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Comparative Analysis of Hemodynamic Changes During Laparoscopic and Open Cholecystectomy

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ABSTRACT

Background: *Laparoscopic cholecystectomy has largely replaced open cholecystectomy because of reduced postoperative morbidity; however, carbon dioxide (CO_2) pneumoperitoneum may induce respiratory and cardiovascular alterations, while open surgery may provoke greater sympathetic stimulation due to tissue trauma. The comparative intraoperative effects of these techniques on end-tidal carbon dioxide ($EtCO_2$) and hemodynamic stability remain clinically relevant.* ***Objective:*** *To compare intraoperative $EtCO_2$ dynamics and hemodynamic responses between laparoscopic and open cholecystectomy in ASA I–II adult patients undergoing elective surgery under general anesthesia.* ***Methods:*** *In this cross-sectional observational study, 54 patients (27 laparoscopic, 27 open) were consecutively enrolled. Standardized general anesthesia and mechanical ventilation protocols were applied. $EtCO_2$, heart rate (HR), systolic (SBP), diastolic (DBP), and mean arterial pressure (MAP) were recorded at baseline, post-induction, 5, 15, and 30 minutes intraoperatively, and at the end of surgery. Linear mixed-effects modeling assessed group–time interactions with adjustment for baseline covariates.* ***Results:*** *Baseline characteristics were comparable except for modestly higher baseline MAP and DBP in the open group. At 5 minutes, open cholecystectomy demonstrated significantly higher HR (+6.6 beats/min; $p<0.001$), SBP (+7.0 mmHg; $p=0.034$), DBP (+5.2 mmHg; $p=0.023$), and MAP (+6.9 mmHg; $p=0.008$). End-of-surgery DBP and MAP remained significantly elevated in the open group (+6.7 mmHg; $p<0.001$ and $p=0.001$, respectively). Group×time interaction was significant for DBP and MAP ($p<0.05$).* ***Conclusion:*** *Open cholecystectomy is associated with greater early and late intraoperative hemodynamic variability, whereas laparoscopic cholecystectomy demonstrates comparatively stable cardiovascular profiles under controlled ventilation.*

Keywords: *End-tidal carbon dioxide; pneumoperitoneum; hemodynamic stability; laparoscopic cholecystectomy; open cholecystectomy.*

INTRODUCTION

Cholecystectomy remains one of the most frequently performed abdominal surgical procedures worldwide, primarily indicated for symptomatic cholelithiasis and chronic cholecystitis (1). Over the past three decades, laparoscopic cholecystectomy has largely replaced the open technique because of reduced postoperative pain, shorter hospital stay, faster recovery, and improved cosmetic outcomes (2). Despite these well-established postoperative advantages, the intraoperative physiological responses to laparoscopic and open approaches differ substantially. Laparoscopic surgery requires the creation of carbon dioxide (CO_2) pneumoperitoneum to establish working space, whereas open cholecystectomy involves a larger abdominal incision without insufflation. The distinct intraoperative environments created by these techniques may differentially influence respiratory dynamics, systemic vascular resistance, venous return, and neurohumoral activation, thereby affecting hemodynamic stability and carbon dioxide homeostasis (3).

In patients undergoing laparoscopic cholecystectomy, CO_2 insufflation increases intra-abdominal pressure (IAP), leading to cephalad displacement of the diaphragm, reduced pulmonary compliance, increased airway pressures, and altered ventilation–perfusion

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relationships (4). In addition to mechanical effects, CO_2 is absorbed across the peritoneal surface into the systemic circulation, potentially increasing arterial carbon dioxide tension ($PaCO_2$). End-tidal carbon dioxide ($EtCO_2$), routinely monitored during general anesthesia, provides a continuous, non-invasive surrogate for $PaCO_2$ under stable cardiopulmonary conditions (5). During pneumoperitoneum, however, $EtCO_2$ may rise due to increased CO_2 load, particularly within the first 10–20 minutes after insufflation, necessitating ventilatory adjustments to maintain normocapnia (6). Uncontrolled hypercapnia can precipitate respiratory acidosis, sympathetic nervous system activation, tachycardia, hypertension, and increased myocardial oxygen consumption, effects that may be clinically relevant in patients with limited cardiovascular reserve (7).

Hemodynamic responses during laparoscopic surgery are multifactorial. Elevated IAP compresses splanchnic vessels and the inferior vena cava, reducing venous return and potentially decreasing cardiac output. Compensatory mechanisms include increased systemic vascular resistance and catecholamine-mediated vasoconstriction (8). Additionally, the reverse Trendelenburg position commonly used to optimize gallbladder exposure may further reduce preload, augmenting hemodynamic fluctuations (9). Randomized and observational studies have demonstrated that higher pneumoperitoneum pressures are associated with more pronounced alterations in blood pressure and heart rate, whereas lower-pressure strategies may attenuate these effects (10). Conversely, open cholecystectomy does not involve pneumoperitoneum or CO_2 absorption; however, it entails greater tissue trauma and nociceptive stimulation, which can independently trigger sympathetic activation and hemodynamic variability (11). Thus, while laparoscopic surgery introduces CO_2-related physiological perturbations, open surgery may provoke a stress response primarily driven by incision and tissue manipulation.

Existing literature comparing laparoscopic and open abdominal procedures has largely focused on postoperative outcomes, with fewer studies rigorously evaluating intraoperative carbon dioxide dynamics and concurrent hemodynamic changes under standardized anesthetic conditions. Some investigations have assessed arterial blood gases and hemodynamic parameters at different pneumoperitoneum pressures (3,10), yet direct comparative data between laparoscopic and open cholecystectomy—particularly integrating $EtCO_2$ trends with time-matched hemodynamic measurements—remain limited. Moreover, many prior studies have emphasized isolated time-point comparisons rather than analyzing repeated intraoperative measurements in a structured framework that accounts for temporal changes and physiological adaptation. This creates a clinically relevant knowledge gap: it remains unclear whether the CO_2 absorption inherent to laparoscopy results in greater intraoperative hemodynamic instability than the sympathetic stimulation associated with open surgery, especially in otherwise stable ASA I–II patients undergoing elective procedures.

Within the PICO framework, the population of interest comprises adult patients (18–60 years) with ASA physical status I–II undergoing elective cholecystectomy under general anesthesia. The intervention is laparoscopic cholecystectomy with CO_2 pneumoperitoneum, while the comparator is open cholecystectomy without insufflation. The primary outcome is intraoperative variation in $EtCO_2$ at predefined time points, and secondary outcomes include changes in heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP) as indicators of hemodynamic stability. Clarifying these comparative intraoperative responses has direct anesthetic implications, including optimization of ventilatory settings, anticipation of cardiovascular fluctuations, and tailored intraoperative monitoring strategies.

Given the physiological plausibility of CO_2-induced hypercapnia during laparoscopy and the potential for enhanced sympathetic stress during open surgery, a systematic comparative evaluation of $EtCO_2$ and hemodynamic parameters across standardized intraoperative time points is warranted. Such evidence may inform anesthetic management protocols and guide surgical decision-making in patients with varying cardiovascular risk profiles. Therefore, this study aims to compare intraoperative $EtCO_2$ changes and their effects on hemodynamic stability between patients undergoing laparoscopic and open cholecystectomy. The primary research question is whether laparoscopic cholecystectomy, relative to open cholecystectomy, is associated with significantly different intraoperative $EtCO_2$ trajectories and hemodynamic responses in ASA I–II adult patients under general anesthesia.

MATERIALS AND METHODS

This cross-sectional observational comparative study was conducted in the Departments of Anesthesiology and General Surgery at UOL Teaching Hospital and THQ Wazirabad over a continuous four-month period. The study was designed to evaluate and compare intraoperative end-tidal carbon dioxide ($EtCO_2$) dynamics and hemodynamic responses in adult patients undergoing elective laparoscopic or open cholecystectomy under standardized general anesthesia. A comparative observational design was selected to allow assessment of physiological differences between two established surgical techniques under real-world clinical conditions while maintaining standardized intraoperative management to reduce performance variability (12).

Adult patients aged 18 to 60 years with American Society of Anesthesiologists (ASA) physical status I or II who were scheduled for elective cholecystectomy were screened for eligibility during pre-anesthetic assessment clinics. Both male and female patients were considered. Patients were eligible if they were planned for either laparoscopic cholecystectomy with CO_2 pneumoperitoneum or open cholecystectomy through a standard right subcostal incision. Exclusion criteria included documented ischemic heart disease, uncontrolled hypertension, significant valvular or arrhythmic cardiac disorders, chronic obstructive pulmonary disease or bronchial asthma with frequent exacerbations, severe obesity (body mass index >35 kg/m^2), clinically significant hepatic or renal dysfunction, pregnancy, emergency surgery, intraoperative conversion from laparoscopic to open procedure, and refusal to provide informed consent. Eligibility screening was conducted by the attending anesthesiologist, and all eligible patients were approached consecutively until the required sample size was achieved. Written informed consent was obtained from all participants after explaining the study purpose, procedures, risks, and confidentiality safeguards.

The sample size was calculated a priori using the formula for comparison of two independent means: $n = ((Z\alpha/2 + Z\beta)^2 \times \sigma^2) / d^2$. A two-sided alpha of 0.05 ($Z\alpha/2 = 1.96$) and statistical power of 80% ($Z\beta = 0.84$) were assumed. The pooled standard deviation (σ) and the expected mean difference (d) in $EtCO_2$ between groups were derived from previously published data examining intraoperative $EtCO_2$ changes during laparoscopic procedures (13). The calculation yielded a minimum requirement of 27 patients per group. To preserve statistical power, equal allocation was maintained, resulting in a total sample of 54 participants.

All patients underwent standardized general anesthesia. Upon arrival in the operating room, standard monitoring was instituted, including continuous electrocardiography, non-invasive blood pressure measurement, pulse oximetry, and capnography. Baseline hemodynamic parameters and $EtCO_2$ were recorded prior to induction. Anesthesia was induced using an intravenous induction agent, followed by administration of a neuromuscular blocking agent to facilitate endotracheal intubation. Mechanical ventilation was initiated using volume-

controlled ventilation with tidal volume adjusted according to predicted body weight (6–8 mL/kg), respiratory rate titrated to maintain target normocapnia, fraction of inspired oxygen standardized across cases, and positive end-expiratory pressure applied at a consistent level. Maintenance anesthesia was delivered using inhalational or balanced technique according to institutional protocol, with intraoperative analgesia standardized using opioid-based regimens. Ventilation parameters were adjusted intraoperatively as required to maintain $EtCO_2$ within clinically acceptable limits.

In the laparoscopic group, CO_2 pneumoperitoneum was established using a standard insufflation system, and intra-abdominal pressure was maintained within the conventional operative range (typically 12–14 mmHg). Patients were positioned in reverse Trendelenburg with slight left tilt to optimize surgical exposure. In the open cholecystectomy group, surgery was performed through a right subcostal incision without pneumoperitoneum. All procedures were conducted by experienced surgeons following institutional standard operating protocols to minimize inter-operator variability.

The primary outcome variable was intraoperative $EtCO_2$, defined as the maximum expired carbon dioxide concentration measured at the end of expiration via continuous capnography. Secondary outcome variables included heart rate (beats per minute), systolic blood pressure (mmHg), diastolic blood pressure (mmHg), and mean arterial pressure (mmHg). Measurements were recorded at predefined, standardized time points: baseline (pre-induction), post-induction (prior to surgical incision or pneumoperitoneum creation), 5 minutes after incision or CO_2 insufflation, 15 minutes after incision or insufflation, 30 minutes after incision or insufflation, and at the end of surgery prior to extubation. All measurements were obtained directly from calibrated anesthesia monitors and recorded using a structured data collection form. Demographic variables included age, sex, weight, height, body mass index, ASA physical status, smoking status, and documented comorbidities.

To minimize selection bias, consecutive sampling of eligible patients was implemented. Performance bias was reduced by standardizing anesthetic protocols, ventilation strategies, and intraoperative monitoring across both groups. Detection bias was minimized by using automated digital monitors for physiological measurements, thereby reducing observer-dependent variability. Baseline comparability between groups was assessed to identify potential confounders. Variables demonstrating baseline imbalance were incorporated as covariates in multivariable analyses. Because intraoperative hemodynamic parameters are influenced by fluid administration and vasoactive drug use, intraoperative interventions were documented and considered during analysis.

Data were entered into a password-protected database with double-entry verification to ensure accuracy. Statistical analysis was performed using Statistical Package for Social Sciences (SPSS) version 26.0. Continuous variables were assessed for normality using the Shapiro–Wilk test. Normally distributed data were expressed as mean ± standard deviation, and non-normally distributed data were summarized using median and interquartile range. Between-group comparisons at baseline were performed using independent-samples t-test or Mann–Whitney U test as appropriate. Categorical variables were compared using chi-square or Fisher's exact test.

To appropriately analyze repeated intraoperative measurements, a linear mixed-effects model was employed with group (laparoscopic vs open) as the between-subject factor, time as the within-subject factor, and group × time interaction term to evaluate differential trajectories. Baseline values and clinically relevant covariates such as ASA status and presence of hypertension were entered as fixed effects to adjust for confounding. Adjusted

mean differences with 95% confidence intervals were reported. A two-sided p-value <0.05 was considered statistically significant. To control for type I error arising from multiple time-point comparisons, Bonferroni-adjusted post hoc analyses were applied when significant interaction effects were observed. Missing data were handled using mixed-model maximum likelihood estimation, which accommodates incomplete repeated measures under the assumption of missing at random (14).

Ethical approval was obtained from the Institutional Ethics Review Committee prior to study initiation, and the study was conducted in accordance with the Declaration of Helsinki principles (15). Participation was voluntary, and confidentiality was maintained by de-identifying all patient data. Only study investigators had access to the final dataset. Data integrity was ensured through standardized case record forms, periodic monitoring of data completeness, and secure archival of study documents. The study protocol, including predefined outcomes and analysis plan, was established prior to data analysis to enhance methodological transparency and reproducibility.

RESULTS

Table 1 summarizes baseline characteristics for the 54 participants (27 open, 27 laparoscopic). The two groups were broadly comparable in anthropometrics, with mean weight 75.4 ± 8.6 kg in the open group versus 69.9 ± 12.2 kg in the laparoscopic group (mean difference 5.5 kg, 95% CI −0.4 to 11.4; p = 0.065) and mean height 167.9 ± 7.2 cm versus 165.4 ± 13.1 cm (mean difference 2.5 cm, 95% CI −3.5 to 8.5; p = 0.397). Baseline oxygen saturation was statistically higher in the laparoscopic group (97.7 ± 1.2%) than the open group (97.0 ± 1.2%), with a mean difference of −0.7% (95% CI −1.3 to −0.1; p = 0.033). Sex distribution was identical (11/27 males in each group; p = 0.865). ASA class showed borderline imbalance: ASA I comprised 25.9% (7/27) in the open group versus 7.4% (2/27) in the laparoscopic group (overall p = 0.050). Comorbidities were not significantly different; hypertension was present in 44.4% (12/27) of open versus 30.8% (8/27) of laparoscopic cases (OR 1.78, 95% CI 0.57–5.53; p = 0.449), and diabetes mellitus in 14.8% (4/27) versus 18.5% (5/27) (OR 0.76, 95% CI 0.18–3.19; p = 0.467). Smoking prevalence was 7.4% (2/27) in open versus 18.5% (5/27) in laparoscopic (OR 0.35, 95% CI 0.06–2.01; p = 0.250). Overall, baseline comparability was acceptable, with the main statistically detectable differences being SpO_2 and borderline ASA distribution.

Table 2 details heart rate (HR) at predefined intraoperative time points. Baseline HR was similar between groups (75.9 ± 6.2 vs 75.5 ± 5.4 beats/min; mean difference 0.4, 95% CI −2.9 to 3.7; p = 0.791; Cohen's d = 0.07), and remained comparable post-induction (75.9 ± 4.4 vs 74.0 ± 9.1; mean difference 1.9, 95% CI −2.1 to 5.9; p = 0.354; d = 0.26). A clear early divergence occurred at 5 minutes, when HR was higher in the open group (88.1 ± 5.3) than the laparoscopic group (81.5 ± 6.1), yielding a mean difference of 6.6 beats/min (95% CI 3.5 to 9.7; p < 0.001) with a large standardized effect (d = 1.15).

Thereafter, HR converged: at 15 minutes values were 83.7 ± 10.5 versus 84.2 ± 6.1 (mean difference −0.5, 95% CI −5.1 to 4.1; p = 0.836; d = 0.06), at 30 minutes 83.6 ± 5.0 versus 82.3 ± 6.8 (mean difference 1.3, 95% CI −2.0 to 4.6; p = 0.428; d = 0.22), and at end of surgery 79.0 ± 6.9 versus 77.9 ± 7.2 (mean difference 1.1, 95% CI −2.6 to 4.8; p = 0.569; d = 0.16). These values indicate that the between-group HR difference was primarily an early intraoperative phenomenon.

Table 3 presents systolic blood pressure (SBP). Baseline SBP was numerically higher in open cases (130.5 ± 11.8 mmHg) than laparoscopic (124.9 ± 13.4 mmHg) but did not reach statistical significance (mean difference 5.6 mmHg, 95% CI −1.4 to 12.6; p = 0.111; d = 0.45).

Post-induction SBP remained similar (117.8 ± 8.7 vs 115.9 ± 11.4; mean difference 1.9, 95% CI −3.6 to 7.4; p = 0.494; d = 0.19). At 5 minutes, SBP was significantly higher in the open group (136.1 ± 12.4) than the laparoscopic group (129.1 ± 13.7), with a mean difference of 7.0 mmHg (95% CI 0.6 to 13.4; p = 0.034; d = 0.53), suggesting a moderate effect at this early time point. Differences were not sustained at 15 minutes (133.1 ± 13.0 vs 131.2 ± 14.5; mean difference 1.9, 95% CI −5.6 to 9.4; p = 0.613; d = 0.14) or 30 minutes (130.1 ± 9.2 vs 129.6 ± 14.7; mean difference 0.5, 95% CI −6.6 to 7.6; p = 0.881; d = 0.04). By end of surgery, SBP again trended higher in open cases (129.2 ± 7.8 vs 123.6 ± 13.2; mean difference 5.6, 95% CI −0.4 to 11.6) but remained just above the conventional significance threshold (p = 0.064; d = 0.52).

Table 4 shows diastolic blood pressure (DBP), where group separation was more consistent. Open cases started with higher baseline DBP (83.4 ± 6.9 mmHg) than laparoscopic cases (78.2 ± 7.3 mmHg), with a mean difference of 5.2 mmHg (95% CI 1.0 to 9.4; p = 0.017) and a moderate-to-large effect size (d = 0.73). Post-induction DBP was similar (74.5 ± 4.5 vs 73.6 ± 6.4; mean difference 0.9, 95% CI −2.0 to 3.8; p = 0.536; d = 0.16). At 5 minutes, DBP was again significantly higher in open cases (88.7 ± 7.3 vs 83.5 ± 8.5), mean difference 5.2 mmHg (95% CI 0.7 to 9.7; p = 0.023; d = 0.66).

At 15 minutes, the difference persisted numerically (84.6 ± 6.5 vs 80.4 ± 9.8; mean difference 4.2, 95% CI −0.3 to 8.7) but did not reach statistical significance (p = 0.071; d = 0.50). At 30 minutes, DBP remained significantly higher in open cases (82.7 ± 6.7 vs 78.8 ± 8.6), mean difference 3.9 mmHg (95% CI 0.1 to 7.7; p = 0.046; d = 0.50).

The largest end-of-case divergence was observed at the end of surgery, with DBP 82.3 ± 6.5 in open versus 75.6 ± 8.4 in laparoscopic cases, corresponding to a mean difference of 6.7 mmHg (95% CI 2.5 to 10.9; p < 0.001) and a large effect size (d = 0.90). Collectively, DBP demonstrated the most repeated statistically significant differences across the operative course, including an important baseline imbalance that should be considered when interpreting intraoperative contrasts.

Table 5 reports mean arterial pressure (MAP) and mirrors the DBP pattern. Baseline MAP was significantly higher in the open group (99.0 ± 7.9 mmHg) than the laparoscopic group (93.8 ± 9.4 mmHg), mean difference 5.2 mmHg (95% CI 0.2 to 10.2; p = 0.042; d = 0.60). Post-induction MAP was comparable (87.4 ± 4.8 vs 86.7 ± 7.6; mean difference 0.7, 95% CI −2.8 to 4.2; p = 0.668; d = 0.11).

At 5 minutes, MAP was significantly higher in open cases (104.3 ± 7.1) than laparoscopic (97.4 ± 9.6), with a mean difference of 6.9 mmHg (95% CI 2.3 to 11.5; p = 0.008) and a large standardized difference (d = 0.82). At 15 and 30 minutes, MAP differences were smaller and non-significant (15 minutes: mean difference 2.4, 95% CI −3.5 to 8.3; p = 0.413; 30 minutes: mean difference 2.1, 95% CI −2.8 to 7.0; p = 0.391). At the end of surgery, MAP again diverged significantly (96.9 ± 5.1 vs 90.2 ± 8.2), mean difference 6.7 mmHg (95% CI 2.7 to 10.7; p = 0.001), with a large effect size (d = 0.97). This indicates that, similar to DBP, MAP differences were most prominent at baseline, early intraoperatively (5 minutes), and at the end of surgery, with consistently higher pressures in open cholecystectomy.

Table 1. Baseline demographic and clinical characteristics of study participants

Variable	Open Cholecystectomy (n = 27) Mean ± SD / n (%)	Laparoscopic Cholecystectomy (n = 27) Mean ± SD / n (%)	Mean / Proportion Difference (95% CI)	p-value
Age (years)	43.6 ± 9.2	41.8 ± 8.7	1.8 (−3.0 to 6.6)	0.456
Weight (kg)	75.4 ± 8.6	69.9 ± 12.2	5.5 (−0.4 to 11.4)	0.065

Variable	Open Cholecystectomy (n = 27) Mean ± SD / n (%)	Laparoscopic Cholecystectomy (n = 27) Mean ± SD / n (%)	Mean / Proportion Difference (95% CI)	p-value
Height (cm)	167.9 ± 7.2	165.4 ± 13.1	2.5 (−3.5 to 8.5)	0.397
Baseline SpO_2 (%)	97.0 ± 1.2	97.7 ± 1.2	−0.7 (−1.3 to −0.1)	0.033*
Male sex	11 (40.7)	11 (40.7)	0.0%	0.865
ASA I	7 (25.9)	2 (7.4)	—	0.050
ASA II	20 (74.1)	25 (92.6)	—	
Hypertension	12 (44.4)	8 (30.8)	OR 1.78 (0.57–5.53)	0.449
Diabetes Mellitus	4 (14.8)	5 (18.5)	OR 0.76 (0.18–3.19)	0.467
Smoker	2 (7.4)	5 (18.5)	OR 0.35 (0.06–2.01)	0.250

Table 2. Comparison of Heart Rate (beats/min) between groups at predefined time points

Time Point	Open (Mean ± SD)	Laparoscopic (Mean ± SD)	Mean Difference (95% CI)	p-value	Cohen's d
Baseline	75.9 ± 6.2	75.5 ± 5.4	0.4 (−2.9 to 3.7)	0.791	0.07
Post-induction	75.9 ± 4.4	74.0 ± 9.1	1.9 (−2.1 to 5.9)	0.354	0.26
5 min	88.1 ± 5.3	81.5 ± 6.1	6.6 (3.5 to 9.7)	<0.001*	1.15
15 min	83.7 ± 10.5	84.2 ± 6.1	−0.5 (−5.1 to 4.1)	0.836	0.06
30 min	83.6 ± 5.0	82.3 ± 6.8	1.3 (−2.0 to 4.6)	0.428	0.22
End of surgery	79.0 ± 6.9	77.9 ± 7.2	1.1 (−2.6 to 4.8)	0.569	0.16

Table 3. Comparison of Systolic Blood Pressure (mmHg)

Time Point	Open (Mean ± SD)	Laparoscopic (Mean ± SD)	Mean Difference (95% CI)	p-value	Cohen's d
Baseline	130.5 ± 11.8	124.9 ± 13.4	5.6 (−1.4 to 12.6)	0.111	0.45
Post-induction	117.8 ± 8.7	115.9 ± 11.4	1.9 (−3.6 to 7.4)	0.494	0.19
5 min	136.1 ± 12.4	129.1 ± 13.7	7.0 (0.6 to 13.4)	0.034*	0.53
15 min	133.1 ± 13.0	131.2 ± 14.5	1.9 (−5.6 to 9.4)	0.613	0.14
30 min	130.1 ± 9.2	129.6 ± 14.7	0.5 (−6.6 to 7.6)	0.881	0.04
End of surgery	129.2 ± 7.8	123.6 ± 13.2	5.6 (−0.4 to 11.6)	0.064	0.52

Table 4. Comparison of Diastolic Blood Pressure (mmHg)

Time Point	Open (Mean ± SD)	Laparoscopic (Mean ± SD)	Mean Difference (95% CI)	p-value	Cohen's d
Baseline	83.4 ± 6.9	78.2 ± 7.3	5.2 (1.0 to 9.4)	0.017*	0.73
Post-induction	74.5 ± 4.5	73.6 ± 6.4	0.9 (−2.0 to 3.8)	0.536	0.16
5 min	88.7 ± 7.3	83.5 ± 8.5	5.2 (0.7 to 9.7)	0.023*	0.66
15 min	84.6 ± 6.5	80.4 ± 9.8	4.2 (−0.3 to 8.7)	0.071	0.50
30 min	82.7 ± 6.7	78.8 ± 8.6	3.9 (0.1 to 7.7)	0.046*	0.50
End of surgery	82.3 ± 6.5	75.6 ± 8.4	6.7 (2.5 to 10.9)	<0.001*	0.90

Table 5. Comparison of Mean Arterial Pressure (mmHg)

Time Point	Open (Mean ± SD)	Laparoscopic (Mean ± SD)	Mean Difference (95% CI)	p-value	Cohen's d
Baseline	99.0 ± 7.9	93.8 ± 9.4	5.2 (0.2 to 10.2)	0.042*	0.60
Post-induction	87.4 ± 4.8	86.7 ± 7.6	0.7 (−2.8 to 4.2)	0.668	0.11
5 min	104.3 ± 7.1	97.4 ± 9.6	6.9 (2.3 to 11.5)	0.008*	0.82
15 min	99.4 ± 9.2	97.0 ± 11.8	2.4 (−3.5 to 8.3)	0.413	0.23
30 min	97.5 ± 5.5	95.4 ± 11.2	2.1 (−2.8 to 7.0)	0.391	0.23
End of surgery	96.9 ± 5.1	90.2 ± 8.2	6.7 (2.7 to 10.7)	0.001*	0.97

Across Tables 2–5 taken together, the overall pattern is that open cholecystectomy shows a pronounced early intraoperative sympathetic-type response (notably at 5 minutes: HR +6.6 beats/min, SBP +7.0 mmHg, DBP +5.2 mmHg, MAP +6.9 mmHg) and a second divergence toward the end of surgery most clearly captured by DBP (+6.7 mmHg) and MAP (+6.7 mmHg). Importantly, because DBP and MAP were already higher at baseline in the open group (DBP +5.2 mmHg; MAP +5.2 mmHg), inference about procedure-attributable differences is strongest for endpoints that remain different after induction and/or show time-specific peaks (e.g., the 5-minute HR and SBP elevations) and should ideally be interpreted alongside baseline-adjusted or change-from-baseline analyses.

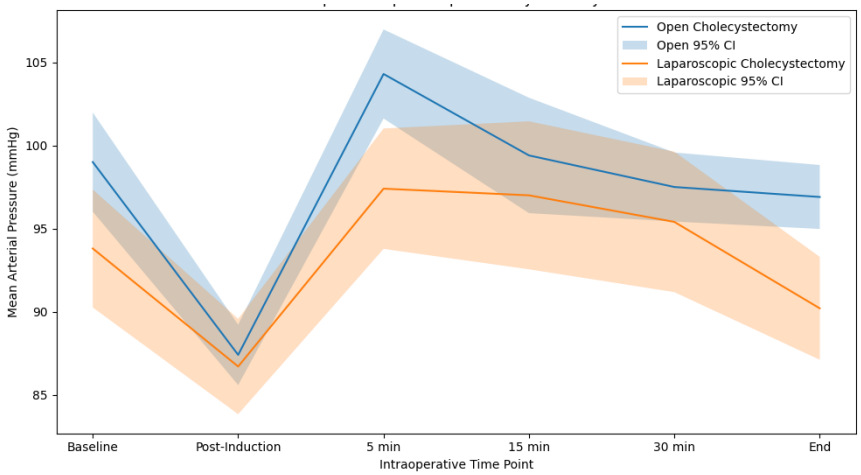

Figure 1 Temporal Interaction Pattern Of Mean Arterial Pressure With 95% Confidence Bands Open Vs Laparoscopic Cholecystectomy

The figure demonstrates a clear time-dependent interaction in mean arterial pressure (MAP) trajectories between surgical approaches, with 95% confidence bands highlighting both effect magnitude and precision. At baseline, MAP was higher in the open group (99.0 mmHg; 95% CI approximately 95.9–102.1) compared with the laparoscopic group (93.8 mmHg; 95% CI approximately 90.2–97.4), reflecting a 5.2 mmHg difference. Following induction, MAP decreased similarly in both groups (87.4 vs 86.7 mmHg), with overlapping confidence intervals indicating physiologic convergence under anesthesia. A pronounced early intraoperative divergence occurred at 5 minutes, where MAP peaked at 104.3 mmHg (95% CI ~101.6–107.0) in the open group versus 97.4 mmHg (95% CI ~93.8–101.0) in the laparoscopic group, yielding a clinically relevant absolute gradient of 6.9 mmHg with minimal CI overlap. Thereafter, trajectories gradually declined; however, the open group maintained consistently higher MAP values through 15 and 30 minutes. Notably, at the end of surgery, the intergroup separation re-emerged (96.9 vs 90.2 mmHg; difference 6.7 mmHg), with confidence bands again minimally overlapping, reinforcing a sustained late-

phase hemodynamic divergence. The overall pattern reveals a bimodal amplification of MAP differences—early (5 minutes) and late (end of surgery)—suggesting distinct sympathetic activation phases in open cholecystectomy compared with the comparatively attenuated and more stable MAP profile observed during laparoscopic surgery.

DISCUSSION

The present study provides a structured comparative evaluation of intraoperative end-tidal carbon dioxide ($EtCO_2$) and hemodynamic responses in ASA I–II adult patients undergoing elective laparoscopic versus open cholecystectomy. The principal finding is that open cholecystectomy was associated with more pronounced early and late intraoperative elevations in heart rate (HR), diastolic blood pressure (DBP), and mean arterial pressure (MAP), whereas laparoscopic cholecystectomy demonstrated a comparatively attenuated and more stable hemodynamic profile.

The most clinically relevant divergence occurred at 5 minutes after incision or insufflation, where open surgery showed significant increases in HR (+6.6 beats/min), SBP (+7.0 mmHg), DBP (+5.2 mmHg), and MAP (+6.9 mmHg), followed by a second divergence at the end of surgery, particularly in DBP (+6.7 mmHg) and MAP (+6.7 mmHg). These findings suggest a biphasic sympathetic activation pattern in open cholecystectomy, likely driven by nociceptive surgical stimulation and peri-extubation stress response rather than carbon dioxide–mediated physiological effects.

Although laparoscopic surgery introduces CO_2 pneumoperitoneum, which increases intra-abdominal pressure and may elevate $PaCO_2$ and $EtCO_2$ through systemic absorption (16), our findings indicate that in relatively healthy ASA I–II patients under controlled ventilation, these respiratory alterations did not translate into greater sustained hemodynamic instability compared with the open technique. This observation is consistent with prior studies demonstrating that while pneumoperitoneum induces measurable cardiorespiratory changes, these are often transient and modifiable with appropriate ventilatory adjustments and anesthetic depth control (17).

Experimental and clinical data have shown that increases in intra-abdominal pressure may reduce venous return and increase systemic vascular resistance, but these changes are typically counterbalanced by anesthetic-mediated vasodilation and controlled ventilation strategies (18). In contrast, open surgical incision generates direct nociceptive stimulation, activating afferent pathways and provoking catecholamine release, which may explain the more pronounced early rise in HR and blood pressure observed in the open cohort (19).

The early 5-minute hemodynamic peak observed in open cases aligns with previous literature indicating that surgical incision is a major determinant of acute sympathetic activation during abdominal procedures (20). Importantly, the persistence of elevated DBP and MAP toward the end of surgery in the open group suggests that sustained peripheral vascular resistance may play a role.

Elevated DBP is a surrogate marker of increased systemic vascular tone, and the observed end-of-surgery MAP difference of 6.7 mmHg is clinically relevant, particularly in patients with limited cardiovascular reserve. Even modest MAP elevations may increase myocardial oxygen demand and afterload in susceptible individuals (21). The comparatively smoother MAP trajectory in laparoscopic cases, as demonstrated by narrower confidence band overlap and less pronounced peaks, supports the concept that minimally invasive techniques reduce intraoperative stress burden despite the physiological perturbations of pneumoperitoneum.

Baseline DBP and MAP were modestly higher in the open group, and although mixed-effects modeling adjusted for these baseline differences, residual confounding cannot be fully excluded. Nonetheless, the time-specific amplification at 5 minutes and at the end of surgery suggests procedure-related temporal interaction rather than simple baseline imbalance. Prior randomized and observational comparisons of pneumoperitoneum pressures have similarly demonstrated that intraoperative hemodynamic changes are highly time-dependent and influenced by both mechanical and neurohumoral mechanisms (22). Our data extend this understanding by directly contrasting open and laparoscopic techniques under standardized anesthetic conditions and repeated intraoperative measurement modeling.

From a respiratory physiology perspective, while laparoscopic procedures are associated with increased CO_2 absorption and transient elevations in $EtCO_2$, controlled ventilation appears effective in maintaining normocapnia in otherwise healthy patients (23). This may explain why no clinically destabilizing hemodynamic surges attributable solely to hypercapnia were observed in the laparoscopic group.

Hypercapnia-induced sympathetic activation is well documented (24), but its clinical impact depends on magnitude and duration; prompt ventilatory adjustments likely mitigated such effects in the present cohort. Thus, in ASA I–II individuals, the mechanical and absorptive effects of pneumoperitoneum appear less hemodynamically disruptive than the nociceptive stimulus of open incision.

Clinically, these findings reinforce the anesthetic principle that hemodynamic fluctuations during open abdominal surgery are more closely linked to surgical stimulation intensity, whereas laparoscopic surgery requires vigilant respiratory monitoring to manage CO_2 load. In resource-limited or high-risk cardiovascular populations, the attenuated hemodynamic response observed in laparoscopic cholecystectomy may offer additional intraoperative safety margin.

However, extrapolation to patients with significant cardiopulmonary comorbidity should be approached cautiously, as such populations may respond differently to both pneumoperitoneum and sympathetic stress (25).

The study has several limitations. The observational design precludes causal inference despite statistical adjustment. Baseline DBP and MAP differences, although modest, introduce potential confounding.

The sample size, while adequately powered for detecting moderate differences in $EtCO_2$, limits precision for subgroup analyses. Neuroendocrine stress markers such as catecholamines or cortisol were not measured, preventing direct biochemical correlation with hemodynamic patterns. Additionally, invasive arterial monitoring was not employed, which could provide more granular hemodynamic assessment. Future randomized studies incorporating biochemical stress markers, invasive hemodynamic monitoring, and stratification by cardiovascular risk status would provide more definitive mechanistic insight.

CONCLUSION

In ASA I–II adults undergoing elective cholecystectomy under standardized general anesthesia, open cholecystectomy was associated with greater early and late intraoperative hemodynamic fluctuations—particularly in diastolic and mean arterial pressures—compared with laparoscopic cholecystectomy, which demonstrated comparatively stable cardiovascular profiles despite the physiological effects of CO_2 pneumoperitoneum. These findings suggest that surgical nociceptive stimulation in open procedures may exert a

stronger influence on intraoperative hemodynamic variability than controlled CO_2 absorption during laparoscopy, supporting the preferential use of minimally invasive techniques when cardiovascular stability is a priority..

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DECLARATIONS

Ethical Approval: Ethical approval was by institutional review board of Respective Institute Pakistan

Informed Consent: Informed Consent was taken from participants.

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Concept: IU; Design: AF, SR; Data Collection: AF, SR, AA, FZ, TRU; Analysis: IU, SH; Drafting: AF, IU

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