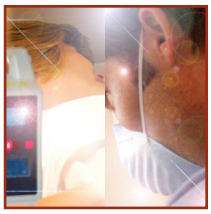

Thoracic Impedance Pneumography–Derived Respiratory Alarms and Associated Patient Characteristics

By Linda K. Bawua, PhD, MS, RN, AGCNS-BC, Christine Miaskowski, PhD, RN, Sukardi Suba, PhD, RN, ACCNS-AG, Fabio Badilini, PhD, George W. Rodway, PhD, RN, Xiao Hu, PhD, and Michele M. Pelter, PhD, RN

Background Respiratory rate (RR) alarms alert clinicians to a change in a patient's condition. However, RR alarms are common occurrences. To date, no study has examined RR alarm types and associated patient characteristics, which could guide alarm management strategies.
Objectives To characterize RR alarms by type, frequency, duration, and associated patient demographic and clinical characteristics.
Methods A secondary data analysis of alarms generated with impedance pneumography in 461 adult patients admitted to either a cardiac, a medical/surgical, or a neurological intensive care unit (ICU). The RR alarms included high parameter limit (≥30 breaths/min), low parameter limit (≤5 breaths/min), and apnea (no breathing ≥20 s). The ICU type; total time monitored; and alarm type, frequency, and duration were evaluated.
Results Of 159 771 RR alarms, parameter limit alarms (n = 140 975; 88.2%) were more frequent than apnea alarms (n = 18 796; 11.8%). High parameter limit alarms were most frequent (n = 131 827; 82.5%). After ICU monitoring time was controlled for, multivariate analysis showed that alarm rates were higher in patients in the cardiac and neurological ICUs (P = .001), patients undergoing mechanical ventilation (P = .005), and patients without a ventricular assist device or pacemaker (P = .02). Male sex was associated with low parameter limit (P = .01) and apnea (P = .005) alarms.
Conclusion High parameter limit RR alarms were most frequent. Factors associated with RR alarms included monitoring time, ICU type, male sex, and mechanical ventilation. Although these factors are not modifiable, these data could be used to guide management strategies.
(*American Journal of Critical Care.* 2022;31:355-365)

CE 1.0 Hour

This article has been designated for CE contact hour(s). See more CE information at the end of this article.

This article is followed by an *AJCC* Patient Care Page on page 366.

doi:https://doi.org/10.4037/ajcc2022295

In the intensive care unit (ICU), respiratory rate (RR) measurement is an essential component of patient monitoring that aids in early recognition of deterioration in a patient's condition.[1-3] Impedance pneumography (IP) devices allow continuous assessment of RR[4,5] and can generate alarms when the RR falls above or below prespecified parameters or when no breaths are detected (apnea). Although prior studies show that RR alarms are common,[6-13] none have examined the specific types of RR alarms and only one examined associated patient characteristics.[13]

A better understanding of the specific types of RR alarms and a comprehensive evaluation of associated patient demographic and/or clinical characteristics could guide alarm management strategies to reduce potential alarm fatigue (ie, desensitization and/or unsafe alarm adjustments) and improve future RR algorithms used in hospital-based bedside monitors.

To gain a clear understanding of prior research on RR type alarms, a systematic literature search was conducted using the following databases: PubMed, Cumulative Index to Nursing and Allied Health Literature (CINAHL), Web of Science, and the Cochrane Library. Keywords used for the database searches included *adult(s), respiration(s), RR measurement, manual, visual, electrocardiogram (ECG)-* or *EKG-derived, impedance, thoracic pneumography,* and *hospital setting.* These terms were combined in strings using the Boolean operands OR and AND to specifically focus on studies that compared different methods to assess RR. Seven studies evaluated the number and/or types of RR alarms using IP in adult hospitalized patients.[6,8-13] Two studies reported on apnea alarms,[9,13] 2 reported on high and low parameter limit alarms,[6,9] and 1 reported on both parameter limit and apnea alarms but did not separate them by parameter limit alarm versus apnea alarm.[8] Of the 7 studies, only one evaluated for associations between patient and clinical characteristics and that study addressed only apnea alarms.[13] That study was done in a postanesthesia care unit for a mean of 101 minutes, and patient and clinical characteristics were limited to sex and surgery type. Therefore, it is unknown which demographic and/or clinical characteristics influence the number and type of IP-derived RR alarms in an ICU population.

Respiratory rate (RR) alarms are common during bedside ECG monitoring and may potentially contribute to alarm fatigue.

The purpose of this secondary data analysis was twofold: (1) from a total of 159 771 RR alarm occurrences, determine the number of each type of alarm (high parameter limit, low parameter limit, and apnea), the total number of minutes the patient was in an alarm condition during the ICU monitoring period, and the median duration (in seconds) of RR parameter limit (≤5 breaths/min or ≥30 breaths/min) and apnea (no breathing ≥20 s) alarms (ie, how long the alarms sounded) and (2) determine if patient demographics (age, sex, race), clinical characteristics (body mass index [BMI, calculated as weight in kilograms divided by height in meters squared], cognitive status, body tremor), smoking status, use of supportive therapies (mechanical ventilation, ventricular assist device, pacemaker), or ICU type (cardiac, medical/surgical, neurological) were associated with the number of RR parameter limit and apnea alarms. Clinical characteristics were selected on the basis of what we hypothesized might increase the number of RR alarms generated using the IP method by affecting the signal quality. For example, higher BMI decreases chest wall compliance, which could affect IP-derived RRs.[14] Although the IP-derived RR method does not use ECG waveforms to measure RR, the skin electrodes used for ECG monitoring are also used for IP-derived RR. We hypothesized that patients who have agitation from nicotine withdrawal, cognitive impairment/confusion, or body tremors (eg, Parkinson disease, alcohol/nicotine withdrawal, other neurological conditions, shivering) could have an increased number of RR alarms as a result of decreased IP signal quality. We also included devices known to cause interference and/or artifact during

About the Authors
Linda K. Bawua is a former PhD student, **Christine Miaskowski** is a professor, **Fabio Badilini** is director of the Center for Physiological Research, and **Michele M. Pelter** is an associate professor, School of Nursing, University of California, San Francisco, California. **Sukardi Suba** is a postdoctoral associate, School of Nursing, University of Rochester Medical Center, Rochester, New York. **George W. Rodway** is an assistant professor, School of Medicine, University of Nevada, Reno, Nevada. **Xiao Hu** is a professor, School of Nursing, Duke University, Durham, North Carolina.

Corresponding author: Michele M. Pelter, PhD, RN, University of California San Francisco, 2 Koret Way, San Francisco, CA 94143-0610 (email: michele.pelter@ucsf.edu).

ECG monitoring (mechanical ventilation, ventricular assist device [VAD], pacemaker) that could contaminate the signal used for IP-derived RR.[8,15-17]

Methods

Study Design

This secondary analysis used data from a comprehensive alarm study conducted during a 1-month period.[8] The University of California, San Francisco, Institutional Review Board approved the research protocol (RB #12-09723).

Sample and Setting

Although the parent study identified the frequency and types of all alarms from the bedside monitors,[8] for this study, we report on only RR alarms. We included 461 consecutive adult patients (>18 years) treated in 1 of 3 ICUs: a 16-bed cardiac unit, a 32-bed medical/surgical unit, or a 29-bed neurological unit. Our sample included all adult ICU patients treated at our hospital during the 1-month study period. Patient data were collected from the electronic health record by our institution's Clinical Research Services. The ICU admission and discharge dates were provided and relevant data were captured including patient demographics (age, race, ethnicity, sex) and clinical characteristics hypothesized to increase the number of RR alarms by affecting IP signal quality. The clinical characteristics collected included BMI, smoking status, cognitive impairment or confusion (eg, delirium, hypoxia), body tremor (eg, Parkinson disease, alcohol/nicotine withdrawal, other neurological conditions, shivering), and devices known to cause interference and/or artifact (mechanical ventilation, VAD, pacemaker).[8,15-17] We calculated ICU monitoring time for each patient by eliminating periods when the patient was detached from the ICU monitor (eg, surgery, cardiac catheterization, non-ICU diagnostic procedure), as evidenced by flat lines on the 7 ECG leads. Hourly RR alarm rates were then calculated by dividing the number of alarms by the patient's total ICU monitoring time.

Alarm Data Capture System and IP RR

The alarm data capture system is shown in Figure 1. The bedside monitors recorded RR using the IP method. Impedance pneumography measures thoracic changes during respirations by measuring the difference in alternating current amplitudes from the ECG limb leads (Figure 2). Although 7 ECG leads are recorded (I, II, III, aVR, aVL, aVF, and V_1), the IP method does not use the ECG waveforms to determine RR. Instead, the right arm, left arm, and/or left leg electrodes are used. Our hospital default is lead II. However, nurses can change to lead I if the patient is a chest versus abdominal breather, and some users change to lead I when frequent alarms occur to improve the IP signal quality. For this study, RR alarms were governed by our hospital's default settings: high RR (≥30 breaths/min), low RR (≤5 breaths/min), and apnea (no breathing ≥20 seconds). Alarms with a duration exceeding 15 minutes were excluded because these alarms most likely occurred when a patient was detached from the monitor (eg, test, surgery).

Data Analysis

Analyses were performed using R version 3.6.[18] Descriptive statistics were calculated for demographic and clinical characteristics, alarm occurrence, the total number of minutes the patient was in an alarm condition during the ICU monitoring period, and the duration of alarms. These data are expressed as means and standard deviations, ranges, and percentages. Although we present the total number of parameter limit and apnea alarms using descriptive statistics, because some patients had frequent RR alarms while others had only a few, we also examined RR parameter limit and apnea alarm *counts* (total number of RR alarms per patient) using median and interquartile range (IQR) statistics. Similarly, medians and IQRs were used to report alarm counts for ICU monitoring time, the total number of minutes the patient was in an alarm condition during the ICU monitoring period, and the duration of alarms.

> Are RR alarms associated with patients' demographic or clinical characteristics or devices used in the intensive care unit?

Associations between demographic (age, sex, race), clinical characteristics (BMI, smoking status, impaired cognitive status/confusion, tremor), ICU type (cardiac, medical/surgical, neurological), use of supportive therapies (mechanical ventilation, VAD, pacemaker), and alarm rates were evaluated with regression models that specified a negative binomial distribution. To further describe these relationships, we used multivariate regression models to examine the number of each type of alarm, controlling for ICU monitoring time. Prior to modeling, BMI and age were transformed into categorical variables. Age was categorized in units of 10 years, and BMI was dichotomized into BMI 25-30 and BMI >30. Results from the multivariate regression models are reported as incidence rate ratios with 95% CIs for each

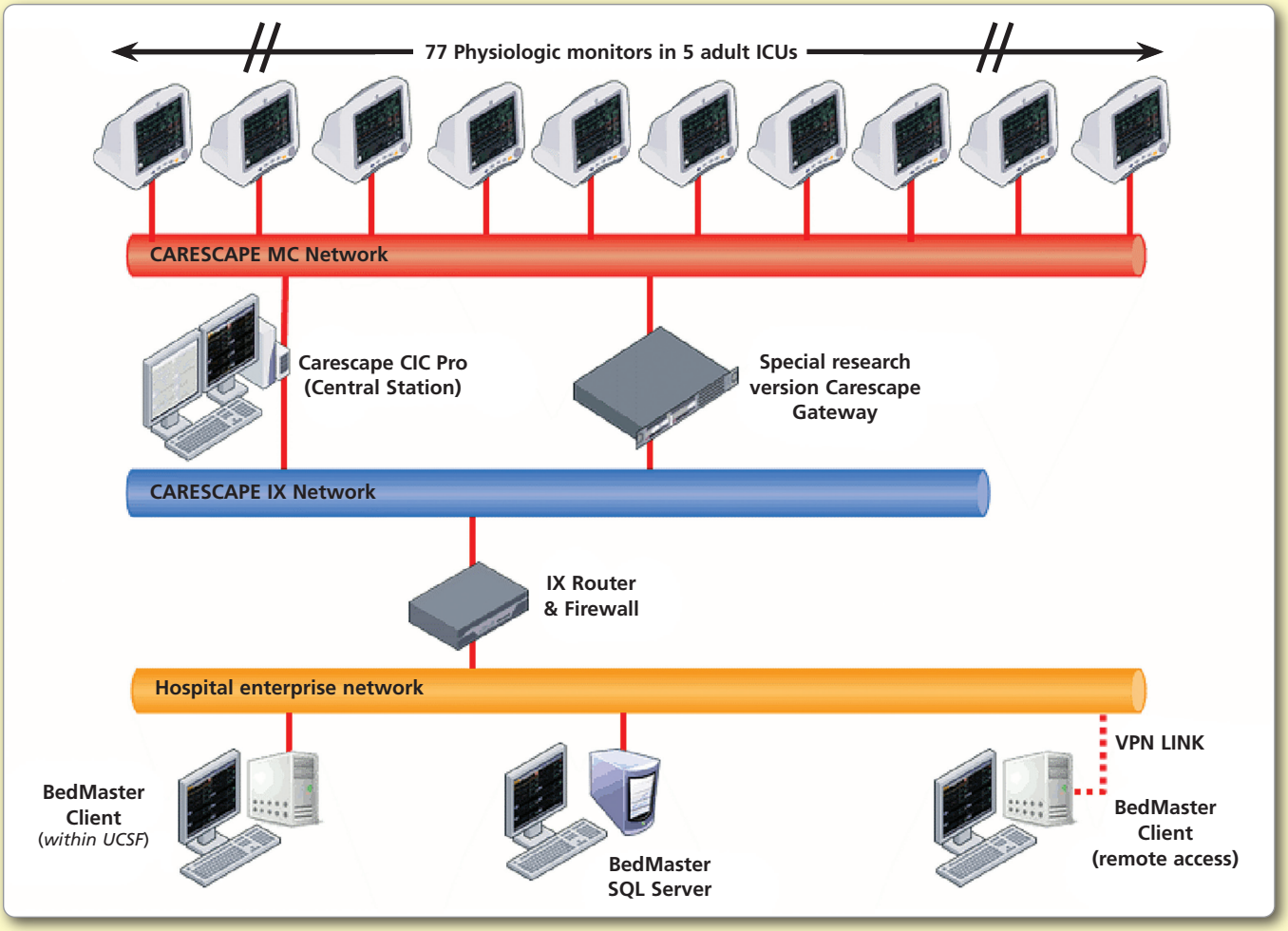

Figure 1 Hospital infrastructure used to capture and store all physiologic monitor waveform and alarm data automatically.[8] Each of the 77 bedside monitors was connected to a CARESCAPE Gateway (GE Healthcare). This system captured all of the physiological waveforms (ie, electrocardiogram, arterial blood pressure, pulse oximetry, respiration), numeric vital signs, and alarm parameter limit settings, as well as all audible and inaudible alarms. Physiological data were stored with BedMasterEx software (Excel Medical Electronics, Inc) and extracted into Extensible Markup Language (XML) files.

Abbreviations: ICU, intensive care unit; UCSF, University of California, San Francisco; VPN, virtual private network.

 doi:10.1371/journal.pone.0110274.g002

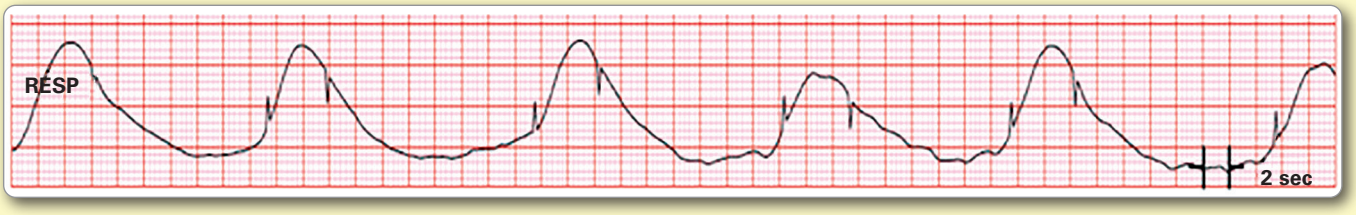

Figure 2 Impedance pneumography respiratory waveform (RESP) generated during a 10-second time frame. Note the upward flag on the inspiratory waveform and the downward flag on the expiratory waveform used by the manufacturer to denote a single breath. In addition to the waveform, a numeric respiratory rate is displayed on the bedside monitor.

candidate covariate with the rating period defined as the ICU monitoring time. Statistical significance was defined as a *P* value less than .05 and 2-tailed tests were used for all analyses.

Results

Characteristics of the Sample

As shown in Table 1, of the 461 ICU patients, 54.2% were male, 61.0% were White, and 43.0%

had cognitive impairment. Mean (SD) age was 59.6 (17.0) years and mean (SD) BMI was 28.1 (8.2). The largest percentage of the patients (42.7%) were admitted to the neurological ICU. Of the sample, 38.6% required mechanical ventilation and 7.4% had a VAD and/or pacemaker. The mean (SD) for total monitoring time for the sample was 45 499 (121) hours.

Number, Type, Duration, and Characteristics of RR Alarms

During the 45 499 hours of monitoring, 159 771 RR alarms occurred; 140 975 (88.2%) were RR parameter limit alarms and 18 796 (11.8%) were apnea alarms. On the basis of the total number of ICU monitoring hours, there were 3.5 RR alarms per hour. Of the 140 975 RR parameter limit alarms, 131 827 (82.5% of total alarms) were high parameter limit alarms.

Table 2 shows comparisons of demographic and clinical characteristics by RR alarm type. Owing to variability in the number of RR alarms, the median values are reported and were used in the statistical analyses. On the basis of the univariate analysis, tremor and smoking status were not included in the multivariate model because the associations were weak ($P > .15$).

High Parameter Limit Alarms. Of the 461 patients, 454 (98.5%) had at least 1 high parameter limit alarm. The median (IQR) for patients' ICU monitoring time was 64 (28-149) hours, alarms per patient was 94 (37-265), number of minutes the patients were in high RR alarms during the ICU monitoring period was 19.6 (6.2-57.7) minutes, and alarm duration was 8 (4-18) seconds. In the bivariate analysis, patients with cognitive impairment, undergoing mechanical ventilation, without a VAD and/or a pacemaker, and in the cardiac or neurological ICU had a higher number of high parameter limit alarms (see Supplemental Table, available online only, at www.ajcconline.org). After monitoring time was controlled for, being in the cardiac or neurological ICU remained significant in the multivariate analysis (Figure 3).

Low Parameter Limit Alarms. Of the 461 patients, 359 (77.9%) had at least 1 low parameter limit alarm. The median (IQR) for patients' ICU monitoring time was 73 (43-182) hours, alarms per patient was 6 (1-21), number of minutes the patients were in low RR alarms during the ICU monitoring period was 2.6 (0.2-18.9) minutes, and alarm duration was 20 (8-87) seconds. In the bivariate analysis, patients with high BMI, undergoing mechanical ventilation, and in the cardiac or neurological ICU had a higher number of low parameter limit alarms (see Supplemental Table, available online only). After monitoring time was controlled for, being male, undergoing mechanical ventilation, not having a VAD or a pacemaker, and being

Table 1
Demographics, clinical characteristics, intensive care unit type, and number of respiratory type alarms (parameter high/low and apnea) in 461 intensive care unit patients

Characteristic	Value[a]
Demographics	
Age, mean (SD), y	59.6 (17.0)
Body mass index,[b] mean (SD)	28.1 (8.2)
Sex	
Male	250 (54.2)
Female	211 (45.8)
Race	
Asian	76 (16.5)
Black/African American	35 (7.6)
Native Hawaiian or Pacific Islander	8 (1.7)
White	281 (61.0)
Patient unable to state or not recorded in electronic health record	61 (13.2)
Factors hypothesized to influence respiratory alarms	
Current smoker	71 (15.4)
Documented cognitive impairment	198 (43.0)
Tremor	36 (7.8)
Type of intensive care unit	
Cardiac (16 beds)	83 (18.0)
Medical/surgical (32 beds)	181 (39.3)
Neurological (29 beds)	197 (42.7)
Use of supportive therapy	
Mechanical ventilation	178 (38.6)
Ventricular assist device or pacemaker	34 (7.4)
Monitoring time, median (IQR), h	63 (28-148)
No. of respiratory type alarms	
Total	159 771
Parameter (high or low)	140 975 (88.2% of total)
High (≥30/min)	131 827 (82.5% of total, range 1-5852)
Low (≤5/min)	9148 (6% of total, range 1-455)
Apnea (no breath ≥20 seconds)	18 796 (11.8% of total, range 1-1208)
Monitoring time per patient, median (IQR), h	63 (28-148)
Total No. of alarms per patient, median (IQR)	136 (55-349)
No. of parameter alarms (high/low) per patient, median (IQR)	114 (45-286)
No. of apnea alarms, median (IQR)	11 (2-41)
Time patient in alarm conditions during intensive care unit monitoring time, median (IQR), minutes	40.6 (13.5-113.6)
Duration of alarm, median (IQR), seconds	10 (4-20)

[a] No. (%) of patients unless otherwise indicated.
[b] Calculated as weight in kilograms divided by height in meters squared.

Table 2
Demographic and clinical characteristics, intensive care unit type, and respiratory alarms by type in 461 ICU patients[a]

Characteristic	Respiratory rate alarm		Apnea alarm, no breath for >20 seconds (n=381)
	High, >30/min (n=454)	Low, < 5/min (n=359)	
Demographics			
Age, mean (SD), y	59.5 (16.9)	59.4 (16.8)	59.5 (17.0)
Body mass index,[b] mean (SD)	28.1 (8.2)	27.9 (7.3)	27.7 (7.2)
Sex, No. (%) of patients			
Male	245 (54.0)	200 (55.7)	217 (57.0)
Female	209 (46.0)	159 (44.3)	164 (43.0)
Race, No. (%) of patients			
Asian	72 (15.9)	52 (14.5)	60 (15.7)
Black/African American	34 (7.5)	30 (8.4)	31 (8.1)
Native Hawaiian or Pacific Islander	52 (11.5)	40 (11.1)	42 (11.0)
White	267 (58.8)	214 (59.6)	223 (58.5)
Unable to state because of acute illness or not recorded in the electronic health record	29 (6.4)	23 (6.4)	25 (6.6)
Factors hypothesized to increase respiratory alarms, No. (%) of patients			
Current smoker	69 (15.2)	60 (16.7)	59 (15.5)
Documented cognitive impairment	196 (43.2)	169 (47.1)	177 (46.5)
Tremor	36 (7.9)	30 (8.4)	33 (8.7)
Mechanical ventilation	176 (38.8)	158 (44.0)	167 (44.0)
Ventricular assist device or pacemaker	33 (7.3)	27 (7.5)	32 (8.4)
Intensive care unit type, No. (%) of patients			
Cardiac (16 beds)	82 (18.1)	70 (19.5)	73 (19.2)
Medical surgical (32 beds)	176 (38.8)	134 (37.3)	144 (37.8)
Neurological (29 beds)	196 (43.2)	155 (43.2)	164 (43.0)
Respiratory alarm characteristics			
ICU monitoring time, median (IQR), h	64 (28-149)	73 (43-182)	71 (40-173)
Total No. (%) of alarms	131827 (82.5)	9148 (6)	18796 (11.8)
No. of alarms per patient, median (IQR)	94 (37-265)	6 (1-21)	11 (2-41)
Time in alarm conditions, median (IQR), minutes	19.6 (6.2-57.7)	2.6 (0.2-18.9)	4.3 (0.6-18.2)
Duration of alarms, median (IQR), seconds	8 (4-18)	20 (8-87)	16 (10-29)

Abbreviation: ICU, intensive care unit.

[a] A patient may have had more than 1 type of alarm.
[b] Calculated as weight in kilograms divided by height in meters squared.

in the cardiac or neurological ICU remained significant in the multivariate analysis (Figure 3).

Apnea Alarms. Of the 461 patients, 381 (82.6%) had at least 1 apnea alarm. The median (IQR) for patients' ICU monitoring time was 71 (40-173) hours, alarms per patient was 11 (2-41), number of minutes the patients were in low RR alarms during the ICU monitoring period was 4.3 (0.6-18.2) minutes, and alarm duration was 16 (10-29) seconds. In the bivariate analysis, patients undergoing mechanical ventilation, without a VAD and/or pacemaker, and in the cardiac or neurological ICU had a higher number of apnea alarms (see Supplemental Table, available online only). After monitoring time was controlled for, being male, not having a VAD and/or pacemaker, and being in the cardiac or neurological ICU remained significant in the multivariate analysis (Figure 3).

In summary, after ICU monitoring time was controlled for, multivariate analysis showed that alarm rates were higher in patients in the cardiac and neurological ICUs ($P = .001$), patients undergoing mechanical ventilation ($P = .005$), and patients without a ventricular assist device or pacemaker ($P = .02$). Male sex was associated with low parameter limit ($P = .01$) and apnea ($P = .005$) alarms (Figure 3).

Discussion

This study is the first to characterize RR parameter limit and apnea alarms in 461 consecutively enrolled ICU patients. During 1 month, there were 159 771 RR alarms during 45 499 hours of ICU monitoring, or 3.5 RR alarms per hour of ICU monitoring. As expected, the duration of ICU monitoring was associated with a higher median number of RR alarms and thus was controlled for in the multivariate analysis. The number

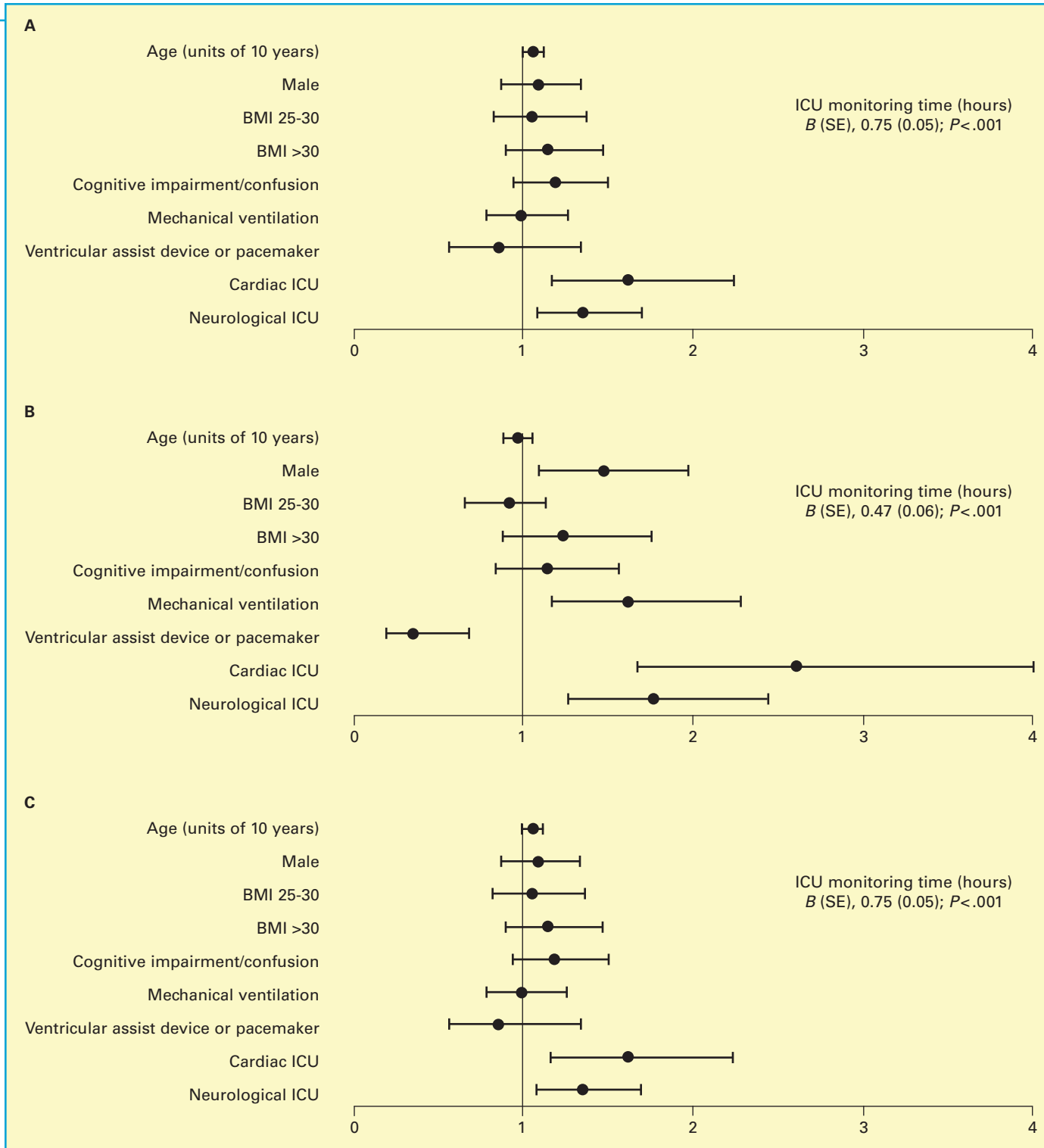

Figure 3 Forest plots of multiple regression analysis for the number of (A) high respiratory parameter limit alarms (≥30/min, (B) low respiratory parameter limit alarms (≤5/min), and (C) apnea alarms (no breathing > 20 seconds) among 461 ICU patients. Results from the multivariate regression models are reported as incidence rate ratios with 95% CIs for each candidate covariate with the rating period defined as the ICU monitoring time. The ICU monitoring time (hours) was significant for all of the respiratory type alarms and was controlled for in the multivariate analysis.

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); ICU, intensive care unit.

of RR parameter limit alarms (82.5%) far exceeded the number of apnea alarms.

The RR parameter limit alarm rates documented in this study were higher than those reported in 2 existing studies.[6,9] In one study of 4104 non-ICU patients,[9] of 612 RR parameter limit alarms, 113 (19%) high parameter limit and 499 (82%) low parameter limit alarms were determined to be true. In the other study, 317 non-ICU patients had 17 243 RR alarms, 4104 (24%) were high and 13 139 (76%) were low parameter limit alarms.[6] The majority of the high parameter limit alarms (3404; 82%) occurred when the RR alarm setting was >30 breaths/min. However, the number of alarms decreased when the high parameter limit was increased to >35 breaths/min (15%), >40 breaths/min (2%), and >45 breaths/min (0.29%). Likewise, the vast majority of the low parameter limit alarms occurred when the RR alarm setting was <12 breaths/min to >10 breaths/min (94%) and very few (0.22%) occurred when the alarm setting was <7 breaths/min. Although our absolute number of RR parameter limit alarms was higher because of our longer monitoring time, we also used the most sensitive high parameter limit setting (>30 breaths/min), similar to Burgess et al.[6] Therefore, it is not surprising that we found high rates for this particular RR alarm. Additionally, the low RR parameter limit setting in our study (<5 breaths/min) was found to be the least sensitive setting in the study by Burgess et al.[6] The RR parameter limit alarm settings used at our hospital (<5 breaths/min and >30 breaths/min), while outside of the "normal" RR range (<12 breaths/min and >20 breaths/min), are similar to those used in other ICUs in the United States. In a survey of 17 US hospitals, RR parameter limit alarms (low and high) ranged from 5 breaths/min to 50 breaths/min.[19] These settings are largely based on research showing that RR alarms are frequent when using <12 breaths/min and >30 breaths/min as limits.[6,20-23] Additional research is warranted to determine optimal RR alarm limit settings for ICU patients that ensure patient safety. Algorithm-based solutions should also be explored. For example, alarm parameter limit settings that adapt to an individual patient's RR or that use RR trends over time could guide alarm settings and identify subtle or dynamic RR changes over time, which might identify early warning signs of respiratory compromise.

Patients treated in the cardiac or neurological ICU have higher RR alarm rates than patients in the medical/surgical ICU.

Another important consideration is problems with the IP method. For example, prior research shows that cardiac artifact can lead to overcounts of respirations.[24,25] Cardiac artifact occurs when pulsatile volume in the aorta is identified by the IP method as respiration, which results in an RR similar to the patient's heart rate. Thus, RR alarms due to cardiac artifact cannot be solved by changing alarm settings. Importantly, patients with a RR of >24 breaths/min are more likely to have a serious in-hospital event.[26] Therefore, making adjusting alarm limits to >30 breaths/min in order to reduce high parameter limit RR alarms may be harmful in patients with respiratory compromise.

In terms of apnea alarms, our median number of alarms per patient (11; IQR, 2-41) was higher than that reported in 2 previous studies. In the study by Gross et al,[9] the median numbers of both true and false apnea alarms were reported (2.6 true per patient; 4.7 false per patient),which if combined are still less than our median number of apnea alarms. In the study by Wiklund et al,[13] investigators reported a median of 2.7 apnea alarms but did not distinguish between true versus false apnea alarms. Because we did not annotate our apnea alarms, we were unable to report the number of true versus false apnea alarms. The reason our apnea alarm rate was higher than those reported in these 2 studies is most likely because we used a more sensitive apnea alarm setting (no breathing ≥20 seconds vs >30 seconds[9]), had a longer monitoring time (48 000 hours versus 1040 hours[9]), used different monitors, and assessed an ICU population.[9,13] It is worth noting that apnea is associated with sleep-disordered breathing (ie, sleep apnea),[27,28] which may have accounted for some of the apnea alarms in our study. However, we were unable to evaluate the number of patients with a history of sleep-disordered breathing because this is not consistently assessed in hospitalized patients.

The duration of alarms varied by type. Low parameter limit alarms had the highest median duration (20 seconds), followed by apnea alarms (16 seconds) and high parameter limit alarms (8 seconds). Because most of the alarms were of short duration, the alarms were most likely due to artifact or signal quality problems. In a study from University of California, San Francisco that evaluated physiologic monitor alarms,[8] of the more than 2.5 million alarms identified, 32% were technical alarms (eg, artifact, lead off, lead fail), which could interrupt the IP signal. This problem might be solved by using an alarm delay in the configuration setting. Of note, prior studies found a reduction in ECG arrhythmia alarms when skin

electrodes were changed daily.[29-31] Although this strategy was implemented to reduce arrhythmia alarms, it is possible that this intervention may improve IP signal quality and reduce RR alarms. This hypothesis warrants further investigation.

The median number of minutes the patient was in alarm condition during the ICU monitoring period varied by RR alarm type. The median value reported is cumulative (multiple alarms), rather than related to a single alarm. High parameter limit alarms had the longest median number of minutes (19.6 minutes), followed by apnea alarms (4.3 minutes), then low parameter limit alarms (2.6 minutes). These findings show that nurses will spend most of their time evaluating high parameter limit alarms, which can distract from patient care. Because we did not annotate the RR alarms as true versus false, it is unknown if the alarms were in fact related to respiratory compromise. A future study evaluating true versus false RR events is needed. Current IP algorithms are limited in that only one ECG lead is used (typically lead I or II), rather than multiple leads, and is predetermined as a default setting. Although the nurse can change the ECG lead used for derived IP RRs, these extra steps disrupt workflow. Algorithms that can automatically search for the best ECG lead(s) to use for an IP signal may improve this problem.[8]

We hypothesized that demographic and/or clinical characteristics associated with ECG arrhythmia alarms would be associated with RR alarms. In the multivariate analysis, for all alarm types, ICU monitoring time was associated with a higher number of alarms. Although this finding is not surprising, it highlights a group of patients who may have high alarm rates. Alarm management strategies should incorporate an evaluation of both length of stay and skin electrode integrity to ensure an optimal IP signal. Across all 3 alarm types, the cardiac or neurological ICUs were associated with higher alarm rates than the medical/surgical ICU. The reason for this finding is not entirely clear. In our prior studies,[8,15,32] cardiac ICU patients had a higher number of arrhythmia alarms due to ECG abnormalities (eg, bundle branch block, pacemaker artifact, low-amplitude QRS). However, given that these ECG abnormalities would not affect the IP signal, they are not likely to be the source of RR alarms. The association between the neurological unit and higher numbers of alarms may be related to changes in cognitive functioning in these patients. The fact that 42.7% of the patients in our study were in the neurological ICU and had cognitive impairment supports this hypothesis.

For low parameter limit alarms, male sex, undergoing mechanical ventilation, and not having a VAD and/or a pacemaker were associated with a higher median number of alarms. For apnea alarms, male sex and not having a VAD and/or a pacemaker were associated with a higher median number of alarms. It is worth noting that male sex was associated with both low parameter limit and apnea alarms, which are mechanistically similar (ie, slow, no breathing). In one study,[33] researchers found that men accumulated more fluid in their torso after changing from a lying to a supine position than women did. Results of several studies indicated that ICU patients receiving mechanical ventilation accumulated excess fluid because of fluid resuscitation.[34-36] Accumulation of fluid in the lungs decreases bioimpedance and thus the IP signal,[37,38] and this may explain these associations.

ICU nurses will spend most of their time addressing high parameter RR alarms.

With regard to VADs and/or pacemakers, we hypothesized that these devices would affect the IP signal because of electrical interference.[39] However, we found the opposite. This finding should be interpreted with caution because of the small number of patients with VADs and/or pacemakers in our sample.

We were somewhat surprised that we observed no associations between BMI and RR alarms. In one study, investigators found that higher BMIs decrease chest wall compliance,[14] which we hypothesized would affect the IP signal. However, BMI was not a factor associated with RR alarms.

Limitations

Several limitations warrant consideration. Although we provide new information on the number and types of RR alarms, we did not annotate the RR alarms as true or false. Therefore, the clinical significance of our findings (ie, true RR alarms) warrants further investigation. Because only 1 vendor's monitor was used, we do not know if our findings are generalizable to other manufacturers that use the IP method. This study was underpowered to examine the association of RR alarms with VADs and/or pacemakers because of the small number of patients with these devices. In addition, we could not reliably evaluate patients for sleep-disordered breathing, which could affect low parameter limit and apnea alarms, because this diagnosis is not always noted in the health history and has not been diagnosed in some patients. Finally, from

our data, we were unable to examine whether a nurse changed the default IP detection lead from lead II (default) to lead I. Therefore, we are unable to report whether an IP lead change increased or decreased RR parameter limit and/or apnea alarms. Despite these limitations, our study represents the most comprehensive evaluation of RR alarms in a consecutive sample of ICU patients done to date.

Conclusions

This study shows that RR parameter limit and apnea alarms are a frequent occurrence. In this study, high parameter limit alarms are the most common alarm. In addition, this study provides new information on demographic (male sex) and clinical (mechanical ventilation, not having a VAD and/or pacemaker, ICU monitoring time, being in a cardiac or neurological ICU) characteristics associated with RR alarms.

To address frequent RR alarms, clinicians should first carefully assess the patient's RR using visual assessment coupled with oxygen saturation levels (Spo_2) to ensure that respiratory compromise is not present (eg, bradypnea, tachypnea). If respiratory compromise is ruled out, widening alarm settings for individual patients may be indicated after thoughtful consideration by the care team. The demographic and clinical characteristics identified in this study, though not modifiable, could explain why select patients may have more frequent RR alarms. In these patients, as previously mentioned, visual assessment should be done to confirm the RR. Bedside clinicians should ensure that the IP signal is optimal (ie, skin electrode contact used for IP RR), which might improve the signal quality used for RR detection.

Future studies are needed to validate true vs false IP-derived RR alarms using visual assessment.

Prospective studies are needed that compare visual assessment of RR with information obtained using IP to guide clinical solutions (ie, skin electrodes, patient factors, device interference) and alarm management strategies. In future studies, researchers should examine true versus false IP RR alarms to facilitate algorithm improvements to enhance the sensitivity and specificity of RR detection.

FINANCIAL DISCLOSURES
The research was supported by an endowment from the Ghana Education Trust Fund (GETFUND) and by the University of California, San Francisco School of Nursing Lipps Research Fund.

SEE ALSO

For more about alarm management visit the *Critical Care Nurse* website, **www.ccnonline.org**, and read the article by Gorisek et al, "An Evidence-Based Initiative to Reduce Alarm Fatigue in a Burn Intensive Care Unit" (August 2021).

REFERENCES
1. Cooper S, Cant R, Sparkes L. Respiratory rate records: the repeated rate? *J Clin Nurs.* 2014;23(9-10):1236-1238.
2. Evans D, Hodgkinson B, Berry J. Vital signs in hospital patients: a systematic review. *Int J Nurs Stud.* 2001;38(6):643-650.
3. Rolfe S. The importance of respiratory rate monitoring. *Br J Nurs.* 2019;28(8):504-508.
4. Gupta AK. *Respiration Rate Measurement Based on Impedance Pneumography.* Application Report. February 2011. Texas Instruments Inc; 2011. Accessed May 26, 2022. https://www.ti.com/lit/an/sbaa181/sbaa181.pdf
5. Redmond C. Transthoracic impedance measurements in patient monitoring analog devices. Accessed August 30, 2021. https://www.analog.com/media/en/technical-documentation/tech-articles/MS-2458_Thoracic-ADAS1000-FINAL.PDF
6. Burgess LP, Herdman TH, Berg BW, Feaster WW, Hebsur S. Alarm limit settings for early warning systems to identify at-risk patients. *J Adv Nurs.* 2009;65(9):1844-1852.
7. Cvach M. Monitor alarm fatigue: an integrative review. *Biomed Instrum Technol.* 2012;46(4):268-277.
8. Drew BJ, Harris P, Zegre-Hemsey JK, et al. Insights into the problem of alarm fatigue with physiologic monitor devices: a comprehensive observational study of consecutive intensive care unit patients. *PLoS One.* 2014;9(10):e110274. doi: 10.1371/journal.pone.0110274
9. Gross B, Dahl D, Nielsen L. Physiologic monitoring alarm load on medical/surgical floors of a community hospital. *Biomed Instrum Technol.* 2011;Suppl:29-36.
10. Ruppel H, De Vaux L, Cooper D, Kunz S, Duller B, Funk M. Testing physiologic monitor alarm customization software to reduce alarm rates and improve nurses' experience of alarms in a medical intensive care unit. *PLoS One.* 2018;13(10):e0205901. doi:10.1371/journal.pone.0205901
11. Siebig S, Kuhls S, Imhoff M, Gather U, Scholmerich J, Wrede CE. Intensive care unit alarms--how many do we need? *Crit Care Med.* 2010;38(2):451-6.
12. Way RB, Beer SA, Wilson SJ. Whats that noise? Bedside monitoring in the Emergency Department. *Int Emerg Nurs.* 2014;22(4):197-201.
13. Wiklund L, Hok B, Stahl K, Jordeby-Jonsson A. Postanesthesia monitoring revisited: frequency of true and false alarms from different monitoring devices. *J Clin Anesth.* 1994;6(3):182-188.
14. Akashiba T, Akahoshi T, Kawahara S, et al. Clinical characteristics of obesity-hypoventilation syndrome in Japan: a multi-center study. *Intern Med.* 2006;45(20):1121-1125.
15. Harris PR, Zegre-Hemsey JK, Schindler D, Bai Y, Pelter MM, Hu X. Patient characteristics associated with false arrhythmia alarms in intensive care. *Ther Clin Risk Manag.* 2017;13:499-513.
16. Nguyen SC, Suba S, Hu X, Pelter MM. Double trouble: patients with both true and false arrhythmia alarms. *Crit Care Nurse.* 2020;40(2):14-23.
17. Suba S, Sandoval CP, Zegre-Hemsey JK, Hu X, Pelter MM. Contribution of electrocardiographic accelerated ventricular rhythm alarms to alarm fatigue. *Am J Crit Care.* 2019;28(3):222-229.
18. R Core Team. R: a language and environment for statistical computing. R Foundation for Statistical Computing. Accessed August 30, 2021. https://www.R-project.org/
19. Association for the Advancement of Medical Instrumentation. *Clinical Alarm Managemet Compendium.* 2015:1-68. Accessed May 26, 2022. https://www.aami.org/docs/default-source/foundation/alarms/alarm-compendium-2015.pdf
20. Cvach M, Kitchens M, Smith K, Harris P, Flack MN. Customizing alarm limits based on specific needs of patients. *Biomed Instrum Technol.* 2017;51(3):227-234.

21. Cvach M, Rothwell KJ, Cullen AM, Nayden MG, Cvach N, Pham JC. Effect of altering alarm settings: a randomized controlled study. *Biomed Instrum Technol.* 2015;49(3):214-222.
22. Cvach MM, Currie A, Sapirstein A, Doyle PA, Pronovost P. Managing clinical alarms: using data to drive change. *Nurs Manage.* 2013;44(11 Safety Solutions):8-12.
23. Bonafide CP, Brady PW, Daymont C. Physiologic monitor alarms for children: pushing the limits. *J Hosp Med.* 2016; 11(12):886-887.
24. Peng ZY, Critchley LA, Fok BS. An investigation to show the effect of lung fluid on impedance cardiac output in the anaesthetized dog. *Br J Anaesth.* 2005;95(4):458-464.
25. Seppa VP. Assessment of breating parameters during running with a wearable bioimpedance device. Tampere University of Technology. 2014. Accessed May 27, 2022. http://urn.fi/URN:ISBN:978-952-15-3437-9
26. Cretikos MA, Bellomo R, Hillman K, Chen J, Finfer S, Flabouris A. Respiratory rate: the neglected vital sign. *Med J Aust.* 2008;188(11):657-659.
27. World Health Organization. Cardiovascular Diseases Fact Sheet. Accessed May 27, 2022. http://www.who.int/mediacentre/factsheets/fs317/en/
28. Javaheri S, Barbe F, Campos-Rodriguez F, et al. Sleep apnea: types, mechanisms, and clinical cardiovascular consequences. *J Am Coll Cardiol.* 2017;69(7):841-858.
29. Cvach MM, Biggs M, Rothwell KJ, Charles-Hudson C. Daily electrode change and effect on cardiac monitor alarms: an evidence-based practice approach. *J Nurs Care Qual.* 2013; 28(3):265-271.
30. Dandoy CE, Davies SM, Flesch L, et al. A team-based approach to reducing cardiac monitor alarms. *Pediatrics.* 2014;134(6): e1686-94. doi:10.1542/peds.2014-1162
31. Turmell JW, Coke L, Catinella R, Hosford T, Majeski A. Alarm fatigue: use of an evidence-based alarm management strategy. *J Nurs Care Qual.* 2017;32(1):47-54.
32. Pelter MM, Fidler R, Hu X. Research: association of low-amplitude QRSs with false-positive asystole alarms. *Biomed Instrum Technol.* 2016;50(5):329-335.
33. Yadollahi A, Singh B, Bradley TD. Investigating the dynamics of supine fluid redistribution within multiple body segments between men and women. *Ann Biomed Eng.* 2015; 43(9):2131-2142.
34. Wiedemann HP, Wheeler AP, Bernard GR, et al; National Heart, Lung, and Blood Institute Acute Respiratory Distress Syndrome Clinical Trials Network. Comparison of 2 fluid-management strategies in acute lung injury. *N Engl J Med.* 2006;354(24):2564-2575.
35. Payen D, de Pont AC, Sakr Y, et al. A positive fluid balance is associated with a worse outcome in patients with acute renal failure. *Crit Care.* 2008;12(3):R74.
36. Slobod D, Yao H, Mardini J, et al. Bioimpedance-measured volume overload predicts longer duration of mechanical ventilation in intensive care unit patients. Article in French. *Can J Anaesth.* 2019;66(12):1458-1463.
37. Shochat M, Charach G, Meyler S, et al. Internal thoracic impedance monitoring: a novel method for the preclinical detection of acute heart failure. *Cardiovasc Revasc Med.* 2006;7(1):41-45.
38. Webster JG. Bioimpedance in cardiovascular medicine. In: Sons W, ed. *Encyclopedia of Medical Devices and Instrumentation.* 2nd ed. Wiley & Sons; 2006:63-110.
39. Watanakeeree K, Suba S, Mackin LA, Badilini F, Pelter MM. ECG alarms during left ventricular assist device (LVAD) therapy in the ICU. *Heart Lung.* 2021;50(6):763-769.

CE 1.0 Hour Category A

Notice to CE enrollees:

This article has been designated for CE contact hour(s). The evaluation demonstrates your knowledge of the following objectives:

1. Identify 3 types of impedance pneumography (IP) alarms.
2. Describe the most common type of IP alarm.
3. Describe 1 patient, 1 clinical factor, and 1 intensive care unit factor associated with IP alarms.

To complete the evaluation for CE contact hour(s) for activity A223153, visit https://aacnjournals.org/ajcconline/ce-articles. No CE fee for AACN members. See CE activity page for expiration date.

Supplemental Table

Occurrence rates of high and low parameter limit and apnea alarms by demographic, clinical characteristics, supportive therapies, and ICU type in 461 ICU patients

Characteristic	No. of patients	No. of high RR parameter alarms (≥30/min), median (IQR)	*P*	No. of low RR parameter alarms (≤5/min), median (IQR)	*P*	No. of apnea alarms (no breath ≥20 s) median (IQR)	*P*
Age, y			.07		.33		.58
18-34	42	75 (31-169)		6 (0-21)		11 (2-29)	
35-49	86	80 (20-318)		6 (1-26)		10 (1-42)	
50-64	138	120 (37-305)		5 (1-24)		13 (3-50)	
65-79	136	83 (42-247)		6 (1-16)		10 (2-41)	
≥80	59	127 (51-236)		4 (1-16)		12 (2-38)	
Sex			>.99		.18		.06
Male	250	88 (34-263)		6 (1-20)		12 (3-41)	
Female	211	97 (38-265)		5 (1-22)		9 (1-42)	
Body mass index[a]			.67		.02[b]		.13
<25	181	81 (35-205)		6 (1-16)		10 (3-30)	
25-29	131	95 (39-230)		4 (1-18)		11 (2-44)	
≥30	144	130 (40-328)		7 (1-30)		14 (2-54)	
Race			.65		.50		.63
White	269	94 (35-260)		6 (1-20)		12 (2-42)	
Not White	192	96 (38-282)		5 (1-22)		11 (2-40)	
Smoking status			.92		.15		.28
Current smoker	71	97 (34-324)		4 (1-14)		8 (2-27)	
Nonsmoker	390	94 (38-245)		6 (1-22)		12 (2-43)	
Cognitive impairment or confusion			<.001		.30		.11
Yes	198	126 (43-344)		8 (1-28)		18 (4-54)	
No	263	77 (35-198)		4 (0-16)		7 (1-30)	
Body tremor (eg, Parkinson disease, alcohol/nicotine withdrawal, other neurological condition, shivering)			.56		.46		.18
Yes	36	143 (65-302)		6 (1-16)		11 (4-32)	
No	425	92 (37-264)		5 (1-21)		11 (2-42)	
Mechanical ventilation			<.001		<.001		<.001
Yes	178	146 (51-483)		14 (4-42)		25 (7-64)	
No	283	73 (34-196)		2 (0-10)		6 (1-26)	
Ventricular assist device or pacemaker			<.001		.18		.03
Yes	34	191 (66-622)		6 (2-20)		19 (3-42)	
No	427	92 (37-247)		6 (1-21)		11 (2-41)	
ICU type			<.001		<.001		<.001
Cardiac	83	150 (44-488)		6 (1-21)		21 (3-60)	
Medical surgical	181	95 (37-206)		4 (0-16)		8 (1-39)	
Neurological	197	84 (37-230)		8 (2-41)		12 (2-35)	

Abbreviations: ICU, intensive care unit; RR, respiratory rate.

[a] Calculated as weight in kilograms divided by height in meters squared. Data were missing for 5 patients.

[b] Tukey honestly significant difference post hoc analysis for low RR: BMI <25 and ≥30 differ at *P*=.02. No difference in BMI <25 versus 25-29, *P*=.82; and 25-29 versus ≥30, *P*=.13.