The Occurrence Rate and Types of Technical Alarms During Continuous ECG Monitoring in the Intensive Care Unit and its Potential Contribution to Alarm Fatigue

by

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Contributions

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The Occurrence Rate and Types of Technical Alarms during Continuous Electrocardiographic Monitoring in the Intensive Care Unit and its Potential Contribution to Alarm Fatigue

Mark Tungol

Abstract

Background: While continuous electrocardiographic (ECG) monitoring in the Intensive Care Unit (ICU) is an important assessment device, technical alarms (i.e., artifact, arrhythmia suspend, and leads off) are frequent and can contribute to alarm fatigue in nurses. For example, we found that of >2.5 million total alarms generated during a one month period, 30% were technical alarms. **Purpose**: Examine the number and type of technical alarms (described below) and demographic and clinical factors associated with these alarms. **Methods**: Secondary analysis in 456 consecutive ICU patients with 48,173 hours of continuous ECG monitoring. Technical alarms examined: (1) artifact (noisy signal); (2) ECG leads off/fail (no ECG signal); and (3) arrhythmia suspend (no arrhythmia detection [software off] due to sustained artifact ≥20 seconds in the prior 30 seconds). Demographics (age, gender, race), ICU type (cardiac, medical/surgical, or neurological), clinical characteristics hypothesized to increase technical alarms (BMI, current smoker, cognitive impairment, tremor) and mechanical ventilation were obtained from the electronic health record. A negative binomial GLM regression model was used to evaluate both univariate and multivariate associations. **Results**: Among the 456 adult ICU patients, 208 (46%) were female and the mean age (years) was 60 ± 17. Admitting ICU was as follows: 18% cardiac (n=83), 39% medical/surgical (n=180), and 43% neurological (n=198). Mean ICU length of stay was 98.54 hours (±121). Mean BMI was 28.1 ± 8; 69 (15%) were current smokers; 195 (43%) had cognitive impairment; 35 (8%) had a tremor and 170 (39%) were treated with mechanical ventilation. There was a total of 572,763 technical alarms, 557,018 artifact (97.3%), 3,378 arrhythmia suspend (0.59%) and 12,367 ECG leads fail (2.2%). Fifty-eight percent of artifact alarms, and more than 60% of arrhythmia suspend and ECG leads fail alarms were two seconds in duration. Patients who were current smokers at admission were more likely to have artifact and arrhythmia suspend alarms (p<0.018). Having a tremor was associated with all three types of technical alarms (p<0.001). Documented cognitive impairment was associated with arrhythmia suspend and ECG leads fail alarms (p<0.018). Being treated with mechanical ventilation was associated with fewer alarms for all three types of technical alarms (p=0.047). There was an association between being Native Hawaiian/Pacific Islander and experiencing ECG lead fail alarms (p=0.039). **Conclusions/Implications for Practice**: The vast majority of technical alarms were for artifact. Arrythmia suspend (software off) due to sustained artifact was uncommon. However, the mean time patients were in this technical alarm condition was 10 minutes, which in ICU patients could be clinically significant. Individual alarms lasted only seconds, which suggests that technical alarms are too sensitive and should be re-designed with a delay (e.g., 5 minutes) before alarming. Patients who were current smokers at admission were more likely to have artifact and arrhythmia suspend alarms. Having a tremor was associated with all three types of technical alarms. Documented cognitive impairment was associated with arrhythmia suspend and ECG leads fail alarms. Whereas, being treated with mechanical ventilation was protective (fewer alarms) for all three types of technical alarms. Patients with these features may require more guided alarm management strategies.

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List of Abbreviations

CI = confidence interval

ECG = electrocardiography

ICU = intensive care unit

IQR = interquartile range

IRB = Institutional Review Board

IRR = incidence rate ratio

kg = kilogram

LVAD = left ventricular assist device

m2 = meters squared

n = number

QI = quality improvement

SD = standard deviation

Introduction

Hospital-based electrocardiographic (ECG) monitors are configured to alarm for a number of different type of arrhythmias, ST-segment changes, and QT interval length, that are designed to alert busy nurses.[1] However, accurate detection of ECG abnormalities/features requires a clean signal. Most ECG devices include technical and/or inoperative alarm algorithms that are designed to notify and inform the nurse when a specific signal quality issue arises to minimize monitoring interruptions. For example, one type of technical alarm is ECG lead off (single or multiple) or ECG leads fail (no signal) that inform the nurse to replace either the skin electrode(s) and/or the lead wire(s). Technical alarms can be configured to either generate an alarm sound (e.g., warning, continuous foghorn tone), or as an inaudible text message alert that flashes on the bedside monitoring screen.[1] While there are no established guidelines for optimal alarm settings, technical alarms for artifact (noisy signal), or when a single ECG lead is off, are typically configured as inaudible text message alerts (flash text on the bedside monitor), thus do not need to be silenced by the nurse. In general, inaudible text is selected for these types of alarms because there is still an ECG signal present; thus, arrythmia detection is maintained. Many hospitals choose to configure some more important technical alarm types using an audible alarm configuration to ensure that a clean ECG signal is established promptly. For instance, when more than one ECG lead is off, or there is an extended period of time in a technical alarm condition (sustained artifact), an audible alarm is used since both of these types of technical issues may turn off, or “suspend” arrhythmia detection software and an arrhythmia could be missed.

While technical alarms (i.e., artifact, ECG lead(s) fail, ECG lead(s) off) are designed to ensure optimal ECG signal quality for arrhythmia detection, these types of alarms are extremely common and can contribute to alarm fatigue in nurses. In a comprehensive one-month ECG alarm study in 461 intensive care unit (ICU) patients, of the more than 2.5 million total alarms generated, 32% (791,632) were technical alarms.[1] Alarm fatigue associated with bedside ECG and physiologic (vitals sign) monitors can create the following unsafe situations in patient care: (1) inadvertently ignoring alarms due to desensitization (i.e., alarm noise is assimilated into a nurses' workflow); (2) lowering the volume of alarms to reduce patient and family stress from alarm noise; (3) completely silencing alarms; and/or (4) delayed response to alarms.[2] Additionally, nurses often experience overload in various forms during their work (e.g., cognitive and physical), which is further compounded by ECG device related alarm fatigue.[3]

Alarm fatigue, and the related responses, set the stage for a major patient safety issue, which has devastating effects on both nurses and patients. Alarm fatigue has been associated with over 650 hospital deaths,[4, 5] and in a retrospective study from 2011, there were 216 patient deaths linked to issues with alarm fatigue.[6] Importantly, these data are dated and because few substantive interventions have been introduced to solve alarm fatigue, morbidity and mortality is likely much higher.

There have been several hospital-based studies that have evaluated technical alarms generated from ECG monitors.[1, 7-12] One observational study conducted in adult ICU patients, showed that 32% (791,632) of more than 2.5 million total alarms were technical alarms and the vast majority (358,277) were for artifact followed by single ECG lead fail (90,547).[1] Technical alarms for arrhythmia suspend and ECG leads off (no signal) were not reported. In a subsequent secondary data analysis from this study, artifact, ECG leads off/fail and arrhythmia suspend were reported in ICU patients with a left ventricular assist device.[10] Artifact was the most common technical alarm (96%) followed by ECG leads fail (3.5%) then arrhythmia suspend (0.5%). Of the remaining studies, technical alarms were examined at pre- and post-quality improvement (QI) project implementation[7-9, 11] and one examined alarm rates when using disposable versus non-disposable ECG lead wires.[12] Two studies examined both artifact and ECG leads off/fail alarms[11,12], two examined both ECG leads off and arrhythmia suspend[7,9] and one examined only ECG leads off.[8] To our knowledge, no study has examined specific technical alarm types in a comprehensive manner (i.e., types, duration, possible patient/clinical factors). A more extensive analysis of technical alarms for these characteristics may help guide hospital-based alarm management strategies and inform monitoring manufacturers on needed improvements to technical alarm algorithms used in bedside ECG monitors.

Purpose

The purpose of this study was twofold: (1) examine the number, type, and duration of technical alarms for: artifact; arrhythmia suspend, and ECG leads fail, and (2) examine whether demographic (age, sex, race) factors, clinical features (body mass index, impaired cognitive status, tremor, smoking), mechanical ventilation, and/or ICU type (medical/surgical, neurological, cardiac) are associated with technical alarms.

Methods

Study Design

This was a secondary data analysis using data from a comprehensive one-month alarm study among a consecutive cohort of adult intensive care unit patients.[1] The occurrence rate, type, and clinical features hypothesized to increase the occurrence of technical alarms (described below) for artifact, arrhythmia suspend, and ECG leads fail were examined for this analysis. The Institutional Review Board (IRB) approved the study with a waiver of patient consent because the alarm data is captured in the background, did not interrupt patient care, and was analyzed retrospectively.

Sample and Setting

The primary study included 461 consecutive adult ICU patients with continuous ECG monitoring from three types of ICU's, including: cardiac (16 beds); medical/surgical (32 beds); and neurological (29 beds), at a large tertiary-quaternary medical center over a 31-day period. For this study, based on our prior work [1, 13-15] we hypothesized that BMI, being a current smoker, having cognitive impairment, a tremor, or mechanical ventilation would be associated with a higher rate of technical alarms. There were five patients (1.08%) who did not have BMI documented and were subsequently excluded, leaving 456 ICU patients available for analysis. Demographics including sex, age, race, and ethnicity were obtained from the electronic health record (EHR). Additionally, clinical features of interest (i.e., ICU type and variables hypothesized to increase technical alarms) and use of mechanical ventilation were also acquired from the EHR.

Alarm Data Capture System

Our data capture system has been described in detail previously.[1, 16] Briefly, all ECG and physiologic monitor waveforms (i.e., seven ECG channels [I, II, III, aVR, aVL, and aVF], arterial blood pressure, pulse oximetry [Sp02], impedance respirations), numeric vital signs, and alarm types (both audible and inaudible) were acquired via a secure data capture system. Data were downloaded to a secure research server approved by our hospital and were extracted into Extensible Markup Language (XML) files for analysis.

Technical Alarm Types

Technical alarm types, called system status alarms by the vendor, we examined, included: (1) artifact (noisy signal); (2) arrhythmia suspend (no arrhythmia detection [software off] due to sustained artifact >20 seconds in the prior 30 seconds); and (3) ECG leads fail (no discernable ECG waveform displayed). **Figure 1** shows the type of technical alarms examined as well as a clean signal ECG. Technical alarms greater than 20 minutes in duration were excluded as we assumed that this likely indicated that the patient was not being monitored (e.g., procedure on/off unit, bathing etc.), but the monitor had not been paused. Alarms for artifact were configured in the bedside monitor as an inaudible text message alert. In this alarm condition, “full” arrhythmia processing is suspended while the lethal arrhythmia algorithm is still active. However, its accuracy may be hindered by the artifact. Alarms for arrhythmia suspend and ECG leads (plural) fail were configured as an audible warning alarm. In these alarm conditions, a repeating foghorn tone sounds, and arrhythmia analysis is suspended until the technical alarm condition is resolved.

Data Analysis

Descriptive statistics were used to describe sample demographics, factors hypothesized to increase the rate of technical alarms, ICU type, length of ICU stay (hours), and frequency and duration of each technical alarm. Descriptive statistics are reported as frequencies for categorical variables and mean ± standard deviation (SD) for normally distributed continuous variables. Data were tabulated in the overall sample and grouped based on the type of technical alarm.

For the statistical analysis, we used medians and interquartile ranges (IQRs) due to the high variability (i.e., one patient could have one while another patient could have hundreds or thousands) in the number of technical alarms generated by patients. Because of this, the following approach was used: (1) occurrence rates for each alarm type were calculated per 10 hours of monitoring; (2) median and 25^{th} and 75^{th} percentiles of the distribution were weighted by monitoring time, and (3) a chi-square test was used to test for deviance of the binomial GLM, where a p-value of <0.05 was used to determine statistical significance. We used a negative binomial GLM regression model to evaluate both univariate and multivariate associations because of the high proportion of patients who did not experience any of the alarm types during the study period. Here, the goal was to identify variables that were significant in the univariate analysis for inclusion in the multivariate analysis. For the multivariate analysis, any variable that was statistically significant in the univariate analysis for any of the technical alarm types was kept in the model.

Results

Entire Sample

As shown in **Table 1**, among the 456 adult ICU patients, 211 (46%) were female and the mean (± SD) age was 60 ± 17 years. Race was consistent with that seen in the San Francisco Bay Area: 74 (17%) Asian, 35 (8%) Black, or African American, 8 (2%) Native Hawaiian, or Pacific Islander, 278 (61%) White, and 61 (13%) were unable to report race due to critical illness. The highest proportion of patients were admitted to the neurological ICU (43%), followed by the medical surgical ICU (39%) then cardiac ICU (18%), which reflects the bed capacity in each unit. The overall mean ICU length of stay was 98.54 ± 121 hours (median (IQR); 51 [26-113] hours. For the variables hypothesized to be associated with technical alarms: mean BMI was 28.1 ± 8; 69 (15%) patients were current smokers; 195 (43%) had cognitive impairment; 35 (8%) had a tremor; and 179 (39%) were treated with mechanical ventilation. The total number of technical alarms was 572,763. Of the total, 557,018 (97%) were artifact alarms, 3,378 (0.6%) were arrhythmia suspend alarms, and 12,367 (2.2%) were ECG leads fail.

Patient Characteristics by Alarm Type

Each technical alarm type was compared by patient demographics, ICU type, clinical features, and mechanical ventilation as illustrated in **Table 2**. All but 5 (*n*=451, 99%) patients generated one or more artifact alarms, 233 (52%) arrhythmia suspend alarms and 438 (97%) ECG leads fail alarms. It's important to note that a single patient could have more than one type of technical alarm. Patients in either the medical surgical or neurological ICUs had the highest proportion of alarms as compared to the cardiac ICU, which again likely reflects the number of beds in each unit.

The proportion of the three technical alarm types compared by, age, sex, ethnicity, race, ICU type, BMI, current smoker, cognitive impairment, tremor, and mechanical ventilation were equivalent (**Table 2**). Due to high variability in the number of technical alarms, the median values are discussed here and were used in the statistical analysis described below. Median ICU monitoring hours was longest in the patients with arrhythmia suspend alarms (91 hours), followed by ECG leads fail (53 hours), then artifact (51 hours). The highest median number of alarms was for artifact (363), followed by ECG lead fail (9), then arrhythmia suspend (4). The median time in an alarm condition was highest for artifact (19:20 min/sec), followed by ECG leads fail (9:26 min/sec), then arrhythmia suspend (2:06 men/sec).

Duration of Technical Alarms

The mean time (minutes:seconds) for artifact, arrhythmia suspend, and ECG leads fail were 67:35, 10:09, and 19:42, respectively. Most of technical alarms were two seconds in length, specifically, 58% (n=323,070) of the artifact alarms, 60.5% (n=2,044) of arrhythmia suspend alarms and 64% (n=7,915). Each type of technical alarm was categorized into duration time frames using the following categories: two seconds to <five minutes; five minutes to <10 minutes; and 10 minutes to <15 minutes. As shown in **Table 3**, 99% of all of the technical alarm types were in the two seconds to <five-minute category.

Univariate and Multivariate Analysis

Artifact. In the univariate analysis, being a current smoker and having a tremor were associated with higher rates of artifact alarms. Not being treated with mechanical ventilation was associated with a higher rate of artifact alarms (**Table 4**). **Figure 2** shows a forest plot of the multivariate analysis. Being a current smoker and having a tremor remained significant predictors of artifact alarms. Patients being treated with mechanical ventilation were less likely to have as many artifact alarms compared to patients who were not being treated with mechanical ventilation. All of the other variables included were not significant.

Arrhythmia Suspend. In the univariate analysis, being a current smoker, having cognitive impairment and having a tremor were associated with higher rates of arrhythmia suspend alarms. Whereas not being treated with mechanical ventilation was associated with a higher rate of arrhythmia suspend alarms (**Table 5**). **Figure 2** shows a forest plot of the multivariate analysis. Being a current smoker, having cognitive impairment and having a tremor remained significant predictors of arrhythmia suspend alarms. Whereas, being treated with mechanical ventilation was protective. All of the other variables included were not significant.

ECG Leads Fail. In the univariate analysis, age, race and having a tremor were associated with higher rates of ECG leads fail alarms. Being a current smoker, having cognitive impairment and treatment with mechanical ventilation were not significant (**Table 6**). **Figure 2** shows a forest plot of the multivariate analysis. The race categories of Native Hawaiian/Pacific Islander and unknown race (patient unable to state due to acute illness) were significant predictors of ECG lead fails alarms. In addition, being treated in the cardiac ICU, having cognitive impairment, and having a tremor remained significant predictors of ECG leads fail alarms. Whereas, being treated with mechanical ventilation was protective. All of the other variables included were not significant.

Discussion

To our knowledge, this is the first study to examine factors associated with three types of technical alarms, specifically artifact, arrhythmia suspend, and ECG leads fail, in 456 consecutive ICU patients. Artifact represented the vast majority of alarms, 97%, followed by ECG leads fail, 2.2%, then arrhythmia suspend, 0.5%. Fifty-eight percent of artifact alarms, and more than 60% of arrhythmia suspend and ECG leads fail alarms were two seconds in duration. Patients who were current smokers on admission were more likely to have artifact and arrhythmia suspend alarms. Having a tremor was associated with all three types of technical alarms. Documented cognitive impairment was associated with arrhythmia suspend and ECG leads fail alarms. Whereas, being treated with mechanical ventilation was protective (fewer alarms) for all three types of technical alarms. Being Native Hawaiian/Pacific Islander was associated with ECG lead fail alarms.

Artifact

Of seven prior published studies that we identified as relevant to compare with our study, artifact was reported in four.[1, 10-12] Two were associated with this secondary data analysis and report the same findings as our study (e.g., artifact was the most common type). Of the two remaining studies one did not report specifically on artifact alarms, rather grouped artifact with other types of alarms.[11] However, Albert et al., did report on artifact alarms.[12] In this study, artifact alarm rates were examined by ECG lead wire type (disposable versus reusable) in 1,611 unique cardiac telemetry unit patients with 2,330 admissions. They found that artifact alarms were the second most common type of technical alarm (ECG leads off/fail most common), which is different than our study where we found the artifact was by far the most common alarm. Their study included cardiac telemetry unit patients, whereas ours included ICU patients. This may suggest that cardiac telemetry unit patients are more susceptible to leads off/fail, which is not entirely surprising given that these patients are more mobile than ICU patients who are mostly in bed. It is worth noting that in their study, the rate of artifact versus ECG leads off/fail were similar (2,993 artifact versus 3,555), suggesting that both types are common. This study is interesting in that they showed that there were fewer artifact alarms in patients who had disposable ECG lead wires that were designed with a patented push-button feature. This study sheds light on one possible solution to reducing artifact alarms.

None of the studies examined patient level factors associated with artifact alarms; hence, our study offers new information. We found that patients who were current smokers at admission, or had a tremor were more likely to have artifact alarms. Our study shows that patients with these characteristics may need more focused alarm management strategies and/or treatment(s). For example, the effects of nicotine withdrawal may need to be treated (**Table 10**). Determining whether a tremor is part of the patient's history could be useful, or if new, may suggest untoward effects of medications (i.e., drug inducted Parkinson's) (**Table 10)**.[17, 18] Interestingly, being treated with mechanical ventilation was protective against artifact alarms. This is in contrast to prior studies our group have published showing that mechanical ventilation was associated with false arrhythmia and respiratory rate type alarms.[13, 14] Sedation during mechanical ventilation may be one explanation, but this finding needs further investigation.

Arrhythmia suspend

Of seven prior published studies that we identified as relevant to compare with our study, arrhythmia suspend was reported in three.[7, 9, 10] One was a secondary data analysis using our dataset that included only three patients with a left ventricular assist device. Arrhythmia suspend was the least common type, as was found in our study.

In a study by Cvach et al., arrhythmia suspend alarms were examined in a pre- and post-QI study assessing whether daily skin electrode changes reduced these types of alarms.[7] The investigators showed that this type of alarm decreased by 60% in the medical progressive care unit and 74% in the cardiology care unit following the intervention. This suggests that daily skin electrode changes may reduce this type of alarm. However, patient and/or clinical characteristics associated with this type of alarm were not reported.

In a study by Graham et al., arrhythmia suspend alarms were examined pre- and post-QI implementation focused on several initiatives (i.e., changing default settings, education on individualizing patient default settings, adjusting audible alarms, and a software modification) in the progressive care unit.[9] Prior to the intervention there were 634 arrhythmia suspend alarms and after the intervention they increased to 1,116. It is unclear why there were more of these types of alarms post-QI implementation, but overall alarm rates for a multitude of other alarm types were reduced post-QI implementation. One intervention used by the investigators was to adjust alarm settings (e.g., warning [foghorn tone] to an inaudible message) to reduce nuisance alarms (true but not actionable). However, it was not described whether arrhythmia suspend was adjusted in their study from a warning alarm to an inaudible message alert. If this adjustment was done, this may explain why there were more arrhythmia suspend alarms postintervention. For example, if there was not an alarm tone generated, the nurse would be less likely to solve this issue because it was set as an inaudible message alert. This type of technical alarm is generated when certain conditions are present, such as ECG leads off or in the case of the monitor in place during this study sustaining artifact >20 seconds in the prior 30 seconds. This indicates that arrhythmia analysis has been suspended (off) which has important clinical implications as an arrhythmia might be missed.

In our study, only 0.6% of the patients had this type of alarm and the mean and median time a patient was in this alarm condition was 10 minutes and 2 minutes respectively. The time within this alarm condition is significant as this may increase the risk for a missed arrhythmia event. We found that patients who were current smokers at admission, those with cognitive impairment, or a tremor were more likely to have this type of technical alarm (**Table 10**). Therefore, nurses should assess for these patient characteristics, and if indicated, consult with the care team on strategies to minimize the effects of these clinical features (i.e., nicotine withdrawal treatment) if possible. These types of patients may also benefit from daily skin electrode changes, which has been shown to reduce artifact that can create this type of alarm.[7, 11]

ECG Leads Fail

Contrary to artifact and arrhythmia suspend, all seven prior published studies that were relevant to compare to our study had measured ECG leads fail alarms.[1, 7-12] In the studies by Shue McGuffin et al. and Sendelbach et al., ECG leads fail alarms were measured, but grouped together with other types of technical alarms (e.g., no signal or telemetry battery low) or measured per day as a mean number of all ECG alarms.[8,11] These two studies implemented several tests of change but it’s not clear how these interventions specifically affected ECG leads fail alarm rates. Our study was designed to measure the occurrence rate of leads fail alarms which was found to be 2.2% (12,367) of all technical alarms. This type of data could be helpful in determining whether a reduction in lead fail/off alarms are due to various interventions proposed in previous studies.

Of note, two QI implementation projects had a specific focus on ECG leads fail/off alarms through several interventions including daily electrode changing, custom alarm parameters, software modification, and clinician education.[7,9] Both studies by Cvach et al. and Graham et al. demonstrated an increase in total lead fail alarms by 39 and 314, respectively.[7,9] In these instances, nurse susceptibility to alarm fatigue and exposure to audible alarms may have been reduced, but arrhythmia detection may also have been impacted. It's unclear whether this was a significant issue since the time in this alarm condition nor clinical features associated with this alarm condition were reported. Within our dataset, we found that documented cognitive impairment and a tremor were associated with ECG lead failure. The mean time within this alarm condition was almost 20 minutes, however, the vast majority of lead fail alarms were between 2 seconds to 5 minutes. These findings offer important evidence that these types of alarms are generated after only a short duration of time in this alarm condition. One solution may be to add a delay for these types of alarms in the configuration setting (**Table 10**). However, the optimal delay time needs further investigation to ensure patient safety.

In the study by Drew et al., 90,547 single lead fail alarms (inaudible message) occurred over a one-month timeframe.[1] It's important to note that ECG leads fail, which we report, will sound an audible foghorn tone. While their study only provided data for single ECG lead failure, our study showed that 99.4% of ECG lead failure alarms were between 2 seconds and 5 minutes in duration. Some of which are likely to be considered a nuisance and exacerbate the level of noise and possibly alarm fatigue within a busy ICU. In a secondary data analysis of this study in patients with an LVAD, there were 854 ECG lead fail alarms during a one month time period.[10] Even though this study provided valuable insight on a clinical feature that affected technical alarm rates in LVAD patients, generalizability is reduced since only three patients were examined.

ECG leads fail alarms can pose an increased risk for alarm fatigue and may compromise patient safety. A randomized study examining the difference in alarm events between disposable and reusable lead wires showed a decrease in total number of all false alarms (i.e. no telemetry, leads off/fail, artifact, and false crisis) when using disposable lead wires.[12] Non inferiority statistical analysis also demonstrated that disposable lead wires may be a reasonable approach as a potential solution for reducing technical alarms during continuous ECG monitoring.

Alarm Duration

For each type of technical alarm, the vast majority were found to be between two seconds and 5 minutes (99.2-99.4%). Duration of alarms between 5 minutes and 15 minutes was extremely uncommon (0.1-0.6%), which may suggest that current technical alarm algorithms are too sensitive and should be designed with a delay (**Table 10**). As previously discussed, our evidence shows that clinical features (e.g., current smoker, documented tremor, or cognitive impairment, etc.) are associated with higher incidence rates for certain types of technical alarms. Technical alarm thresholds should also be adjusted with the goal to reduce nuisance alarms caused by known clinical features from the patient's EHR (**Table 10**).

Limitations

Several limitations warrant consideration. While we provide new information on the number and types of technical alarms, we did not correlate technical alarms with a patient's status at the time of the alarm (i.e., bathing, changing electrodes, repositioning, tests at the bedside, etc.). This means the nurse may have been at the bedside with the patient and the alarm had minimal impact on alarm burden. Because only one vendor's monitor was used, we do not know if our findings are generalizable to other device manufacturers. The study's retrospective design did not allow us to evaluate how alterations in alarm settings would impact the number of alarms identified. Despite these limitations, our study represents the most comprehensive evaluation of technical alarms in a consecutive sample of ICU patients done to date.

Conclusions

The vast majority of technical alarms were for artifact. Arrythmia suspend (software off) due to sustained artifact was uncommon. However, the mean time patients were in this technical alarm condition was 10 minutes, which in ICU patients could be important since an arrhythmia could be missed during this time. Individual alarms lasted only seconds, which may indicate that technical alarms are too sensitive and should be re-designed with a delay (e.g., 5 minutes) before alarming. Patients who were current smokers at admission were more likely to have artifact and arrhythmia suspend alarms. Having a tremor was associated with all three types of technical alarms. Documented cognitive impairment was associated with arrhythmia suspend and ECG leads fail alarms. For all three types of technical alarms, patients being treated with mechanical ventilation were less likely to cause artifact alarms. Patients with these features may require more guided alarm management strategies.

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Table 1 Demographics and clinical features of the 456 adult intensive care unit patients with technical alarms during continuous ECG monitoring

Variable of Interest	n (%)
Demographics n=456	
Overall Age (mean ± SD, in years)	60 ± 17
Categories	
18 to 34	42 (9)
35 to 49	86 (19)
50 to 64	138 (30)
65 to 79	132 (29)
80 or older	58 (13)
Gender	
Female	208 (46)
Male	248 (54)
Ethnicity	
Hispanic	52 (11)
Non-Hispanic	396 (87)
Unable to state	8 (2)
Race	
Asian	74 (16)
Black or African American	35 (8)
Native Hawaiian or Pacific Islander	8 (2)
White	278 (61)
Unknown declined to state	61 (13)
Intensive Care Unit Type	
Cardiac (16 beds)	81 (18)
Medical Surgical (32 beds)	180 (40)
Neurological (29 beds)	195 (43)
Factors Hypothesized to Increase the Rate of Technical Alarms	
Body Mass Index (kg/m^2)	28.1 ± 8
Cognitive Impairment	195 (43)
Current Smoker	69 (15)
Mechanical Ventilation	179 (39)
Tremor	35 (8)
Intensive Care Unit Length of Stay (hours)	
Mean + SD	98.54 ± 121
Median (IQR)	51 (26 – 113)
Number and Type of Technical Alarm	
Total of All Types	**572,763**
Artifact	557,018 (97.3)
Arrhythmia Suspend	3,378 (0.59)
ECG Leads Fail	12,367 (2.2)

Table 2 Frequency of technical alarms in 456 ICU patients by type: artifact, arrhythmia suspend, and ECG leads fail compared by demographics, clinical features, ICU unit type and mechanical ventilation. Note: a patient could have more than one type of technical alarm.

Variable of Interest N=456 ICU Patients	**Artifact 557,018 Alarms 451 Patients n (%)**	**Arrhythmia Suspend 3,378 Alarms 233 Patients n (%)**	**ECG Leads Fail 12,367 Alarms 438 Patients n (%)**
Age (mean ± SD, in years)	60 ± 17	60 ± 18	59 ± 17
Sex (self-identified)			
Female	205 (46)	101 (43)	196 (45)
Male	246 (55)	132 (57)	242 (55)
Ethnicity			
Hispanic or Latino	52 (12)	27 (11)	51 (12)
Non-Hispanic	91 (86)	202 (86)	379 (86)
Unable to state	8 (2)	4 (2)	8 (2)
Race			
Asian	73 (16)	40 (17)	71 (16)
Black/African American	34 (8)	21 (9)	35 (8)
Native Hawaiian/Pacific Islander	8 (2)	5 (2)	8 (2)
White	275 (61)	138 (59)	264 (60)
Unable to state	61 (13)	29 (12)	60 (14)
ICU Type			
Cardiac (16 beds)	81 (18)	38 (16)	79 (18)
Medical/Surgical (32 beds)	178 (39)	98 (42)	175 (40)
Neurological (29 beds)	192 (43)	97 (42)	184 (42)
Variables Hypothesized to Increase rate of Technical Alarms			
Body Mass Index	28 ± 8	28 ± 8	28 ± 8
Current Smoker	68 (15)	36 (16)	65 (15)
Cognitive Impairment	193 (43)	118 (51)	189 (43)
Tremor	35 (8)	27 (12)	35 (8)
Mechanical Ventilation	178 (40)	104 (45)	177 (40)
Monitoring Hours in ICU			
Mean + SD	99 ± 121	144 ± 149	102 ± 123
Median	51	91	53
Minimum and Maximum	3 – 743	3 – 743	5 – 743
Number of Alarms			
Mean	1235 ± 2568	15 ± 31	28 ± 59
Median (IQR)	363 (138 – 1,160)	4 (2 – 4)	9 (4 – 28)
Minimum - Maximum	1 – 21,752	1 – 256	0 – 795
Time in Alarm Condition During ICU Monitoring (minutes:seconds)			
Mean + SD	67:35 ± 69	10:09 ± 26	19:42 ± 34
Median (IQR)	19:20 (6:42 – 60:39)	2:06 (0:34 – 9:03)	9:26 (3:09 – 22:56)

Table 3 Technical alarms in 456 intensive care unit patients grouped by duration categories

Technical Alarm Type	Duration Category		
	2 sec to <5 min	**5 min to <10 min**	**10 min to <15 min**
Artifact 557,018 Alarms	552,561 (99.2)	3,343 (0.6)	1,114 (0.2)
Arrhythmia Suspend 3,378 Alarms	3,358 (99.4)	17 (0.5)	3 (0.1)
ECG Leads Fail 12,367 Alarms	12,293 (99.4)	50 (0.4)	24 (0.2)

Table 4 Occurrence rates of technical alarms for artifact by demographic, ICU type and factors hypothesized to increase the number of technical alarms in 456 ICU patients
[1]Rate is per 10 hours of monitoring.
[2]Median and 25th and 75th percentiles of the distribution are weighted by monitoring time.
[3]Chi-squared test for deviance of negative binomial GLM with single characteristic as predictor versus null model.

Artifact Alarms Rate[1]				
Characteristics	n	Median[2]	(IQR)[2]	p-value[3]
Age, y.				0.08
18 to 34	42	94.7	(20.6 - 194.0)	
35 to 49	86	108.3	(39.6 - 169.9)	
50 to 64	138	99.8	(56.4 - 185.5)	
65 to 79	132	67.4	(23.2 - 135.2)	
80 plus	58	106.0	(28.2 - 148.3)	
Gender				0.60
Female	208	93.0	(40.0 - 165.0)	
Male	248	84.7	(36.9 - 175.7)	
Race				0.50
Asian	74	89.4	(26.2 - 164.9)	
Black or African American	35	67.2	(48.9 - 115.9)	
Native Hawaiian or Pacific Islander	8	77.8	(50.5 - 111.9)	
White	278	95.9	(35.0 - 196.7)	
Unknown or decline to state	61	86.2	(49.0 - 121.1)	
ICU Type				0.25
Neurological	195	86.2	(38.9 - 144.0)	
Medical-Surgical	180	99.3	(38.8 - 185.6)	
Cardiac	81	79.6	(23.3 - 173.1)	
BMI (kg/m2)				0.13
<25	183	88.7	(31.6 - 199.1)	
25-30	131	98.7	(37.4 - 160.9)	
30+	142	73.8	(42.7 - 134.6)	
Smoker				<0.001
No	387	77.8	(32.4 - 165.0)	
Yes	69	121.1	(78.0 - 180.7)	
Cognitive Impairment				0.41
No known cognitive problem	261	83.9	(35.7 - 159.5)	
Cognitive problem documented	195	86.2	(37.1 - 185.6)	
Tremor				<0.001
No or undocumented	421	80.6	(35.4 - 150.9)	
Yes	35	197.5	(73.8 - 390.0)	
Mechanical Ventilation				0.01
No	277	112.8	(50.4 - 207.5)	
Yes	179	76.7	(30.9 - 137.1)	

Table 5 Occurrence rates of arrhythmia suspend alarms by demographic, ICU type and factors hypothesized to increase the number of technical alarms in 456 ICU patients
[1]Rate is per 10 hours of monitoring.
[2]Median and 25th and 75th percentiles of the distribution are weighted by monitoring time.
[3]Chi-squared test for deviance of negative binomial GLM with single characteristic as predictor versus null model.

Arrhythmia Suspend Alarms Rate[1]				
Characteristics	n	Median[2]	(IQR)[2]	p-value[3]
Age, y.				0.10
18 to 34	42	0.3	(0.0 - 0.9)	
35 to 49	86	0.3	(0.0 - 0.8)	
50 to 64	138	0.4	(0.1 - 0.9)	
65 to 79	132	0.2	(0.0 - 0.4)	
80 plus	58	0.2	(0.0 - 0.4)	
Gender				0.07
Female	208	0.3	(0.0 - 0.6)	
Male	248	0.2	(0.0 - 0.8)	
Race				0.07
Asian	74	0.2	(0.0 - 0.4)	
Black or African American	35	0.2	(0.0 - 0.5)	
Native Hawaiian or Pacific Islander	8	0.1	(0.1 - 0.2)	
White	278	0.3	(0.0 - 0.9)	
Unknown or decline to state	61	0.3	(0.0 - 0.6)	
ICU Type				0.49
Neurological	195	0.2	(0.0 - 0.4)	
Medical-Surgical	180	0.3	(0.0 - 0.8)	
Cardiac	81	0.3	(0.0 - 1.0)	
BMI (kg/m2)				0.17
<25	183	0.2	(0.0 - 0.9)	
25-30	131	0.2	(0.0 - 0.8)	
30+	142	0.3	(0.0 - 0.6)	
Smoker				<0.001
No	387	0.2	(0.0 - 0.6)	
Yes	69	0.5	(0.1 - 0.9)	
Cognitive Impairment				0.007
No known cognitive problem	261	0.1	(0.0 - 0.7)	
Cognitive problem documented	195	0.3	(0.1 - 0.8)	
Tremor				<0.001
No or undocumented	421	0.2	(0.0 - 0.6)	
Yes	35	1.0	(0.3 - 2.7)	
Mechanical Ventilation				0.009
No	277	0.3	(0.0 - 0.9)	
Yes	179	0.2	(0.0 - 0.6)	

Table 6 Occurrence rates of electrocardiographic leads off by demographic, ICU type and factors hypothesized to increase the number of technical alarms in 456 ICU patients
[1]Rate is per 10 hours of monitoring.
[2]Median and 25th and 75th percentiles of the distribution are weighted by monitoring time.
[3]Chi-squared test for deviance of negative binomial GLM with single characteristic as predictor versus null model.

ECG Leads Fail Alarms Rate[1]				
Characteristics	n	Median[2]	(IQR)[2]	p-value[3]
Age, y.				0.005
18 to 34	42	1.4	(1.0 - 2.9)	
35 to 49	86	1.8	(1.2 - 3.5)	
50 to 64	138	2.2	(1.3 - 3.2)	
65 to 79	132	1.6	(0.9 - 2.2)	
80 plus	58	1.7	(1.2 - 2.6)	
Gender				0.94
Female	208	1.7	(1.1 - 2.7)	
Male	248	1.7	(1.2 - 3.0)	
Race				<0.001
Asian	74	1.7	(1.0 - 2.1)	
Black or African American	35	1.2	(0.9 - 2.8)	
Native Hawaiian or Pacific Islander	8	1.6	(0.9 - 1.8)	
White	278	2.0	(1.3 - 3.4)	
Unknown or decline to state	61	1.6	(1.2 - 2.9)	
ICU Type				0.53
Neurological	195	1.7	(1.2 - 3.0)	
Medical-Surgical	180	1.7	(1.0 - 3.1)	
Cardiac	81	1.8	(1.3 - 2.7)	
BMI (kg/m2)				0.51
<25	183	1.6	(1.1 - 2.5)	
25-30	131	2.0	(1.1 - 3.3)	
30+	142	1.8	(1.2 - 3.3)	
Smoker				0.48
No	387	1.7	(1.1 - 2.8)	
Yes	69	2.2	(1.4 - 3.4)	
Cognitive Impairment				0.05
No known cognitive problem	261	1.8	(1.2 - 2.7)	
Cognitive problem documented	195	1.7	(1.2 - 3.1)	
Tremor				<0.001
No or undocumented	421	1.7	(1.2 - 2.6)	
Yes	35	2.9	(1.5 - 5.6)	
Mechanical Ventilation				0.16
No	277	2.0	(1.2 - 3.1)	
Yes	179	1.7	(1.2 - 2.7)	

Table 7 Negative binomial regression model of number of artifact alarms
[1]IRR = Incidence Rate Ratio, CI = Confidence Interval

Characteristic	**IRR[1]**	**95% CI[1]**	**p-value**
Age in years			
18 to 34	—	—	
35 to 49	0.85	0.57, 1.24	0.41
50 to 64	0.97	0.67, 1.38	0.87
65 to 79	0.77	0.53, 1.10	0.16
80 plus	0.89	0.57, 1.38	0.60
Gender			
Female	—	—	
Male	0.97	0.80, 1.19	0.80
Race			
White	—	—	
Asian	0.85	0.65, 1.14	0.26
Black or African American	0.90	0.64, 1.32	0.58
Native Hawaiian or Pacific Islander	1.07	0.55, 2.43	0.87
Unknown or decline to state	0.89	0.67, 1.21	0.45
Intensive care unit type			
Medical-Surgical	—	—	
Neurological	0.87	0.70, 1.08	0.19
Cardiac	0.96	0.72, 1.30	0.81
BMI (kg/m2)			
<25	—	—	
25-30	0.81	0.64, 1.02	0.071
30+	0.86	0.68, 1.09	0.20
Current smoker			
No	—	—	
Yes	1.61	1.23, 2.14	<0.001
Cognitive impairment			
No known cognitive problem	—	—	
Cognitive problem documented	1.12	0.89, 1.42	0.31
Tremor			
No or undocumented	—	—	
Yes	1.91	1.33, 2.84	<0.001
Mechanical Ventilation			
No	—	—	
Yes	0.80	0.64, 1.00	0.047

Table 8 Negative binomial regression model of number of arrhythmia suspend alarms
[1]IRR = Incidence Rate Ratio, CI = Confidence Interval

Characteristic	**IRR**[1]	**95% CI**[1]	**p-value**
Age in years			
18 to 34	—	—	
35 to 49	0.60	0.28, 1.22	0.15
50 to 64	0.89	0.44, 1.70	0.72
65 to 79	0.65	0.31, 1.28	0.20
80 plus	0.72	0.32, 1.60	0.41
Gender			
Female	—	—	
Male	1.25	0.85, 1.83	0.23
Race			
White	—	—	
Asian	0.96	0.57, 1.66	0.89
Black or African American	1.40	0.75, 2.85	0.31
Native Hawaiian or Pacific Islander	0.30	0.07, 1.87	0.14
Unknown or decline to state	0.65	0.38, 1.15	0.12
Intensive care unit type			
Medical-Surgical	—	—	
Neurological	0.69	0.46, 1.05	0.071
Cardiac	1.31	0.78, 2.25	0.32
BMI (kg/m2)			
<25	—	—	
25-30	0.77	0.49, 1.20	0.22
30+	0.95	0.62, 1.47	0.80
Current smoker			
No	—	—	
Yes	1.98	1.20, 3.39	0.006
Cognitive impairment			
No known cognitive problem	—	—	
Cognitive problem documented	1.63	1.08, 2.46	0.018
Tremor			
No or undocumented	—	—	
Yes	3.78	1.96, 7.91	<0.001
Mechanical Ventilation			
No	—	—	
Yes	0.65	0.43, 0.98	0.035

Table 9 Negative binomial regression model of number of ECG leads off alarms
[1]IRR = Incidence Rate Ratio, CI = Confidence Interval

Characteristic	**IRR[1]**	**95% CI[1]**	**p-value**
Age in years			
18 to 34	—	—	
35 to 49	0.80	0.56, 1.13	0.20
50 to 64	1.13	0.81, 1.56	0.45
65 to 79	0.79	0.56, 1.09	0.16
80 plus	1.07	0.72, 1.59	0.72
Gender			
Female	—	—	
Male	0.89	0.75, 1.07	0.21
Race			
White	—	—	
Asian	0.96	0.75, 1.24	0.75
Black or African American	0.77	0.56, 1.08	0.12
Native Hawaiian or Pacific Islander	1.97	1.07, 4.04	0.039
Unknown or decline to state	1.60	1.24, 2.08	<0.001
Intensive care unit type			
Medical-Surgical	—	—	
Neurological	1.05	0.86, 1.27	0.65
Cardiac	1.43	1.11, 1.86	0.006
BMI (kg/m2)			
<25	—	—	
25-30	0.95	0.77, 1.17	0.60
30+	0.94	0.76, 1.16	0.56
Current smoker			
No	—	—	
Yes	0.97	0.76, 1.25	0.80
Cognitive impairment			
No known cognitive problem	—	—	
Cognitive problem documented	1.30	1.08, 1.58	0.008
Tremor			
No or undocumented	—	—	
Yes	1.84	1.34, 2.59	<0.001
Mechanical Ventilation			
No	—	—	
Yes	0.78	0.64, 0.95	0.014

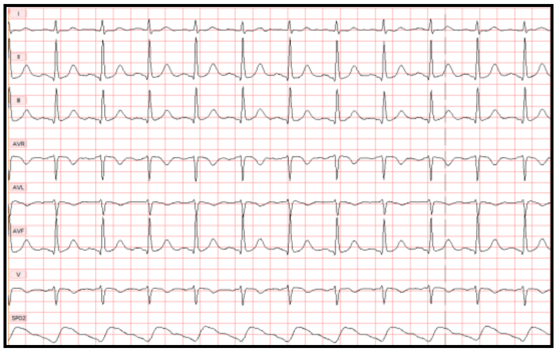
Table 10 Implications for Clinical Practice and Industry

	Implications

Artifact	• Nurses should assess patient for:
	  ○ Nicotine withdrawal if a current smoker at admission
	  ○ History or etiology for tremor
	• Mechanical ventilation was protective

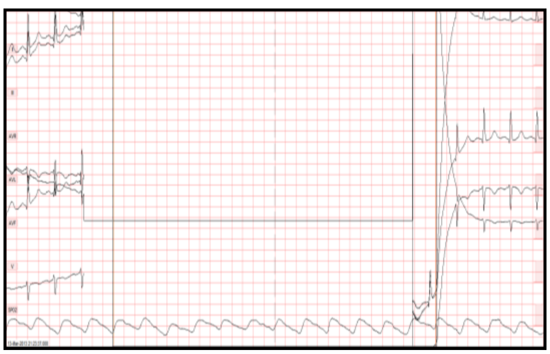
Arrhythmia Suspend	• Nurses should assess patient for:
	  ○ Nicotine withdrawal if a current smoker at admission
	  ○ History or etiology for tremor & cognitive impairment
	• Mechanical ventilation was protective

ECG Leads Fail	• Nurses should assess patient for: ○ History or etiology for tremor & cognitive impairment • Mechanical ventilation was protective
Alarm Duration	• Hospitals should consider changing default setting • Industry should develop new algorithms



a) Clean ECG signal

b) Artifact



c) Arrhythmia suspend

d) ECG leads fail

Figure 1 Illustrates a clean ECG signal and three types of technical alarms: b) artifact; c) arrhythmia suspend; and d) ECG leads fail. Shown on each ECG (top to bottom) are leads I, II, III, V (V1), aVR, aVL, aVF and Sp02).

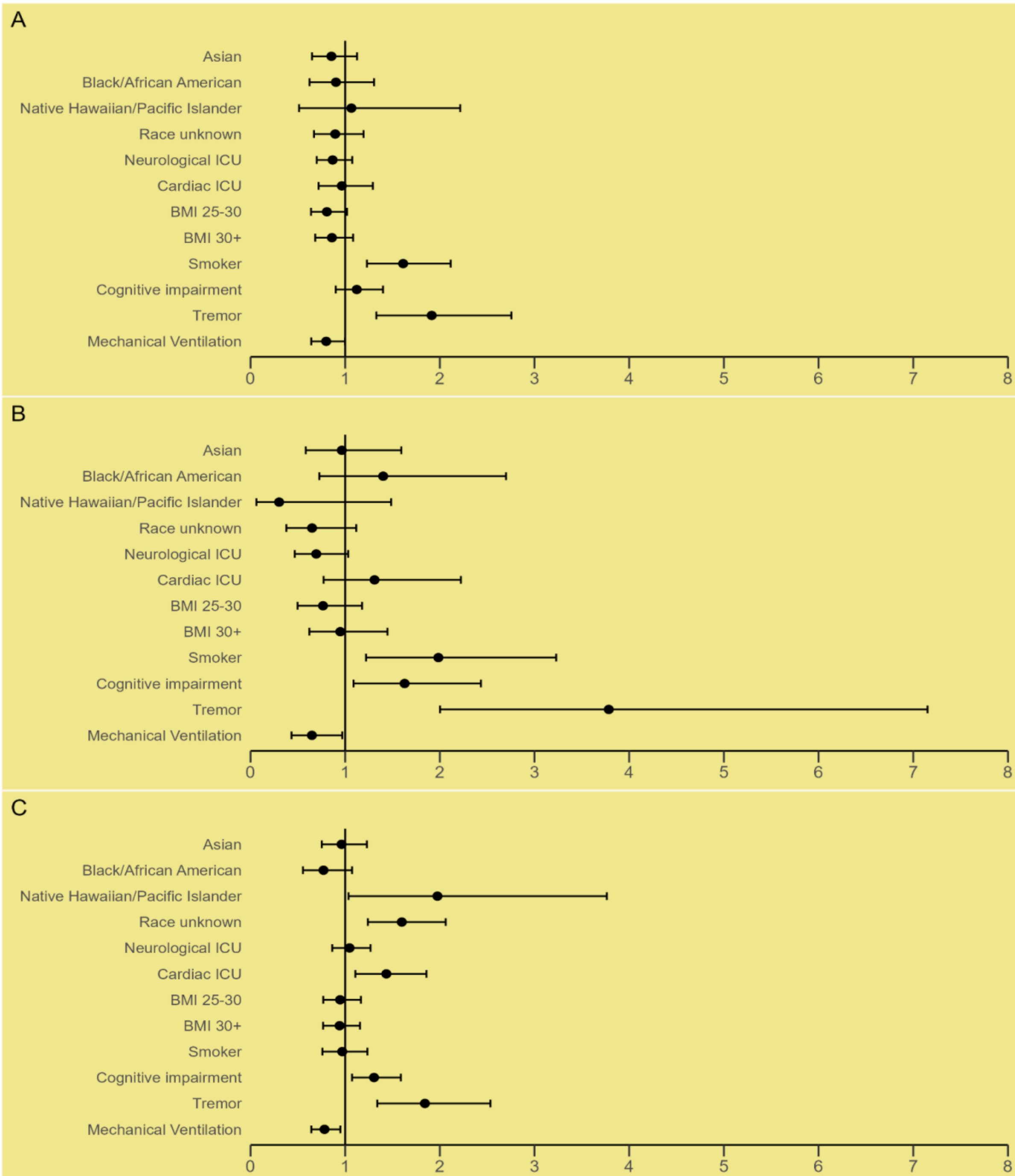


Figure 2 Forest plots of each technical alarm type: (a) artifact, (b) arrhythmia suspend, & (c) ECG leads off

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