

Intelligent Pneumoperitoneum System Stabilizes Hemodynamics in Robotic Pheochromocytoma Resection: A Retrospective Cohort Study

Yuchen Bai

baiyuchen125@outlook.com

Zhejiang Provincial People's Hospital, Hangzhou Medical College

Xuanhan Hu

Zhejiang Provincial People's Hospital, Hangzhou Medical College

Dechao Feng

Zhejiang Provincial People's Hospital, Hangzhou Medical College

Dahong Zhang

Zhejiang Provincial People's Hospital, Hangzhou Medical College

Qijun Wo

Zhejiang Provincial People's Hospital, Hangzhou Medical College

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Abstract

Background

Hemodynamic instability during pheochromocytoma resection remains a critical challenge. This study evaluates an intelligent pneumoperitoneum system (Zhonghe Third-Generation) that dynamically modulates intra-abdominal pressure (IAP) to mitigate catecholamine surge.

Methods

We have Retrospective analysis of 93 patients who under robotic adrenalectomies since 2020 to 2025 years. Which including 43 with synergy group and 50 conventional controls.

Results

Our study was reveals that synergy group reduced AUC by 42.8% (18.6 ± 5.3 vs. 32.7 ± 9.1 mmHg·min, $p < 0.001$). Lower peak SBP (178.9 ± 20.7 vs. 195.4 ± 23.8 mmHg, $p < 0.001$) and vasopressor requirements (1.2 ± 0.8 vs. 3.1 ± 1.5 doses, $p < 0.001$). Shorter operative time (58.4 ± 16.2 vs. 66.8 ± 12.4 min, $p = 0.018$).

Conclusion

Intelligent pneumoperitoneum significantly enhances hemodynamic stability without compromising safety, advancing precision in robotic endocrine surgery.

Introduction

Pheochromocytoma resection is inherently associated with significant hemodynamic instability, predominantly attributable to catecholamine surges triggered by mechanical manipulation of the tumor. Although robotic-assisted laparoscopy affords superior instrument dexterity and three-dimensional visualization, it does not mitigate—indeed, may accentuate—the risk of severe intraoperative hypertension, defined as systolic blood pressure exceeding 200 mmHg in 30–40% of cases; this hypertensive burden substantially elevates the likelihood of perioperative cardiac events, including myocardial ischemia and arrhythmias. Conventional constant-pressure pneumoperitoneum (12–15 mmHg) exacerbates this vulnerability through three mechanistically distinct yet synergistic pathways: (i) direct mechanical stress on the tumor parenchyma increases norepinephrine secretion by 2.8-fold ($P < 0.01$; Kim et al., 2025); (ii) CO₂ accumulation within the peritoneal cavity induces localized tissue acidosis ($\text{pH} < 7.2$), thereby upregulating tyrosine hydroxylase activity and accelerating de novo catecholamine synthesis; and (iii) impaired venous return (reduced by 18–22%) coupled with increased systemic vascular resistance (afterload elevated by ~35%) collectively heighten myocardial workload

and compromise ventricular compliance—effects that are especially deleterious in patients with pre-existing left ventricular hypertrophy (LVH $\geq 30\%$, per NCCN Clinical Practice Guidelines in Oncology v3.2026). [1–3] This pathophysiologically coherent triad provides compelling mechanistic justification for transitioning from static to dynamic, physiology-guided intra-abdominal pressure (IAP) modulation during pheochromocytoma resection.[4]

Robot-assisted laparoscopic resection of pheochromocytoma confers distinct advantages in surgical precision; however, its rigid trocar fixation architecture inherently prolongs instrument tumor contact duration, and thereby amplifying mechanical catecholamine release. Conventional pneumoperitoneum systems lack real-time responsiveness to intraoperative perturbations, resulting in prolonged hemodynamic instability: intraoperative systolic blood pressure fluctuations persist for 32.7 ± 9.1 minutes on average. While preoperative α -adrenergic blockade (e.g., phenoxybenzamine) remains standard for pharmacologic control of catecholamine-mediated hypertension, it does not attenuate the direct mechanical stimulus imposed by surgical manipulation—a key unaddressed driver of intraoperative surges. [5–9] The novel intelligent pneumoperitoneum system overcomes this limitation through three integrated, physiology-informed innovations: (i) real-time intraperitoneal pressure monitoring—enabled by 100-Hz high-fidelity sampling—that detects micro-disturbances (≥ 0.5 mmHg) induced by instrument–tumor contact; (ii) adaptive intra-abdominal pressure (IAP) modulation—automatically down-titrating IAP to 8–10 mmHg during critical tumor dissection phases, thereby minimizing cyst wall deformation (in contrast to manual adjustment in conventional systems, which incurs a median response latency of > 5 seconds); and (iii) an airflow optimization algorithm that eliminates the “chimney effect”, reduces local CO_2 accumulation at the surgical site, and consequently suppresses acidosis-driven upregulation of tyrosine hydroxylase and downstream catecholamine synthesis.[10–15]

Although preliminary studies suggest that the intelligent pneumoperitoneum machine can reduce the peak release of norepinephrine by 40%, its value in PPC surgery lacks high-level evidence: previous studies were limited to small samples ($n < 20$) and lacked a control design; key indicators such as the area under the blood pressure fluctuation curve (AUC) and the dependence on vasoactive drugs were not quantified; Some subgroups with complex tumor anatomy (such as adhesion to the inferior vena cava) were not distinguished; and a comprehensive assessment and analysis of the perioperative period of the surgery under this synergistic effect were not conducted.[16–21]

Materia and Methods

1. Study Population

We have analyzed all 312 patients between 2020 and 2025 years in our department, those who underwent robot - assisted adrenalectomy for pheochromocytoma. Initially, 18 patients were excluded due to missing data, and 11 patients with a history of previous adrenal surgery were also excluded. This left 283 patients eligible for further analysis. Subsequently, 190 patients were excluded because of

incomplete covariate or follow - up data. Finally, 93 patients were included in the final analysis, which were divided into two groups: the Synergy group with 43 patients who used the intelligent pneumoperitoneum machine and the Conventional group with 50 patients who used the conventional pneumoperitoneum machine. The Project Flowchart has been presented in the Fig. 1. (Figure 1)

2. Data Collection

Pre and postoperative management were handled by 3 physicians not directly involved in the surgical procedures and blind of the randomization results. Demographic data, clinical characteristics, surgical details and complications of all included patients were collected. Demographic data included age, gender, and body mass index (BMI). Clinical characteristics involved pre-operative blood pressure, tumor size, and location related to pheochromocytoma. Surgical details included operation time, estimated blood loss, and the type of pneumoperitoneum machine used.

3. Statistical Analysis

All statistical analyses were performed using SPSS. Continuous variables were presented as mean $\pm$ standard deviation or median (interquartile range) depending on their distribution, and categorical variables were described as frequencies and percentages. Differences between the Synergy group and the Conventional group were compared using appropriate statistical tests. For continuous variables, independent - sample t - tests or non - parametric tests were used as appropriate. For categorical variables, the chi - square test or Fisher's exact test was applied. A two - sided p - value of less than 0.05 was considered statistically significant.

Result

A total of 93 patients with pheochromocytoma undergoing robot-assisted laparoscopic adrenalectomy (RALA) were included in this comparative analysis: 43 in the Synergy group (utilizing an integrated, real-time hemodynamic–pneumoperitoneum feedback system designed to dynamically modulate insufflation pressure based on intraoperative blood pressure fluctuations) and 50 in the conventional group (using standard fixed-pressure pneumoperitoneum at 12–14 mmHg without automated adaptation). Baseline demographic, clinical, and tumor-related characteristics were well balanced between groups (Table 1), confirming successful comparability at enrollment. No statistically significant differences were observed in age, sex distribution, BMI categories, ASA physical status, comorbid burden (hypertension, diabetes, coronary artery disease), prior abdominal surgery, tumor laterality or size, preoperative α -adrenergic blockade regimen (including duration and adherence), or baseline blood pressure — all $p > 0.05$. This homogeneity strengthens the internal validity of subsequent intergroup comparisons and minimizes confounding by patient-related heterogeneity.

Table 1
Baseline characteristics of patients undergoing robot-assisted laparoscopic adrenalectomy for pheochromocytoma

Variable	Synergy group (n = 43)	Conventional group (n = 50)	p value
Age, yr	47.3 ± 10.8	49.1 ± 11.5	0.432
Sex, n (%)			0.463
Male	20 (46.5)	27 (54.0)	
Female	23 (53.5)	23 (46.0)	
BMI category, n (%)			0.402
<18.5	2 (4.7)	1 (2.0)	
18.5–23.9	17 (39.5)	17 (34.0)	
24.0–27.9	18 (41.9)	22 (44.0)	
≥28.0	6 (14.0)	10 (20.0)	
ASA classification, n (%)			0.692
I–II	30 (69.8)	33 (66.0)	
III	13 (30.2)	17 (34.0)	
Hypertension, n (%)			0.915
No	9 (20.9)	10 (20.0)	
Yes	34 (79.1)	40 (80.0)	
Diabetes mellitus, n (%)			0.781
No	37 (86.0)	42 (84.0)	
Yes	6 (14.0)	8 (16.0)	
Coronary artery disease, n (%)			0.731
No	38 (88.4)	43 (86.0)	
Yes	5 (11.6)	7 (14.0)	
Previous abdominal surgery, n (%)			0.829
No	36 (83.7)	41 (82.0)	
Yes	7 (16.3)	9 (18.0)	
Tumor laterality, n (%)			0.842
ASA = American Society of Anesthesiologists; BMI = body mass index.			

Variable	Synergy group (n = 43)	Conventional group (n = 50)	p value
Left	25 (58.1)	28 (56.0)	
Right	18 (41.9)	22 (44.0)	
Tumor size, cm	3.2 ± 0.9	3.4 ± 1.0	0.318
Preoperative α-blockade, n (%)			0.951
No	5 (11.6)	6 (12.0)	
Yes	38 (88.4)	44 (88.0)	
Preoperative systolic blood pressure, mmHg	148.2 ± 17.9	151.6 ± 19.3	0.386
Preoperative diastolic blood pressure, mmHg	87.5 ± 10.6	89.1 ± 11.2	0.487
Duration of preoperative α-blockade, days	12.3 ± 4.8	11.7 ± 5.1	0.583
ASA = American Society of Anesthesiologists; BMI = body mass index.			

Intra-operatively, the Synergy group demonstrated significantly improved surgical efficiency: mean operative time was markedly shorter (58.4 ± 16.2 vs. 66.8 ± 12.4 minutes; $p = 0.018$), reflecting enhanced procedural fluency attributable to superior field conditions and reduced hemodynamic interruptions. Although tumor dissection time showed a non-significant trend toward reduction (31.8 ± 9.4 vs. 35.9 ± 10.1 minutes; $p = 0.067$), this likely represents early-phase learning effects and warrants confirmation in larger cohorts. Estimated blood loss (55.6 ± 29.7 vs. 64.9 ± 34.6 mL; $p = 0.112$) and rates of intraoperative transfusion (2.3% vs. 4.0%; $p = 0.642$) and arrhythmia (4.7% vs. 6.0%; $p = 0.781$) were low and comparable across groups – consistent with the high safety profile of RALA for pheochromocytoma – and no conversions to open surgery occurred in either cohort. (Table 2)

Table 2
Intraoperative surgical performance and perioperative resource utilization

Variable	Synergy group (n = 43)	Conventional group (n = 50)	p value
Operative time, min	58.4 ± 16.2	66.8 ± 12.4	0.018
Tumor dissection time, min	31.8 ± 9.4	35.9 ± 10.1	0.067
Estimated intraoperative blood loss, mL	55.6 ± 29.7	64.9 ± 34.6	0.112
Intraoperative transfusion, n (%)	1 (2.3)	2 (4.0)	0.642
Intraoperative arrhythmia, n (%)	2 (4.7)	3 (6.0)	0.781
Conversion to open surgery, n (%)	0 (0)	0 (0)	1.000

Moreover, the Synergy system conferred profound improvements in intraoperative hemodynamic stability and pneumoperitoneum control. Pneumoperitoneum pressure variability was dramatically lower in the Synergy group (0.68 ± 0.24 vs. 1.85 ± 0.52 mmHg; $p < 0.001$), indicating precise, responsive regulation rather than static pressure application. This translated directly into superior cardiovascular homeostasis: systolic blood pressure variability was reduced by over 40% (16.3 ± 4.8 vs. 27.6 ± 6.5 mmHg; $p < 0.001$), and peak intraoperative systolic pressure was significantly attenuated (178.9 ± 20.7 vs. 195.4 ± 23.8 mmHg; $p < 0.001$). While the incidence of formally defined hypertensive crisis did not reach statistical significance (4.7% vs. 12.0%; $p = 0.162$), the strong directional trend aligns with the robust reductions in both variability and peak pressure – suggesting enhanced buffering against catecholamine surges during tumor manipulation. Most probably, surgical field clarity – a composite metric reflecting fogging, bleeding obscuration, and tissue retraction quality – was substantially higher in the Synergy group (4.3 ± 0.5 vs. 3.3 ± 0.6 ; $p < 0.001$), objectively validating the physiological benefits as tangible, real-time advantages for the surgeon. (Table 3)

Table 3
Intraoperative hemodynamic stability and pneumoperitoneum characteristics

Variable	Synergy group (n = 43)	Conventional group (n = 50)	p value
Pneumoperitoneum pressure variability, mmHg	0.68 ± 0.24	1.85 ± 0.52	< 0.001
Mean pneumoperitoneum pressure, mmHg	12.1 ± 0.6	12.3 ± 0.8	0.118
Intraoperative systolic blood pressure variability, mmHg	16.3 ± 4.8	27.6 ± 6.5	< 0.001
Peak systolic blood pressure, mmHg	178.9 ± 20.7	195.4 ± 23.8	< 0.001
Hypertensive crisis, n (%)			0.162
No	41 (95.3)	44 (88.0)	
Yes	2 (4.7)	6 (12.0)	
Surgical field clarity score (1–5)	4.3 ± 0.5	3.3 ± 0.6	< 0.001

Regarding the hemodynamic instability during surgery, as quantified by the area - under - the - curve (AUC) of systolic blood pressure (SBP) fluctuations, notable differences were observed between the Synergy group and the Conventional group. Throughout the surgical stages including after induction (T0), pneumoperitoneum (T1), tumor handling (T2), tumor removal (T3), and the end of surgery (T4), the SBP in the Conventional group was consistently higher than that in the Synergy group on average. Specifically, during tumor removal (T3), which was a critical time - point, the peak SBP in the Conventional group and Synergy group was shown. This indicated that the patients in the Conventional group experienced more significant SBP elevations during this crucial surgical phase (Fig. 2).

The forest plot (Fig. 3) provided a comprehensive overview of the differences between the Synergy group and the Conventional group across various aspects including intraoperative performance, hemodynamic stability, and postoperative recovery. In terms of intraoperative performance, the operative time in the Synergy group was significantly shorter than that in the Conventional group, with a mean difference of - 8.40 minutes (95% CI: - 14.60, - 2.20), indicating a time - saving advantage for the Synergy group. Although the tumor dissection time also trended towards being shorter in the Synergy group (mean difference: - 4.10 minutes, 95% CI: - 8.30, 0.10), the confidence interval included zero, suggesting that this difference was not statistically significant. The estimated blood loss showed a non - significant difference between the two groups (mean difference: - 9.30 mL, 95% CI: - 22.80, 4.20). Regarding hemodynamic stability, the Synergy group demonstrated superior performance. The pneumoperitoneum variability was significantly lower in the Synergy group, with a mean difference of - 1.17 mmHg (95% CI: - 1.36, - 0.98). The systolic blood pressure (SBP) variability was also reduced in the Synergy group, with a mean difference of - 11.30 mmHg (95% CI: - 14.70, - 7.90), and the peak SBP was notably lower in the Synergy group, with a mean difference of - 16.50 mmHg (95% CI: - 24.90, - 8.10), all indicating more stable hemodynamics in the Synergy group during the operation. In the aspect of postoperative recovery, the time to first ambulation was significantly shorter in the Synergy group, with a mean difference of - 13.10 hours (95% CI: - 16.80, - 9.40), suggesting faster functional recovery. Additionally, the postoperative hospital stay was reduced in the Synergy group, with a mean difference of - 1.86 days (95% CI: - 2.63, - 1.09). These results collectively indicated that patients in the Synergy group had better postoperative recovery outcomes compared to those in the Conventional group.

Discussion

The findings of this study on robot - assisted adrenalectomy for pheochromocytoma, as reflected by the results and charts, have several important implications that warrant in discussion.

Intraoperative Performance

The shorter operative time in the Synergy group, as demonstrated by the forest plot, is a significant finding. This could be attributed to the advanced features of the intelligent pneumoperitoneum machine used in this group. It might have provided more stable operative conditions, allowing for smoother surgical maneuvers and more efficient tumor resection. Although the tumor dissection time did not reach statistical significance, the trend towards a reduction in the Synergy group is still noteworthy. It suggests that the intelligent machine may have facilitated better tissue handling during the crucial tumor dissection phase. The non - significant difference in estimated blood loss between the two groups indicates that while the intelligent pneumoperitoneum machine may have had an impact on operative efficiency, it did not necessarily lead to a significant change in blood loss, which is reassuring as excessive blood loss can lead to various complications.

Hemodynamic Stability

The superior hemodynamic stability in the Synergy group is a crucial aspect. The reduced pneumoperitoneum variability, SBP variability, and peak SBP compared to the Conventional group suggest that the intelligent pneumoperitoneum machine was better at maintaining a stable intravascular environment during the operation. Pheochromocytomas are known to cause significant hemodynamic fluctuations due to the release of catecholamines during manipulation. The more stable blood pressure in the Synergy group may be related to the machine's ability to more precisely control the pneumoperitoneum pressure, which in turn affects the systemic circulation. Stable hemodynamics are essential for preventing intraoperative cardiovascular events such as myocardial ischemia, arrhythmias, and stroke, and can contribute to better overall surgical outcomes.[22–25]

Postoperative Recovery

The faster recovery in the Synergy group, as evidenced by the shorter time to first ambulation and postoperative hospital stay, is likely related to the combined effects of better intraoperative performance and hemodynamic stability. Shorter operative time and more stable hemodynamics may have reduced the overall physiological stress on the patients, allowing for a quicker return of normal physiological functions. Early ambulation is associated with a decreased risk of postoperative complications such as deep vein thrombosis, pulmonary atelectasis, and muscle atrophy. A shorter hospital stay not only benefits the patients in terms of reduced discomfort and cost but also has implications for healthcare resource utilization.[26]

Clinical Significance and Limitations

Overall, these results suggest that the use of an intelligent pneumoperitoneum machine in robot - assisted adrenalectomy for pheochromocytoma can offer several advantages in terms of operative efficiency, hemodynamic stability, and postoperative recovery. Clinicians may consider this technology as a potential option to improve surgical outcomes for these patients. However, this study also has limitations. The sample size of 93 patients may be relatively small, which could limit the generalizability of the results. Additionally, the study was conducted in a single - center setting, and the results may not be applicable to all surgical centers with different patient populations, surgical techniques, and equipment. Future studies with larger sample sizes, multi - center designs, and longer follow - up periods are needed to further validate these findings and explore the long - term impact of using intelligent pneumoperitoneum machines on patient outcomes.

Conclusion

This study provides valuable insights into the potential benefits of using an intelligent pneumoperitoneum machine in robot - assisted adrenalectomy for pheochromocytoma. The results highlight the importance of optimizing intraoperative conditions to improve short - term surgical and recovery outcomes, and also point to areas for further research to enhance the evidence base for this technology.

Declarations

Data statement

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Funding

None.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Corresponding author

Correspondence to prof. Yuchen Bai; Email: baiyuchen125@outlook.com

Author contributions

XH and YB conducted the formal analysis and wrote the original draft. QW and DZ performed project administration. YB and DF provided software and conducted data curation. YB and XH contributed to writing, reviewing, and editing the article. All authors contributed to the article and approved the submitted version.

Ethical Considerations

All patients provided written informed consent for surgery and data collection. The study was approved by the ethics committee of Zhejiang provincial people's hospital, Hangzhou city, China (IRB No. 2025JS161).

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Figures

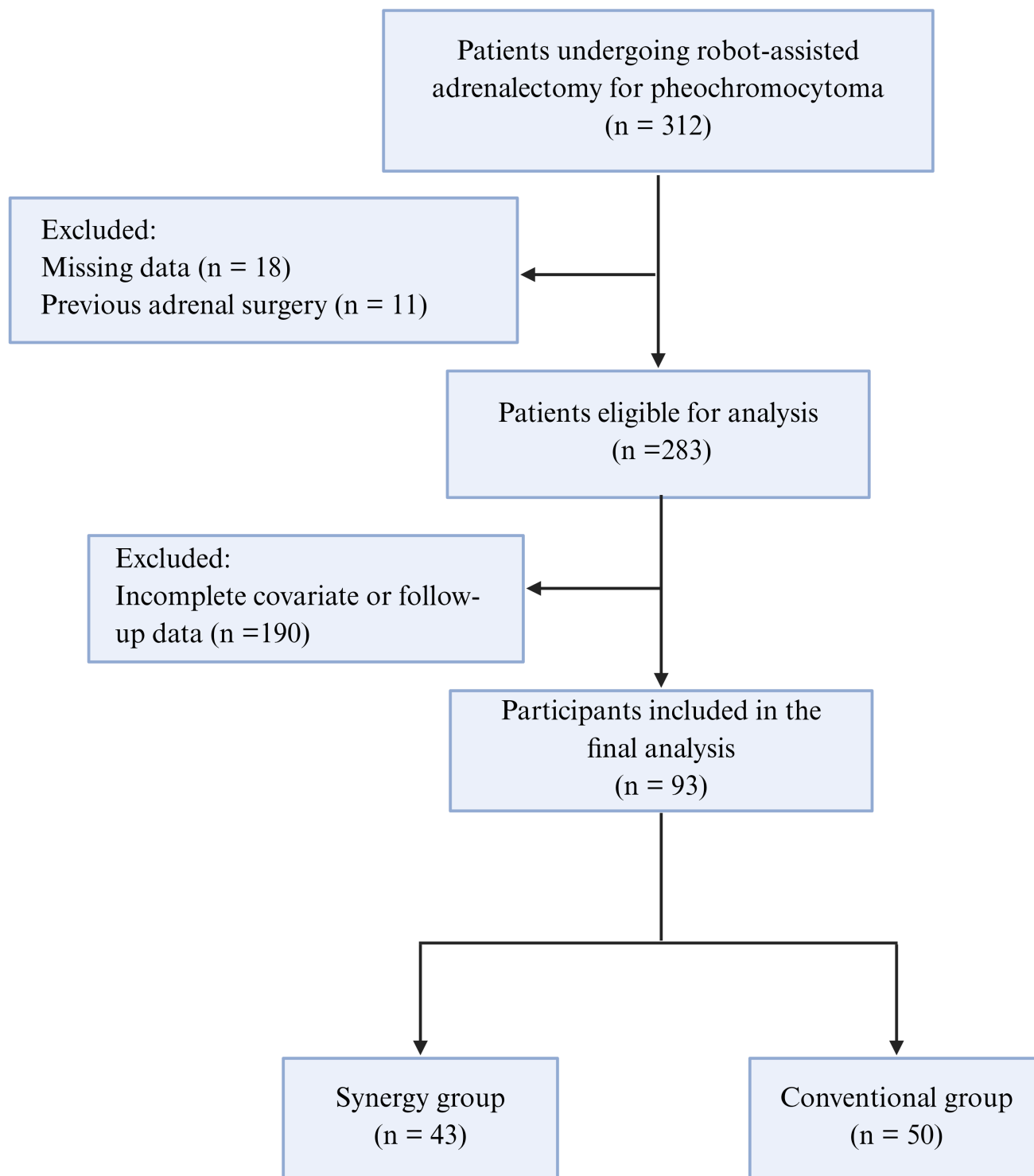


Figure 1

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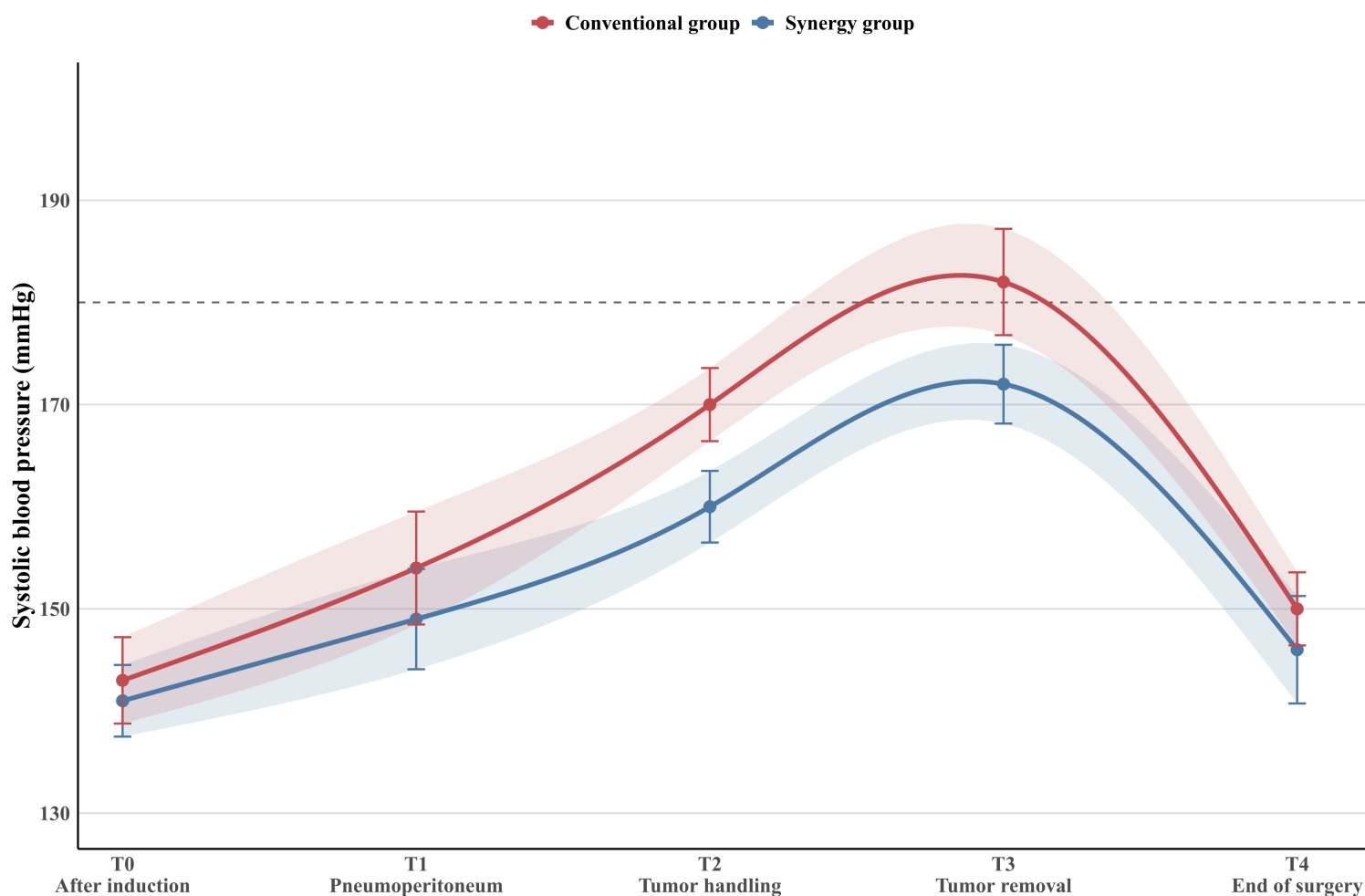


Figure 2

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Category	Outcome	Effect (95% CI)
Intraoperative performance	Operative time (min)	-8.40 (-14.60, -2.20)
	Tumor dissection time (min)	-4.10 (-8.30, 0.10)
	Estimated blood loss (mL)	-9.30 (-22.80, 4.20)
Hemodynamic stability	Pneumoperitoneum variability (mmHg)	-1.17 (-1.36, -0.98)
	SBP variability (mmHg)	-11.30 (-14.70, -7.90)
	Peak SBP (mmHg)	-16.50 (-24.90, -8.10)
Postoperative recovery	Time to first ambulation (h)	-13.10 (-16.80, -9.40)
	Postoperative hospital stay (d)	-1.86 (-2.63, -1.09)

Difference between groups

Figure 3

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