification and prediction of postoperative complications [6–9]. Yet how CPET parameters shift after resection, and which variables govern those shifts, have not been systematically described.

Published evidence regarding the influence of resection extent on postoperative cardiopulmonary function is inconsistent. Several investigators reported better exercise preservation after sublobar procedures compared with lobectomy [10, 11], while others observed comparable functional outcomes between anatomical and non-anatomical operations [12, 13]. A common methodological shortcoming is the restriction to two-group comparisons—usually sublobar versus lobar—which precludes systematic evaluation of dose-response patterns across graded levels of resection. Moreover, the independent contributions of patient-level characteristics (age, sex, BMI, baseline functional capacity) to postoperative CPET change have been inadequately explored within multivariable frameworks. Should patient-level variables, rather than resection magnitude itself, prove to be the dominant drivers of CPET response, clinical attention would need to shift toward individualized preoperative assessment and tailored rehabilitation strategies.

We designed the present study to examine factors associated with cardiopulmonary exercise capacity changes after lung resection, pursuing three specific aims: (1) characterize within-group pre-to-postoperative CPET alterations across three surgical categories (wedge resection, segmentectomy, lobectomy); (2) test whether resection extent bears an independent association with postoperative CPET parameters after adjustment for key confounders; and (3) identify patient-level variables independently linked to the magnitude of CPET parameter change. We hypothesized that measurable CPET shifts would occur after resection, that a dose-response gradient would link resection extent to CPET change, and that patient-level characteristics would independently predict postoperative CPET outcomes.

Methods

Study design and reporting

This retrospective cohort analysis was conducted at the Department of Thoracic Surgery, Qinhuangdao First Hospital, Qinhuangdao, Hebei, China. The Institutional Review Board of Qinhuangdao First Hospital approved the study (approval number: 2025B-011-01). Because of the retrospective, observational design, the requirement for individual written informed consent was waived. All procedures conformed to the

Declaration of Helsinki (2013 revision). Reporting adhered to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines [14].

Participants

The study population comprised consecutive patients undergoing pulmonary resection at our institution between July 2023 and July 2026 who had completed both preoperative and postoperative symptom-limited CPET assessments. Eligibility required: (1) age ≥ 18 years; (2) histopathologically confirmed pulmonary lesion warranting surgery; (3) paired preoperative and postoperative CPET with documented attainment of anaerobic threshold; and (4) complete clinical and CPET datasets.

Group allocation—wedge resection, segmentectomy, or lobectomy—was non-randomized and governed by tumor features, patient comorbidity, and surgeon preference.

Exclusion criteria were: (1) inability to perform adequate CPET due to musculoskeletal or neurological constraints; (2) failure to reach anaerobic threshold during CPET ($n = 3$); (3) concurrent major cardiac surgery; (4) prior neoadjuvant chemotherapy or radiotherapy; (5) missing essential clinical or CPET data.

Surgical procedures

Three resection categories were included. Wedge resection (non-anatomical) involved peripheral excision without adherence to segmental anatomy. Segmentectomy (anatomical) entailed removal of one or more bronchopulmonary segments with individual ligation of segmental vessels and bronchi and division of intersegmental planes. Lobectomy (anatomical) consisted of removal of an entire lung lobe with standard hilar dissection. All operations were performed by experienced thoracic surgeons using conventional techniques. The specific procedure was guided by tumor size, anatomical location, pathological stage, and intraoperative findings.

CPET protocol

CPET protocol

Symptom-limited CPET was performed on an electronically braked cycle ergometer within one week before surgery and at the postoperative follow-up visit. The protocol followed a standardized incremental ramp design consistent with American Thoracic Society/American College of Chest Physicians (ATS/ACCP) guidance [4]. Each test included four phases: (1) 3-minute resting baseline; (2) 3-minute warm-up at 20–30 W; (3) individually titrated incremental loading at 10–20 W/min until symptom limitation; (4) ≥ 3 -minute recovery.

Breath-by-breath gas exchange measurements were obtained using calibrated metabolic analyzers (Vmax Encore, CareFusion, or equivalent). Continuous 12-lead ECG and pulse oximetry were recorded throughout. Anaerobic threshold was identified independently by two investigators blinded to patient identity and clinical data, using the V-slope method.

Outcome measures

Outcome measures

The following CPET variables were recorded at both time points:

1. AT HR (bpm): Heart rate at the anaerobic threshold
2. Peak HR (bpm): Maximum heart rate attained during exercise
3. AT O₂ pulse (mL/beat): Oxygen consumption divided by heart rate at AT
4. Peak O₂ pulse (mL/beat): Maximum oxygen pulse recorded
5. AT EqCO₂ (mmHg): Ventilatory equivalents for CO₂ at AT
6. Time to AT (min): Elapsed time from exercise onset to anaerobic threshold
7. Time to peak (min): Total exercise duration to peak exertion
8. Peak RER: Maximum respiratory exchange ratio (VCO₂/VO₂)
9. HRR utilization (%): Fraction of heart rate reserve consumed between AT and peak exercise, computed as $(\text{Peak HR} - \text{AT HR}) / (\text{Peak HR} - \text{Resting HR}) \times 100$.

Postoperative CPET values (peak HR, peak O₂ pulse, HRR, time to AT, time to peak, and peak RER) were compared across the three groups via ANCOVA. The primary endpoints for multivariable regression were changes (Δ) in five CPET variables: Δ Peak HR, Δ HRR, Δ time to AT, Δ time to peak, and Δ peak O₂ pulse.

Statistical analysis

Distributional normality was assessed with the Shapiro-Wilk test. Normally distributed variables were expressed as mean $\pm$ SD and evaluated with paired t-tests (within-group) or one-way analysis of variance (ANOVA) (between-group). Non-normal variables were summarized as median (IQR) and tested with Wilcoxon signed-rank tests (within-group) or Kruskal-Wallis tests (between-group). Categorical variables were tabulated as n (%) and analyzed by chi-squared or Fisher's exact test.

The analytical plan had five components:

1. **(A) Within-group paired comparisons:** Preoperative and postoperative CPET values were compared within each surgical group using paired t-tests or Wilcoxon signed-rank tests.
2. **(B) ANCOVA across three surgical groups:** For each postoperative CPET endpoint, a model was fitted with surgical group as the between-subjects factor and preoperative baseline value, age, sex, BMI, and follow-up duration as covariates. Adjusted marginal means and 95% confidence intervals (CIs) were extracted. Post-hoc pairwise comparisons with Bonferroni correction were performed only when the omnibus F-test was significant.
3. **(C) Dose-response trend test:** Linear trend tests regressed Δ CPET values against ordinal resection extent (wedge = 1, segmentectomy = 2, lobectomy = 3).

4. **(D) Multivariable linear regression:** A model was fitted for each Δ CPET endpoint, incorporating resection extent (ordinal), age, sex, BMI, smoking history, preoperative baseline value, and follow-up duration as predictors. Missing data were handled through listwise deletion. Standardized β coefficients enabled cross-variable comparison. Model fit was summarized by adjusted R^2 .
5. **(E) Sensitivity analysis:** All core analyses (ANCOVA and trend tests) were repeated in patients whose follow-up fell between 6 and 18 months.

Post-hoc power calculations were performed for ANCOVA comparisons using Cohen's f from the observed F -statistics. Two-sided $P < 0.05$ was considered significant. Analyses were conducted in Python (scipy, numpy, pandas, statsmodels).

Results

3.1 Patient characteristics

Of 152 patients meeting initial screening criteria, three were excluded because anaerobic threshold data were absent from CPET recordings, leaving 149 for analysis: wedge resection ($n = 47$), segmentectomy ($n = 53$), and lobectomy ($n = 49$) (Fig. 1).

STROBE flow diagram illustrating participant selection. A total of 152 patients who underwent lung resection (wedge resection $n = 48$, segmentectomy $n = 54$, lobectomy $n = 50$) between July 2023 and July 2026 were screened. Of these, 149 patients had complete paired preoperative and postoperative CPET data and were included in the analysis (wedge resection $n = 47$, segmentectomy $n = 53$, lobectomy $n = 49$). Three patients were excluded due to the absence of anaerobic threshold data during CPET.

Baseline characteristics are shown in Table 1. Groups were well balanced for age ($P = 0.158$), BMI ($P = 0.887$), preoperative forced expiratory volume in 1 second (FEV_1) % predicted ($P = 0.238$), sex distribution ($P = 0.733$), smoking history ($P = 0.297$), hypertension ($P = 0.983$), and diabetes ($P = 0.964$). No preoperative CPET parameter differed significantly between groups (all $P > 0.1$). Follow-up duration did differ across groups ($P = 0.035$); the segmentectomy cohort had a longer mean follow-up interval (13.8 ± 4.3 months) than the wedge cohort (10.2 ± 5.9 months). Follow-up duration was therefore retained as a covariate in all subsequent adjusted models.

Table 1
Baseline characteristics of study participants

Variable	Wedge (n = 47)	Segmentectomy (n = 53)	Lobectomy (n = 49)	P-value
Age, years	58.3 ± 10.9	59.5 ± 9.5	62.6 ± 8.1	0.158
Male, n (%)	18 (38.3%)	17 (32.1%)	19 (38.8%)	0.733
BMI, kg/m ²	24.2 ± 3.4	24.3 ± 2.2	24.6 ± 3.4	0.887
Smoking history, n (%)	15 (31.9%)	10 (18.9%)	11 (22.4%)	0.297
Hypertension, n (%)	14 (29.8%)	16 (30.2%)	14 (28.6%)	0.983
Diabetes, n (%)	4 (8.5%)	5 (9.4%)	4 (8.2%)	0.964
Pre-op FEV ₁ % predicted	91.5 ± 16.7	91.3 ± 16.6	87.6 ± 17.8	0.238
Follow-up interval, months	10.2 ± 5.9	13.8 ± 4.3	11.5 ± 6.0	0.035
Pre-op AT HR, bpm	106.2 ± 13.1	106.5 ± 11.0	108.3 ± 15.7	0.794
Pre-op Peak HR, bpm	135.1 ± 17.2	135.6 ± 17.7	138.0 ± 20.4	0.792
Pre-op AT O ₂ pulse, mL/beat	6.7 ± 1.7	6.7 ± 1.8	6.8 ± 2.1	0.952
Pre-op Peak O ₂ pulse, mL/beat	9.6 ± 2.2	8.9 ± 1.8	9.4 ± 2.4	0.355
Pre-op AT EqCO ₂ , mmHg	28.2 ± 3.7	27.7 ± 3.0	28.3 ± 3.9	0.729
Pre-op Time to AT, min	9.1 ± 1.4	9.7 ± 1.3	9.3 ± 1.1	0.112
Pre-op Time to peak, min	11.7 ± 1.6	12.3 ± 1.6	12.0 ± 1.1	0.102
Pre-op Peak RER	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	0.147
Pre-op HRR, %	51.7 ± 15.3	51.3 ± 14.2	50.8 ± 13.9	0.933

Data are presented as mean ± SD or n (%). P-values from Kruskal-Wallis test for continuous variables and chi-squared test for categorical variables.

3.2 Changes in CPET parameters after lung resection

Paired testing uncovered significant pre-to-postoperative shifts across all three groups, although the breadth of affected parameters differed (Table 2, Fig. 2).

Paired pre- and postoperative CPET parameter values across the three surgical groups. Each panel displays the individual paired trajectories (thin lines) and group-level mean ± 95% CI (thick lines with shaded bands) for patients undergoing wedge resection (n = 47), segmentectomy (n = 53), and lobectomy (n = 49).

Parameters include peak heart rate, heart rate reserve utilization, time to anaerobic threshold, time to peak exercise, peak O₂ pulse, and AT ventilatory equivalent for CO₂.

Segmentectomy produced the most extensive changes. Five of nine CPET endpoints showed significant pre-versus-post differences. Peak HR rose from 135.6 ± 17.7 to 141.5 ± 17.3 bpm ($P = 0.012$). AT EqCO₂ increased from 27.7 ± 3.0 to 28.7 ± 2.9 mmHg ($P < 0.001$). Time to AT shortened from 9.5 (8.7–10.1) to 8.7 (8.2–9.0) min ($P < 0.001$), and time to peak shortened from 11.8 (11.5–13.0) to 11.5 (11.0–11.9) min ($P < 0.001$). HRR rose from $51.3 \pm 14.2\%$ to $55.8 \pm 17.1\%$ ($P = 0.048$).

Wedge resection had two significant shifts. Time to AT shortened from 9.1 ± 1.4 to 8.7 ± 1.0 min ($P = 0.005$). HRR rose from $51.7 \pm 15.3\%$ to $56.4 \pm 12.4\%$ ($P = 0.028$; corroborated by Wilcoxon signed-rank test, $P = 0.044$).

Lobectomy showed changes in two parameters. Time to AT shortened from 9.3 ± 1.1 to 8.7 ± 0.8 min ($P < 0.001$), and time to peak shortened from 12.0 ± 1.1 to 11.3 ± 1.1 min ($P < 0.001$).

Shortening of time to AT was the sole parameter that reached significance uniformly across all groups (all $P \leq 0.005$). Time to peak decreased significantly in segmentectomy and lobectomy, whereas the wedge group showed only a non-significant tendency ($P = 0.167$). Apart from time to AT, no other parameter changed significantly in all three groups: AT HR, AT O₂ pulse, peak O₂ pulse (all groups), and peak RER (all groups) remained essentially stable.

Table 2
Within-group paired comparisons of CPET parameters (pre- vs. postoperative)

Parameter	Wedge Pre-op	Wedge Post-op	P	Seg Pre-op	Seg Post-op	P	Lob Pre-op	Lob Post-op	P
AT HR (bpm)	106.2 ± 13.1	104.4 ± 11.9	0.312	106.5 ± 11.0	109.0 ± 13.5	0.134	108.3 ± 15.7	108.7 ± 15.1	0.769
Peak HR (bpm)	135.1 ± 17.2	137.7 ± 18.0	0.193	135.6 ± 17.7	141.5 ± 17.3	0.012*	138.0 ± 20.4	137.4 ± 17.6	0.777
AT O ₂ pulse (mL/beat)	6.7 (5.5–7.8)	7.1 (6.0–8.6)	0.198	6.5 (5.4–7.8)	6.8 (5.7–8.2)	0.180	6.7 (5.3–8.4)	7.0 (5.3–8.6)	0.160
Peak O ₂ pulse (mL/beat)	9.6 ± 2.2	9.8 ± 2.3	0.402	8.9 ± 1.8	9.2 ± 2.0	0.205	9.4 ± 2.4	9.3 ± 2.3	0.962
AT EqCO ₂ (mmHg)	28.2 ± 3.7	28.8 ± 3.5	0.073	27.7 ± 3.0	28.7 ± 2.9	< 0.001***	28.3 ± 3.9	28.9 ± 3.8	0.081
Time to AT (min)	9.1 ± 1.4	8.7 ± 1.0	0.005**	9.5 (8.7–10.1)	8.7 (8.2–9.0)	< 0.001***	9.3 ± 1.1	8.7 ± 0.8	< 0.001***
Time to peak (min)	11.6 (10.9–12.4)	11.5 (10.7–12.2)	0.167	11.8 (11.5–13.0)	11.5 (11.0–11.9)	< 0.001***	12.0 ± 1.1	11.3 ± 1.1	< 0.001***
Peak RER	1.2 ± 0.1	1.2 ± 0.1	0.875	1.2 ± 0.1	1.2 ± 0.2	0.650	1.1 (1.1–1.2)	1.1 (1.1–1.2)	0.937
HRR (%)	51.7 ± 15.3	56.4 ± 12.4	0.028*	51.3 ± 14.2	55.8 ± 17.1	0.048*	50.8 ± 13.9	53.2 ± 12.6	0.360

Data are presented as mean ± SD for normally distributed data or median (IQR) for non-normally distributed data, as determined by Shapiro-Wilk test. Paired t-tests were used for normally distributed variables; Wilcoxon signed-rank tests were used for non-normally distributed variables. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

3.3 Resection extent bears no independent association with postoperative CPET changes

ANCOVA was used to compare adjusted postoperative CPET parameters across the three groups, with correction for preoperative baseline value, age, sex, BMI, and follow-up duration (n = 145; three patients lacking follow-up data and one additional patient with incomplete covariate data were excluded). As displayed in Table 3, no inter-group difference attained statistical significance for any of the six endpoints (Fig. 3).

Forest plot displaying adjusted marginal means and 95% confidence intervals for six postoperative CPET parameters across wedge resection, segmentectomy, and lobectomy groups. Models are adjusted for preoperative baseline value, age, sex, BMI, and follow-up duration (n = 146). F-statistics and P-values from ANCOVA are shown for each parameter. No inter-group difference reached statistical significance.

Adjusted postoperative peak HR was 138.2 bpm (95% CI: 134.7–141.8) for wedge resection, 141.2 bpm (95% CI: 137.6–144.8) for segmentectomy, and 137.1 bpm (95% CI: 133.5–140.7) for lobectomy ($F(2,137) = 1.270$, $P = 0.284$). Adjusted postoperative peak O₂ pulse ($P = 0.620$), HRR ($P = 0.490$), time to AT ($P = 0.283$), time to peak ($P = 0.384$), and peak RER ($P = 0.565$) likewise did not differ across groups.

Linear trend testing with ordinal coding of resection extent produced no significant trends for Δ peak HR ($P = 0.256$), Δ HRR ($P = 0.115$), Δ time to AT ($P = 0.380$), or Δ peak O₂ pulse ($P = 0.355$). A near-significant trend emerged for Δ time to peak (slope = -0.248 , $R^2 = 0.028$, $P = 0.045$), pointing to a modest tendency for greater exercise-time reduction with increasing resection extent. This finding warrants cautious interpretation, given that the model accounted for only 2.8% of total variance (Fig. 6).

Dose-response analysis showing the relationship between ordinal resection extent (wedge = 1, segmentectomy = 2, lobectomy = 3) and Δ CPET values. Each panel displays the mean Δ CPET value ($\pm$ 95% CI) for each surgical group, with the linear trend test P-value shown. While some parameters show nominal trends, no dose-response relationship reached statistical significance after adjustment, indicating that resection extent does not independently determine the magnitude of CPET change.

Table 3
ANCOVA comparison of postoperative CPET parameters across three surgical groups

Parameter	Wedge (n = 47)	Segmentectomy (n = 53)	Lobectomy (n = 49)	F(2,137)	P
Peak HR, adjusted mean (95% CI)	138.2 (134.7–141.8)	141.2 (137.6–144.8)	137.1 (133.5–140.7)	1.270	0.284
Peak O ₂ pulse, adjusted mean (95% CI)	9.54 (9.15–9.93)	9.38 (8.99–9.78)	9.25 (8.86–9.64)	0.480	0.620
HRR, adjusted mean (95% CI)	56.7 (52.9–60.5)	55.3 (51.4–59.1)	53.3 (49.5–57.1)	0.716	0.490
Time to AT, adjusted mean (95% CI)	8.72 (8.48–8.96)	8.46 (8.22–8.70)	8.70 (8.46–8.93)	1.272	0.283
Time to peak, adjusted mean (95% CI)	11.56 (11.31–11.82)	11.37 (11.12–11.63)	11.30 (11.05–11.56)	0.963	0.384
Peak RER, adjusted mean (95% CI)	1.17 (1.14–1.21)	1.19 (1.16–1.23)	1.17 (1.13–1.20)	0.574	0.565

ANCOVA models adjusted for preoperative baseline value, age, sex, BMI, and follow-up duration. No post-hoc pairwise comparisons were performed as all overall F-tests were non-significant.

3.4 Patient-level variables associated with CPET changes

Multivariable linear regression was used to identify covariates independently linked to CPET parameter change. Predictors included resection extent (ordinal), age, sex, BMI, smoking history, preoperative baseline value, and follow-up duration (Table 4).

ΔPeak HR (adjusted $R^2 = 0.27$): Two covariates independently predicted changes in peak HR, and BMI showed a marginal association. Higher preoperative peak HR was the strongest predictor (standardized $\beta = -0.56$, unstandardized $\beta = -0.45$, 95% CI: -0.57 to -0.32 , $P < 0.001$)—patients with elevated baseline values tended to have larger postoperative reductions. Older age independently predicted smaller increases (or larger decreases) in peak HR (standardized $\beta = -0.20$, unstandardized $\beta = -0.30$, 95% CI: -0.55 to -0.05 , $P = 0.017$). Higher BMI showed a trend toward predicting smaller changes (standardized $\beta = -0.12$, unstandardized $\beta = -0.60$, 95% CI: -1.32 to 0.12 , $P = 0.102$), though this did not reach statistical significance under independent verification due to multicollinearity (condition number $> 5 \times 10^6$). Resection extent was not associated with Δpeak HR (standardized $\beta = -0.04$, unstandardized $\beta = -0.81$, 95% CI: -3.52 to 1.89 , $P = 0.552$).

ΔHRR (adjusted $R^2 = 0.05$): Preoperative HRR alone predicted changes in HRR (standardized $\beta = -0.23$, unstandardized $\beta = -0.79$, 95% CI: -1.38 to -0.21 , $P = 0.008$). Patients with higher baseline HRR tended to show larger postoperative increases. No other covariate reached significance, and resection extent was unrelated (standardized $\beta = -0.13$, $P = 0.114$). The low adjusted R^2 indicates the modeled covariates captured only a small fraction of HRR-change variance.

ΔTime to AT (adjusted $R^2 = 0.50$): Preoperative time to AT had a strong inverse relationship with change (standardized $\beta = -0.68$, unstandardized $\beta = -0.63$, 95% CI: -0.75 to -0.52 , $P < 0.001$), accounting for roughly half the model's explained variance. Patients with longer baseline time to AT tended to show larger postoperative reductions. No other covariate, including resection extent (standardized $\beta \approx 0.00$, $P = 0.986$), was significant.

ΔTime to peak (adjusted $R^2 = 0.44$): Preoperative time to peak was strongly linked to change magnitude (standardized $\beta = -0.68$, unstandardized $\beta = -0.55$, 95% CI: -0.66 to -0.44 , $P < 0.001$). Resection extent was not associated (standardized $\beta = -0.09$, unstandardized $\beta = -0.13$, 95% CI: -0.32 to 0.06 , $P = 0.177$).

ΔPeak O₂ pulse (adjusted $R^2 = 0.10$): Two covariates independently predicted changes. Preoperative peak O₂ pulse was inversely related to change (standardized $\beta = -0.44$, unstandardized $\beta = -0.30$, 95% CI: -0.45 to -0.15 , $P < 0.001$). Male sex was positively associated with larger increases (standardized $\beta = 0.25$, unstandardized $\beta = 0.78$, 95% CI: 0.06 to 1.50 , $P = 0.034$). Resection extent was not significant ($P = 0.323$).

Taken together, resection extent failed to independently predict any ΔCPET parameter across the five models (all $P > 0.05$), echoing the ANCOVA findings (Fig. 4). Preoperative baseline value was the single most consistent and dominant correlate, reaching significance in every model with the largest standardized β in each (Fig. 5).

Forest plot displaying standardized regression coefficients (β) and 95% confidence intervals from multivariable linear regression models for each ΔCPET endpoint. Models are adjusted for surgical extent, age, sex, BMI, smoking history, preoperative baseline value, and follow-up duration. Preoperative baseline value was the most consistent predictor across all five CPET change endpoints. Resection extent was not independently associated with any ΔCPET parameter.

Scatter plots showing the relationship between preoperative (x-axis) and postoperative (y-axis) values for key CPET parameters across all 149 patients. Each point represents one patient, colored by surgical group (wedge resection, segmentectomy, lobectomy). The dashed diagonal line represents the identity line (no change). The plot illustrates the strong inverse relationship between baseline values and postoperative changes, with patients having higher baseline values tending to show greater declines.

Table 4
Multivariable linear regression: factors associated with changes in CPET parameters

ΔCPET parameter	Factor	Unstandardized β	95% CI / Standardized β	P	Adj. R²
ΔPeak HR (n = 145)	Surgical extent	-0.81	(-3.52, 1.89) / -0.04	0.552	0.27
	Age	-0.30	(-0.55, -0.05) / -0.20	0.017	
	BMI	-0.60	(-1.32, 0.12) / -0.12	0.102	
	Pre-op Peak HR	-0.45	(-0.57, -0.32) / -0.56	< 0.001	
ΔHRR (n = 145)	Surgical extent	-8.33	(-18.68, 2.03) / -0.13	0.114	0.05
	Pre-op HRR	-0.79	(-1.38, -0.21) / -0.23	0.008	
ΔTime to AT (n = 145)	Surgical extent	-0.002	(-0.18, 0.18) / $\approx$ 0.00	0.986	0.50
	Pre-op Time to AT	-0.63	(-0.75, -0.52) / -0.68	< 0.001	
ΔTime to peak (n = 145)	Surgical extent	-0.13	(-0.32, 0.06) / -0.09	0.177	0.44
	Pre-op Time to peak	-0.55	(-0.66, -0.44) / -0.68	< 0.001	
ΔPeak O₂ pulse (n = 145)	Surgical extent	-0.15	(-0.44, 0.15) / -0.08	0.323	0.10
	Sex (male)	0.78	(0.06, 1.50) / 0.25	0.034	
	Pre-op Peak O ₂ pulse	-0.30	(-0.45, -0.15) / -0.44	< 0.001	

Models adjusted for surgical extent (ordinal), age, sex, BMI, smoking history, preoperative baseline value, and follow-up duration. Only significant predictors and surgical extent are displayed. — indicates standardized β not reported due to scale differences.

3.5 Sensitivity analysis

Restriction to patients with follow-up between 6 and 18 months (n = 104; wedge, n = 30; segmentectomy, n = 44; lobectomy, n = 30) yielded results consistent with the primary analysis. All six ANCOVA comparisons remained non-significant (postoperative peak HR, P = 0.368; peak O₂ pulse, P = 0.328; HRR, P = 0.428; time to AT, P = 0.173; time to peak, P = 0.165; peak RER, P = 0.349).

The dose-response trend for Δ time to peak, borderline in the primary analysis ($P = 0.045$), became non-significant ($P = 0.071$), suggesting this finding was partly shaped by the distribution of follow-up intervals. All other trend tests remained non-significant (Δ peak HR, $P = 0.504$; Δ HRR, $P = 0.366$; Δ time to AT, $P = 0.439$; Δ peak O_2 pulse, $P = 0.409$).

No significant group $\times$ follow-up time interactions were detected for any CPET parameter (Δ peak HR, $P = 0.251$; Δ HRR, $P = 0.160$; Δ time to AT, $P = 0.217$; Δ peak O_2 pulse, $P = 0.442$), indicating that the pace of postoperative CPET change did not differ across surgical groups over the observation window.

3.6 Post-hoc power analysis

Post-hoc power calculations for the ANCOVA comparisons pointed to limited sensitivity for detecting small effects. Cohen's f ranged from 0.084 to 0.136 (small to very small), yielding power estimates between 0.13 and 0.29 across all six parameters—all well below the conventional 0.80 threshold. To achieve 80% power for a medium effect (Cohen's $f = 0.25$) at $\alpha = 0.05$ in a three-group ANCOVA would require roughly 159 patients (53 per group).

Discussion

Three principal findings emerged from this analysis of 149 patients undergoing wedge resection, segmentectomy, or lobectomy with paired pre- and postoperative CPET. First, time to AT shortened consistently in all three groups, with segmentectomy producing the broadest pattern of parameter changes. Second, once preoperative baseline and patient characteristics were accounted for, resection extent showed no independent association with either postoperative CPET levels or the magnitude of change. Third, preoperative baseline value dominated as the correlate of CPET change across every parameter, with age and BMI contributing independent predictive value for selected outcomes.

Comparison with prior literature

The observation that resection extent lacks independent association with postoperative CPET change contrasts with several earlier reports implicating lobectomy in greater functional loss. Larsen et al. [15] documented significant VO_{2peak} decline after lobectomy but not after sublobar resections. Brunelli et al. [17] described stepwise FEV_1 and diffusing capacity of the lung for carbon monoxide (DLCO) recovery following major resection, with the steepest gains occurring between three and six months. Yet other groups have painted a more complex picture: Nugent et al. [12] found VO_{2peak} to be maintained after both lobectomy and sublobar resection, with significant reductions confined to pneumonectomy patients; Win et al. [9] reported that exercise capacity fell postoperatively but returned to baseline by six months irrespective of resection type. Our contribution to this literature is to demonstrate that, when preoperative baseline, age, sex, BMI, and follow-up duration are modeled simultaneously, postoperative CPET profiles do not differ in any clinically meaningful way across three distinct surgical categories.

Methodological differences likely account for much of the discrepancy between our null findings and earlier positive results. The majority of prior work contrasted only two groups (sublobar versus lobar), an approach that may artificially inflate apparent differences by collapsing wedge resection and segmentectomy into a

single category. Our three-group design, supplemented by ordinal dose-response testing, provides a more granular perspective on the resection-extent–function relationship. Additionally, our use of ANCOVA with baseline adjustment—rather than direct comparison of raw postoperative values—may reconcile apparent differences that actually originate from preoperative imbalances between groups.

Why resection extent does not emerge as an independent factor

Multiple factors could account for the absence of a dose-response gradient. Compensatory mechanisms in the remaining lung tissue—such as hyperinflation, perfusion redistribution, and improved ventilation-perfusion matching in preserved lobes—may buffer the functional consequences of larger resections [18]. Supporting this notion, Tu et al. [20] demonstrated substantial volumetric expansion of residual lobes following lobectomy, partially offsetting the loss of parenchyma. The borderline Δ HRR trend ($P = 0.115$) and the attenuation of the Δ time to peak trend on sensitivity analysis ($P = 0.045 \rightarrow 0.071$) jointly suggest that any genuine resection-extent effect, if present, is modest and would demand larger samples for reliable detection. Post-hoc power analysis corroborated that the sample was underpowered for small effects (Cohen's $f < 0.15$). The substantial inter-individual variability in CPET change—reflected in the low adjusted R^2 for certain models (0.05 for Δ HRR)—further implicates determinants beyond resection extent, such as intrinsic cardiopulmonary reserve, baseline physical activity, and engagement in postoperative rehabilitation.

Influence of preoperative baseline values, age, and BMI

Across every regression model, preoperative baseline value stood out as the strongest correlate of CPET change. Part of this relationship is statistical in nature: regression to the mean dictates that patients starting from high baselines have more room to decline, whereas those with low baselines encounter a floor effect. A physiological explanation also exists. Patients entering surgery with stronger functional capacity may undergo proportionally greater deconditioning or perturbation, while those with already diminished reserve have limited scope for further deterioration. From a clinical standpoint, these observations reinforce the importance of conducting a thorough preoperative CPET assessment before attempting to interpret postoperative changes.

Age exerted an independent effect on Δ peak HR (standardized $\beta = -0.20$, $P = 0.017$). Older patients exhibited smaller postoperative increases—or larger decreases—in peak HR, a pattern consistent with the well-described age-related decline in chronotropic competence and cardiovascular adaptability [21, 22]. From a practical perspective, elderly patients may possess a narrower capacity for cardiac adjustment following lung resection, a consideration that deserves attention during perioperative risk assessment and rehabilitation planning.

BMI demonstrated a marginal association with Δ peak HR (standardized $\beta = -0.12$, $P = 0.102$), with heavier patients showing a tendency toward attenuated CPET shifts. Although this association fell short of statistical significance—likely owing to extreme multicollinearity among covariates (condition number $> 5 \times 10^6$)—the direction of effect hints that greater metabolic demands, altered cardiovascular loading, and possibly lower relative exercise intensity may contribute to blunted CPET responses in patients with higher BMI. Male sex

was associated with larger peak O₂ pulse increases (standardized $\beta = 0.25$, $P = 0.034$), a finding that likely reflects sex-based differences in stroke volume dynamics and peripheral oxygen extraction [23].

Clinical implications

These findings carry several practical implications for preoperative counseling and postoperative management. The absence of an independent effect of resection extent on CPET change provides tentative support for the notion that anatomical and non-anatomical resections permit broadly comparable medium-term cardiopulmonary adaptation—although definitive confirmation will require larger studies. This consideration enters the ongoing discussion about optimal resection strategy for small peripheral nodules, where arguments about functional preservation sometimes tip the balance toward limited resection [24, 25]. Our data suggest that, from a cardiopulmonary perspective, the distinction among wedge, segmentectomy, and lobectomy may be less consequential than traditionally assumed, and that oncological priorities should take precedence when both options are technically feasible.

Of greater clinical relevance, our data indicate that patient-specific characteristics—particularly age, BMI, and preoperative functional capacity—account for much of the postoperative CPET variation. This observation supports a transition from procedure-centric to patient-centric frameworks in perioperative functional evaluation. Preoperative CPET could furnish individualized prognostic information that strengthens risk stratification, guides rehabilitation intensity, and refines patient counseling beyond what resection category alone can offer [19].

Limitations

This study has several limitations that merit discussion. As a single-center retrospective analysis, causal inference is not feasible and generalizability may be constrained—operative indications, surgical techniques, and postoperative protocols likely differ across institutions. Follow-up timing was not standardized (median 12 months, range 1–29 months), and the three groups differed in follow-up duration ($P = 0.035$). Although follow-up duration was included as a covariate and results were corroborated in a 6–18 month sensitivity subset, residual confounding by assessment timing cannot be entirely excluded.

With $n = 149$, the study had limited power to detect small inter-group effects (post-hoc power < 0.29 for all ANCOVA comparisons). Null findings regarding resection extent should therefore be interpreted as inconclusive rather than definitive; a larger multicenter cohort would be necessary to exclude small but clinically meaningful effects. Post-hoc power for the six ANCOVA comparisons ranged from 0.13 to 0.29 (Cohen's f : 0.084–0.136), indicating that the sample was adequately powered only for medium-to-large effects. The consistent null associations between resection extent and CPET change across multiple analytical approaches cannot be regarded as evidence of absence—small effects may simply have escaped detection. Likewise, clinical implications regarding outcome comparability across resection categories should be regarded as preliminary and hypothesis-generating.

The absence of systematic pulmonary function test data prevented examination of the CPET–spirometry relationship; combined CPET and PFT analysis would yield a more comprehensive picture of postoperative recovery. Although CPET equipment varied across the study period (Vmax Encore and equivalent instruments), all devices were calibrated to the same standard. We did not capture postoperative

rehabilitation participation, cardiac comorbidities, or medication regimens—factors that could have influenced CPET trajectories. As an exploratory analysis, the regression models presented here should not be applied to individual-level prediction. Finally, no independent replication cohort was available, and all findings await confirmation in separate populations.

Conclusions

In this single-center retrospective cohort of 149 patients, lung resection was accompanied by significant changes in exercise timing and heart rate parameters. Time to AT shortened consistently across all three surgical groups. However, resection extent did not independently predict postoperative CPET values or the magnitude of change once baseline values and patient characteristics were taken into account—although the limited statistical power of this sample necessitates caution when interpreting these null results. Preoperative baseline value emerged as the strongest correlate of CPET change for every parameter, with age providing additional independent predictive value and BMI showing a marginal association. Taken together, these data indicate that individual patient attributes—rather than the volume of resected tissue—explain most of the variability in postoperative cardiopulmonary adaptation. Prospective multicenter studies with standardized follow-up are warranted to confirm these observations and to evaluate the contribution of modifiable factors such as structured physical rehabilitation.

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board of Qinhuangdao First Hospital (approval number: 2025B-011-01). The requirement for individual informed consent was waived due to the retrospective observational nature of the study. All procedures were performed in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Jianping Ji: Conceptualization, Data curation, Formal analysis, Writing—original draft. Zixiao Wang: Methodology, Software, Validation. Chao Wang: Data collection. Jian Li: Data collection. Huaguang Liang: Supervision, Writing—review & editing. All authors read and approved the final manuscript.

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STROBE statement

This study is reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines for cohort studies. A completed STROBE checklist is available as Additional File 1.

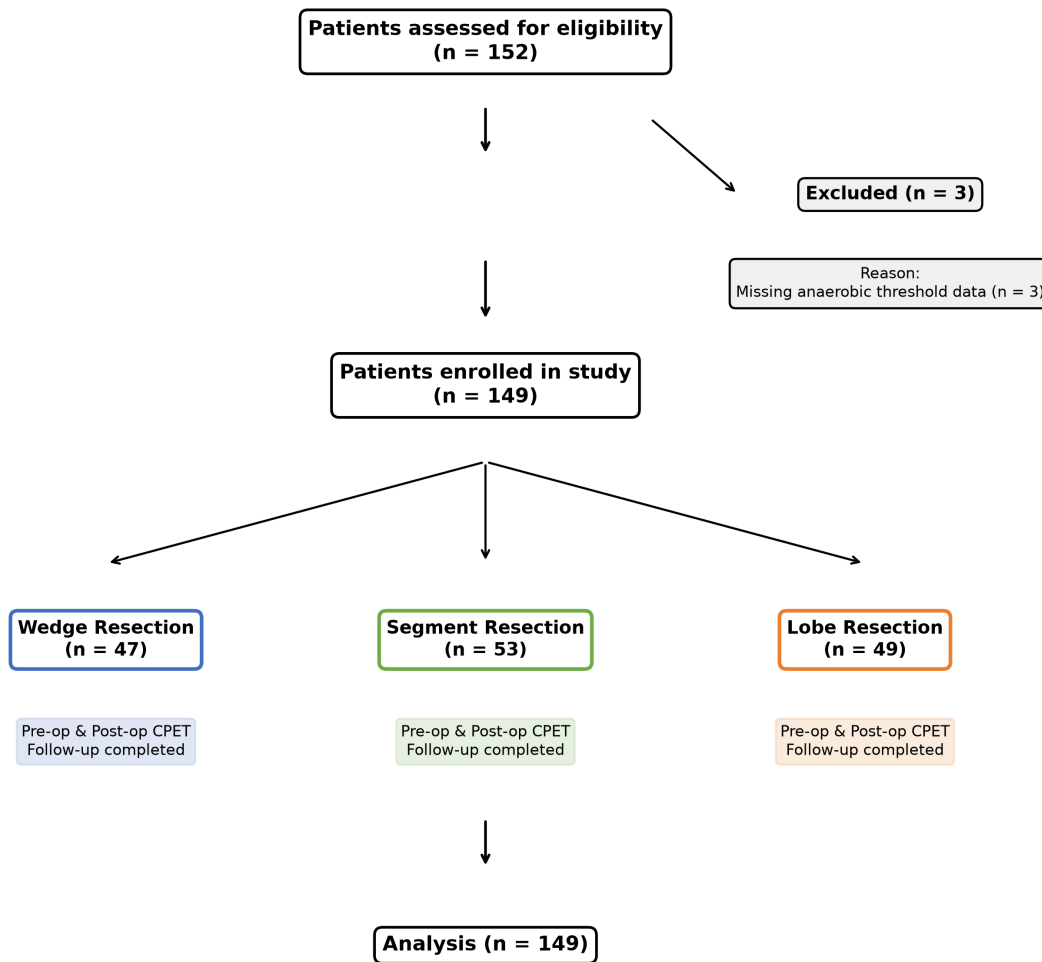
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Figures



- Primary comparison: ANCOVA (adjusted for baseline, age, sex, BMI, follow-up)
- Dose-response: linear trend test across wedge → segment → lobe
- Multivariable regression: standardized β for Δ CPET predictors
- Recovery trajectory: follow-up time $\times$ surgical extent interaction
- Sensitivity: restricted to 6–18 month follow-up (n = 104)

STROBE Flow Diagram — CPET After Lung Resection

Figure 1

Participant selection flow diagram

STROBE flow diagram illustrating participant selection. A total of 152 patients who underwent lung resection (wedge resection n = 48, segmentectomy n = 54, lobectomy n = 50) between July 2023 and July 2026 were screened. Of these, 149 patients had complete paired preoperative and postoperative CPET data and were

included in the analysis (wedge resection n = 47, segmentectomy n = 53, lobectomy n = 49). Three patients were excluded due to the absence of anaerobic threshold data during CPET.

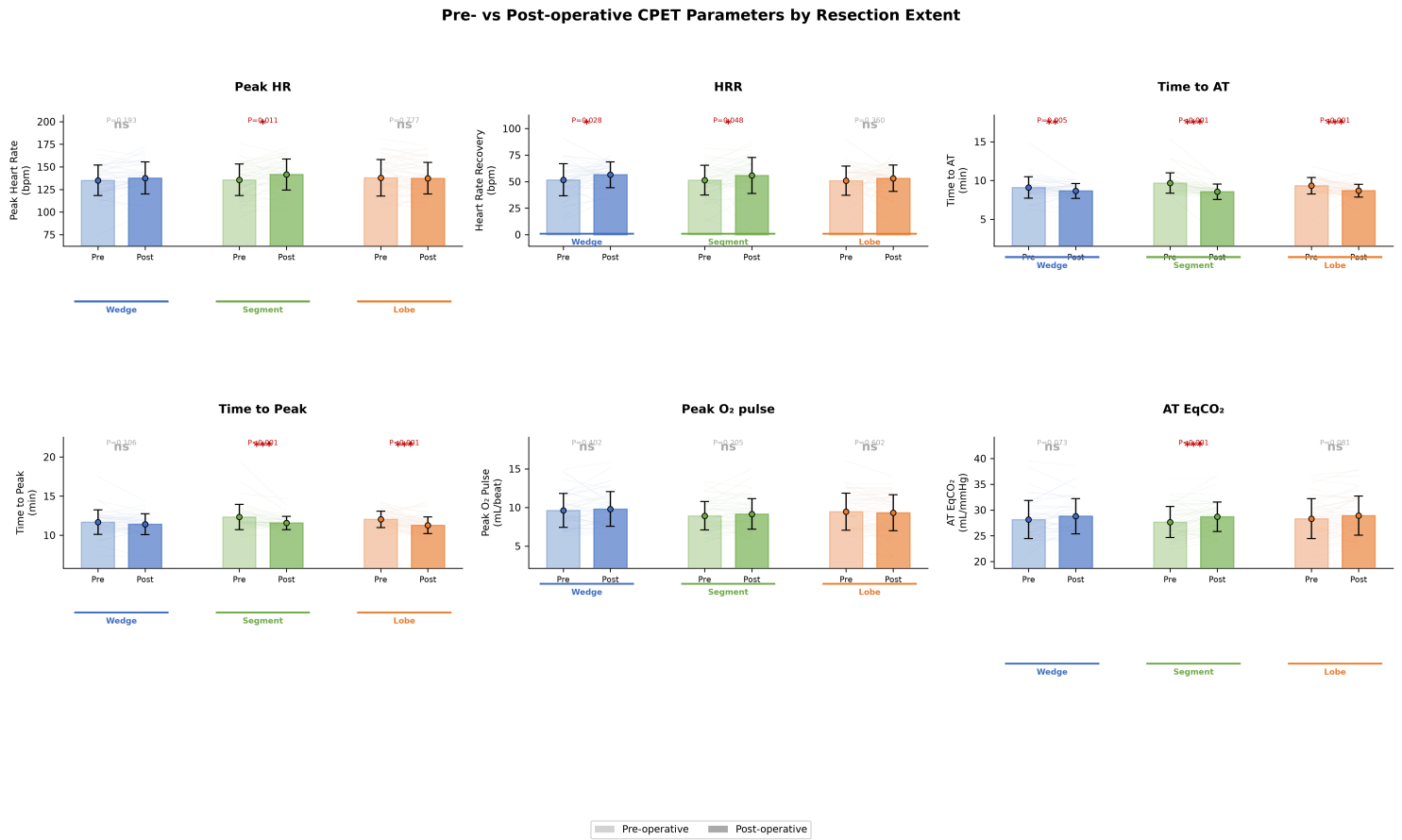
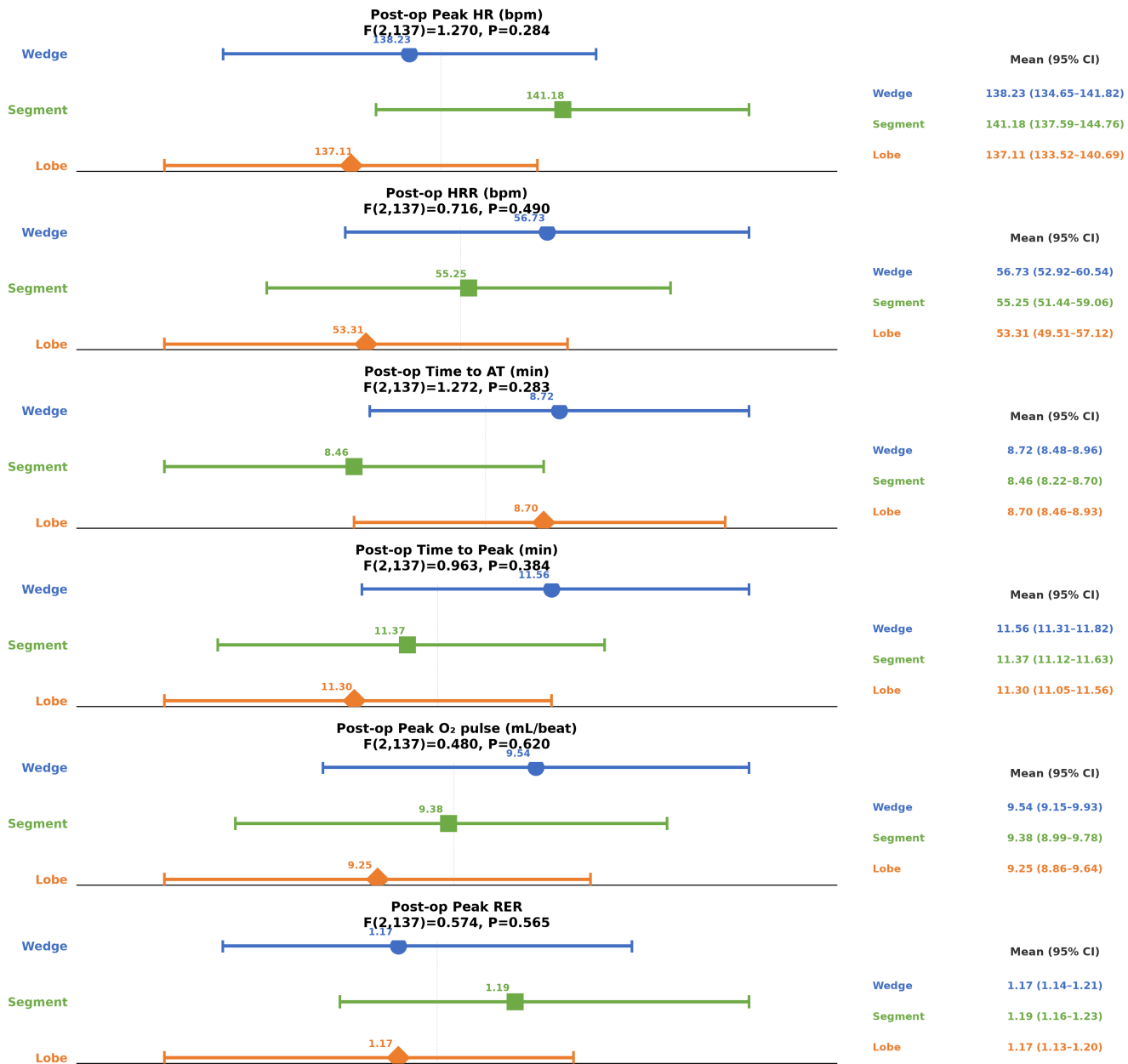


Figure 2

Within-group paired changes in CPET parameters

Paired pre- and postoperative CPET parameter values across the three surgical groups. Each panel displays the individual paired trajectories (thin lines) and group-level mean ± 95% CI (thick lines with shaded bands) for patients undergoing wedge resection (n = 47), segmentectomy (n = 53), and lobectomy (n = 49). Parameters include peak heart rate, heart rate reserve utilization, time to anaerobic threshold, time to peak exercise, peak O₂ pulse, and AT ventilatory equivalent for CO₂.

ANCOVA-Adjusted Post-operative CPET Means (95% CI)



Adjusted for pre-operative baseline, age, sex, BMI, and follow-up time (n = 145). All P > 0.05: no significant group differences after adjustment.

Figure 3

ANCOVA-adjusted postoperative CPET parameter comparisons across surgical groups

Forest plot displaying adjusted marginal means and 95% confidence intervals for six postoperative CPET parameters across wedge resection, segmentectomy, and lobectomy groups. Models are adjusted for preoperative baseline value, age, sex, BMI, and follow-up duration (n = 146). F-statistics and P-values from ANCOVA are shown for each parameter. No inter-group difference reached statistical significance.

Dose-Response Relationship: ΔCPET Parameters Across Surgical Extent

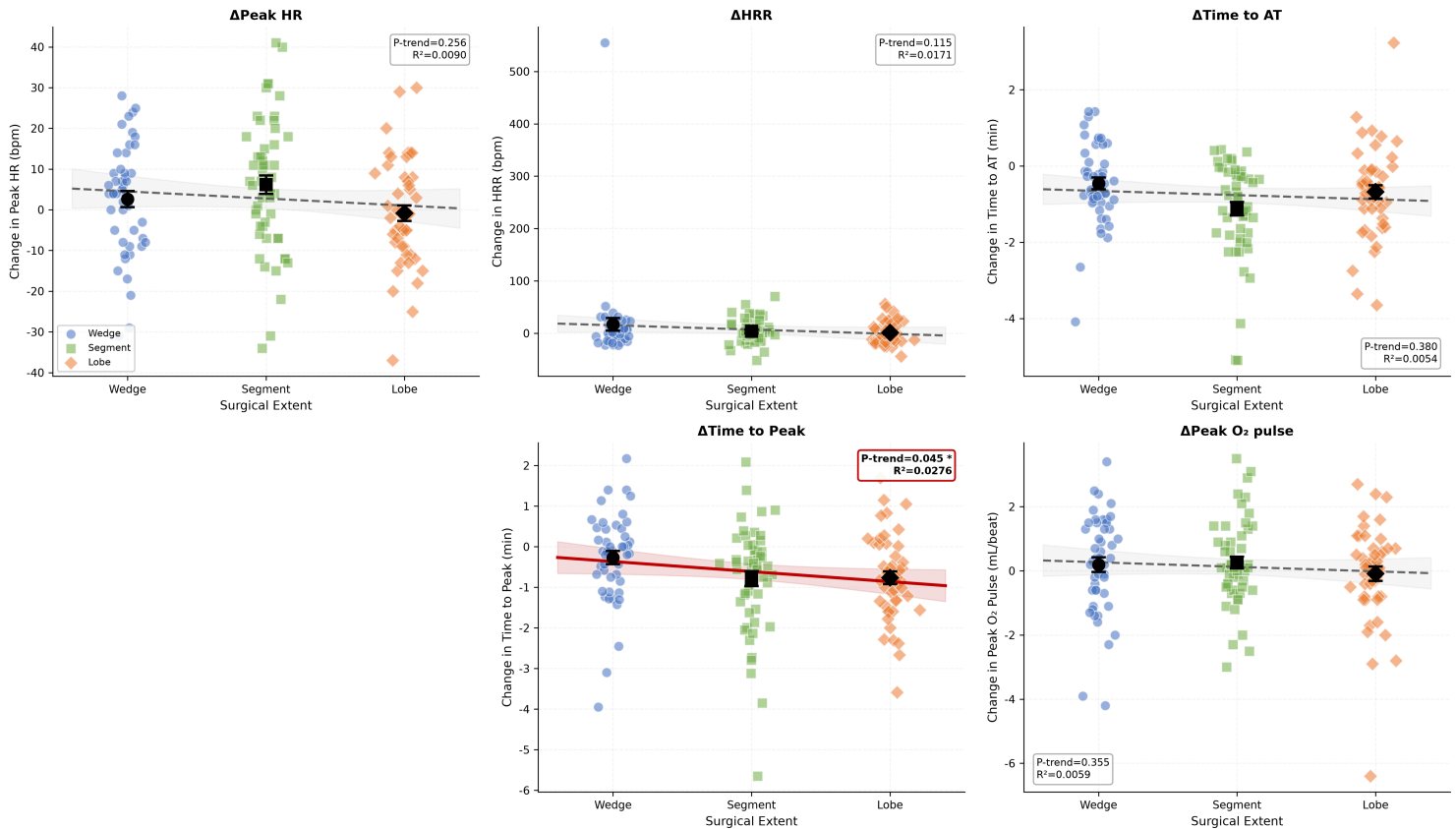


Figure 4

Figure 6. Dose-response relationship between resection extent and CPET changes

Dose-response analysis showing the relationship between ordinal resection extent (wedge = 1, segmentectomy = 2, lobectomy = 3) and ΔCPET values. Each panel displays the mean ΔCPET value ($\pm$ 95% CI) for each surgical group, with the linear trend test P-value shown. While some parameters show nominal trends, no dose-response relationship reached statistical significance after adjustment, indicating that resection extent does not independently determine the magnitude of CPET change.

Multivariable Regression: Standardized Predictors of ΔCPET Parameters

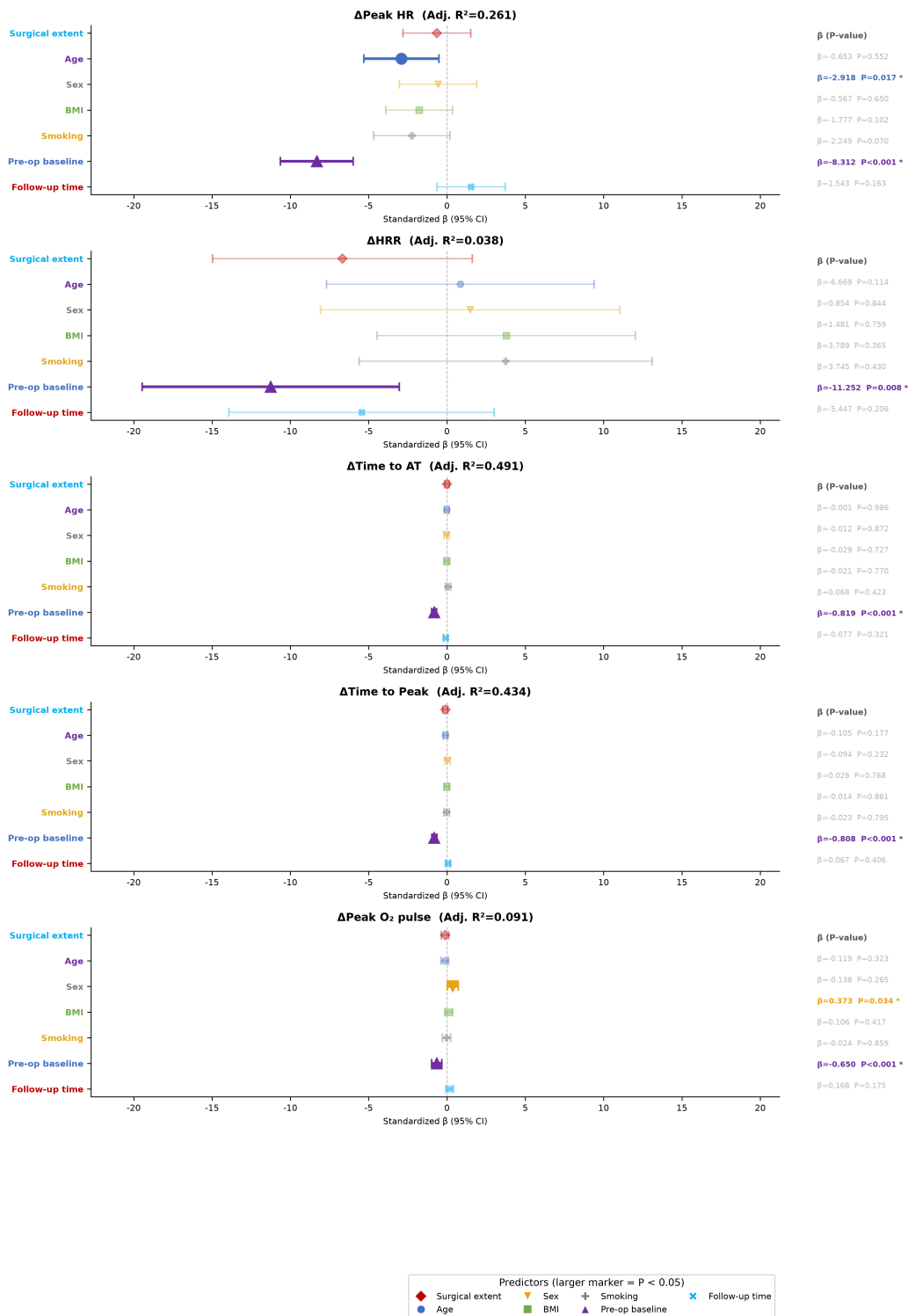


Figure 5

Figure 4. Multivariable regression: standardized coefficients for factors associated with CPET changes

Forest plot displaying standardized regression coefficients (β) and 95% confidence intervals from multivariable linear regression models for each ΔCPET endpoint. Models are adjusted for surgical extent, age, sex, BMI, smoking history, preoperative baseline value, and follow-up duration. Preoperative baseline

value was the most consistent predictor across all five CPET change endpoints. Resection extent was not independently associated with any Δ CPET parameter.

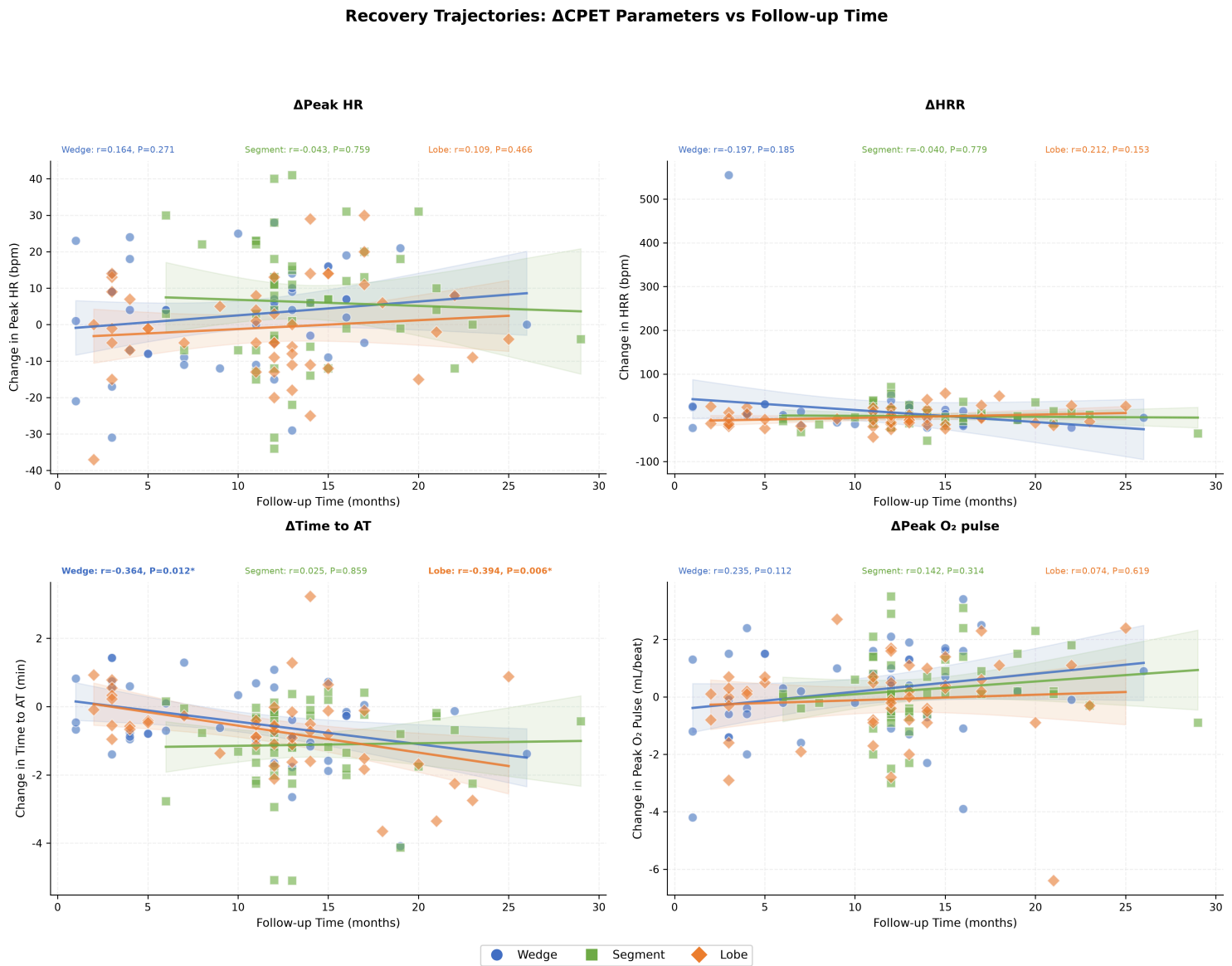


Figure 6

Figure 5. Trajectory scatter plot: preoperative vs. postoperative CPET values

Scatter plots showing the relationship between preoperative (x-axis) and postoperative (y-axis) values for key CPET parameters across all 149 patients. Each point represents one patient, colored by surgical group (wedge resection, segmentectomy, lobectomy). The dashed diagonal line represents the identity line (no change). The plot illustrates the strong inverse relationship between baseline values and postoperative changes, with patients having higher baseline values tending to show greater declines.