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Intraoperative mechanical power and postoperative pulmonary complications: association and threshold analysis in adult intra-abdominal surgery

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Abstract

Background Postoperative pulmonary complications (PPCs) contribute to perioperative morbidity and mortality. Mechanical powers (MPs) determined using different deviations from originally described MP have been shown to be associated with PPCs. We aimed to evaluate the association between a standardized derivation of MP and PPCs and to explore a threshold associated with increased risk in multicentre cohort of adults undergoing intra-abdominal surgery.

Methods Data on adult patients who underwent intra-abdominal surgery under general anaesthesia were obtained from the Multicentre Perioperative Outcomes Group registry. The primary outcome was a composite of PPCs comprising an expanded subset of diagnoses consistent with European Perioperative Clinical Outcome definitions. The association between intraoperative MP and PPCs was evaluated using multivariable logistic regression, adjusting for patient, surgical, and institutional factors.

Results Among 79,149 patients from 56 institutions, 4,812 (6.1%) developed PPCs. Each 1 J/ min increase in MP was associated with 5% higher odds of PPCs (OR = 1.05, 95% CI [1.05–1.06]; p < 0.0001). Receiver operating characteristic analysis identified a threshold of 12 J/ min (sensitivity = 0.54, specificity = 0.51), above which patients had 54% higher adjusted odds of PPCs (OR_{adj} = 1.54, 95% CI [1.42–1.66]; p < 0.0001).

Conclusions Higher MP was associated with increased risk of PPCs in patients undergoing intra-abdominal surgery. Although MP values above 12 J min^{-1} were associated with significantly increased odds of PPCs, this threshold demonstrated notably low standalone discriminatory performance. Further research is required to evaluate whether MP-directed lung-protective ventilation strategy could prospectively improve clinical outcomes.

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Keywords General anaesthesia, Intra-abdominal surgery, Lung-protective ventilation, Mechanical power, Postoperative pulmonary complications

Background

Globally, around 300 million major surgical procedures are performed each year [1], with an estimated incidence of postoperative pulmonary complications (PPCs) ranging from 1 to 35% depending on the definition and severity of PPCs and with significant impact on morbidity and mortality [2–4]. In the United States, more than 1 million PPCs occur annually with 46,200 related deaths and 4.8 million hospitalization days [5].

In 2016, Gattinoni et al. introduced mechanical power (MP) as an essential variable of invasive mechanical ventilation [6]. They showed that MP in J min^{-1}, which reflects the energy delivered by the mechanical ventilator onto the respiratory system over time, is superior than traditional mechanical ventilation parameters in estimating the contribution of different ventilator-related factors causing lung injury [6, 7].

To date, five large studies have investigated the association between different derivations of intraoperative MP and PPCs in adult patients undergoing general anaesthesia with two-lung ventilation [8–12]. However, important methodological heterogeneity exists across these studies, including variations in MP calculation, use of averaged ventilatory variables, limited multicentre representation, and lack of clinically applicable thresholds for risk stratification.

Therefore, we conducted a large multicentre retrospective cohort study using the Multicenter Perioperative Outcomes Group (MPOG) database to evaluate the association between a standardized derivation of MP and PPCs in patients undergoing intra-abdominal surgery and to identify a threshold associated with increased risk. We hypothesized that higher intraoperative MP would be independently associated with increased odds of PPCs and that increasing MP exposure would demonstrate a dose-dependent relationship with PPCs risk.

Methods

Study design

This retrospective observational cohort study was approved by the Institutional Review Board of the American University of Beirut (#BIO-2024–0016), which granted a waiver of informed consent. It was registered on Open Science Framework (OSF) (https://doi.org/10.17605/OSF.IO/WRQ6B). The study was reported in accordance with the Reporting of Studies Conducted Using Observational Routinely Collected Health Data (RECORD) extension to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (Supplementary Digital Content S1) [13, 14]. This study used data from the Multicentre Perioperative Outcomes Group (MPOG), a perioperative registry derived from electronic health records of more than 70 hospitals across the United States, Canada, and the Middle East. Data quality is ensured through a multistep validation process, including automated diagnostics, routine manual chart review, and monthly institutional attestations [15]. Data acquisition through uploads of electronic medical record systems from each participating institution, data storage, and secure transfer have been described elsewhere [16, 17]. Approval from the MPOG peer-review Clinical Research Committee was obtained on August 19th 2024 prior to data access.

Study population

The study included adults in-patients undergoing general anaesthesia for intra-abdominal surgeries with endotracheal intubation and receiving pressure controlled (PCV) or volume-controlled ventilation (VCV), with available electronic documentation of intraoperative ventilation parameters. We excluded patients undergoing robotic surgeries and those positioned prone or in steep Trendelenburg because pneumoperitoneum and positional changes significantly alter chest wall compliance, which can elevate Pplat, and thus calculated MP, independent of true lung distending stress. We also excluded cases with one lung ventilation, those who have had previous recorded surgery within 30 days, those who develop postprocedure aspiration pneumonia, those with a known history of lung transplantation and American Society of Anaesthesiologists (ASA) physical status classification 5 or 6. Cases missing the exposure, the outcome or important confounders were excluded. Surgical cases performed between the dates of January 1 st, 2017, and July 31 st, 2024, were included.

Exposure variable

Mechanical power and other relevant ventilation variable values (V_T, RR, PEEP, P_{plat} and P_{peak}) were extracted from electronic medical records on a per minute basis for the entire period of intraoperative mechanical ventilation. The most accurate way to calculate MP is to measure a true pressure–volume curve and integrate numerically to get work, and then multiply by respiratory rate. This method

is difficult to implement in clinical setting [18]. Thus, to calculate the MP, for VCV, we used a validated simplified equation by Gattinoni et al.: MP (J min^{-1}) = 0.098 × RR x V_T x (P_{peak} – [(P_{Plat} – PEEP)/2]) [6]. For PCV, we used a validated surrogate equation by Becher et al.: MP (J min^{-1}) = 0.098 × RR x V_T x (P_{Peak}) [19]. Recognizing that transient elevation in MP may contribute to lung injury [20], and to mitigate the influence of data artifacts or outliers at extreme values, we selected the 80th percentile of the highest calculated intraoperative MP value for each patient to capture sustained high-exposure conditions.

Primary outcome

The primary outcome is a composite of PPCs comprising an expanded subset of diagnoses consistent with European Perioperative Clinical Outcome (EPCO) definitions. It is derived from the Agency for Healthcare Research and Quality (AHRQ)- pulmonary complications definition, based on International classification of diseases (ICD 9/10) codes documented from day of surgery through 7 days after surgery [21], as used in prior published studies [22, 23] (Supplementary Digital Content S2). Sensitivity analyses were performed to classify the outcome based on the mechanism of the respiratory complications (pneumonia, respiratory failure, pneumothorax, pulmonary edema, and others).

Statistical analyses

We defined statistical analyses, confounding variables and study outcomes prior to accessing data for analyses. Categorical variables were summarized as frequencies and percentages, while continuous variables were presented as means with standard deviations or medians with interquartile ranges (25th, 75th percentiles), as appropriate. A complete case analysis was performed for missing outcome, exposure, and confounder data. The frequency distribution of intraoperative MP was assessed and presented using histograms, and box plots were used to display the distribution of MP across case years. Preoperative characteristics and perioperative events were compared between patients with and without PPCs using standardized mean differences (SMD), with 0.2, 0.5, and 0.8 representing small, medium, and large differences, respectively [24]. Least absolute shrinkage and selection operator (LASSO) regression was used as a supplementary method for covariate selection.

Before model construction, collinearity among variables was assessed using the condition index; if the index was > 30, Pearson's correlation matrix was developed. Variables strongly correlated with MP (correlation ≥ 0.70) were reviewed and considered for removal [25]. We adjusted the analyses for predefined confounders selected on the basis of prior evidence and clinical rationale [8, 26]. The association between intraoperative MP and PPCs was evaluated using multivariable logistic regression, adjusting for potential confounders, including age, sex, ASA physical status, emergency status, body mass index (BMI), comorbidities (chronic pulmonary disease, congenital heart disease, complicated diabetes, liver disease, metastatic cancer, obesity, other neurological disorders, pulmonary circulation disorders, and renal failure), body region (upper versus lower abdominal), laparoscopic surgery, volume of crystalloids administered, surgery duration, and preoperative haemoglobin ≤ 10 g/dl. Institution was included as a random effect in the model (Supplementary Digital Content S3). Model discrimination was evaluated using the c-statistic (AUC). Receiver operating characteristic (ROC) curve analyses were conducted to explore potential intraoperative MP thresholds associated with PPCs. Sensitivity and specificity were calculated for each threshold, and the threshold that provided optimal balance between sensitivity and specificity was selected. The primary regression analysis was repeated using mechanical power categorized by a threshold of 12 J/min, as well as the duration and cumulative exposure above this threshold. Associations with postoperative pulmonary complications (PPCs) were expressed as odds ratios (ORs) with 95% confidence intervals (CIs) and p-values.

Given a sample of 79,149 cases, and the incidence of PPCs and assuming that R^2 of other covariates is 10% of the outcome, we have 96% power to detect odds ratios as small as 1.05 per 1 J/min, which means a 5% increase in risk for one-unit increase in mechanical ventilation [8].

All statistical analyses were performed using R version 4.4.2 (R Foundation for Statistical Computing, Vienna, Austria). A two-sided p-value < 0.05 was considered statistically significant.

Sensitivity analyses

We conducted several sensitivity analyses to confirm the robustness of the findings of the primary analyses across patient subgroups, alternative MP definitions, individual outcomes, and potential confounders.

The analyses were repeated in high-risk subgroups including upper abdominal incision, emergency surgery, ASA III–IV, surgeries lasting ≥ 3 h, and laparoscopic procedures. Furthermore, we explored alternative categorizations and normalizations of MP: MP was normalized to ideal body weight (IBW) [20, 27], body mass index (BMI) [28], and pulmonary compliance. We calculated mean MP per case instead of the 80th percentile and analysed it separately. We also examined the association of MP with specific PPCs, including pneumonia, respiratory failure, pneumothorax, pulmonary oedema, and other complications. We adjusted for the modified ARISCAT score, which incorporates age, haemoglobin, type of surgical incision, duration of surgery,

and emergency status alongside other confounders. We also repeated the primary analysis while including driving pressure as a covariate to assess the extent to which mechanical power provides information beyond this individual ventilatory component. We conducted inverse probability of treatment weighting (IPTW) analyses using stabilized weights, with extreme weights trimmed at the 1st and 99th percentiles to improve model stability, and repeated the weighted analyses. Finally, we compared cases with complete versus missing ventilation parameters to assess potential bias (Supplementary Digital Content S7).

Results

Study characteristics

A total of 196,285 adult patients from 56 institutions with available ventilation mode data undergoing intra-abdominal surgeries under general anaesthesia were initially screened. After exclusions, the final cohort for analysis consisted of 79,149 patients (Fig. 1). The density distribution of intraoperative MP comparing mean, median, and 80th percentile is depicted in Fig. 2. The distribution of mechanical power 80th percentile across case years is presented in Supplementary Digital Content S4.

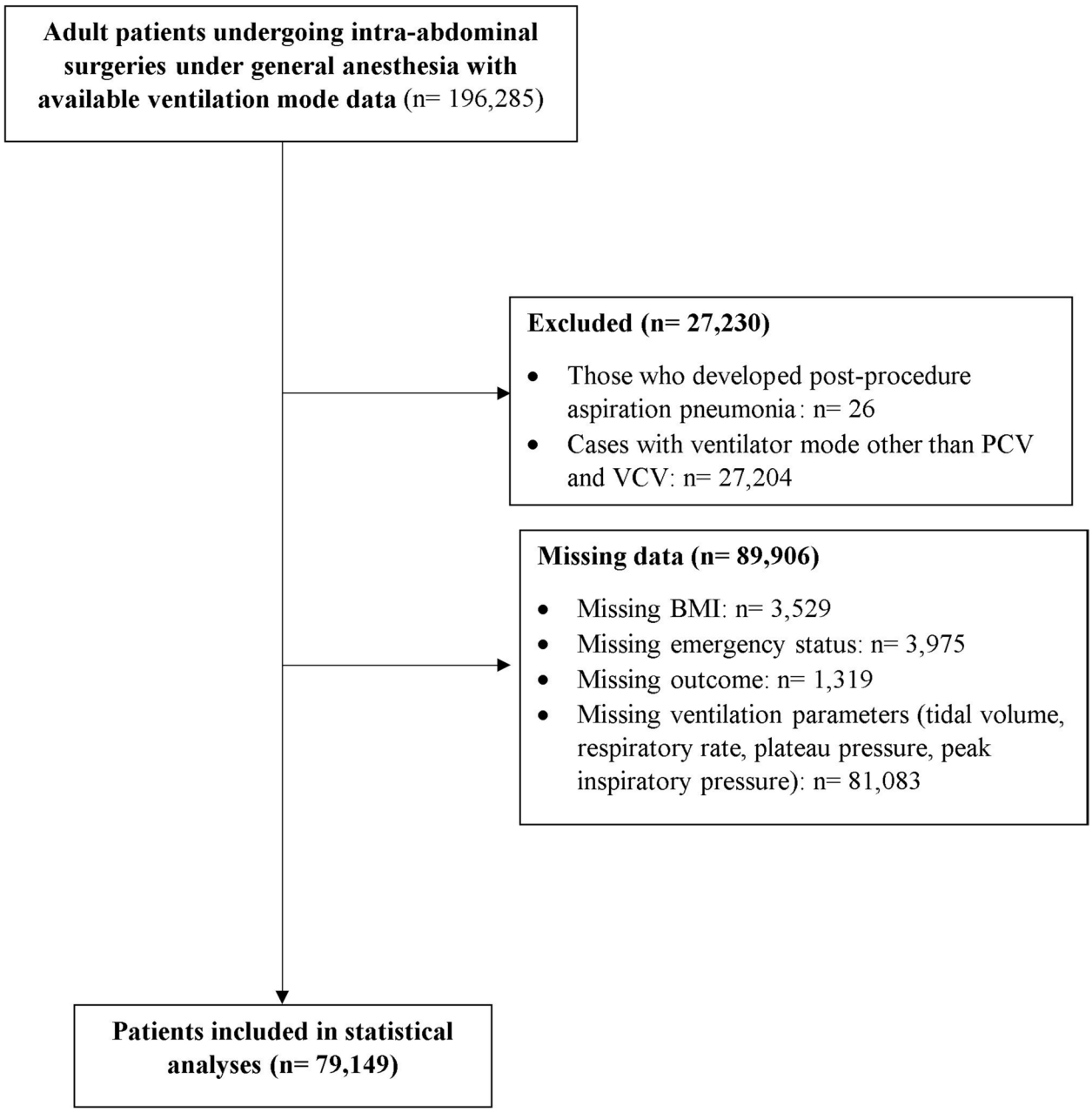


Fig. 1 STROBE Diagram showing the number of participants assessed for eligibility, those excluded, and the final cohort included in the analysis

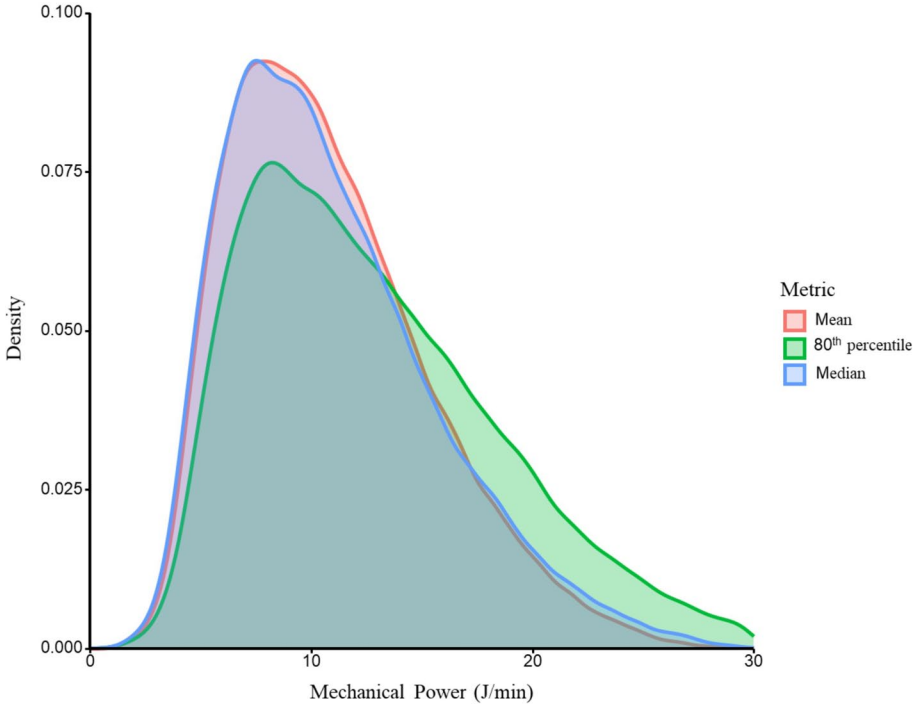


Fig. 2 Density Distribution of Intraoperative Mechanical Power Comparing Mean, Median, and 80th Percentile. The red line represents the mean, the green line corresponds to the 80th percentile, and the blue line represents the median

Demographics and perioperative characteristics of study participants are provided in Table 1. Table 2 summarizes intraoperative ventilation and respiratory parameters. Postoperative outcomes are summarized in Table 3.

Primary analysis

Overall, 4,812 of 79,149 patients (6.1%) experienced PPCs. Higher MP was significantly associated with increased odds of PPCs, with each 1 J min^{-1} increase in MP corresponding to a 5% increase in the odds (OR = 1.05, 95% CI [1.05–1.06]; p < 0.0001). The adjusted probability of PPCs increased with MP, ranging from 0.9% (95% CI [0.4–2.2%]) at 5 J min^{-1}, to 3.3% (95% CI [1.4–7.8%] at 30 J min^{-1} (Fig. 3). The multivariable logistic regression model for predicting PPCs incorporating perioperative covariates demonstrated excellent discrimination (AUC = 0.85) (Supplementary Digital Content S5).

In contrast, ROC analysis using mechanical power alone identified 12 J min^{-1} as the threshold providing the best balance between sensitivity and specificity, with a sensitivity of 0.54 and specificity of 0.51 (Supplementary Digital Content S6). In patients with MP < 12 J min^{-1} (n = 40,697), 2,247 (5.5%) developed PPCs, compared to 2,565 (6.7%) in those with MP ≥ 12 J min^{-1} (n = 38,452). Patients with MP above the threshold of 12 J min^{-1} had 54% higher odds of PPCs compared with those below it (OR_{adj} = 1.54, 95% CI [1.42–1.66]; p < 0.0001).

Secondary analysis

We further evaluated the effect of duration and cumulative exposure to high MP (≥ 12 J/min) on PPC risk, with each additional 10 min increasing the odds by 2% (OR = 1.02, 95% CI [1.01–1.02], p < 0.0001). Similarly, each 100 J·min increase in cumulative mechanical power above 12 J/min was associated with 2% higher odds of PPCs (OR = 1.02, 95% CI [1.01–1.03], p < 0.0001).

Sensitivity analyses

Multiple sensitivity analyses confirmed the robustness of the primary findings (Supplementary Digital Content S7). The association between higher mechanical power and PPCs remained statistically significant across subgroups, including upper abdominal surgery, emergency procedures, ASA III–IV status, prolonged surgery, and laparoscopic approaches. The association persisted when mechanical power was normalized to ideal body weight, body mass index, and pulmonary compliance, and when mean values were used instead of 80th percentile. Similar results were observed for individual PPC components. Additional adjustment using a modified ARISCAT score

Table 1 Demographics and perioperative characteristics

Variable		N = 79,149	No PPCs (n = 74,337)	PPCs (n = 4,812)	SMD
Age (Yr)		54.90 ± 16.20	54.45 ± 16.18	62.28 ± 14.67	0.507
Sex	Female	48,926 (61.8%)	46,452 (62.5%)	2,474 (51.4%)	0.225
	Male	30,223 (38.2%)	27,885 (37.5%)	2,338 (48.6%)	
ASA status classification	I	1,565 (2.0%)	1,560 (2.1%)	5 (0.1%)	0.888
	II	26,683 (33.7%)	26,226 (35.3%)	457 (9.5%)	
	III	46,644 (58.9%)	43,542 (58.6%)	3,102 (64.5%)	
	IV	4,257 (5.4%)	3,009 (4.1%)	1,284 (25.9%)	
Emergency		5,690 (7.2%)	4,547 (6.1%)	1,143 (23.8%)	0.511
BMI (kg m^{-2})		29.70 ± 8.03	29.75 ± 8.00	28.95 ± 8.44	−0.097
Chronic pulmonary disease		17,774 (22.0%)	15,608 (21.0%)	1,836 (38.2%)	0.383
Congenital heart disease		6,526 (8.2%)	5,251 (7.1%)	1,275 (26.5%)	0.539
Complicated diabetes		9,678 (12.2%)	8,332 (11.2%)	1,346 (28.0%)	0.432
Liver disease		11,905 (15.0%)	10,672 (14.4%)	1,233 (25.6%)	0.285
Metastatic cancer		12,622 (15.9%)	11,584 (15.6%)	1,038 (21.6%)	0.154
Neurological disorders		4,681 (5.9%)	3,634 (4.9%)	1,047 (21.8%)	0.512
Pulmonary circulation disorders		3,773 (4.8%)	2,887 (3.9%)	886 (18.4%)	0.474
Renal failure		10,107 (12.8%)	8,631 (11.6%)	1,476 (30.7%)	0.480
Rheumatoid Arthritis/Collagen Vascular Diseases		3,174 (4.0%)	2,867 (3.9%)	307 (6.4%)	0.115
Valvular disease		5,165 (6.5%)	4,370 (5.9%)	795 (16.5%)	0.342
Smoking status	Current User	441 (0.6%)	403 (0.5%)	38 (0.8%)	0.169
	Former User	16,394 (20.7%)	15,093 (20.3%)	1,301 (27.0%)	
	Non-user	19,071 (24.1%)	18,083 (24.3%)	988 (20.5%)	
	Unknown	43,243 (54.6%)	40,758 (54.8%)	2,485 (51.6%)	
Surgical body region	Lower Abdomen	30,550 (38.6%)	29,462 (39.6%)	1,088 (22.6%)	0.374
	Upper Abdomen	48,599 (61.4%)	44,875 (60.4%)	3,724 (77.4%)	
Laparoscopic		37,502 (47.4%)	36,203 (48.7%)	1,299 (27.0%)	−0.459
Neuromuscular reversal agent	Neostigmine	13,524 (17.1%)	12,899 (17.4%)	625 (13.0%)	0.112
	Sugammadex	65,625 (82.9%)	61,438 (82.7%)	4,187 (87.0%)	
Preoperative Haemoglobin	> 10 g/dL	64,341 (81.3%)	60,883 (81.9%)	3,458 (71.9%)	0.240
	≤ 10 g/dL	14,808 (18.7%)	13,454 (18.1%)	1,354 (28.1%)	
Vasopressor infusion		23,348 (29.0%)	20,222 (27.2%)	2,759 (57.3%)	0.664
Intraoperative crystalloids volume (mL)		1400 (901, 2168)	1400 (900, 2070)	2000 (1000, 3500)	0.371
Anesthesia duration (minutes)		198 (152, 280)	196 (151, 274)	256 (180, 394)	0.492
Surgery duration (minutes)		135 (94, 208)	133 (93, 204)	175 (103, 296)	0.323

Data presented as n (%), mean ± SD, and median (Q1, Q3)

ASA American Society of Anaesthesiologists, *BMI* Body Mass Index, *CRNA* Certified Registered Nurse Anaesthetist, *ETT* Endotracheal Tube, *ICU* Intensive Care Unit, *PACU* Post-Anesthesia Care Unit, *PPCs* Postoperative Pulmonary Complications, *SMD* Standardized Mean Difference

and driving pressure yielded similar association. The results using inverse probability weighting were consistent with the primary mixed-effects model. Comparisons between cases with complete and missing ventilation data showed minimal differences.

Discussion

This large multicentre retrospective observational cohort study demonstrates that higher intraoperative MP during abdominal surgery in adult patients is associated with an increased risk of PPCs. This association remained consistent after adjustment for established risk factors for PPCs. Patients ventilated with both volume-controlled and pressure-controlled modes were included, and mode-specific equations were applied with the use of P_{plat} rather than the P_{peak} or a mix between P_{peak} and P_{plat} to accurately estimate delivered energy. The study period spanned from 2017 to 2024, beginning one year after the introduction of the MP concept to ensure clinical familiarity among anesthesiologists [6].

Table 2 Intraoperative Ventilation and Respiratory Parameters

Variable		N = 79,149	No PPCs (n = 74,337)	PPCs (n = 4,812)	SMD
Respiratory rate (breaths min^{-1})		13.89 ± 3.02	13.85 ± 2.99	14.45 ± 3.37	0.186
Tidal volume (L)		0.47 ± 0.07	0.47 ± 0.07	0.46 ± 0.07	−0.086
PEEP (cmH_2O)		5.39 ± 1.86	5.38 ± 1.85	5.58 ± 1.98	0.104
Peak inspiratory pressure (cmH_2O)		22.33 ± 6.88	22.29 ± 6.88	22.95 ± 6.94	0.095
Plateau pressure (cmH_2O)		19.56 ± 5.95	19.52 ± 5.95	20.14 ± 5.92	0.105
Ventilator mode	PCV	50,928 (64.3%)	47,795 (64.3%)	3,133 (65.1%)	−0.017
	VCV	28,221 (35.7%)	26,542 (35.7%)	1,679 (34.9%)	
Mechanical power (J min^{-1})		12.74 ± 5.62	12.69 ± 5.6	13.48 ± 5.85	0.137
Driving pressure (cmH_2O)		14.29 ± 5.73	14.27 ± 5.73	14.63 ± 5.66	0.063
ETT size		7.21 ± 0.42	7.20 ± 0.41	7.29 ± 0.46	0.217
FiO_2 (%)		65.10 ± 17.88	64.86 ± 17.75	68.72 ± 19.40	0.208
SpO_2 (%)		94 (90, 96)	94 (91, 96)	91 (85, 95)	−0.583
Ventilation duration (minutes)		161 (117, 241)	158 (116, 235)	226 (141, 383)	0.511
Pressure limit (cmH_2O)		50 (45, 50)	50 (45, 50)	50 (45, 50)	0.000
Pulmonary compliance (mL cmH_2O^{-1})		35.92 ± 14.06	36.01 ± 14.09	34.56 ± 13.55	−0.105

Data presented as n (%), mean ± SD, and median (Q1, Q3)

ETT Endotracheal Tube, *FiO_2* Fraction of Inspired Oxygen, *PCV* Pressure-Controlled Ventilation, *PEEP* Positive End-Expiratory Pressure, *PPCs* Postoperative Pulmonary Complications, *SMD* Standardized Mean Difference, *SpO_2* Peripheral Oxygen Saturation; *VCV* Volume-Controlled Ventilation

Table 3 Postoperative Outcomes

Variable		N = 80,541	No PPCs (n = 75,621)	PPCs (n = 4,920)	SMD
Hospital length of stay (Days)		3 (1, 6)	3 (1, 5)	9 (5, 18)	1.225
30-day hospital mortality		805 (1.0%)	368 (0.5%)	437 (9.1%)	0.411
Postoperative destination	Unknown destination	4,940 (6.2%)	4,081 (5.5%)	859 (17.9%)	0.757
	Intensive-care unit	1,849 (2.3%)	942 (1.3%)	907 (18.8%)	
	Post-anaesthesia care unit	72,360 (90.8%)	69,314 (93.2%)	3,046 (63.3%)	

Data presented as n (%) and median (Q1, Q3)

PPCs Postoperative Pulmonary Complications, *SMD* Standardized Mean Difference

In our primary analysis, higher intraoperative mechanical power was independently associated with an increased risk of postoperative pulmonary complications. This association remained consistent when alternative methods of quantifying mechanical power were used, supporting the robustness of the finding. Similarly, a study that evaluates the association between intraoperative chemical power and MP and a collapsed composite of PPCs found that every 1 J min^{-1} increment in MP was associated with a 5% increased risk of PPCs [10]. Moreover, a study conducted by Santer et al. on adult surgical patients undergoing general anaesthesia for elective non-cardiac surgery showed that every 5 J min^{-1} increase in MP was associated with a 31% greater odds of reintubation [8].

Mechanical power, which reflects the total energy delivered to the lung, integrates both static and dynamic components of ventilation. It represents the interplay between the magnitude of lung strain and the frequency of strain cycles [6, 29]. In simpler terms, MP can be described as the product of the work of breathing per breath (volume × pressure) and the RR. Mathematically, the MP will increase with the exponent of 2 of the V_T, the exponent of 1.4 of the RR and the exponent of 1 of PEEP [6]. When adjusting ventilator settings, it is essential to consider all these variables together. For example, lowering V_T while compensating with a higher RR—a strategy often used to reduce P_{peak}—has not been shown to improve pulmonary outcomes [30]. In our study, MP was independently associated with PPCs, even after adjusting for driving pressure. Although mechanical power incorporates driving pressure, this additional adjustment was performed to determine whether MP provides prognostic information beyond this single component. Similarly, prior investigations have confirmed that MP remains independently associated with outcomes after controlling for driving pressure, V_T, and RR [8]. These findings underscore the value of MP as a comprehensive and

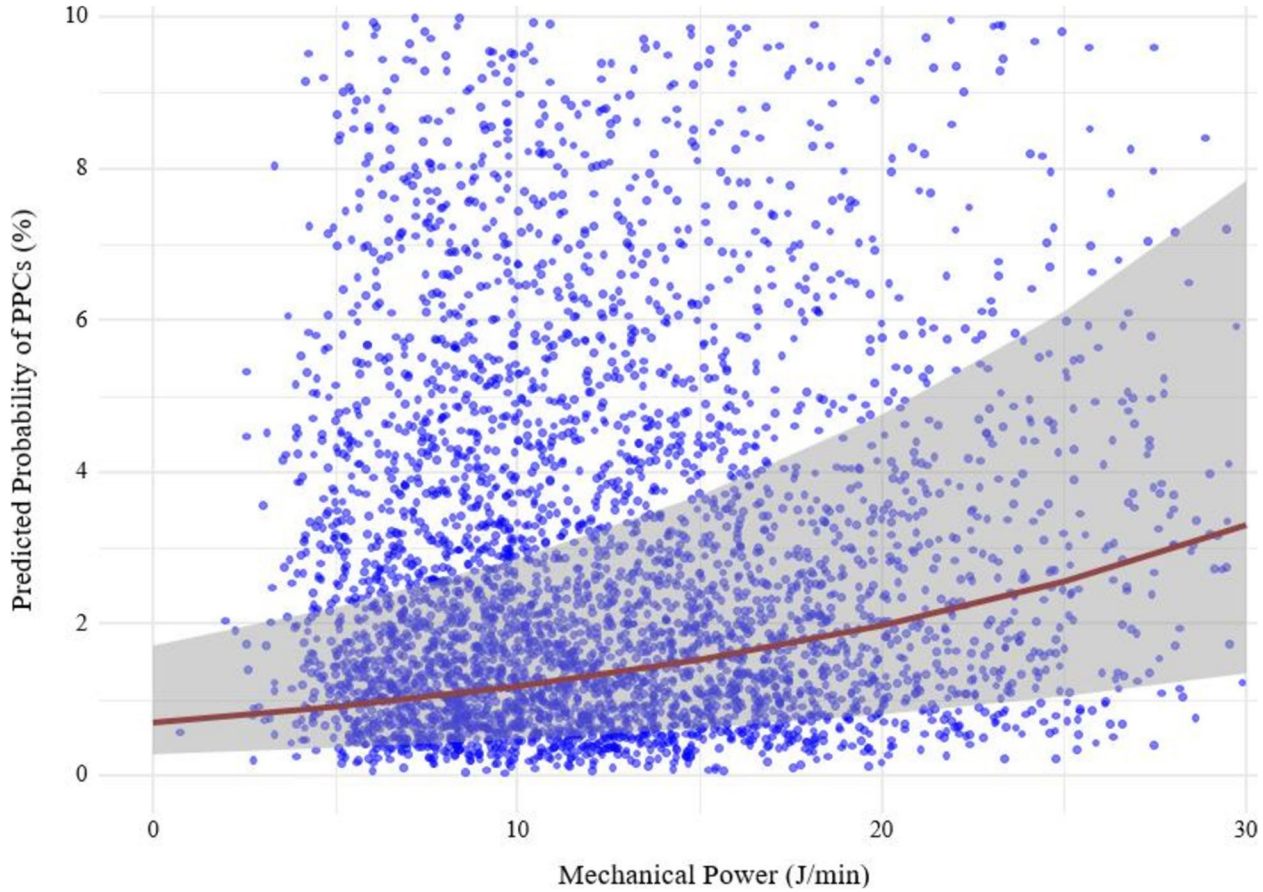


Fig. 3 Adjusted Probability of Postoperative Pulmonary Complications by Mechanical Power. The red line with grey shaded area represents the adjusted predicted probability of postoperative pulmonary complications across the range of mechanical power, with 95% confidence intervals. Blue dots show individual patient predicted probabilities. Overall, the adjusted probability of PPCs increased with MP, ranging from 0.9% (95% CI [0.4-2.2%]) at 5 J/min, at 3.3% (95% CI[1.4-7.8%]) at J/min

universal metric to guide intraoperative ventilation strategies, with the goal of reducing PPCs.

To better capture exposure to injurious intraoperative ventilatory support, we considered the 80th percentile of intraoperative MP rather than mean or median values. The 80th percentile curve highlights the upper tail of mechanical power exposure, capturing elevated intraoperative mechanical power beyond the levels indicated by mean or median values. This approach highlights peaks in ventilatory energy that may contribute to acute lung stress. In fact, a study conducted on patients with acute respiratory failure found that cumulative exposure to higher mechanical ventilation intensities, evaluated through daily measurements of MP, was associated with harm, even when the duration of exposure was short [12]. Moreover, our results were consistent when mean was used instead of the 80th percentile of the highest value of MP, indicating that both transient elevations and sustained/recurrent exposure to higher MP contribute to PPCs risk.

Although a value around 12 J min^{-1} provided the best statistical balance between sensitivity and specificity, PPC risk increased in a dose-dependent manner across the spectrum of MP exposure. Specifically, patients exposed to MP of $\geq$ 12 J min^{-1} had higher adjusted odds of PPCs compared with those with lower exposure (< 12 J min^{-1}). Several studies in critically ill patients have identified an MP threshold of 17 J min^{-1} [31]. In the surgical population, Muller et al. reported that the probability of PPCs started to increase after 15 J min^{-1} of delivered MP [10]. In their analysis, the authors used the time-weighted average of intraoperative MP, which may explain the observed difference. Furthermore, our study has shown that beyond 12 J/min, even relatively small increments in exposure- 10 min above the threshold, or an additional 100 J/min of cumulative MP-were associated with a

measurable (2%) increase in the odds of PPCs, supporting a cumulative dose–response relationship between higher mechanical power exposure and PPC risk. Importantly, the threshold value should be interpreted as a reference point associated with elevated risk. It does not constitute a standalone clinical decision rule but instead highlights a range of ventilatory energy exposure that may provide a clinical target for intraoperative lung-protective ventilation strategies.

The results of multiple sensitivity analyses further support the robustness of our current findings. The association between higher intraoperative MP and PPCs persisted in high-risk groups. Results were consistent when MP was normalized to IBW and BMI, reducing the likelihood that body size confounded the observed effect. Likewise, when adjusting MP for IBW and BMI, Santer found that the risk of reintubation increased by 44% with each 0.1 J min^{-1} kg^{-1} of IBW increase in MP, and by 17% with each 0.1 J min^{-1} kg^{-1} m^{-2} increase in MP [8]. When normalized by the compliance of respiratory system, MP remained predictive of PPCs. This highlights that MP is not merely a surrogate for reduced lung compliance, but an independent predictor of PPCs [12]. Further adjustment using a modified ARISCAT score including age, haemoglobin level, surgical incision, duration of surgery and emergency procedure produced similar effect estimates, suggesting that MP provides prognostic information beyond established clinical predictors.

This study has several notable strengths. It draws on data from 56 institutions and represents the second-largest investigation to date examining intraoperative MP. By leveraging a large multicentre registry with rigorous data quality processes, the study minimizes the risk of bias related to single-centre practices. To enhance accuracy, MP was calculated using ventilatory mode–specific equations and plateau rather than peak airway pressures. Also, we established the protocol in advance of the analysis, enhancing the methodological rigor and credibility of the study. Finally, a comprehensive set of sensitivity analyses was performed, all of which confirmed the robustness and consistency of the results.

Limitations of the current study include the retrospective design, which precludes causal inference. Despite extensive multivariable adjustment, residual confounding remains an important limitation of this analysis. In particular, unmeasured and inadequately captured variables such as intraoperative lung mechanics not recorded in the registry, clinician-driven ventilation adjustments in response to evolving patient physiology, pre-existing pulmonary pathology not fully captured in administrative data, and incomplete medications documentation may have influenced both ventilatory management and postoperative outcomes, introducing potential omitted variable bias. Furthermore, thousands of patients were excluded because of missing data, however, a comparison between cases with missing and complete data showed only minimal differences (SMD < 0.1) suggesting that the two groups were comparable. To calculate MP, we used a simplified previously validated equation [32]. However, the gold standard method for calculating MP is the geometric method, defined as the area between the inspiratory limb of the pressure and the volume axis. This method is unpractical without a ventilator automatically measuring the delivered mechanical energy. While we focused on the 80th percentile to reflect high-risk periods while excluding potential artifacts, the optimal metric for harmful mechanical energy remains uncertain. In addition, the threshold was derived and evaluated within the same dataset, and formal internal validation techniques such as bootstrapping or split-sample validation were not performed. Although similar thresholds have been reported in prior cohorts, external validation in independent populations is required before generalizing these findings. The modest sensitivity and specificity observed limit its use as a predictive instrument in routine clinical practice. Moreover, our primary outcome, was a composite of PPCs derived from ICD9/10 codes documented until 7 days after the surgery. While the use of a composite outcome improves statistical efficiency, it may obscure differences between individual PPC components. Nevertheless, sensitivity analyses evaluating individual PPC components separately demonstrated consistent findings. In addition, outcome ascertainment relied on the accuracy, completeness, and variable mapping practices of each institution. Although MPOG coordinating centre performs routine quality checks, some data elements may not be fully captured. Lastly, although this study is multicentre, most institutions were large academic centres, which may limit generalizability to smaller or lower-resource hospitals.

Conclusion

In conclusion, among patients undergoing general anaesthesia for intra-abdominal surgery, higher intraoperative MP was a significant predictor of PPCs. A value around 12 J min^{-1} was associated with higher complication rates and may represent a clinically relevant exposure range. Further research is required to evaluate whether MP-guided lung-protective ventilation approach could prospectively enhance clinical outcomes.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s44158-026-00423-6.

Supplementary Material 1: Online Supplementary File S1. RECORD Statement.

Supplementary Material 2: Online Supplementary File S2. Definitions of Primary Outcome Variables and Outcomes Used in Sensitivity Analyses.

Supplementary Material 3: Online Supplementary File S3. Results of the Primary Multivariable Logistic Regression Model.

Supplementary Material 4: Online Supplementary File S4. Distribution of Mechanical Power Across Case Years (2017–2024).

Supplementary Material 5: Online Supplementary File S5. ROC Curve of the Multivariable Logistic Regression Model for Predicting Postoperative Pulmonary Complications.

Supplementary Material 6: Online Supplementary File S6. ROC Curve of Mechanical Power for Predicting Postoperative Pulmonary Complications.

Supplementary Material 7: Online Supplementary File S7. Sensitivity Analyses. Table S7.1. Association of Mechanical Power Normalized to Ideal Body Weight and BMI with Postoperative Pulmonary Complications. Table S7.2. Modified ARISCAT Score. Table S7.3. Characteristics of Included vs Excluded Cases (Missing Ventilation Parameters). Figure S7.1. Forest Plot of the Association Between Mechanical Power and Specific Postoperative Pulmonary Complications. Figure S7.2. Standardized Mean Differences of Baseline Covariates Before and After Inverse Probability Weighting for MP ≥ 12 J/Min vs. Mechanical Power < 12 J/Min.

Acknowledgements

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Clinical trial number

Not applicable.

Authors' contributions

Mohamad El-Khatib: Conceptualization, methodology, investigation, supervision, and writing the original draft; Thuraya HajAli: Methodology, data curation, formal analysis, and writing the original draft; Carine Zeeni: Investigation, methodology, and writing the original draft; Amro Khalili: Investigation, methodology, and writing the original draft; Rasha Shreim: Methodology and writing the original draft; Michael Mathis: Methodology, data curation, and writing the original draft; Nancy Abou Nafeh: Conceptualization, methodology, investigation, supervision, and writing the original draft; Marie Aouad: Conceptualization, methodology, supervision, and writing the original draft. All authors contributed to revising the manuscript and approving it before submission.

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Data availability

The datasets involved in this study are defined as limited datasets per United States Federal Regulations and require execution of a data use agreement for transfer or use of the data. They are derived from data shared within the Multicenter Perioperative Outcomes Group (MPOG). The investigative team is able to share data securely and transparently conditional on: (i) receipt of a detailed written request identifying the requestor, purpose and proposed use of the shared data, (ii) use of a secure enclave for the sharing of personally identifiable information and (iii) the request is permissible within the confines of existing data use agreements executed between MPOG members.

Declarations

Ethics approval and consent to participate

This retrospective observational cohort study was approved by the Institutional Review Board of the American University of Beirut (#BIO-2024–0016), which granted a waiver of informed consent.

Consent for publication

A waiver of informed consent was obtained.

Competing interests

MRM has received research grant support from the National Institutes of Health (NIDDK, NHLBI) and from industry sponsorship (Chiesi, USA) paid to the University of Michigan, unrelated to the present work.

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