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Respiration and the Airway

RESPIRATION AND THE AIRWAY

Ventilation and outcomes following robotic-assisted abdominal surgery: an international, multicentre observational study

Assessment of Ventilation during general AnesThesia for Robotic surgery (AVATaR) Study Investigators†, for the PROtective VEntilation (PROVE) Network*

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Abstract

Background: International data on the epidemiology, ventilation practice, and outcomes in patients undergoing abdominal robotic-assisted surgery (RAS) are lacking. The aim of the study was to assess the incidence of postoperative pulmonary complications (PPCs), and to describe ventilator management after abdominal RAS.

Methods: This was an international, multicentre, prospective study in 34 centres in nine countries. Patients ≥18 yr of age undergoing abdominal RAS were enrolled between April 2017 and March 2019. The Assess Respiratory Risk in Surgical Patients in Catalonia (ARISCAT) score was used to stratify for higher risk of PPCs (≥26). The primary outcome was the incidence of PPCs. Secondary endpoints included the preoperative risk for PPCs and ventilator management.

Results: Of 1167 subjects screened, 905 abdominal RAS patients were included. Overall, 590 (65.2%) patients were at increased risk for PPCs. Meanwhile, 172 (19%) patients sustained PPCs, which occurred more frequently in 132 (22.4%) patients at increased risk, compared with 40 (12.7%) patients at lower risk of PPCs (absolute risk difference: 12.2% [95% confidence intervals (CI), 6.8–17.6%]; $P<0.001$). Plateau and driving pressures were higher in patients at increased risk, compared with patients at low risk of PPCs, but no ventilatory variables were independently associated with increased occurrence of PPCs. Development of PPCs was associated with a longer hospital stay.

Conclusions: One in five patients developed one or more PPCs (chiefly unplanned oxygen requirement), which was associated with a longer hospital stay. No ventilatory variables were independently associated with PPCs.

Clinical trial registration: NCT02989415.

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Keywords: abdominal surgery; intraoperative ventilation; postoperative pulmonary complications; robotic-assisted surgery; robotic surgery

Editor's key points

- Data on the epidemiology, ventilation practice, and outcomes in patients undergoing robotic-assisted abdominal surgery are lacking.
- This international, multicentre, prospective study in 34 centres (nine countries) is the first to describe postoperative pulmonary complications after robotic-assisted abdominal surgery.
- Overall, 172/905 (19%) patients sustained postoperative pulmonary complications, which occurred more frequently in patients with an ARISCAT (Assess Respiratory Risk in Surgical Patients in Catalonia) score >26.
- No intraoperative ventilatory variables were independently associated with developing postoperative pulmonary complications.
- Postoperative pulmonary complications, chiefly defined by unplanned oxygen requirement, were associated with prolonged hospitalisation.

Robotic-assisted laparoscopic surgery (RAS) is increasingly used worldwide.[1] Pneumoperitoneum, necessary for optimal exposure of the operating field during abdominal RAS, has a negative impact on respiratory mechanics, especially when combined with Trendelenburg positioning.[2] Carbon dioxide (CO_2) insufflation into the peritoneal cavity, as commonly used for pneumoperitoneum, increases the intra-abdominal pressure and induces a cephalad displacement of the diaphragm, decreasing the compliance of the respiratory system and functional residual capacity.[3] Trendelenburg positioning also promotes a cephalad shift of abdominal organs, further restricting diaphragm movements and thoracic expansions. Together, these changes promote atelectasis, and increase the risk of postoperative pulmonary complications (PPCs).[3–7]

Despite the growing use of RAS, the epidemiology, intraoperative ventilator management, and clinical outcomes of this surgical approach are poorly defined. The primary aim of the Assessment of Ventilation during general AnesThesia for Robotic surgery (AVATaR) study was to determine the incidence of PPCs in patients undergoing RAS. Secondary aims were to describe the preoperative risk for PPCs according to the Assess Respiratory Risk in Surgical Patients in Catalonia (ARISCAT) risk score,[8] and to characterise current ventilation practices during anaesthesia for RAS. In addition, we aimed to determine the associations between preoperative risk for PPCs according to the ARISCAT, intraoperative ventilation variables and parameters with the development of PPCs. This report focuses on patients undergoing abdominal RAS.

Methods

A full description of the methods is provided in Supplement 3.

Study design and overview

The AVATaR study was an investigator-initiated, international, multicentre, prospective observational study. The study protocol is available in Supplement 1. During the fixed 30 days selected by local investigators in each centre, all consecutive patients planned for RAS were screened. A statistical analysis plan was written before cleaning and closing the database; both the protocol and statistical analysis plan have been published.[9] The Institutional Review Board at each study site approved the study protocol. If applicable, written informed consent was obtained from all patients. The AVATaR study was registered at clinicaltrials.gov (study identifier NCT02989415).

Inclusion criteria

Patients were eligible for participation in the AVATaR study if they were 18 yr or older and scheduled to undergo an abdominal procedure requiring robotic-assisted surgery.

Exclusion criteria

Pregnant patients and those in whom the procedure was converted to open, or laparoscopic-assisted surgery without the use of a robot were excluded. As the current report focuses on abdominal RAS patients, patients who underwent RAS outside of the abdominal cavity were excluded from this analysis.

Data collection

The ARISCAT score for PPCs was calculated for each patient.[8] Ventilatory variables and vital signs were collected hourly for the first 6 h of surgery and in four specific periods intraoperatively, defined as follows: (1) 5 min after induction of anaesthesia and start of intraoperative ventilation (T_1); (2) 5 min after insufflation of pneumoperitoneum (T_2); (3) 5 min after positioning, that is immediately before start of the surgical procedure (T_3); and (4) 5 min after abdominal exsufflation and repositioning of the patient (T_4). Intraoperative complications were collected from the start until the end of intraoperative ventilation, and PPCs in the postoperative period until day 5 or hospital discharge, whichever came first.

Ventilatory parameters

Driving pressure was calculated as plateau pressure minus PEEP and only in patients in whom the plateau pressure was available. Tidal volume (V_T) was corrected for predicted body weight (PBW). Static respiratory system compliance (C_{RS}) was calculated as V_T divided by the difference between the plateau pressure and PEEP; dynamic respiratory system compliance (C_{dyn}) as V_T divided by the difference between peak pressure and PEEP.

Primary outcome

The primary outcome was the incidence of PPCs, defined as a collapse composite outcome of unplanned supplementary

oxygen, acute respiratory failure, pneumonia, acute respiratory distress syndrome (ARDS), or pneumothorax developing within the first 5 postoperative days or until hospital discharge (full definition in Table 1, Supplement 3). Data collectors were instructed on how to collect each PPC. Any use of supplementary oxygen other than normal standard of care was defined as 'unplanned need of oxygen'. Patients discharged before the end of follow-up without any PPCs were considered as without PPCs at day 5.

Secondary outcomes

Secondary outcomes were:

1. Preoperative risk for PPCs.
2. Ventilatory variables (tidal volume, peak, plateau, and driving pressure levels) related to PPCs.
3. Incidence of perioperative complications: severe PPCs (excluding the unplanned need of oxygen from the composite), intraoperative complications (full definition in Table 1, Supplement) including the need for unplanned mechanical ventilation after surgery and unplanned ICU admission.
4. Hospital length of stay and mortality.

Statistical analysis

Part of the analysis plan has been published previously.[7] Patients were stratified according to the preoperative risk for PPCs, with patients at increased risk having an ARISCAT risk score for PPCs $\geq$26 *vs* individuals at lower risk (ARISCAT risk score <26). Baseline characteristics were reported as numbers and percentages, mean (standard deviation) or median (lower–upper quartiles), as appropriate.

The incidence of PPCs was reported as number and percentage and time until the first PPC was assessed using Kaplan-Meier survival curves. The incidence of secondary outcomes and intraoperative complications according to the risk for PPCs were reported. Risk differences among the groups for binary outcomes were derived with a mixed-effect generalised linear model with binomial distribution and an identity link considering centres as random effect. Mean differences for continuous outcomes were assessed with a mixed-effect generalised linear model with Gaussian distribution, also considering centres as random effect. The impact of the risk for PPCs, and of development of PPCs, on hospital length of stay was assessed using Kaplan-Meier survival curves and reported as hazard ratios and 95% confidence interval estimated from a (shared frailty) Cox proportional hazard model with centres as random effect.

Comparison of ventilatory variables between groups over time was done using mixed-effect longitudinal models with random intercepts for patients and centres and considering an interaction between the group and time. The impact of ventilatory variables on the development of PPCs was assessed using mixed-effect generalised linear models with binomial distribution and with centres as random effect. Ventilatory variables were analysed either based on their mean or highest value during the four key intraoperative time points assessed. Because a high multicollinearity was expected among driving pressure, peak pressure, and PEEP, one model included only driving pressure and another only peak pressure and PEEP. Ventilatory variables with a *P* value <0.1 in the univariable models were considered for inclusion in the multivariable model. In addition to univariable models, all analyses described above were reassessed in multivariable models adjusted by a baseline risk model (full description in Supplement 3). In these multivariable models, all continuous variables were standardised to achieve better convergence, and results represent the change in the outcome according to increase in one standard deviation of the continuous predictor.

Post hoc analysis

Owing to the considerable number of missing plateau pressure values, we conducted one *post-hoc* analysis using a surrogate of driving pressure computed from peak pressure (driving peak pressure = peak pressure − PEEP), and the impact of this variable on the incidence of PPCs was assessed. Cumulative distribution plots were used to show the differences in the mean of ventilatory parameters according to the preoperative risk for PPCs. In a second *post hoc* analysis, the impact of ventilatory mode and the combination of ventilatory mode (volume-controlled *vs* pressure-controlled ventilation), and type of anaesthesia (volatile *vs* non-volatile anaesthesia) on the occurrence of PPCs was assessed in an univariable model, and in a model adjusted by the ARISCAT risk score for PPCs.

Significance level for all outcomes was 0.05, without adjustment for multiple comparisons. Reported *P* values were two-sided, and because the amount of missing data was negligible only complete case analyses were carried out. All analyses were performed using R software, version 3.6.0 (R Core Team, Vienna, Austria).

Results

Patient characteristics

Between April 2017 and March 2019, 34 hospitals in nine countries screened patients for the AVATaR study. Of 1167 eligible patients, 1015 patients were enrolled (Fig. 1). A total of 110 patients were excluded either because of conversion to open surgery (59 patients), or because abdominal intervention was not conducted (51 patients). Of the remaining 905 patients, 590 (65%) patients were at increased risk for PPCs, and 315 (35%) patients at low risk for PPCs (Table 1). The main surgical intervention was radical prostatectomy, followed by hysterectomy and nephrectomy. Intraoperative (Table 2) and ventilation characteristics were similar between the risk groups, although plateau and driving pressures were higher in patients at increased risk for PPCs after insufflation and positioning (Supplement 3) (see Fig. 2).

Primary outcome

Postoperative pulmonary complications within the first 5 postoperative days occurred in 172 (19.0%) patients, with unplanned supplementary oxygen the most frequent component (Table 3).

Secondary outcomes

Preoperative risk (ARISCAT score) for postoperative pulmonary complications

Compared with patients at lower risk, patients at increased risk developed PPCs more often (unadjusted absolute difference, 12.2% [6.8–17.6]; *P*<0.001), but not after adjustment for

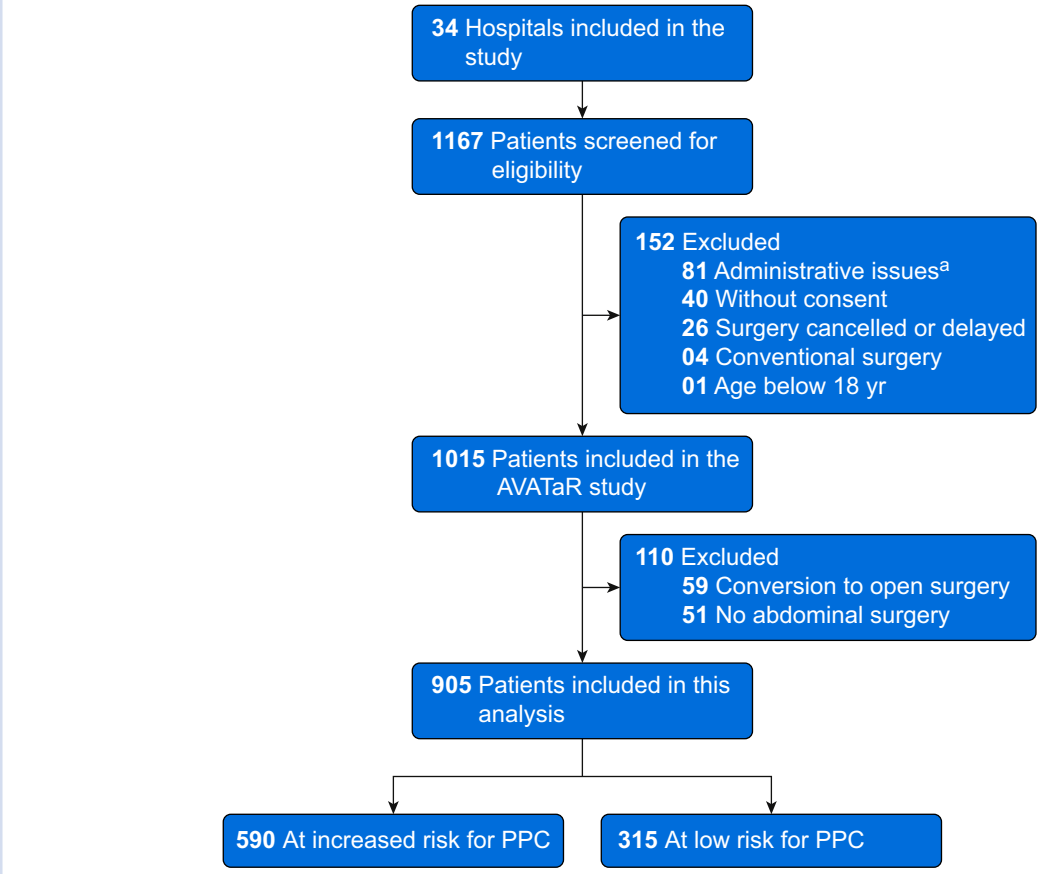

Fig 1. Study flowchart. [a]Absence of investigator or problems in data collection. AVATaR, Assessment of Ventilation during general AnesThesia for Robotic surgery; PPC, postoperative pulmonary complication.

confounders (adjusted absolute difference, 5.00% [−0.39 to 10.43]; P=0.072).

Ventilatory variables and postoperative pulmonary complications

Patients who developed PPCs had higher mean peak pressures during the procedure (Table 6, Supplement 3). After adjustment for the baseline risk model (Table 7, Supplement 3), no ventilatory variable was associated with development of PPCs.

Severe postoperative pulmonary complications and intraoperative complications

The incidence of severe PPCs (i.e. excluding the unplanned need of oxygen from the composite) and intraoperative complications was similar across risk groups (Table 3). The need for unplanned ventilation after surgery was also similar among the risk groups. The incidence of PPC and severe PPC according to incision and procedure are shown in Supplement 3.

Hospital stay and mortality

Patients who developed one or more PPCs had a longer hospital stay compared with patients who did not develop a PPC (Adjusted hazard ratio (aHR), 0.78 [0.62–0.96]; P=0.023) (Supplement 3). In-hospital mortality was similar between the risk groups.

Post hoc analyses: ventilatory variables

Driving pressure and driving peak pressure were strongly correlated (R^2=0.873, P<0.001) (Fig. 7, Supplement 3), but driving peak pressure did not differ between risk groups (Fig. 8, Supplement 3). Mean and highest driving peak pressure were not associated with increased risk for PPCs after adjustment for confounders (Table 8, Supplement 3). The incidence of PPCs was not different between pressure-controlled and volume-controlled ventilation (Figs 9 and 10, Supplement 3).

Discussion

The results of this international observational study in patients undergoing abdominal RAS can be summarised as follows: (1) one in five patients developed one or more PPCs, mainly unplanned need for supplementary oxygen; (2) the number of patients that developed severe PPCs, that is excluding unplanned need for supplementary oxygen from the collapsed endpoint, was low; (3) two-thirds of the patients were at increased risk for PPCs; (4) volume-controlled mode was preferred; (5) lung-protective ventilation was used in two-thirds of patients; (6)

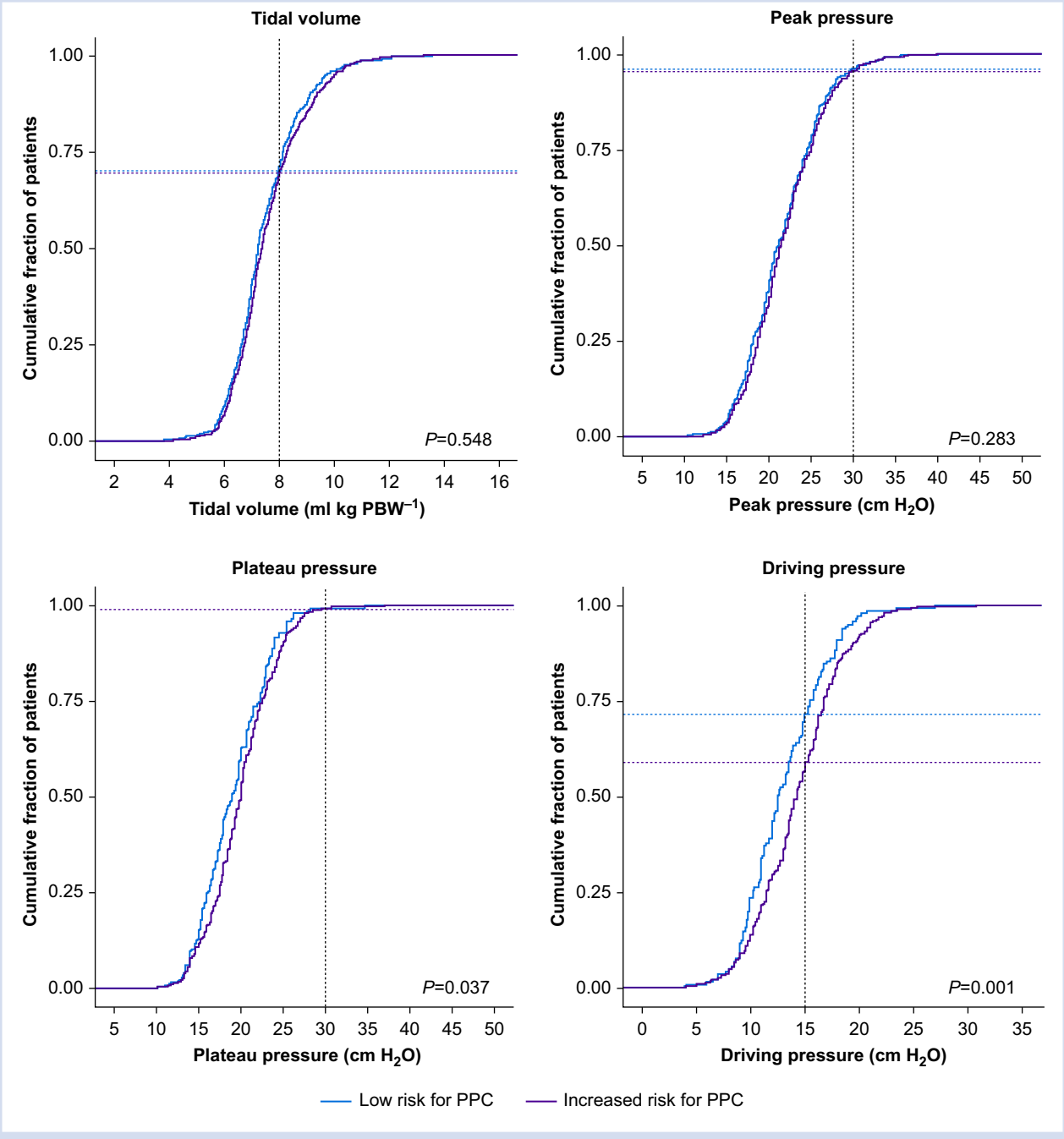

Fig 2. Cumulative distribution plots for tidal volume, peak, plateau and driving pressure according to the risk for postoperative pulmonary complications. Lines represent the cumulative distribution of the mean of the values of each variable observed through the four key intraoperative periods. PBW, predicted body weight; PPC, postoperative pulmonary complication.

recruitment manoeuvres were applied in 15% of the cases, and if used mainly after insufflation of the abdominal cavity; and (7) intraoperative hypotension occurred frequently mandating use of vasoactive drugs. No ventilatory parameter was independently associated with the occurrence of PPCs. Importantly, patients who developed PPCs had longer hospital stay.

The AVATaR study has several strengths. It was an international multicentre study representing practice in many countries worldwide. The design of the study avoided the effects of changes over time, because data were collected within a relative short time window. The outcomes and data analysis were defined before the start of the study and data collection. Indeed, the protocol and statistical analysis plan was published previously.[8] This is the largest prospective investigation to date describing intraoperative ventilation and the association between ventilatory variables and PPCs and

Table 1 Characteristics of the included patients according to risk of postoperative pulmonary complications. Data are median (quartile 25%–quartile 75%) or *n* (%). [†]More than one type of incision is allowed. ARISCAT, Assess Respiratory Risk in Surgical Patients in Catalonia; COPD, chronic obstructive pulmonary disease; Hb, haemoglobin; SpO_2, pulse oximetry; PPC, postoperative pulmonary complications.

	All patients (*n*=905)	Increased risk (*n*=590)	Low risk (*n*=315)	*P* value
Age, yr	64 (56–70)	65 (58–70)	60 (48–67)	<0.001
Range	19–93	19–93	19–80	–
Female sex	239 (26.4)	142 (24.1)	97 (30.8)	0.035
BMI, kg m^{-2}	27.3 (24.4–30.5)	27.4 (24.8–30.6)	27.0 (24.9–29.9)	0.034
ASA physical status				<0.001
1	191 (21.1)	98 (16.6)	93 (29.5)	
2	590 (65.2)	391 (66.3)	199 (63.2)	
3	119 (13.1)	97 (16.4)	22 (7.0)	
5	5 (0.6)	4 (0.7)	1 (0.3)	
ARISCAT	26 (19–34)	34 (26–38)	19 (18–19)	<0.001
<26	315 (34.8)	0 (0.0)	315 (100.0)	<0.001
26–44	553 (61.1)	553 (93.3)	0 (0.0)	
≥45	37 (4.1)	37 (6.7)	0 (0.0)	
Functional status				0.052
Independent	887 (98.0)	575 (97.5)	312 (99.0)	
Partially dependent	17 (1.9)	15 (2.5)	2 (0.6)	
Totally dependent	1 (0.1)	0 (0.0)	1 (0.3)	
Co-morbidities				
Hypertension	366 (40.4)	264 (44.7)	102 (32.4)	<0.001
Coronary disease	55 (6.1)	44 (7.5)	11 (3.5)	0.026
Atrial fibrillation/flutter	35 (3.9)	25 (4.2)	10 (3.2)	0.543
Heart failure	10 (1.1)	8 (1.4)	2 (0.6)	0.513
Diabetes mellitus	120 (13.3)	78 (13.2)	42 (13.3)	1.000
COPD	27 (3.0)	18 (3.1)	9 (2.9)	1.000
Asthma	52 (5.7)	36 (6.1)	16 (5.1)	0.632
Smoking	204 (22.5)	140 (23.7)	64 (20.3)	0.277
Obstructive sleep apnoea	40 (4.4)	31 (5.3)	9 (2.9)	0.133
Active neoplasia	618 (68.3)	423 (71.7)	195 (61.9)	0.003
Liver cirrhosis	2 (0.2)	2 (0.3)	0 (0.0)	0.771
Anaemia (Hb <10 g dl^{-1})	25 (2.8)	25 (4.2)	0 (0.0)	<0.001
Chronic kidney disease	24 (2.7)	20 (3.4)	4 (1.3)	0.094
Haematological disease	7 (0.8)	5 (0.8)	2 (0.6)	1.000
Use of immunosuppression	3 (0.3)	2 (0.3)	1 (0.3)	1.000
Complications ≤30 days before surgery				
Respiratory infection	11 (1.2)	11 (1.9)	0 (0.0)	0.034
Use of mechanical ventilation	0 (0.0)	0 (0.0)	0 (0.0)	–
Transfusion of blood products	3 (0.3)	1 (0.2)	2 (0.6)	0.580
Vital signs				
Ventilatory rate, bpm	15 (13–16)	15 (13–16)	15 (13–17)	0.881
Heart rate, beats min^{-1}	71 (64–80)	72 (64–80)	71 (64–80)	0.841
Mean arterial pressure, mm Hg	97 (88–106)	97 (88–106)	95 (88–107)	0.646
SpO_2, %	97 (96–98)	97 (96–98)	98 (97–99)	<0.001
Laboratory tests				
Haemoglobin, g dl^{-1}	14.3 (13.1–15.3)	14.3 (13.2–15.3)	14.3 (13.1–15.3)	0.909
Leukocytes, cells mm^{-3}	6500 (5472–7870)	6500 (5540–7830)	6480 (5230–7890)	0.634
Creatinine, mg dl^{-1}	0.90 (0.79–1.05)	0.90 (0.79–1.05)	0.90 (0.79–1.02)	0.386
Condition of the procedure				0.380
Elective	899 (99.3)	587 (99.5)	312 (99.0)	
Urgency	5 (0.6)	2 (0.3)	3 (1.0)	
Emergency	1 (0.1)	1 (0.2)	0 (0.0)	
Expected duration of surgery, h				<0.001
≤ 2	68 (7.5)	3 (0.5)	65 (20.6)	
2–3	378 (41.8)	167 (28.3)	211 (67.0)	
>3	459 (50.7)	420 (71.2)	39 (12.4)	
Incision*				
Peripheral	28 (3.1)	17 (2.9)	11 (3.5)	0.761
Low abdomen	754 (83.3)	466 (79.0)	288 (91.4)	<0.001
High abdomen	261 (28.8)	231 (39.2)	30 (9.5)	<0.001
Surgical procedure				<0.001
Prostatectomy	499 (55.1)	335 (56.8)	164 (52.1)	
Nephrectomy	77 (8.5)	61 (10.3)	16 (5.1)	
Hysterectomy	104 (11.5)	62 (10.5)	42 (13.3)	
Bariatric	16 (1.8)	11 (1.9)	5 (1.6)	
Sacrocolpopexy	10 (1.1)	5 (0.8)	5 (1.6)	

Continued

Table 1 Continued

	All patients (*n*=905)	Increased risk (*n*=590)	Low risk (*n*=315)	*P* value
Cholecystectomy	13 (1.4)	7 (1.2)	6 (1.9)	
Colorectal	52 (5.7)	36 (6.1)	16 (5.1)	
Hernia repair	32 (3.5)	12 (2.0)	20 (6.3)	
Cystectomy	23 (2.5)	20 (3.4)	3 (1.0)	
Pyloroplasty	1 (0.1)	1 (0.2)	0 (0.0)	
Pyeloplasty	14 (1.5)	5 (0.8)	9 (2.9)	
Gastrectomy	6 (0.7)	5 (0.8)	1 (0.3)	
Oesophagectomy	2 (0.2)	2 (0.3)	0 (0.0)	
Pancreatectomy	5 (0.6)	5 (0.8)	0 (0.0)	
Lymphadenectomy	8 (0.9)	3 (0.5)	5 (1.6)	
Hepatectomy	2 (0.2)	2 (0.3)	0 (0.0)	
Other gynaecological	19 (2.1)	6 (1.0)	13 (4.1)	
Other urological	18 (2.0)	11 (1.9)	7 (2.2)	
Other	4 (0.4)	1 (0.2)	3 (1.0)	

Table 2 Intraoperative characteristics according to the risk of postoperative pulmonary complications. Data are median (quartile 25%–quartile 75%) or *n* (%). †As clinically diagnosed and informed by the investigators.

	All patients (*n*=905)	Increased risk (*n*=590)	Low risk (*n*=315)	*P* value
Type of anaesthesia				<0.001
Total intravenous	304 (33.6)	179 (30.4)	125 (39.7)	
Volatile	174 (19.2)	95 (16.1)	79 (25.1)	
Balanced	426 (47.1)	315 (53.5)	111 (35.2)	
Use of antibiotic prophylaxis	858 (94.9)	567 (96.3)	291 (92.4)	0.018
Use of neuraxial blockade	180 (19.9)	89 (15.1)	91 (28.9)	<0.001
Epidural	30 (16.7)	17 (19.1)	13 (14.3)	0.555
Spinal	147 (81.7)	70 (78.7)	77 (84.6)	
Combined	3 (1.7)	2 (2.2)	1 (1.1)	
Use of Trendelenburg	757 (83.6)	492 (83.4)	265 (84.1)	0.848
Type of Trendelenburg				0.377
Normal (<40° of the bed)	405 (53.5)	270 (54.9)	135 (50.9)	0.377
Accentuated (≥40° of the bed)	343 (45.3)	215 (43.7)	128 (48.3)	
Reverse	9 (1.2)	7 (1.4)	2 (0.8)	
Pressure of CO_2 insufflation, mm Hg	12.0 (12.0–15.0)	12.0 (12.0–15.0)	12.0 (12.0–15.0)	0.190
Use of opioids				0.056
Short acting	562 (62.2)	348 (59.1)	214 (68.2)	
Long acting	89 (9.9)	63 (10.7)	26 (8.3)	
Both	220 (24.4)	157 (26.7)	63 (20.1)	
Use of neuromuscular blocking agent	897 (99.2)	586 (99.3)	311 (99.0)	0.956
Neuromuscular block monitoring	553 (61.2)	384 (65.1)	169 (53.8)	0.001
Reversal of neuromuscular block	745 (82.4)	495 (84.0)	250 (79.4)	0.095
Residual muscle paralysis†	24 (2.7)	20 (3.4)	4 (1.3)	0.100
Total fluid, ml	1500 (1000–2000)	1500 (1000–2087)	1500 (1000–2000)	<0.001
Crystalloids, ml	1500 (1000–2000)	1500 (1000–2000)	1500 (1000–2000)	<0.001
Synthetic colloid, ml†				
Overall	0 (0–0)	0 (0–0)	0 (0–0)	0.321
Patients who used	500 (250–500)	500 (250–500)	500 (275–500)	0.520
Albumin, ml†				
Overall	0 (0–0)	0 (0–0)	0 (0–0)	0.138
Patients who used	500 (150–1000)	500 (300–1000)	325 (237–412)	0.604
Urine output, ml	170 (0–350)	200 (0–400)	90 (0–300)	<0.001
Blood loss, ml	100 (50–250)	100 (50–300)	100 (0–200)	<0.001
Fluid balance, ml	1100 (680–1600)	1165 (700–1682)	1000 (650–1500)	0.030
Temperature at the end of surgery, °C	36.4 (36.0–36.7)	36.4 (36.0–36.7)	36.3 (36.0–36.6)	0.264
Transfusion of blood products	2 (0.2)	0 (0.0)	2 (0.6)	0.232
Red blood cells	1 (0.1)	0 (0.0)	1 (0.3)	0.750
Fresh frozen plasma	0 (0.0)	0 (0.0)	0 (0.0)	–
Platelets	1 (0.1)	0 (0.0)	1 (0.3)	0.750
Cryoprecipitate	0 (0.0)	0 (0.0)	0 (0.0)	–
Duration of surgery, min	180 (135–230)	190 (150–240)	150 (116–185)	<0.001
Duration of anaesthesia, min	218 (180–270)	236 (192–290)	190 (157–237)	<0.001

Table 3 Clinical outcomes according to the risk of postoperative pulmonary complications. Data are mean ± standard deviation, median (quartile 25% – quartile 75%) or *n* (%). †Adjusted by the baseline risk model excluding total ARISCAT and intraoperative complications. ‡For the individual components, a patient can be scored for more than one (the sum of the numbers of each individual component will not result in the total number of postoperative pulmonary complications). ¶Effect estimate is risk difference and *p* value calculated generalised linear model with binomial distribution and an identity link and with centres as random effect. §Effect estimate is mean difference and *P* value calculated from a generalised linear model with Gaussian distribution and with centres as random effect. ARDS, acute respiratory distress syndrome; CI, confidence interval; IQR, inter-quartile range.

	All patients (*n*=905)	Increased risk (*n*=590)	Low risk (*n*=315)	Unadjusted analyses		Adjusted analyses†	
				Effect estimate (95% CI)	*P* value	Effect estimate (95% CI)	*P* value
Primary outcome							
Postoperative pulmonary complications‡	172 (19.0)	132 (22.4)	40 (12.7)	12.21 (6.82–17.60)¶	<0.001	5.00 (−0.39 to 10.43)¶	0.072
Unplanned need of oxygen	169 (18.7)	131 (22.2)	38 (12.1)	12.62 (7.27–17.96)¶	<0.001	5.47 (0.13–10.84)¶	0.047
Acute respiratory failure	7 (0.8)	5 (0.8)	2 (0.6)	0.21 (−0.99 to 1.41)¶	0.728	−0.04 (−1.32 to 1.23)¶	0.946
Pneumonia	4 (0.4)	4 (0.7)	0 (0.0)	0.68 (−0.23 to 1.59)¶	0.143	0.66 (−0.32 to 1.62)¶	0.186
ARDS	1 (0.1)	0 (0.0)	1 (0.3)	−0.31 (−0.77 to 0.14)¶	0.183	−0.43 (−0.94 to 0.04)¶	0.092
Pneumothorax	0 (0.0)	0 (0.0)	0 (0.0)	–	–	–	–
Secondary outcomes							
Severe postoperative pulmonary complications	11 (1.2)	8 (1.4)	3 (1.0)	0.40 (−1.10 to 1.90)¶	0.598	0.01 (−1.59 to 1.61)¶	0.990
Intraoperative complications							
Desaturation	34 (3.8)	16 (2.7)	18 (5.7)	−2.40 (−5.10 to 0.25)¶	0.076	−3.73 (−6.53 to −1.04)¶	0.008
Unplanned recruitment manoeuvres	50 (5.5)	32 (5.4)	18 (5.7)	−0.16 (−3.37 to 3.05)¶	0.923	−1.39 (−4.78 to 1.97)¶	0.423
Need for ventilatory pressure reduction	19 (2.1)	12 (2.0)	7 (2.2)	−0.15 (−2.17 to 1.86)¶	0.882	−0.65 (−2.79 to 1.46)¶	0.549
Hypotension	195 (21.5)	139 (23.6)	56 (17.8)	5.29 (−0.19 to 10.77)¶	0.059	4.03 (−1.69 to 9.79)¶	0.172
Need for unplanned vasoactive drugs	109 (12.1)	85 (14.4)	24 (7.6)	3.62 (−0.53 to 7.79)¶	0.088	1.55 (−2.76 to 5.86)¶	0.485
Acute new arrythmia	9 (1.0)	5 (0.8)	4 (1.3)	−0.29 (−1.69 to 1.09)¶	0.684	−0.31 (−1.81 to 1.14)¶	0.684
Unplanned ventilation after surgery	4 (0.4)	3 (0.5)	1 (0.3)	0.21 (−0.72 to 1.12)¶	0.660	−0.20 (−1.20 to 0.76)¶	0.687
Continued	3 (23.1)	2 (16.7)	1 (100.0)				
Reintubation	1 (7.7)	1 (8.3)	0 (0.0)				
New use of mechanical ventilation	2 (0.2)	2 (0.3)	0 (0.0)	0.34 (−0.30 to 0.98)¶	0.297	−0.10 (−0.78 to 0.57)¶	0.767
Admission to intensive care unit	63 (7.0)	50 (8.5)	13 (4.1)	6.00 (2.60–9.38)¶	0.001	0.87 (−2.38 to 4.12)¶	0.602
Hospital length of stay, days	3.5 (4.3)	5.1 (6.2)	3.2 (3.6)	0.97 (0.39–1.55)§	0.001	0.12 (−0.43 to 0.68)§	0.665
Median (IQR)	2 (1–4)	3 (1–5)	2 (1–4)				
Hospital mortality	13 (1.4)	9 (1.5)	4 (1.3)	0.23 (−1.46 to 1.90)¶	0.792	−0.26 (−2.04 to 1.50)¶	0.776

intraoperative events in patients undergoing abdominal RAS. The study is also the first and largest prospective study assessing the incidence of PPCs according to recent PPC definition in this group of patients.

The incidence of PPCs reported in the present study is different from those in previous smaller investigations in robotic surgery.[10–13] A lower incidence of PPCs was reported during gynaecological RAS,[10,11] whereas a higher incidence of PPCs was found after RAS for prostatectomy.[12,13] The reason for this discrepancy is uncertain. A possible explanation is that some studies were retrospective in design,[10,11] and PPCs were often not well described or not defined *a priori*.[12,13]

Our reported incidence of PPCs also differs from that in patients undergoing non-robotic surgeries.[14,15] The LAS VEGAS investigators reported a lower incidence of PPCs,[15] although that study included various types of surgical patients, and in general patients had a lower ARISCAT score for PPCs. In contrast, a retrospective study in a general non-robotic surgical population found a higher incidence of PPCs.[14] However, patients in this study were likely at a higher risk for PPCs as they presented higher ASA scores, underwent surgery lasting $\geq$2 h, and often presented with obstructive sleep apnoea, preoperative anaemia and need for emergency surgery, all known risk factors for PPCs.[9,15] Of note, the incidence of severe PPCs in those studies[14,15] was higher than in our current study, probably because of the difference in the risk of the population included. However, as in previous studies, the majority of the PPCs developed withing the first 2 postoperative days.

In our study, the incidence of PPCs was lower than predicted based on the ARISCAT score. Also, the ARISCAT score for PPCs did not have an independent association with the occurrence of PPCs in the multivariate analysis. Taken together, this suggests a poor predictive performance of the ARISCAT score in this specific patient population. This may be expected as robotic surgeries were not included in the development of the score. However, ARISCAT was chosen because it is a well-defined predictive score in surgical patients and to allow comparison with previous studies.[15] Nevertheless, future studies are necessary to recalibrate the ARISCAT score for PPCs in patients undergoing abdominal RAS.

The ventilatory management during abdominal RAS frequently followed current recommendations.[16] Volume-controlled ventilation was the most frequently used mode, similar to other surgical populations.[14,15] This may also explain why the tidal volume did not vary over time in our cohort, despite changes in intra-abdominal pressure and patient positioning. Compared with other studies,[14,15] PEEP was higher, as were the peak, plateau, and driving pressures. These differences may, at least in part, have been triggered by intraoperative changes in respiratory mechanics induced by intra-abdominal gas insufflation and Trendelenburg position. Importantly, C_{RS} and C_{dyn} at extubation remained lower than at induction, probably reflecting some degree of atelectasis even after the end of surgery.

No ventilatory variable was independently associated with development of PPCs after adjustment for several confounders. In abdominal RAS, airway pressures increase because of changes in the compliance of the chest wall.[17] One remarkable finding is that the driving pressure (calculated from plateau pressure) had no association with the development of PPCs. However, because of positioning and insufflation, transpulmonary pressures probably remained at an acceptable level, and this could explain these findings. Indeed, recent data indicated that most of the intraoperative increase in driving pressures during robotic laparoscopic surgery is distributed to the chest wall and not to transpulmonary pressures.[17] In addition, a recent randomised clinical trial in obese patients did not find any benefit of PEEP on the development of PPCs even achieving a lower driving pressure with the strategy.[18] Also, because the amount of missing plateau pressures in the present study could have biased these results, a sensitivity analysis considering peak pressure in the driving pressure calculation was used, and no association between this variable and the incidence of PPCs was found.

Intraoperative haemodynamic complications occurred more frequently than respiratory complications. Further studies are warranted to determine the relevance of these intraoperative events for patient outcomes. The findings that patients are at increased risk for PPCs, and that those who actually developed PPCs had longer hospital length of stay, are in line with previous findings.[14,15,19] Interestingly, in this context, although the need for supplementary oxygen is usually seen as a relative mild PPC, it is associated with a longer stay in hospital[14,15,20] and increased incremental cost after surgery.[21,22]

Several limitations are to be acknowledged. First, the design of the AVATaR study allowed only recording of data that was collected as part of standard care, and not additional laboratory or radiographic examinations outside of routine clinical practice. This could mean that some PPCs may have been missed. Also, although data collectors were instructed to ignore standard supplementary oxygen when collecting PPCs, we cannot exclude that this may have been scored as a PPC in some patients. Nevertheless, an association between this mild PPC and length of hospital stay was found. Second, several sources of bias remained. Indeed, anaesthesiologists may have changed their practice and management while they were observed. Also, selection bias may have occurred, because anaesthesiologists in participating centres may have specific interests in RAS and intraoperative ventilation during RAS, and so their practice may not be representative of average clinical practice. As the follow-up was limited to 5 days or hospital discharge, any complication or hospital readmission occurring beyond that was not considered; this was also true for readmission. Because this is an observational study, and to keep consistency with a previous study,[16] atelectasis was not considered in the definition of PPCs, and this could have influenced the incidence of complications. Although the heterogeneity of procedures increases the external validity of the study, it prevents, at least in part, firm conclusions regarding associations between ventilation settings and outcomes. In addition, 5% of the patients were converted to open procedures and excluded from the present analysis. Thus, the findings should not be extrapolated to this group of patients. Also, PPCs and other complications could not be graded according to any specific scale. Owing to the pragmatic design of this study, we had to restrict collection of intraoperative and other complications to keep maximum adherence with the study. Finally, the observational nature of the AVATaR study does not allow for determination of a causal relationship to be inferred between the studied variables.

Conclusions

Patients undergoing abdominal RAS developed PPCs frequently in the postoperative period. The most frequent PPC

was unplanned need for supplementary oxygen. Lung-protective ventilation was frequently used, and a low tidal volume was often set, yet peak pressures were high. None of the ventilatory variables collected had an independent association with occurrence of PPCs. Occurrence of PPCs in these patients, also if mild, was associated with a longer hospital stay. The findings of this study may help in framing new hypotheses and support sample size calculations for future clinical trials of abdominal RAS.

Authors' contributions

Full access to all of the data in the study and responsibility for the integrity of the data and the accuracy of the data analysis: VNFQ, ASN.
Accuracy and completeness of data and for fidelity of the study to the protocol: The Writing Group.
Study design: VNFQ, LGVdC, RPB, FT, LDB, JC, DSC, UCD, JRG, VG, JPC, SNTH, MWH, AFK, RM, IM, GM, GHM, IPP, RCFC, AT, JS, MFVM, PP, MGdA, MJS, ASN.
Statistical analyses: VNFQ, ASN.
All authors are responsible for acquisition, analyses, or interpretation of data; drafting of the manuscript; critical revision of the manuscript for important intellectual content.
Administrative, technical, or material support: PP, MGdA, MJS, ASN.
Supervision: PP, MGdA, MJS, ASN.

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Declarations of interest

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Appendix A. Supplementary data

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