Journal of Clinical Anesthesia 52 (2019) 93–98

Contents lists available at ScienceDirect

Journal of Clinical Anesthesia

journal homepage: www.elsevier.com/locate/jclinane

Original contribution

Minute ventilation assessment in the PACU is useful to predict postoperative respiratory depression following discharge to the floor: A prospective cohort study

Roman Schumann[a,*], Brian Harvey[b], Farhad Zahedi[a], Iwona Bonney[a]

[a] Department of Anesthesiology and Perioperative Medicine, Tufts Medical Center, 800 Washington Street, Box # 298, Boston, MA 02111, United States of America
[b] Respiratory Motion Inc., 411 Waverley Oaks Road, Building 1, Suite 150, Waltham, MA 02452, United States of America

ARTICLE INFO

Keywords:
Postoperative respiratory depression
Respiratory volume monitor
Minute ventilation
Tidal volume
Respiratory rate

ABSTRACT

Study Objective.

Reliably identifying patients at risk for postoperative respiratory depression (RD) remains an unmet need. We hypothesized that defined low minute ventilation events (LMVe) near the end of the post-anesthesia care unit (PACU) stay identifies patients at RD risk on the general hospital floor (GHF).

Design: Prospective observational study.

Setting: Tertiary care, urban academic medical center. PACU and GHF during the first postoperative night.

Patients: One hundred-and-nineteen adult, ASA I – III patients undergoing elective surgery under general anesthesia completed the study.

Interventions: Data collection from a non-invasive respiratory volume monitor and the patients' medical record perioperatively through the first postoperative night.

Measurements: Minute ventilation (MV), tidal volume (TV) and respiratory rate (RR) were measured continuously in the PACU and on the GHF. MV was counted as the percent of individual predicted MV (MV_{PRED}), and RD was defined as ≥1 LMVe/h on the GHF. Based on the number of LMVes within 30 min before PACU discharge, patients were grouped into A, 'Not-At-Risk': 0 LMVe and B, 'At-Risk': ≥1 LMVes. Unpaired *t*-test, Mann-Whitney *U* test, ANOVA, Kruskal-Wallis test, Fisher's exact test, sensitivity and specificity and ROC curve analyses were applied as appropriate.

Main results: One hundred-and-six (89%) and 13 (11%) patients met Group A and B criteria respectively. The latter had more LMVe/h on the GHF (median 0.81 vs 0, $p \leq 0.001$), and their MV_{PRED} was significantly less. Following opioid administration, the LMVe likelihood was 43% in Group B and 5.6% in Group A. As a predictor for RD on the GHF, the number of LMVe in the last 30 min of PACU, had positive and negative predictive values of 61.5% and 90.6%, respectively.

Conclusion: Minute ventilation assessment in the PACU as described in this study can be useful to identify patients at risk for postoperative respiratory depression.

1. Introduction

Objective and easy to obtain parameters to determine the risk of developing respiratory depression have remained elusive. An unmet need exists for an objective monitoring option in the risk assessment for respiratory depression postoperatively and following the administration of opioids. The latter are commonly used postoperatively and contribute to respiratory depression in susceptible patients, and multiple terms including "Opioid-Induced Respiratory Depression" (OIRD) have been introduced. The Joint Commission on Hospital Accreditation identified OIRD as a "safety target" and the "main hazard of opioid use" and therefore recommended additional monitoring for patients receiving opioids [1]. However, standard physiologic monitors including pulse oximetry may not be useful for risk assessment and only capture the late stages of respiratory depression [2–4]. Clinical assessment and the use of risk scores such as the STOP-Bang score or a diagnosis of obstructive sleep apnea appear limited in their ability to predict postoperative respiratory depression [5]. Currently there are no universally agreed upon objective parameters of respiratory mechanics that define respiratory depression. However, an increased rate of defined low

* Corresponding author.
E-mail address: RSchumann@tuftsmedicalcenter.org (R. Schumann).

https://doi.org/10.1016/j.jclinane.2018.09.005
Received 2 June 2018; Received in revised form 16 August 2018; Accepted 8 September 2018

minute ventilation events and decreased predicted minute ventilation are reasonable and relevant components that may characterize respiratory depression of any etiology. A Food and Drug Administration-approved, impedance-based, non-invasive respiratory volume monitor (RVM) is now available to continuously measure minute ventilation (MV), tidal volume (TV) and respiratory rate (RR) in non-intubated patients. The RVM provides real-time continuous respiratory volume metrics when tested against spirometry and ventilator measurements, with 90% accuracy for MV and TV, and 98% accuracy for RR [6,7]. The RVM data allow distinguishing between respiratory volumes associated with hypoventilation [8], versus obstructed breaths [6]. We conducted a prospective observational cohort study using the RVM and employed predetermined threshold MV parameters to detect respiratory depression. We hypothesized that the presence of defined low minute ventilation events (LMVe) near the end of post-anesthesia care unit (PACU) stay can identify patients at risk for respiratory depression post-operatively following discharge to the general hospital floor (GHF).

2. Materials and methods

2.1. IRB and consent

This prospective, observational study was approved by the Tufts Health Sciences Institutional Review Board at Tufts Medical Center, and all subjects provided written informed consent before enrollment.

2.2. Experimental design

Patients were monitored with an impedance-based RVM (ExSpiron, Respiratory Motion, Inc., Waltham, MA). Continuous respiratory data (MV, TV, and RR) were collected via a three-electrode PadSet placed on the patient's chest. Inclusion criteria were adults weighing ≥ 80 pounds, ASA physical status classification I–III presenting for elective surgery under general anesthesia with positive pressure ventilation. Patients whose condition or procedure would interfere with electrode placement were excluded. Clinical and research personnel were blinded to the RVM measurements during the study.

RVM data collection started preoperatively and continued during surgery, throughout the PACU stay, and for the first post-operative night (PON1) on the GHF. Additional data collected included patient demographics, anthropometrics, STOP-Bang scores, procedure type, diagnosis, OSA diagnosis, ASA physical status classification, medical history, and current medications used. A previous diagnosis of OSA was recorded if the patient stated having been diagnosed by formal testing (Polysomnography), however written confirmation of OSA and its severity was not available for all patients. Opioids administered pre- and intra-operatively, in the PACU, and on the GHF were also recorded. A balanced anesthetic technique using volatile inhalational anesthetics and neuromuscular blockade was employed according to the anesthesia team's preference and could include midazolam, propofol, ketamine and opioids (fentanyl, hydromorphone, oxycodone, and morphine) as needed. Total opioids administered intraoperatively, in the PACU, and the GHF were converted to morphine milligram equivalents (MME) and normalized by patient body weight [9]. Times from start and end of surgery, PACU enter and end time, and GHF enter and end of study time were collected.

2.3. Data and statistical analysis

Minute Ventilation was expressed as a percent of each patient's predicted MV (MV_{PRED}), calculated based on the patient's body surface area and sex [10,11]. A low MV event (LMVe) was defined as a ≥2 min period of MV < 40% MV_{PRED}. Minute ventilation < 40% MV_{PRED} was chosen as a parameter based on the Acute Respiratory Distress Syndrome network (ARDSnet) protocol for successful extubation [8,12]. LMVe rate was calculated as the total number of LMVe divided by the duration of monitoring. Apnea was defined as a respiratory pause of 30 s or longer.

Based on respiratory parameters assessed within the last 30 min prior to PACU discharge, patients were categorized as follows: Group A, Not-At-Risk for respiratory depression: defined as 0 LMVe and Group B, At-Risk for respiratory depression: defined as ≥1 LMVes. For the purpose of this study, the outcome of respiratory depression was defined as ≥1 LMVe/h on the GHF. The study hypothesis was that ≥1 LMVe within 30 min of PACU discharge predicts respiratory depression on the GHF.

We calculated the sensitivity, specificity, negative predictive values (NPV), and positive predictive values (PPV) of this classification method to identify patients who experienced a high rate of LMVe (i.e., ≥1 LMVe/h) on the GHF. Further, within each group we identified patients who did and did not receive IV opioids on the GHF (hydromorphone). We compared the likelihood for these opioids to be associated with a subsequent LMVe as well as the overall rate of LMVe on the GHF between these subgroups.

The Lilliefors test was used to determine distribution of the data. For normally distributed data the unpaired *t*-test was conducted for inter-group comparisons, and the Mann-Whitney *U* test was employed for not normally distributed data. ANOVA was utilized for 4-group comparisons (i.e., Groups A and B subdivided by GHF IV opioids) for normally distributed data, and the Kruskal-Wallis test was applied for data that was not normally distributed. The Fisher's exact test was performed for categorical variables as appropriate. Data are presented as mean ± SD for normally distributed data, and as median and interquartile range for non-normally distributed data. All analyses were performed in Matlab 2014b (MathWorks, Natick, MA). Results were considered statistically significant at a $p < 0.05$.

We performed a post-hoc analysis of the ability of five additional parameters to predict respiratory depression (≥1 LMVe/h) on the GHF. The average MV over the last 30 min in PACU was calculated and patients with average MV below a chosen threshold were identified as "at-risk." This threshold value was varied from 40% to 100% of MV_{PRED} in order to generate a receiver operating characteristic (ROC) curve and identify the optimal sensitivity and specificity. We also examined the ROC curve for the combination of MV_{PRED} below a threshold (< 40%) and ≥1 LMVe/h within 30 min of PACU discharge as a predictor and also tested thresholds for age (≥50, ≥60, and ≥70 years), BMI (≥30, ≥35, ≥40, and ≥45 kg/m^2) and STOP-Bang score (≥5).

3. Results

One hundred-and-fifty patients were recruited, of which 31 did not complete the study. Specifically, 14 patients withdrew early, 7 patients stayed in the PACU overnight and were excluded from the data analysis, and 10 patients had technically inadequate RVM data. Therefore, data of 119 patients were available for the analysis. Baseline clinical characteristics, monitoring parameters and opioid consumption are presented in Table 1. Patients underwent a variety of procedure types including orthopedic ($n = 19$, knee and hip replacements), gynecologic ($n = 30$, total abdominal hysterectomies; bilateral salpingo-oophorectomies, laparoscopic supracervical hysterectomies, sarcocervicopexies, robotic assisted total hysterectomies), bariatric ($n = 56$, laparoscopic sleeve gastrectomies and one gastric bypass) and miscellaneous general surgical cases ($n = 14$, prostatectomies, colorectal surgeries, cholecystectomy, hernia repairs, femoral-femoral bypass grafting) (Table 1). The proportion of patients with a positive OSA diagnosis was not statistically significantly different ($P = 0.143$, Fisher's exact test) between Group A and Group B.

Table 2 summarizes the LMVe and MV data. The LMVe rate was substantially lower in Group A compared to Group B in both the PACU (median of 0 LMVe per hour in Group A vs. median of 0.81 LMVe per hour in Group B, $P < 0.001$) and on the GHF (median of 0 LMVe per hour vs. 1.56 LMVe per hour in Group B, $P < 0.001$) (Table 2). In

Table 1
Patient characteristics, monitoring durations, Total Morphine Milligram Equivalents administered by hospital location, adjusted to patient body weight and procedure types.

	Population	Group A	Group B	*P*-Value
N (%)	119	106 (89%)	13 (11%)	–
Males/females	18/111	10/96	8/5	–
Weight, kg	100.9 (30.1)	100.8 (29.8)	101.9 (33.8)	0.903 [1]
Height, cm	164.9 (9.5)	163.7 (8.6)	174.4 (11.3)	< 0.001 [1]
BMI, kg/m^2	37.0 (10.0)	37.4 (10.0)	33.1 (9.3)	0.141 [1]
Age, years	50.9 (13.6)	50.0 (13.6)	58.0 (12.0)	0.044 [1]
OSA diagnosis (%)	25 (21%)	20 (19%)	5 (38%)	0.143 [2]
STOP-Bang score	3 [2–4]	3 [2–4]	4 [2–6]	0.281 [3]
STOP-Bang ≤ 2	38 (32%)	35 (33%)	3 (23%)	0.644 [2]
STOP-Bang 3–4	54 (45%)	48 (45%)	6 (46%)	
STOP-Bang ≥ 5	27 (23%)	23 (22%)	4 (31%)	
OSA diagnosis and STOP-Bang ≥ 5	18 (15%)	14 (13%)	4 (31%)	0.109 [2]
OSA diagnosis or STOP-Bang ≥ 5	34 (29%)	29 (27%)	5 (38%)	0.516 [2]
DOM PACU, hours	3.3 [2.4–4.6]	3.2 [2.4–4.4]	4.3 [2.8–5.9]	0.261 [3]
DOM GHF, hours	12.1 [6.7–14.2]	12.0 [6.2–14.1]	13.2 [9.0–14.7]	0.421 [3]
Intraoperative opioids, MME/kg	0.30 [0.19–0.45]	0.29 [0.18–0.44]	0.37 [0.23–0.53]	0.240 [3]
PACU opioids, MME/kg	0.08 [0.03–0.15]	0.08 [0.03–0.14]	0.12 [0.07–0.16]	0.240 [3]
GHF opioids, MME/kg	0.17 [0–0.31]	0.17 [0–0.30]	0.17 [0–0.36]	1.0 [3]
Procedure duration, hours	1.6 [1.1–2.5]	1.6 [1.1–2.4]	2.0 [1.1–3.8]	0.241 [3]
Procedures	*N* = 119	*N* = 106	*N* = 13	–
Orthopedic	19	16	3	–
Gynecologic	30	28	2	–
General	14	10	4	–
Bariatric	56	52	4	–

Group A, no Low Minute ventilation event (LMVe) within 30 min of PACU discharge. Group B, ≥1 LMVe within 30 min of PACU discharge. OSA = Obstructive Sleep Apnea; DOM = Duration of Monitoring; MME = Total Morphine Milligram Equivalents. Data presented as means (SD) or as median [Q1-Q3]. P-values were calculated using unpaired t-test[1], Fisher's exact test[2], and Mann-Whitney U test[3].

Group A, 70% (n = 74) had no LMVe on the GHF and 98.2% of GHF monitored time was LMVe-free. While not different in the PACU, the LMVe duration was significantly longer in Group B on the GHF (P = 0.048). The percent of MV_{PRED} was significantly less in Group B in the PACU and this difference between groups increased during the stay on the GHF (P = 0.004 and P < 0.001, respectively).

Fig. 1 compares the rate of LMVe for patients in Group A and Group B. Group B patients experienced a significantly higher rate of LMVe compared to Group A patients in both the PACU (P < 0.001) and the GHF (P < 0.001, Fig. 1A). Fig. 1B shows the distribution of the LMVe rate over time during the stay on the GHF with a peak between 6 and 8 h following GHF arrival. Fig. 2 demonstrates the differences in achieved MV_{PRED} between groups on the GHF. The MV of patients in Group A was significantly higher in both the PACU (P = 0.004) and the GHF (P < 0.001) (Fig. 2A). Group B patients demonstrated a consistently lower MV throughout their monitored time on the GHF (Fig. 2B).

Group A and B patients received a similar total dose of opioids intraoperatively, in the PACU, and on the GHF (Table 1). Further, both groups had a similar likelihood to receive IV opioids while on the GHF (Group A: 45/109 vs. Group B: 6/11; P = 1.0, Fisher's exact test). An LMVe was observed within 30 min of administration in 3.4% and 44.4% of the total IV opioid doses administered in Group A and Group B, respectively (Table 4, Fisher's exact test, P < 0.001). These data correspond to an odds ratio to experience a LMVe after an opioid in Group B of 13.2. In the cohort that did not receive IV opioids on the GHF, Group B had six times more LMVes/h compared to Group A (P < 0.001). Within each group, IV opioid administration on the GHF did not influence the hourly LMVe rate (Table 3).

We assessed the sensitivity, specificity, negative predictive values (NPV), and positive predictive values (PPV) of our PACU LMVe threshold to identify patients who experienced a high rate of LMVe (i.e. ≥1 LMVe/h) on the GHF (Table 4). The classification method had a high PPV (61.5%) to identify patients who will have a high rate of LMVe on the GHF as well as a high NPV (90.6%) identifying patients that will have a small number of LMVe on the GHF.

The results of the post-hoc analysis for additional parameters to predict respiratory depression in this population are shown in Fig. 3. A threshold value of 70% MV_{PRED} yielded an optimal balance of sensitivity (55.6%) and specificity (81.2%). Combining ≥1 LMVe in the last 30 min of the PACU with 70% MV_{PRED} resulted in slightly improved sensitivity (66.7%) and similar specificity (80.2%). Classifying patients based on age, BMI, and STOP-Bang score yielded predictors with ROC curves similar to the performance of a random parameter.

4. Discussion

In this observational cohort study, we applied a respiratory volume monitor (RVM) in the immediate perioperative period that accurately measures MV, TV, and RR to identify a subset of patients that may be susceptible to postoperative respiratory depression following recovery room discharge. Adapted from prior data, we defined patients that experienced at least one low minute ventilation event (LMVe, < 40% MV_{PRED} for ≥2 min) within 30 min of recovery room discharge as 'at-risk' for subsequent respiratory depression on the general hospital floor [5]. This parameter identified 11% of our participants who not only had a significantly higher rate of LMVes in the recovery room, but also on the hospital floor compared to the majority of 89% of patients who did not exhibit this parameter. In 'at-risk' patients the hourly LMVe rate increased on the GHF with a maximum occurrence at approximately

Table 2
Respiratory monitoring results. Data are presented as median [Q1-Q3] or as mean (SD) for normally distributed data. *P*-values were calculated using Mann-Whitney *U* test[1] and unpaired *t*-test[2].

		Population	Group A	Group B	P-Value
PACU	Percent MV_{PRED}	93 [77–128]	100 [81–130]	75 [61–87]	0.004 [1]
	LMVe per hour	0 [0–0.36]	0 [0–0.11]	0.81 [0.43–1.60]	< 0.001 [1]
	LMVe duration, minutes	3.2 [2.8–4.7]	3.2 [2.8–4.5]	3.8 [2.7–5.0]	0.634 [1]
	% Time without LMVe	100 [98–100]	100 [99–100]	93 [90–98]	< 0.001 [1]
	Apneas per hour	0 [0–0.14]	0 [0–0.02]	0 [0–0.22]	0.217 [1]
GHF	Percent MV_{PRED}	97 [79–138]	100 [85–143]	64 [52–82]	< 0.001 [1]
	LMVe per hour	0 [0–0.38]	0 [0–0.23]	1.56 [0.31–2.24]	< 0.001 [1]
	LMVe duration, minutes	4.3 (1.2)	4.1 (1.0)	4.9 (1.5)	0.048 [2]
	% Time without LMVe	100 [97–100]	100 [99–100]	89 [80–98]	< 0.001 [1]
	Apneas per hour	0 [0–0.08]	0 [0–0.08]	0 [0–0.10]	0.797 [1]

PACU = Post Anesthesia Care Unit; GHF = general hospital floor, MV_{PRED} = predicted minute ventilation; LMVe = low minute ventilation event.

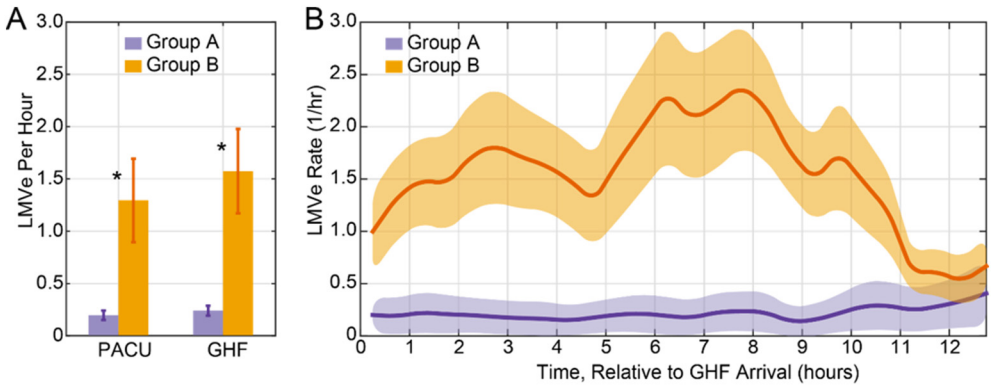

Fig. 1. A. Rate of low minute ventilation events (LMVe) per monitored hour, for patients classified as Group A (purple; N = 106; no LMVe within 30 min of PACU discharge) and Group B (orange; $N = 13$; ≥ 1 LMVe within 30 min of PACU discharge) in the PACU and GHF. Group B patients experienced a significantly higher rate of LMVe compared to Group A patients in both the PACU ($P < 0.001$) and GHF ($P < 0.001$) (Mann-Whitney U test). **B.** Time course of LMVe rate over time during the stay on the GHF for patients in Groups A and B. Solid lines represent the mean LMVe rate while shaded regions represent the standard error of the mean. Group B patients experienced the highest rate of LMVe between 6 and 8 h following GHF arrival. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

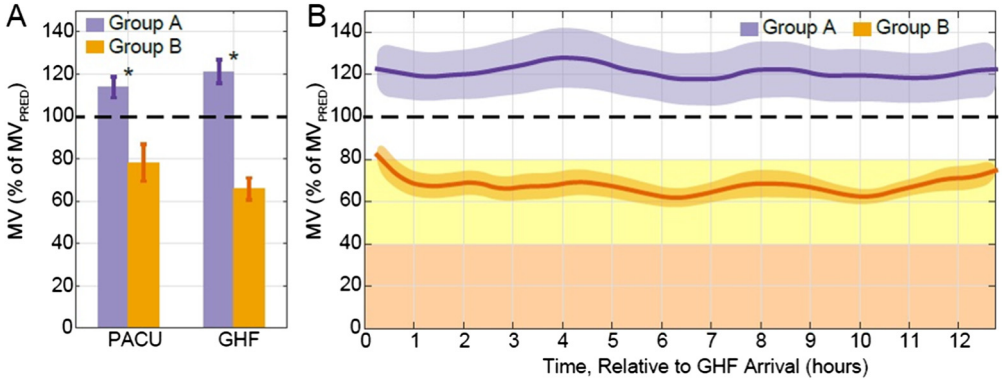

Fig. 2. A. Minute Ventilation (MV), presented as percent of predicted MV (MV_{PRED}), for patients classified as Group A (purple; $N = 106$; no LMVe within 30 min of PACU discharge) and Group B (orange; $N = 13$; ≥ 1 LMVe within 30 min of PACU discharge) in the PACU and on the general hospital floor (GHF). MV of patients in Group A were significantly higher in both the PACU ($P = 0.004$) and GHF ($P < 0.001$) (Mann-Whitney U test). **B**. Time course of percent of MV following arrival to the GHF for patients in Group A and Group B. Solid lines represent the mean LMVe rate while shaded regions represent the standard error of the mean. Dash black line = 100% of MV_{PRED}; Yellow shaded region: 40–80% of MV_{PRED}; Orange shaded region: 0–40% of MV_{PRED}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Effect of IV opioids on incidence of low minute ventilation events (LMVe). P-values were calculated using Fisher's exact test [1], Kruskal-Wallis test [2] and one way ANOVA [3].

	Group A		Group B		P-Value
Received IV opioids on the GHF?	Yes	No	Yes	No	
N	45	61	6	7	1.0 [1]
Post-opioid LMVe likelihood (%)	5.6	N/A	43.8	N/A	< 0.001 [1]
LMVe per hour	0.22	0.25	1.48	1.67	< 0.001 [2]
LMVe duration, minutes	4.1	4.1	4.6	5.2	0.201 [3]

Table 4
Sensitivity-specificity table for PACU classification method to predict low minute ventilation events (LMVe) on the general hospital floor (GHF).

		GHF		
		≥1 LMVe/h	< 1 LMVe/h	
PACU	Group B	8	5	*61.5% PPV*
	Group A	10	96	*90.6% NPV*
		44.4% Sensitivity	*95.0% Specificity*	

Group A, no LMVe within 30 min of PACU discharge. Group B, ≥1 LMVe within 30 min of PACU discharge. PPV = positive predictive value; NPV = negative predictive value.

6 h. In addition, this 'at-risk' group exhibited a significantly lower sustained predicted MV in the PACU as well as on the GHF compared to their 'not-at-risk' counterparts, and in contrast to the latter, their MV also worsened on the floor compared to their PACU measurements. The time course of this postoperative respiratory pattern in 'at-risk' patients corresponds to the finding that a majority of respiratory depression events occur within the first 12–24 h following surgery [13,14]. The observation that respiratory depression is most likely to occur on the GHF, underscores the need for effective continuous electronic monitoring in vulnerable patients. Our study suggests that it is feasible to collect LMVe frequency and sustained reduced predicted MV measured in real-time trending, in the recovery room in order to identify patients at risk for continued respiratory depression. The results of this study also demonstrate that a vast majority of patients monitored in the PACU likely do not require continued floor monitoring, as < 1 LMVe/h during PACU stay was associated with a 90% negative predictive value and a 94.7% specificity for subsequent LMVes on the general hospital floor for 'not-at-risk' patients.

Although serious events associated with postoperative OIRD are rare, a recent closed claims analysis of 92 cases revealed that > 75% involved permanent brain injury or death [13]. Risk factors and co-morbidities that may be associated with OIRD have been described but don't appear to be reliable or consistently successful for identifying patients that will experience postoperative OIRD. A recent review describes advantages and shortcomings of traditional and newer electronic monitoring systems and the need to standardize objective criteria that consistently identify respiratory depression in order to allow research advances that ultimately reduce risk [15]. At least three different patterns of respiratory depression resulting in unexpected death have been described that may not be equally captured by the different monitoring systems [16]. Type II respiratory depression described as progressive, unidirectional hypoventilation and CO_2 narcosis likely due to opioids and sedatives may be the most frequent and relevant form postoperatively. Simplistically, respiratory depression may be understood as a state of hypoventilation that can be defined by respiratory parameters that can be measured with respiratory mechanics. As for the

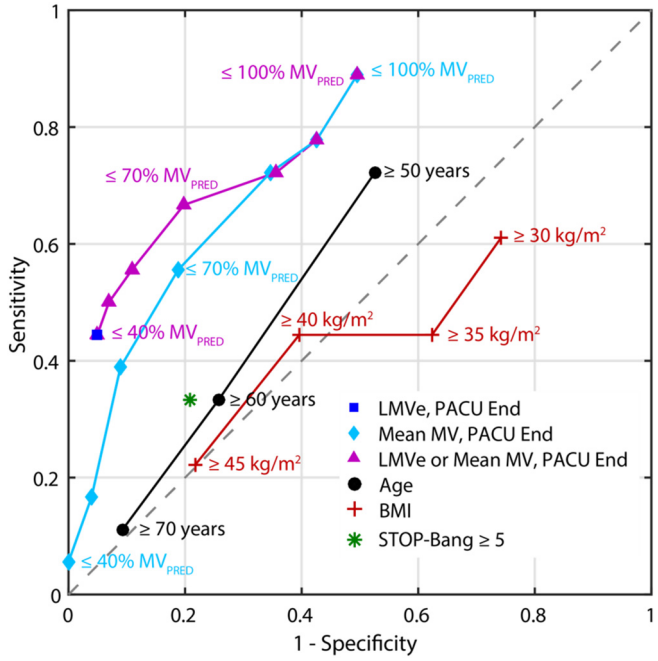

Fig. 3. Receiver operating characteristic (ROC) curves of six different parameters to predict a high rate of LMVes (i.e. ≥ 1 LMVe/h) on the GHF. Three parameters included objective minute ventilation parameters from the RVM during the last 30 min in the PACU (PACU End). Specifically, patients were stratified based on whether or not they experienced an LMVe (blue square), had an average MV less than a threshold (cyan diamonds), or either a LMVe or MV less than a threshold (magenta triangle). Additional parameters tested were age, body mass index, and STOP-Bang score. The dashed gray line indicates the performance of a random chance parameter.
LMVe = low minute ventilation event, GHF = general hospital floor, RVM = respiratory volume monitor, PACU = post-anesthesia care unit, MV = minute ventilation, BMI = body mass index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

timing of OIRD monitoring, > 50% of OIRD events occur in the first 12 h after surgery and approximately 75% occur in the first 24 h, indicating that prolonged monitoring for an identified population "at risk" would be the most effective to prevent a serious event [14].

The average duration of LMVes was longer in 'at-risk' patients in the PACU and reached a statistically significant difference on the GHF, but was clinically quite close between groups at between 4 and 5 min. Intravenous opioid administration on the floor did not significantly increase the LMVe frequency or duration within each group. However, it dramatically increased the likelihood of an LMVe within 30 min in the at-risk group compared to their counterparts from 5.6% to 43.8% with an odds ratio of 13.2. Further research is required to better understand the complex physiology of postoperative respiratory depression and the mechanisms that drive an increased LMVe likelihood, when LMVe rate or duration following intravenous opioids on the GHF did not appear to be significantly affected. This result is difficult to explain and requires further study.

Our study is limited by the small sample size and the technology in so far as only patients that allow placement of the chest wall monitoring pads can be included, and by the relatively obese patient population. A study with a larger sample size is warranted to confirm our results. We did not specifically examine the contribution to our findings of sedatives that may have been administered. Our study did not examine the pediatric population. The study protocol included RVM measurements beginning preoperatively which prevented inclusion of certain patients/procedures such as prone and thoracic cases because of the conditions of the disposable equipment placement. It remains unclear to what degree pre-existing respiratory conditions including asthma and COPD could influence our findings. There is a possibility that the study results may have been influenced by respiratory and other interventions in the PACU or on the floor which were not individually tracked. The study monitor and the measure of LMVes as used here have never been shown to actually predict adverse outcomes, and we did not include clinical safety outcomes such as frequency of oxygen desaturations or activations of respiratory response teams. To include OIRD outcomes would be desirable but would require a completely different study protocol and sample size which we did not plan for with this initial cohort.

In summary, one or more LMVe in the last 30 min prior to PACU discharge is a feasible parameter to distinguish patients 'at-risk' for respiratory depression on the GHF. In addition to a continued higher rate of LMVes, these patients had diminished minute ventilation in the PACU that deteriorated on the GHF. The combination of a threshold frequency of ≥1 LMVe and a predicted minute ventilation of ≤70% in the last 30 min of PACU stay derived from the RVM should be further investigated in a larger study for the ability to objectively identify postoperative patients requiring continued RVM or other feasible electronic monitoring with appropriate alarm settings on the GHF.

Disclosures

Roman Schumann, MD receives royalties for 2 obesity related chapters in Up-To-Date, UTD Inc., Waltham, MA, USA. Brian Harvey, PhD, was an employee of Respiratory Motion Inc., Waltham, MA, USA.

Acknowledgments

RespiratoryMotion Inc. Waltham, MA, USA provided the monitors and disposables used for study purposes and statistical support.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Joint Commission on Accreditation of Healthcare Organizations Sentinel Event Alert. Safe use of Opioids in Hospitals. vol. 49. 2012. p. 1–5.
[2] Jubran A. Pulse oximetry. Crit Care 2015;19:272.
[3] Shah A, Shelley KH. Is pulse oximetry an essential tool or just another distraction? The role of the pulse oximeter in modern anesthesia care. J Clin Monit Comput 2013;27:235–42.
[4] Ralston AC, Webb RK, Runciman WB. Potential errors in pulse oximetry. I. Pulse oximeter evaluation. Anaesthesia 1991;46:202–6.
[5] Schumann R, Kwater AP, Bonney I, Ladd D, Kim J, Gupta A, et al. Respiratory volume monitoring in an obese surgical population and the prediction of postoperative respiratory depression by the STOP-bang OSA risk score. J Clin Anesth 2016;34:295–301.
[6] Voscopoulos C, Brayanov J, Ladd D, Lalli M, Panasyuk A, Freeman J. Special article: evaluation of a novel noninvasive respiration monitor providing continuous measurement of minute ventilation in ambulatory subjects in a variety of clinical scenarios. Anesth Analg 2013;117:91–100.
[7] Voscopoulos CJ, MacNabb CM, Brayanov J, Qin L, Freeman J, Mullen GJ, et al. The evaluation of a non-invasive respiratory volume monitor in surgical patients undergoing elective surgery with general anesthesia. J Clin Monit Comput 2015;29:223–30.
[8] Voscopoulos CJ, MacNabb CM, Freeman J, Galvagno SM, Ladd D, George E. Continuous noninvasive respiratory volume monitoring for the identification of patients at risk for opioid-induced respiratory depression and obstructive breathing patterns. J Trauma Acute Care Surg 2014;77:S208-15.
[9] Gammaitoni AR, Fine P, Alvarez N, McPherson ML, Bergmark S. Clinical application of opioid equianalgesic data. Clin J Pain 2003;19:286–97.
[10] Du Bois D, Du Bois E. Clinical Calorimetry Tenth Paper: A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med (Chic) 1916;XVII:863–71.
[11] American Academy of Respiratory Care Protocol Committee. Subcommittee adult critical care. Adult mechanical ventilator protocols. 2003.
[12] National Institutes of Health National Heart Lung and Blood Institute Acute Respiratory Distress Syndrome Clinical Network. Mechanical ventilation protocol

summary. http://www.ardsnet.org/files/ventilator_protocol_2008-07.pdf; 2008, Accessed date: 21 January 2017.
[13] Lee LA, Caplan RA, Stephens LS, Posner KL, Terman GW, Voepel-Lewis T, et al. Postoperative opioid induced respiratory depression: a closed claims analysis. Anesthesiology 2015;122:659–65.
[14] Jungquist CR, Smith K, Nicely KLW, Polomano RC. Monitoring hospitalized adult patients for opioid-induced sedation and respiratory depression. Am J Nurs 2017;117:S27–35.
[15] Gupta RK, Edwards DA. Monitoring for opioid induced respiratory depression. APSF newsletter. 32. 2018. p. 70–2.
[16] Curry JP, Lynn LA. Threshold monitoring, alarm fatigue, and the patterns of unexpected hospital death. APSF Newsletter. 26. 2011. p. 32–5.