Ventilator Alarms in Intensive Care Units: Frequency, Duration, Priority, and Relationship to Ventilator Parameters

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Ventilator alarms have long been presumed to contribute substantially to the overall alarm burden in the intensive care unit. In a prospective observational study, we determined that each ventilator triggered an alarm cascade of up to 8 separate notifications once every 6 minutes. In 1 intensive care unit with different ventilator manufacturers, the distribution of high-priority alarms was manufacturer dependent with 8.6% of alarms from 1 type and 89.8% of alarms from another type of ventilator. Alarm limits were not a function of patient-specific ventilator settings. (Anesth Analg XXX;XXX:00–00)

Providers in intensive care units (ICUs) are exposed to frequent alarms, many of which may not require action by a provider.[1,2] Excess alarm exposure may affect patient safety,[3,4] disturb sleep,[5] and are consistently listed among the top ventilator-associated events reported to the Food and Drug Administration.[6,7] Despite their presumed importance, the frequency of ventilator alarms has not been systematically quantified.[6,8]

The number of times a device signals an alarm condition may not fully represent the alarm burden. For example, in Johns Hopkins Hospital (JHH) adult ICUs, ventilator alarms are communicated to providers in multiple ways (Supplemental Digital Content, Figure 1, http://links.lww.com/AA/C583), and a single alarm may trigger a cascade of up to 8 notifications. Although a primary notification is conveyed through visual and auditory signals generated by the ventilator to staff in close proximity, supplemental alarm notifications are sent through the nurse call system (Telligence; GE Healthcare, Chicago, IL) and to Wi-Fi phones through the hospital's middleware system (Connexall; GlobeStar Systems Inc, Toronto, ON, Canada).

To determine the frequency of ventilator alarms at JHH, we evaluated the frequency, duration, and type of ventilator alarms in 3 adult ICUs and examined factors influencing alarm settings.

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Accepted for publication August 17, 2018.

Funding: Supported, in part, by a grant from the Association for the Advancement of Medical Instrumentation (AAMI).

The authors declare no conflicts of interest.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website (www.anesthesia-analgesia.org).

Reprints will not be available from the authors.

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DOI: 10.1213/ANE.0000000000003801

METHODS

This manuscript adheres to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. The Johns Hopkins Medicine Institutional Review Board deemed this project as quality improvement and waived the requirement for informed consent. We conducted a prospective observational study in March 2017 in the cardiovascular surgical ICU (CVSICU), medical ICU (MICU), and neurocritical care unit (NCCU) at an academic tertiary care medical center in an urban setting (JHH, Baltimore, MD).

We evaluated Puritan Bennett 840 (PB840; Medtronic, Minneapolis, MN) ventilators in the MICU, NCCU, and CVSICU and Hamilton G5 (G5; Hamilton Medical, Reno, NV) ventilators in the CVSICU. During the study period, each ICU used additional ventilators not included in our study. Once randomly selected, all study ventilators stayed in the same ICU for the study duration.

To collect ventilator parameters and alarm data, we used 18 device-to-network bridge Capsule axons (Qualcomm Life, Inc, San Diego, CA) connected to the study ventilators, of which 17 consistently provided data. Ventilator parameters and alarm settings data were transmitted from the ventilator to a dedicated server every 10 seconds or less for PB840, and less frequently for G5 ventilators. Ventilator parameters included respiratory rate, ventilation mode, tidal volume, minute volume, spontaneous minute volume, spontaneous expired tidal volume, spontaneous ventilation type, and spontaneous respiratory rate. Alarm settings included inspiratory pressure upper and lower alarm limit, respiratory rate upper alarm limit, and minute volume upper and lower alarm limit. We collected alarm codes according to the specific alarm label and priority as defined by manufacturer; ventilator type; ICU; and time, date, and duration of alarm. Ventilator alarms included apnea, high and low inspiratory pressure, high and low minute volume, expired minute volume, loss of positive end-expiratory pressure, patient disconnect, circuit occlusion, high airway pressure, high respiratory rate, high spontaneous inspired time, high tidal volume, inspiration too long, low expired mandatory and spontaneous tidal volume, low oxygen supply pressure, and volume

Table. Set and Measured Ventilator Parameters, Alarm Settings, and Alarms Across Adult Intensive Care Units

		CVSICU		MICU	NCCU
Ventilator Parameters, Settings, and Alarms[a]	**Overall**	**PB840**	**G5**	**PB840**	**PB840**
Set parameters					
Ventilation mode, %					
A/C	46.9	0.5	-	65.9	45.3
SIMV-PS	7.3	41.1	-	<0.01	1.1
SPONT-PS	42.4	46.7	-	34.1	52.6
SPONT-VS	2.4	11.8	-	0	1.1
SIMV	0.6	-	59.3	-	-
SPONT	0.1	-	12.3	-	-
Other	0.3	-	28.4	-	-
Tidal volume, L	0.41 (0.08)	0.53 (0.05)[b]	0.53 (0.05)[b]	0.38 (0.06)	0.39 (0.08)
Set respiratory rate, breaths/min	11.70 (11.48)	7.79 (9.75)	-	14.63 (11.53)	9.69 (11.17)
Pressure support, cm H_2O	3.54 (4.60)	4.77 (2.25)	5.18 (3.18)	3.45 (5.88)	3.02 (3.25)
Measured parameters					
Tidal volume, L	0.44 (0.20)	0.53 (0.26)	0.55 (0.13)	0.41 (0.17)	0.42 (0.18)
Spontaneous tidal volume, L	0.24 (0.29)	0.46 (0.30)	0.47 (0.17)	0.15 (0.25)	0.25 (0.28)
Spontaneous respiratory rate, breaths/min	5.69 (9.10)	-	5.69 (9.10)	-	-
Respiratory rate, breaths/min	21.87 (9.04)	19.79 (8.96)	21.03 (5.70)	24.23 (8.83)	19.80 (8.81)
Minute volume, L/min	9.70 (4.18)	11.79 (6.11)	11.18 (2.64)	9.84 (3.61)	8.38 (3.29)
Spontaneous minute volume, L/min	4.32 (5.75)	8.58 (8.05)	-	2.96 (4.77)	4.10 (4.53)
Alarm settings					
Inspiratory pressure upper alarm limit, cm H_2O	49.13 (6.41)	46.54 (5.39)[b]	46.44 (5.92)[b]	52.23 (6.04)	46.35 (5.41)
Respiratory rate upper alarm limit, breaths/min	48.27 (4.19)	48.59 (3.71)	44.34 (8.44)	49.98 (1.28)	46.02 (5.36)
Minute volume upper alarm limit, L/min	18.70 (3.16)	-	18.70 (3.16)	-	-
Minute volume lower alarm limit, L/min	3.07 (0.72)	3.75 (0.99)	3.10 (0.30)	2.95 (0.70)	2.91 (0.28)
Alarms					
Total alarms, n	10,905	1263	522	4374	4746
Total ventilator-hours, n	1555	214	92	649	600
Duration of alarms, s	20.4 (34.2)	30.7 (58.0)	26.5 (45.8)	17.2 (29.9)	20.0 (26.3)
Alarms with duration ≤15 s, %	60.0	50.9	57.5	64.2	58.8
Alarms with duration >15 s, %	40.0	49.1	42.5	35.8	41.2
Type of alarm, %					
Apnea	1.7	0.6	2.9	2.1	1.3
High inspiratory pressure	34.2	26.5	47.3	35.3[c]	33.8[c]
High minute volume	4.0	13.4	2.7	4.2	1.6
High respiratory rate	17.8	11.5[c]	9.8[c]	20.4	18.0
High tidal volume	3.0	2.9	-	1.6	4.3
Low expired mandatory tidal volume	12.9	11.7[c]	-	11.5[c]	15.9
Low expired spontaneous tidal volume	8.6	9.3[c]	-	7.6	10.2[c]
Low minute volume	9.3	5.3	12.8	10.2[c]	9.1[c]
Patient disconnect	3.8	4.4	23.9	2.4[c]	2.7[c]
Other[d]	4.9	14.3	0.6	4.7	3.1
Alarm priority, %					
Low	75.5	82.1	0.0	80.7	77.1
Medium	10.9	9.3	10.2	10.2	12.0
High	13.7	8.6	89.8	9.1	10.8

Abbreviations: ANOVA, analysis of variance; A/C, assist control; CVSICU, cardiovascular surgical ICU; G5, Hamilton G5 ventilator; ICU, intensive care unit; MICU, medical ICU; NCCU, neurosciences ICU; PB840, Puritan Bennett 840 ventilator; SD, standard deviation; SIMV, synchronized intermittent mandatory ventilation; SIMV-PS, SIMV with pressure support; SPONT, spontaneous; SPONT-PS, SPONT with pressure support; SPONT-VS, SPONT with volume support.

[a]All data are presented as mean (SD) unless otherwise specified. ANOVA for continuous variables and χ^2 test for categorical variables were used to compare PB840 ventilator parameters and settings between the ICUs; whereas *t* test for continuous variables and χ^2 test for categorical variables were used to compare ventilator parameters and settings between the 2 ventilator types (PB840 and G5) in CVSICU.

[b]Nonsignificant differences when comparing ventilator parameters and settings between the 2 ventilator types (PB840 and G5) in CVSICU. All other comparisons concerning set and measured ventilator parameters, and alarm settings are statistically significant ($P < .001$).

[c]Nonsignificant differences between the 2 groups. All other comparisons concerning types of alarms are statistically significant ($P < .05$).

[d]Other alarms included (a) for PB840 ventilator: circuit occlusion, expired minute volume, high airway pressure, inspiration too long, low inspiratory pressure, low oxygen supply pressure, and volume not delivered (for volume support ventilation); and (b) for G5 ventilator: loss of positive end-expiratory pressure.

not delivered (for volume support ventilation mode only). We excluded alarms that occurred during setup; the PB840 high spontaneous inspiratory time alarm (which occurs during noninvasive ventilation); the G5 failure to cycle and operator messages (which appear on the ventilator as visual alarms), and technical or device fault. Alarm priority is predefined by ventilator manufacturers. For the G5 ventilator, alarm indicators include high, medium, and low priority, operator message, and technical fault.[9] The PB840 ventilator alarms are designated high, medium, and low priority or device fault. Priority is either preassigned or based on the duration of the measured parameter deviation from the alarm setting.[10] However, once an alarm is generated, its priority remains fixed, although additional alarms of higher priority may be generated if the alarm condition remains unresolved.

Statistical Analyses

We counted all alarm notifications occurring at time zero as the initial notification cascade, and notifications at the 15-second mark were tallied as an additional notification cascade (Supplemental Digital Content, Figure 1, http://links.lww.com/AA/C583). Notifications to the “buddy nurse” and to the charge nurse were not included in the analyses because it was not possible to verify whether acknowledgments actually occurred along the notification timeline. We determined the number of alarms per ventilator-hour (1 hour of ventilation on a single ventilator). Next, we assessed how many alarms reached respiratory therapists (RTs) and nurses via Wi-Fi phones by comparing proportions of the alarms that persisted for >15 seconds across ICUs and by ventilator types. Ventilator parameters, settings, and alarms (1) across the CVSICU, MICU, and NCCU, (2) between the 2 ventilator types in the CVSICU were compared by Student t test for continuous variables and χ^2 test for categorical variables. To compare alarm distributions during the 24-hour period, we used a goodness-of-fit test to a uniform distribution and one determined from the average across all units. Finally, we performed linear regression of: (1) set and measured respiratory rate on respiratory rate upper alarm limit and (2) minute volume on minute volume lower alarm limit. All analyses were performed with Stata 14 version 14.2 (StataCorp LLC, College Station, TX) and Mathematica 10 (Wolfram Research, Champaign, IL).

RESULTS

We collected ventilator parameter settings from March 2 to March 16, 2017, and ventilator alarm data from March 2 to March 19, 2017. Data were acquired from at most 6 ventilators in the CVSICU, 5 in the MICU, and 6 in the NCCU. The average (range) number of ventilators used per day on the 3 units during the study period was 5 (2–8) in the CVSICU, 10 (5–16) in the MICU, and 6 (3–9) in the NCCU. These data are summarized in Table and demonstrate different patterns for each ICU and ventilator type ($P < .001$ for comparisons further specified in Table and its legend).

A total of 10,905 ventilator alarms were initiated over 1555 ventilator-hours in the 3 study ICUs. The mean (standard deviation) number of alarms per ventilator-hour was 6 (3) in the CVSICU, 7 (4) in the MICU, 8 (2) in the NCCU, and 7 (4) overall. In the CVSICU, the mean (standard deviation) number of alarms per ventilator-hour by ventilator type was 8 (2) for the PB840 and 6 (5) for the G5. All alarms in the CVSICU and NCCU (with no delay in notification) and 2.5% of alarms in the MICU (with a 60-second delay in notification) resulted in a cascade of supplemental alarm notifications through the nurse call system. Overall, ventilator alarm conditions did not resolve within 15 seconds 40.0% of the time, leading to 2.8 additional Wi-Fi phone notifications per ventilator-hour to RTs and nurses through our alarm notification middleware. The distribution of alarms by duration and priority across adult ICUs and ventilator types is given in Figure. Alarms were randomly distributed over the 24-hour

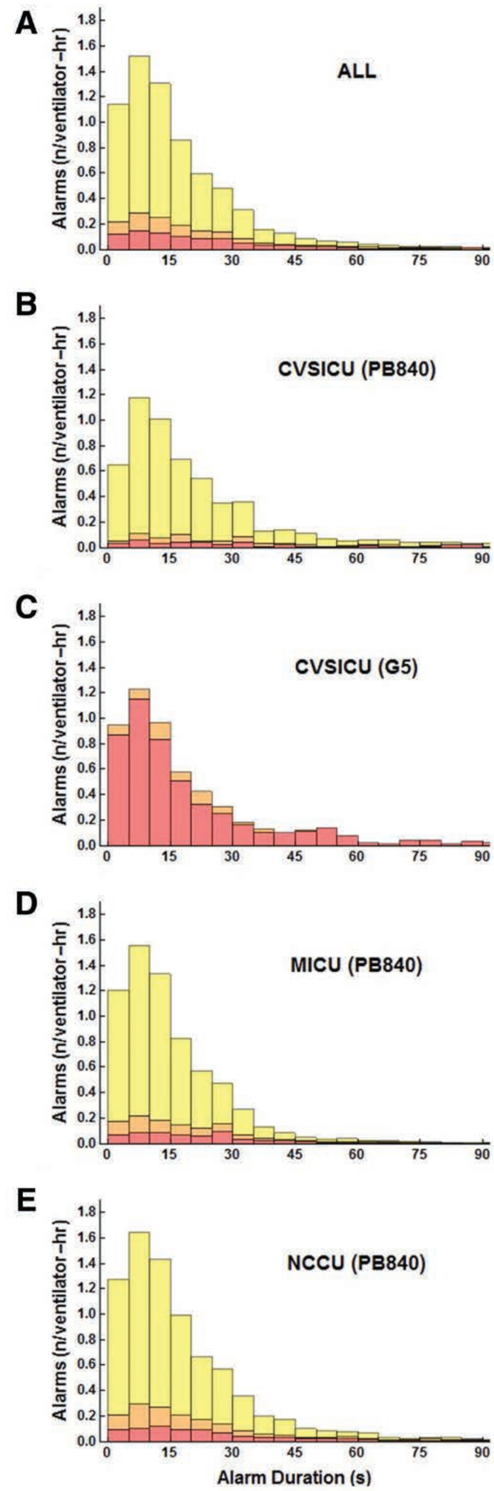

Figure. Distribution of alarms by duration and priority (red = high, orange = medium, yellow = low) across adult ICUs and different ventilator types. A, All ICUs and ventilators in total. B, Alarms from the Puritan Bennett 840 (PB840) ventilator in the CVSICU. C, Alarms from the Hamilton G5 ventilator in the CVSICU. D, Alarms from the PB840 in the MICU. E, Alarms from the PB840 in the NCCU. Alarms unresolved after 15 s triggered additional notification to respiratory therapists and nurses via Wi-Fi phone in 40% of instances. Note also the difference in the alarm priority between the 2 ventilator types in the CVSICU. CVSICU indicates cardiovascular surgical ICU; ICU, intensive care unit; MICU, medical ICU; NCCU, neurosciences critical care unit.

day ($P > .99$) when compared to a uniform alarm distribution (Supplemental Digital Content, Figure 2, http://links.lww.com/AA/C583), except for CVSICU ($P < .001$). Only the CVSICU exhibited a temporal pattern of alarm distribution that differed from the average over all units ($P < .001$).

Alarm data across the different ICUs and ventilator types are summarized in Table. Overall, the 3 most common alarms were high inspiratory pressure (34.2%), high respiratory rate (17.8%), and low expired mandatory tidal volume (12.9%). Although only 8.6% of PB840 ventilator alarms in the CVSICU were classified as high priority (range, 8.6%–10.8% among all ICUs), G5 alarms for the same patient population (Figure) were classified predominantly as high priority (89.8%). Such difference is attributed to differences in manufacturer-specific alarm definitions of priorities rather than differences in the underlying population.

Ventilator alarm limits were not clinically meaningfully adjusted based on ventilator parameters (eg, for an increase in measured respiratory rate of 10 breaths/min, respiratory rate upper alarm limit is adjusted by ≈1 breath/min) (Supplemental Digital Content, Table 1, http://links.lww.com/AA/C583).

DISCUSSION

This study supports the long-held assumption that the contribution of ventilator alarms to the overall alarm burden in the ICU is substantial. Overall, we observed 7.0 initial alarm cascades per ventilator-hour. Forty percent of those, or 2.8 per ventilator-hour, triggered additional notification cascades of RTs and nurses via the Wi-Fi phone system, increasing the total to 9.8 notification cascades per ventilator-hour or approximately 1 every 6 minutes for each ventilator in use. These data reinforce previous reports of high overall alarm prevalence in ICUs[2,11,12] and the operating room.[13,14] High inspiratory pressure, high respiratory rate, and low expired mandatory tidal volume were the most frequently triggered alarms in all 3 ICUs. Despite accepted definitions of alarm priority,[15] in the CVSICU, we found that different ventilator manufacturers prioritized alarms differently, so that high priority alarms accounted for only 8.6% of PB840 alarms, but 89.8% of G5 alarms. Finally, we found that ventilator alarm settings were not meaningfully adjusted with ventilator settings.

ACKNOWLEDGMENTS

The authors thank the Association for the Advancement of Medical Instrumentation Foundation for its contribution to funding a portion of this project; Qualcomm Life, Inc, San Diego, CA, for loaning us 18 Capsule Axons, which were used to collect patient and device data electronically; Yih-Jang Chang, MS, and Robert Frank, CET, who provided information technology support to organize data collected from the Capsule Axons; and Rachel Reynolds, BS, who provided support in analyzing ventilator alarm data.

DISCLOSURES

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