https://doi.org/10.15360/1813-9779-2022-3-21-29

The Efficacy and Safety of Automatic Modes During Respiratory Support After Cardiac Surgery

Alexander A. Yeremenko, Roman D. Komnov*, Ekaterina A. Koshek

B.V. Petrovsky Russian Research Center for Surgery
2 Abrikosov Lane, 119435 Moscow, Russia

Респираторная поддержка после кардиохирургических операций: преимущества и безопасность автоматизированного управления

А. А. Ерёменко, Р. Д. Комнов*, Е. А. Кошек

Российский научный центр хирургии им. академика Б. В. Петровского,
Россия, 119991, г. Москва, ГСП-1, Абрикосовский пер., д. 2

For citation: *Alexander A. Yeremenko, Roman D. Komnov, Ekaterina A. Koshek.* The Efficacy and Safety of Automatic Modes During Respiratory Support After Cardiac Surgery. *Obshchaya Reanimatologiya = General Reanimatology.* 2022; 18 (3): 21–29. https://doi.org/10.15360/1813-9779-2022-3-21-29 [In Russ. and Engl.]

Summary

Aims. To compare the efficacy and safety of semiautonomous Adaptive Support Ventilation (ASV) and fully automated (closed-loop, Intellivent-ASV) mechanical ventilation and oxygenation versus conventional mechanical ventilation mode during respiratory support in cardiac surgery patients.

Material and methods. In this study, 40 adult patients were ventilated by conventional mechanical ventilation managed by 8 physicians (control group), whereas other two groups patients were ventilated by Intellivent-ASV (n=40) or in a semiautomatic ASV mode (n=40). The groups received standard care, except for the modes of ventilation.

Results. In the Intellivent-ASV group, the number of manual changes in ventilator settings was significantly lower: 0 (0–0) versus 2 (2–3) (ASV) and 4 (3–5) in the control group (P<0.0001). There were significant differences in the duration of respiratory support in ICU which was 226±31 min (Intellivent group) vs 259±66 (ASV) and 271±78 min (control) (P=0.0042; P_{1-2}=0.0167; P_{1-3}=0.009). The Intellivent-ASV group patients received more protective ventilation than patients in the semiautomated and physician-controlled groups (lower values of driving pressure (6 (6–7) cm H_2O vs. 6 (6–7) and 7 (7–9) cm H_2O (P<0.0001)), tidal volume (6 (6–7) vs. 7 (7–7.7) and 7 (7–8) ml/kg/PBW (P<0.0001)), FiO_2 (26 (24–30)% vs. 34 (30–35)% and 34 (30–38)%) with no differences between the groups in paO_2/FiO_2. There were no significant differences between the groups in frequency of undesirable events and duration of ICU stay.

Conclusion. The use of intelligent technologies makes it possible to interactively individualize respiratory support, significantly reducing clinician's involvement in this process without compromising patient safety and the quality of ventilation.

Keywords: automatic weaning, Intellivent-ASV; intellectual modes of ventilation; ASV; cardiac surgery; intensive care

Conflict of interest. The authors declare no conflict of interest.

The full text version of the paper is available at www.reanimatology.com.

Introduction

Mechanical ventilation (MV) is an important and integral step in the rehabilitation of patients after open-heart surgery.

Current protocols and guidelines for rapid recovery after surgical interventions recommend striving to minimize the time of postoperative respiratory support. [1] It is becoming a worldwide trend to transfer the patient to spontaneous breathing after cardiac surgery after warming the patient up, achieving sufficient arterial gas exchange, hemodynamic stability and adequate hemostasis [2]. However, even during short-term ventilation support, it is important to follow basic principles of MV: safety, comfort, fast transition to assisted modes [3]. Clinicians pay great attention to safety of respiratory support, taking into consideration the possibility of ventilator-associated damage in

Correspondence to:

Roman D. Komnov
E-mail: drrkom@mail.ru

Адрес для корреспонденции:

Роман Дмитриевич Комнов
E-mail: drrkom@mail.ru

initially intact lungs when setting damaging ventilatory support parameters such as respiratory volume more than 6 ml/kg of ideal (predicted) body weight or low PEEP [4].

Thus, present-time intensive care unit (ICU) physicians are under a heavy burden of compliance with all standards of protective mechanical ventilation for each patient. As the number of patients per physician is always more than one, keeping track of the ever-changing respiratory needs of a patient becomes very challenging. Contrary to popular belief, there is currently no convincing evidence in favor of using any particular ventilatory mode in clinical practice [2].

Improvements in ventilators and feedback (control systems) have made it possible to use «intelligent respiratory support technology», where devices continuously adapt to the patient's breathing patterns and respiratory needs. They provide patient-ventilator-patient feedback (working in a closed loop control), not only reducing the load on the medical staff, but often selecting the optimal parameters of ventilation with greater speed and accuracy [5]. In fact, the device can replace some functions of a physician in selecting the optimal ventilation mode.

Published studies have shown the effectiveness and safety of these regimens in patients with various respiratory conditions (ARDS, bronchoobstructive syndrome, chronic obstructive pulmonary disease), brain lesions, and for postoperative respiratory support [8–20]. However, almost all studies compared intelligent technologies with traditional modes, while comparisons of ASV and Intellivent-ASV modes are lacking.

The aim of the study was to compare the efficacy and safety of intelligent modes with partial and fully autonomous control of ventilation (ASV and Intellivent-ASV) and traditional protocol with control of ventilation parameters by ICU physician in the early postoperative period of cardiac surgery patients.

Material and Methods

This single-center prospective randomized observational comparative study was approved by the local ethical committee of B. V. Petrovsky Russian Research Center of Surgery and was carried out at the department of cardiac intensive care of the Center. The envelope method was used for randomization.

The study included 120 patients, 40 patients per each group, who underwent heart or major vessel surgery from January 2016 to December 2019. The envelope method was used for randomization. Patient characteristics are shown in Table 1. The number of patients in the groups was calculated using G*Power 3.1 software. Based on the previous pilot study, which included 3 groups of 15 patients, we determined the mean value of the «need to manually change ventilator settings», which was 1, 2, and 4, respectively, and the standard deviation was 2.

We also estimated the effect size, which was 0.62. With a significance level of 0.05, the power of the study was 95%, the minimum required total number of subjects was 45 in total or 15 in each group.

The secondary endpoint «tidal volume in ml/kg PBW» was also calculated.

The mean value in the groups was 6, 7, and 7, respectively, and the standard deviation was 1. The estimated effect size was 0.47. With a significance level of 0.05, the power of the study was 95%, the required total number of subjects was 75 in total or 25 per group.

To get some reserve in case of unforeseen circumstances, we selected 40 people in each group, or 120 in total, which exceeded the minimum required number.

Inclusion criteria were admission to the intensive care unit after cardiac and ascending aorta surgery; age over 18 years; body mass index from 18 to 35 kg/m^2.

Preoperative exclusion criteria were severe renal (GFR < 30 ml/min), hepatic (aspartate and alanine aminotransferases [AST and ALT] > 80 IU/L) or cardiac failure (left ventricular ejection fraction less than 30%). Postoperative exclusion criteria were bleeding, perioperative myocardial infarction, hemodynamic instability, need for high doses of vasopressors drugs (vaso-inotropic score >12) or need for intra-aortic balloon pump counterpulsation, resistant hypoxemia with PaO_2/FiO_2 less than 150 mmHg, allergic reactions in perioperative period, seizures, delirium, and cerebrovascular accident.

The primary endpoint of the study was a comparative assessment of the burden on the ICU medical staff based on the number of approaches to the machine, manipulations with ventilator parameters, and time spent on changing manual ventilator settings. The secondary endpoint of the study was the duration of postoperative ventilatory support in the ICU, the incidence of adverse events during patient weaning, and the safety of the ventilation performed.

The anesthesiological specifics of patient management, doses of analgesics, hypnotics, and muscle relaxants were taken into account. There were no significant differences between the groups in the intraoperative oxygenation, respiratory volumes, and PEEP values used in the operating room (Table 1).

In the conventional approach group, ventilation was performed using Hamilton G-5 or C-2 ventilators by Hamilton, Switzerland, and Servo-I ventilators by Maquet. Intellivent-ASV and ASV modes were used on Hamilton G-5 and C-2 (ASV) machines.

Table 1. Baseline characteristics of patients, types of surgery, and perioperative data.

Parameter	Values in groups			*P*
	Intellivent-ASV (*n*=40)	ASV (*n*=40)	Conventional mode (*n*=40)	
Age, years	59±8	59 (55–66)	59±11	0.9185
Sex (male/female)	27/13	24/16	30/10	0.1701
Height, cm	171±9	170±9	174 (167–177)	0.8706
Weight, kg	84 (71–95)	84±14	82±12	0.3755
PBW, kg	68 (52–75)	65±10	67±8	0.1529
BMI, kg/m^2	27.9±4	28.6±4	27.2±3.6	0.9185
Preoperative SpO_2 on ambient air	96 (95–97)	96 (95–96)	96 (95–97)	0.6971
PaO_2/FiO_2 before transfer to ICU, mmHg	310 (290–345)	319±88	336±90	0.4534
Vt, ml/kg PBW	8 (7–9)	9 (8–10)	9 (8–9)	0.0757
PEEP; cmH_2O	7 (6–8)	7 (5–8)	6 (5–8)	0.2159
CABG	18	20	16	
CABG + valve surgery	2	5	2	
Valve surgery (replacement or repair)	12	9	12	
Aortic root replacement (David/Bentall procedure)	8	4	10	
Extended septal myectomy	0	2	0	

Note. Data are given as median (interquartile range) or mean (±SD) SD — standard deviation. Vt — tidal volume; BMI — body mass index; PBW — predicted body weight; PEEP — positive end expiratory pressure; CABG — coronary artery bypass graft.

The choice of ventilation mode was made upon admission to ICU using the envelope method.

The adaptive support ventilation (ASV) is a partially automatic mode that continuously adjusts respiratory support to the patient's condition and clinical needs based on respiratory biomechanics. In fact, it is designed to interactively maintain the «respiratory comfort» state and focused on «weaning» the patient from the ventilator as soon as possible. In this mode, the ventilator's microprocessor adjusts the inspiratory pressure to achieve the target tidal volume and respiratory rate, minimizing respiratory work, based on OTIS [6] and Mead [7] equations. In addition, the number of mandatory and spontaneous breaths is automatically adjusted depending on the patient's respiratory drive.

The Intellivent-ASV mode provides fully automatic control of patient ventilation parameters to achieve adequate gas exchange by adjusting Vt (tidal volume), MV (respiratory minute volume), PEEP (positive end expiratory pressure) and FiO_2 (inspiratory fraction of oxygen). This algorithm is implemented through continuous monitoring of respiratory biomechanics parameters and information from pulse oximetry and capnography sensors integrated into the device. Inspiratory pressure and optimal respiratory rate to minimize respiratory work are calculated, as in the basic mode, based on the OTIS and Mead equations. Also in this mode, there is an option for early activation of automated patient weaning.

After surgical intervention, the patients were admitted to the intensive care unit under continuous drug sedation with propofol (1–2 mg/kg/h) being on the Oxylog transport ventilator. Medication-assisted sedation was continued until the patient was warmed up and the oxygenation and hemodynamic parameters were stabilized (60–90 minutes after admission to the ICU) (no significant differences in the duration of sedation between the groups were recorded).

The patients were treated according to standard protocols for cardiac surgery postoperative patients [2]. Analgesia was performed according to a multimodal protocol with a combination of nonsteroidal anti-inflammatory drugs and paracetamol with central analgesics (nefopam, tramadol).

Respiratory support in the study groups.

In the Intellivent-ASV group, during initial setting of the ventilator, the physician adusted height and sex of the patient (for the microprocessor to calculate the ideal body weight), permission to automatically control the minute ventilation, FiO_2 and PEEP level, if necessary, to alter the $EtCO_2$ and SpO_2 target values, as well as the permission to automatically perform spontaneous breathing test. Further respiratory support was carried out in automatic mode, minute ventilation was changed continuously if necessary, according to $EtCO_2$ values. Optimal respiratory rate ratio, supportive pressure level, tidal volume were calculated by the microprocessor of the machine to reduce respiratory work based on individual pulmonary biomechanics, while PEEP and FiO_2 were also controlled automatically according to pulse oximetry data. When respiratory drive was restored and the patient's own respiratory activity increased, the sequence of mandatory and spontaneous breaths gradually changed. After a complete restoration of spontaneous breathing and a short observation period (10–60 minutes' duration preset by a physician when setting the mode), the machine conducted the spontaneous breathing test. If the test was successful, the machine alerted the medical staff prompting the physician to decide whether the tracheal extubation was possible.

In the ASV group, when setting up the device, the physician adjusted the height and weight of the patient, the target «minute ventilation replacement percentage» (with the «physiological» minute ventilation calculated as 100 ml/kg ideal body weight/min considered as 100%). Intensivists also set the FiO_2 and PEEP levels, the limit of maximum airway pressure, ETS (expiratory trigger sensitivity, the threshold flow value as a percentage of maximum which prompts expiration-inspiration switch), as well as the inspiratory trigger sensitivity. Noteworthy, when performing respiratory support, most doctors leave the initial settings of inspiratory trigger sensitivity and ETS unchanged and only adjust FiO_2, PEEP and percentage of minute ventilation replacement (increasing or decreasing its value depending on capnography or $PaCO_2$ results [20]).

In the physician-guided group, the initial mode of ventilation was Synchronized Intermittent Mandatory Ventilation (SIMV) with breaths controlled by volume (Volume Control, VC) or pressure (Pressure Control, PC). The doctor manually set FiO_2, PEEP, tidal volume or inspiratory pressure, respiratory rate, and inspiration-expiration ratio. After the patient awakened and muscle tone was restored, the physician reduced the number of mandatory breaths and, if necessary, adjusted the tidal volume and support pressure of spontaneous breaths. After the patient's respiratory drive was restored, respiratory support until spontaneous breathing initiation was continued in Pressure Support (PS) Ventilation mode.

The parameters of respiratory support and the decision to extubate the trachea in all three groups were decided by the intensivist treating the patient. The study involved 8 doctors, each of whom participated in respiratory support in four to five patients per each group. The researcher recorded and documented all the physicians' actions and measured the time spent.

The researcher recorded the following parameters:

1) Directly related to the setting of respiratory support such as changes in mechanical and assisted ventilation modes (changes in the frequency of mandatory and spontaneous breaths), the frequency of parameter correction; the values of Vt, PS, PEEP, driving pressure, and FiO_2.

2) Physician-related such as number of approaches and adjustments made to settings, total time spent at the ventilator, and the need for adjustment if apnea or bradypnea develops.

3) Related to the duration of respiratory support such as total time of respiratory support in ICU, the time of mechanical and assisted (without mandatory breathing) ventilation, time from awakening to restoration of spontaneous breathing, and the time from restoration of spontaneous breathing to the start of assisted ventilation.

Arterial gas exchange and acid-base status were analyzed during ventilation, 30 minutes after the start of assisted ventilation, and 15 minutes before tracheal extubation using blood gas and electrolyte analyzer (Gem Premier 4000, Instrumentation Laboratory, USA).

In all three groups, readiness for extubation was assessed according to local criteria based on the international «Evidence-based guidelines for weaning and discontinuation of ventilatory support» which included full awakening, following commands, absence of agitation, with FiO_2 less than 0.4, PaO_2/FiO_2 more than 200 mmHg, positive end-expiratory pressure <7 cm H_2O, stable hemodynamics, arterial blood pH>7.3, $PaCO_2$ between 35 and 45 mmHg, body temperature above 36°C.

To assess the safety of respiratory support, the Vt (tidal volume), driving pressure ($\triangle$P, which can be calculated as expiratory plateau pressure minus applied PEEP), FiO_2, and PEEP were recorded, and mechanical power (an aggregate measure of ventilation aggressiveness based on respiratory rate, PEEP, $\triangle$P, and Vt) was calculated [22] using simplified equations [23].

The data were processed using parametric and nonparametric statistical methods. The raw data were collected, adjusted, organized and visualized using Microsoft Office Excel 2016 software. Statistical analysis was performed using STATISTICA 10.0 (StatSoft.Inc.) software. Normality of quantitative variable distribution was assessed using the Shapiro–Wilk test. Normally distributed quantitative variables were pooled into variational series, where the arithmetic mean (*M*) and standard deviations (*SD*) were calculated. Quantitative variables with non-normal distribution were characterized using median (*Me*) and interquartile range (25^{th} and 75^{th} percentiles) values. Nominal data were described using absolute values and percentiles. The significance of intergroup differences in quantitative variables with normal distribution was assessed using the single-factor analysis of variance by performing the Bonferroni multiple comparison test or *F*-test. When comparing several samples of quantitative data with non-normal distribution, the Kruskal–Wallis test was used. Nominal data were compared using Pearson's χ^2 test and Fisher's exact test. Differences were considered significant if *P*-value was < 0.05.

Results and Discussion

According to the obtained data, the more the machine was involved in the ventilator control (transition from physician control to ASV and Intellivent-ASV modes), the less the physician participated in the respiratory support. The time spent on ventilation control in the Intellivent-ASV group was almost three times less than in the ASV group and four times less than in the physician-guided group (Table 2). In the Intellivent-ASV mode, there

Table 2. Respiratory support in the study groups.

Parameter	Values in groups			*P*
	Intellivent-ASV (*n*=40)	ASV (*n*=40)	Conventional mode (*n*=40)	
Duration of respiratory support in ICU (time to tracheal extubation), min	226±31	259±66	271±78	0.0042 p_{1-2}=0.0167 p_{1-3}=0.009
Number of physician's approaches to the ventilator per patient	2(1–2)	3 (2–4)	4 (3–5)	<0.0001 p_{1-2}=0.0001 p_{1-3}<0.0001 p_{2-3}=0.0112
Numbers of manual ventilator setting changes per patient	0 (0-0)	2 (2–3)	4 (3–5)	<0.0001 p_{1-2}<0.0001 p_{1-3}<0.0001 p_{2-3}=0.0003
Physician's time spent at ventilator per patient, sec	35 (27–45)	99±35	164±69	<0.0001 p_{1-2}<0.0001 p_{1-3}<0.0001 p_{2-3}=0.0045
During mechanical ventilation (with mandatory breaths)				
PaO_2/FiO_2, mmHg	358 (330–380)	373±64	372±50	0.3038
SpO_2, %	98 (97–99)	100 (99–100)	99 (99–100)	<0.0001 p_{1-2}<0.0001 p_{1-3}=0.0001
FiO_2, %	26 (24–30)	34 (30–35)	34 (30–38)	<0.0001 p_{1-2}<0.0001 p_{1-3}<0.0001
PaO_2, mmHg	95 (85–104)	123 (109–133)	125 (107–140)	<0.0001 p_{1-2}<0.0001 p_{1-3}<0.0001
$PaCO_2$, mmHg	42 (40–44)	39(37–42)	38 (37–41)	0.0002 p_{1-2}=0.005 p_{1-3}=0.0003
pH	7.39±0.04	7.4±0.04	7.41±0.04	0.0469
Tidal Volume (Vt), ml/kg PBW	6 (6–7)	7 (6–7.7)	7 (7–8)	<0.0001 p_{1-2}=0.0016 p_{1-3}=0.0001
△P (driving pressure), cmH_2O	6 (6–7)	6 (6–7)	7.3 (7–9)	<0.0001 p_{1-3}=0.0001 p_{2-3}=0.0005
PEEP, cmH_2O	5 (5–7)	8 (7–10)	7 (6–9)	<0.0001 p_{1-2}=0.0001 p_{1-3}=0.0004
Mechanical power, J/min	8 (6–9)	8 (6–9)	9 (7–11)	0.0797
Duration of mechanical ventilation, min	132±36	169±68	189±71	0.0002 p_{1-2}=0.0012 p_{1-3}=0.0002
During the period without mandatory breaths in Intellivent-ASV and ASV groups and in PSV mode in control group				
PaO_2/FiO_2 mmHg	371±45	364±62	385±49	0.19
Increase in PaO_2/FiO_2 ratio from the admission to ICU, *n*	34 (85%)	29 (72.5%)	27 (67.5%)	0.147
SpO_2, %	98 (97–98)	99 (99–100)	99 (98–100)	<0.0001 p_{1-2}<0.0001 p_{1-3}=0.0001
FiO_2, %	26±4	31 (30–35)	30 (30–36)	<0.0001 p_{1-2}<0.0001 p_{1-3}<0.0001
PaO_2, mmHg	91 (84–104)	115 (105–130)	120 (109–137)	<0.0001 p_{1-2}=0.0001 p_{1-3}<0.0001
$PaCO_2$, mmHg	40±2	38 (37–41)	38 (36–40)	0.0553
pH	7.39±0.03	7.4±0.04	7.4±0.03	0.406
Tidal Volume (Vt), ml/kg PBW	8 (7–8)	7.5 (7–8)	8 (7–9)	0.0573
PS, cmH_2O	5 (5–5)	5 (5–7)	8 (7–9)	<0.0001 p_{1-3}<0.0001 p_{2-3}<0.0001
PEEP, cmH_2O	5 (5–5)	7 (5–8)	7 (5–8)	<0.0001 p_{1-2}<0.0001 p_{1-3}<0.0001
Duration of spontaneous ventilation*, min	90 (75–103)	80 (60– 110)	60 (60–105)	0.0462 p_{1-3}=0.0162

Table 2.

Parameter	Values in groups			*P*
	Intellivent-ASV (*n*=40)	ASV (*n*=40)	Conventional mode (*n*=40)	
Time from awakening to spontaneous ventilation, min	0 (0–0)	0 (0–12)	30 (0–60)	<0.0001 p_{1-3}<0.0001 p_{2-3}=0.0087
Time from the restoration of spontaneous breathing to the change of mandatory breathing mode, min	0	0	39 (25–46)	<0.0001 p_{1-3}<0.0001 p_{2-3}<0.0001
Follow-up after tracheal extubation				
Tracheal reintubation	0	0	0	
NIV during first 12 hours after tracheal extubation	2	1	1	
Length of stay in ICU, days	1 (1–1)	1 (1–1)	1 (1–1)	—
Postoperative length of stay in hospital, days	7 (7–8)	8 (7–10)	8 (8–10)	0.0411
Hospital mortality, *n*	0	0	0	

Note. Data are given as median (interquartile range) or mean (±SD). SD — standard deviation. NIV — noninvasive ventilation. * — here, «duration of spontaneous ventilation» means time spent without any mandatory breaths in the Intellivent-ASV and ASV groups and time spent in Pressure Support Ventilation in the control group.

was practically no need for parameter adjustments, while in the ASV group such correction was necessary twice less frequently compared to the physician-controlled group.

The compared groups also had significant differences in the time from the patient's admission to the ICU to tracheal extubation. In the fully automatic parameter control group, the duration of respiratory support was, on average, 15% shorter than in the semiautomatic group and in the physician-guided group (Table 2).

In groups using intelligent modes, the number of mandatory breaths was automatically reduced upon restoration of the patient's respiratory drive and actually assisted ventilation was initiated with full restoration of spontaneous breathing by awakening. This is in line with the current guidelines recommending assisted MLV without physician-guided mandatory breaths for most patients needing respiratory support, since it enables better inflation of lung bases, prevents atrophy of respiratory muscles, promotes more equal gas distribution, shortens respiratory support duration and reduces the frequency of ventilator-associated pneumonia [24]. Besides, the level of pressure support during assisted MLV is significantly lower when using intelligent technologies.

In the physician-controlled group, the time from the restoration of spontaneous breathing to the physician-guided decrease of ventilator-delivered breaths or switching to PSV mode was on average 39 minutes, and the patient's awakening and recovery of spontaneous breathing did not always coincide with the switching to less aggressive modes, and this period averaged 30 minutes. Perhaps, this could be the cause of more common incidence of such adverse events as anxiety, associated with tachycardia, tapping on the bed, tachypnea episodes and interfering with the machine work in the physician-controlled group. In the Intellivent-ASV group such episodes were observed in five patients out of 40 (12.5%), in the ASV group in 4 out of 40 (10%), while in the control group in 9 out of 40 (22.5%), but the differences were not significant.

During the transition to spontaneous breathing, a proportion of patients developed bradypnoea (20(50%) in the Intellivent-ASV group, 12 (30%) in ASV group and 15 (37.5%) in conventional mode group. However, in the Intellivent-ASV group mandatory breaths were activated automatically, and mechanical respiratory support continued until the possibility to minimize the ventilator-delivered breathing appeared again, while in the physician-controlled group, backup ventilation was activated with mandatory breaths in the pressure mode (full mechanical ventilation), which entailed the need to correct the ventilation mode by the physician and in some cases led to asynchrony. No significant differences were found between the groups for such episodes. Importantly, in the automated groups, mandatory breaths after resuming spontaneous breathing were reduced automatically, while in the physician-controlled group, this required physician's intervention.

The data obtained in the study suggest that the use of intelligent modes can significantly reduce the workload on the staff, increasing the safety of postoperative ventilation. With limited resources available, the use of these techniques can be an important factor in improving patient outcomes.

The results of our study are largely comparable with those of studies conducted in cardiac surgical patients: in the Intellivent-ASV group, staff participation in controlling the machine and changing ventilation parameters was required less frequently [13–15]. In ASV group, staff participation was required more often than in fully automatic group, but both time spent at the ventilator and frequency of settings adjustments were still significantly lower than in fully physician-controlled group.

Table 3. Main parameters of respiratory monitoring after tracheal extubation.

Time	Parameter	Values in groups			*P*
		Intellivent-ASV (*n*=40)	ASV (*n*=40)	Conventional mode (*n*=40)	
30 minutes after tracheal extubation on air	SpO_2	94 (93–95)	94±2	94±2	0.1614
	PaO_2/FiO_2	335 (321–345)	317 (300–352)	337 (302–365)	0.3071
	$PaCO_2$	39 (38–41)	39 (36–41)	38 (37–41)	0.3400
12 hours after tracheal extubation on air	SpO_2	95 (94–96)	95 (93–95)	94.5 (93–96)	0.0489
	PaO_2/FiO_2	347 (335–361)	338 (302–397)	332 (300–369)	0.2725
	$PaCO_2$	39±2	39 (38–41)	39 (38–41)	0.7742

Note. Data are given as median (interquartile range) or mean (±SD) SD — standard deviation.

In contrast to our results, A. J. Beijers and E. Fot [13, 15] have demonstrated that the duration of machine support in the studied groups did not differ, which can be explained by the difference in local protocols of ventilation. Meanwhile, when the semi-automatic technique was used, the respiratory support time in ASV group was almost the same as the data obtained by the researchers, while the duration of ventilation in the group of conventional modes in their study was longer, which again can be explained by the difference in local protocols [16–20].

Significant differences between the groups were observed for almost all parameters used to assess the safety of respiratory support (tidal volume, driving pressure (△P), FiO_2, PEEP level) (Table 2). Tidal volume was lower during mandatory ventilation in the Intellivent-ASV mode, while during assisted ventilation the tidal volume values were equal in all three study groups with lower PS value in «intelligent» groups. Very importantly, in these groups lower driving pressure during the ventilation with forced inspiration was found.

The level of FiO_2 and PEEP in all phases of respiratory support was lower in the Intellivent-ASV group. We consider it an important achievement to be able to work at lower values of FiO_2, because prevention of hyperoxia is one of the aims of protective ventilation, while the disadvantages of hyperoxia (increased frequency of absorptive atelectasis and lung injury) were well demonstrated by S. R. Pannu and R. Panvar [25, 26].

No significant differences in the values of mechanical power were obtained.

During respiratory support we noted that PaO_2 and SpO_2 values were significantly lower in the Intellivent-ASV group, while they were absolutely physiological and no significant differences in PaO_2/FiO_2 ratio was observed in all groups neither during ventilation (Table 2), nor after transition to spontaneous breathing, nor 12 hours after tracheal extubation (Table 3). Despite the obtained differences in $PaCO_2$ values, the parameters remained within the physiological ranges in all groups (Tables 2 and 3).

Intelligent modes belong to autonomous robotic and semi-robotic technologies operating in a fully closed circuit, when based on pulse oximetry, capnography and breathing mechanics data, the ventilator automatically selects the optimal ventilation parameters to achieve the target gas exchange rates and, as the patient stabilizes, switches from full mechanical ventilation through assisted modes to spontaneous breathing, without the participation of medical staff performing the supervising and controlling functions. In semi-robotic technology, the ventilator selects the most appropriate and safe respiratory support pattern for a specific patient, making it much easier to personalize the respiratory support provided without the relentless supervision of the physician.

Better understanding of modern principles of protective ventilation and subsequent implementation of the acquired skills in practice is a positive aspect of intelligent modes. We noted that after starting to use intelligent technologies our colleagues significantly more often in routine practice set lower values of inspiratory/expiratory pressure, lower values of Vt and FiO_2 and more actively and earlier switched the patients on «conventional» ventilation modes to spontaneous breathing.

Among the study limitations one can consider the «human factor»: as mentioned earlier, the study involved 8 doctors, each of whom has his own experience and long-held algorithms when performing lung ventilation. In addition, the number of physician approaches to the machine and the time spent on changing ventilation modes may have depended on personal characteristics and basic training in ventilation.

Conclusion

Compared with the conventional protocols of mechanical ventilation in the early postoperative period of cardiac surgery patients, the use of intelligent technologies of respiratory support was characterized by interactive personalization and adjustment of respiratory support, significantly reducing physician involvement in this process and providing the safest ventilation parameters.

References

1. *Gregory A.J., Engelman D.T., Williams J.B.* Cardiac Surgery ERAS p 488. In book O. Ljungqvist, N.K. Francis, R. D. Urman Enhanced recovery after surgery: a complete guide to optimizing outcomes. Cham; Springer Nature Switzerland AG; 2020. DOI: 10.1007/978-3-030-33443-7 ISBN 978-3-030-33442-0.
2. *Dabbagh A., Esmailian F., Aranki S.* Postoperative critical care for adult cardiac surgical patients. Second edition, Cham; Springer International Publishing AG, part of Springer Nature; 2018. DOI: 10.1007/978-3-319-75747-6 ISBN 978-3-319-75746-9.
3. *Chatburn R.L., Mireles-Cabodevila E.* Closed-loop control of mechanical ventilation: description and classification of targeting schemes. *Respiratory Care*. 2011; 56 (1): 85–102. DOI: 10.4187/respcare. 00967. PMID: 21235841.
4. *Serpa Neto A., Simonis F.D., Schultz M.J.* How to ventilate patients without acute respiratory distress syndrome? *Curr Opin Crit Care*. 2015; 21: 65–73. DOI: 10.1097/MCC.0000000000000165. PMID: 25501019.
5. *Кассиль В.Л.* Интеллектуальные методы ИВЛ и ВВЛ. В книге *В.Л. Кассиль, А.А. Еременко, Ю.Ю. Сапичева, М. А, Выжигина:* Принципы механической вентиляции легких в интенсивной терапии. М.: МЕДпресс-информ; 2017: 225-228. ISBN 978-5-00030-507-2. [*Kassil V.L.* Intellectual methods of mechanical ventilation and ventilatory support. In: *V.L. Kassil, A.A. Eremenko, Yu.Yu. Savicheva, M. A., Vyzhigina.* Principles of mechanical ventilation in intensive care. M.: MEDpress-inform (in Russ.); 2017: 225-228. ISBN 978-5-00030-507-2.6].
   Otis A.B., Fenn W.O., Rahn H. Mechanics of breathing in man. *J Appl Physiol.*1950; 2: 592–607. DOI: 10.1152/jappl.1950.2.11.592. PMID: 15436363.
7. *Mead J., Turner J.M., Macklem P.T., Little J.B.* Significance of the relationship between lung recoil and maximum expiratory flow. *J Appl Physiol.* 1960; 22 (1): 95–108. DOI: 10.1152/jappl.1967.22.1.95. PMID: 6017658.
8. *Belliato M.* Automated weaning from mechanical ventilation. *World J Respirol.* 2016; 6 (2): 49–53. DOI: 10.5320/wjr.v6.i2.49.
9. *Arnal J-M., Garnero A., Novonti D., Demory D., Ducros L., Berric A., Donati S.Y., Corno G., Jaber S., Durand-Gasselin J.* Feasibility study on full closed-loop control ventilation (Intellivent-ASV) in ICU patients with acute respiratory failure: a prospective observational comparative study. *Critical Care*. 2013; 17: R196. PMID: 24025234. DOI: 10.1186/cc12890.
10. *Arnal J.M., Garnero A., Novotni D., Corno G., Donati S.Y., Demory D., Quintana G., Ducros L., Laubscher T., Durand-Gasselin J.* Closed loop ventilation mode in Intensive Care Unit: a randomized controlled clinical trial comparing the numbers of manual ventilator setting changes. *Minerva Anestesiologica.* 2018; 84 (1): 58–67. DOI: 10.23736/ S0375-9393.17.11963-2. PMID: 28679200.
11. *Arnal J-M., Saoli M., Aude Garnero A.* Airway and transpulmonary driving pressures and mechanical powers selected by Intellivent-ASV in passive, mechanically ventilated ICU patients. *Heart Lung.* 2020; 49 (4): 427–434. DOI: 10.1016/j.hrtlng.2019.11.001. PMID: 31733881.
12. *Bialais E., Wittebole X., Vignaux L., Roeseler J., Wysocki M., Meyer J., Reychler G., Novotni D., Sottiaux T., Laterre P.F., Hantson P.* Closed-loop ventilation mode (IntelliVent®-ASV) in intensive care unit: a randomized trial. *Minerva Anestesiol.* 2016; 82: 657–668. PMID 26957117.
13. *Beijers A.J., Roos A.N., Bindels A.J.* Fully automated closed-loop ventilation is safe and effective in post-cardiac surgery patients. *Intensive Care Med.* 2014; 40 (5): 752–753. DOI: 10.1007/s00134-014-3234-7. PMID 24577110.
14. *Lellouche F., Bouchard P.A., Simard S., L'Her E., Wysocki M.* Evaluation of fully automated ventilation: a randomized controlled study in post-cardiac surgery patients. *Intensive Care Medicine.* 2013; 3: 463–471. DOI: 10.1007/s00134-012-2799-2. PMID: 23338569.
15. *Fot E.V., Izotova N.N., Yudina A.S., Smetkin A.A., Kuzkov V.V., Kirov M.Y.* Automated weaning from mechanical ventilation after off-pump coronary artery bypass grafting. *Front Med (Lausanne)*. 2017; 4: 31. DOI: 10.3389/fmed.2017.00031. PMID 28377920.
16. *Gruber P.C., Gomersall C.D., Leung P., Joynt G.M., Ng S.K., Ho K.M., Underwood M.J.* Randomized controlled trial comparing adaptive-support ventilation with pressure-regulated volume-controlled ventilation with automode in weaning patients after cardiac surgery. *Anesthesiology.* 2008; 109 (1): 81–87. DOI: 10.1097/ALN. 0b013e31817881fc. PMID: 18580176.
17. *Zhu F., Gomersall C.D., Ng S.K., Underwood M.J., Lee A.* A randomized controlled trial of adaptive support ventilation mode to wean patients after fast-track cardiac valvular surgery. *Anesthesiology.* 2015; 122 (4): 832–840. DOI: 10.1097/ALN.0000000000000589. PMID: 25569810.
18. *Yazdannik A., Zarei H., Massoumi G.* Comparing the effects of adaptive support ventilation and synchronized intermittent mandatory ventilation on intubation duration and hospital stay after coronary artery bypass graft surgery. *Iran Journal of Nursing and Midwifery Research*. 2016; 21 (2): 207–212. DOI: 10.4103/1735-9066.178250. PMID: 27095997.
19. *Tam M.K.P., Wong W.T., Gomersall C.D., Tian Q., Ng S.K., Leung C.C.H., Underwood M.J.* A randomized controlled trial of 2 protocols for weaning cardiac surgical patients receiving adaptive support ventilation. *J Crit Care.* 2016; 33: 163–168. DOI: 10.1016/j.jcrc. 2016.01.018. PMID: 27006266.
20. *Еременко А.А., Комнов Р.Д.* Интеллектуальный режим аппаратной вентиляции легких при ранней активизации кардиохирургических пациентов. *Общая реаниматология*. 2020; 16 (1): 4–15. DOI: 10.15360/1813-9779-2020-1-4-15. [*Eremenko A.A., Konnov R.D.* Smart mode of mechanical ventilation during early activation of cardiosurgical patients. *General reanimatology/Obshchaya reanimatologya.* (in Russ.). 2020; 16 (1): 4–15. DOI: 10.15360/1813-9779-2020-1-4-15].
21. *MacIntyre N.R., Cook D.J., Ely E.W.Jr., Epstein S.K., Fink J.B., Heffner J.E., Hess D., Hubmayer R.D., Scheinhorn D.J.* Evidence-based guidelines for weaning and discontinuing ventilatory support: a collective Task Force facilitated by the American College of Chest Physicians, the American Association for Respiratory Care, and the American College of Critical Care Medicine. *Chest.* 2001; 120 (6): 375S–95S. DOI: 10.1378/chest.120.6_suppl.375S. PMID: 11742959.
22. *Silva P.L., Macedo Rocco P.R., Pelosi P.* Ten reasons to use mechanical power to guide ventilator settings in patients without ARDS. In book: Annual update in intensive care and emergency medicine 2020 Cham. Springer Nature Switzerland AG; 2020. DOI: 10.1007/978-3-030-37323-8_3. ISBN 978-3-030-73230-1.

23. *Becher T., van der Staay M., Schädler D., Frerichs I., Weiler N.* Calculation of mechanical power for pressure-controlled ventilation. *Intensive Care Med.* 2019; 45 (9): 1321–1323. DOI: 10.1007/s00134-019-05636-8. PMID: 31101961.
24. *Putensen C., Muders T., Varelmann D., Wrigge H.* The impact of spontaneous breathing during mechanical ventilation. *Current Opinion in Critical Care.* Lippincott Williams and Wilkins; 2006; 12 (1): 13–18. DOI: 10.1097/01.ccx.0000198994.37319.60. PMID: 16394778.
25. *Pannu S.R., Dziadzko M.A., Gajic O.* How much oxygen? Oxygen titration goals during mechanical ventilation. *Am J Respir Crit Care Med.* 2016; 193: 4–5. DOI: 10.1164/rccm.201509-1810ED. PMID: 26720783.
26. *Panwar R., Hardie M., Bellomo R., Barrot L., Eastwood G.M., Young P.J., Capellier G., Harrigan P.W., Bailey M.* Conservative versus liberal oxygenation targets for mechanically ventilated patients. A pilot multicenter randomized controlled trial. *Am J Respir Crit Care Med.* 2016; 193: 43–51. DOI: 10.1164/rccm.201505-1019OC. PMID: 26334785.

Received 2021.10.21
Accepted 2022.03.24