Title
Double Trouble: Patients with Both True and False Arrhythmia Alarms and Their Impact on Alarm Fatigue

Author
CHIU, STELLA

Publication Date
2018

Peer reviewed|Thesis/dissertation

Double Trouble: Patients with Both True and False Arrhythmia Alarms and Their Impact on Alarm Fatigue

by

Stella Chiu

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Nursing

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, SAN FRANCISCO

Approved:

Dedication and Acknowledgements

Thank you to Michele Pelter for being the most supportive and patient mentor.

I dedicate this thesis to my husband, Dang, and my daughter, who are my constant source of motivation.

Abstract

Background: Critical care nurses are exposed to an excessive number of clinical alarms in the patient care environment. Prior studies show that the vast majority of arrhythmia alarms are false and can lead to alarm fatigue. Patients with both true and false arrhythmia alarms present a unique challenge, because exposure to false alarms can desensitize nurses to true alarms and may lead to missed true events. **Objectives:** The purpose of this study was to examine patients with both true and false arrhythmia alarms and determine: (1) frequency of patients with true and false arrhythmia alarms in a sample of 461 intensive care unit (ICU) patients, (2) patient, clinical, and electrocardiographic characteristics associated with both true and false alarms, and (3) the number and types of true and false arrhythmia alarms (e.g., asystole, ventricular fibrillation, ventricular tachycardia, accelerated ventricular rhythm, pause, and ventricular bradycardia). **Methods:** This was a secondary analysis utilizing data from the UCSF Alarm Study. **Results:** In 461 ICU patients, 71 (15%) patients had a total of 10,699 true and false arrhythmias alarms: 1,348 (13%) were true and 9,351 (87%) were false. Compared to patients without true and false alarms, the presence of ventricular pacemaker, bundle branch block, altered mental status, mechanical ventilation, left ventricular assist device, and cardiac ICU admission were associated with the presence of true and false alarms ($p = 0.001$). Patients with both true and false alarms had longer length of ICU stay than patients without both true and false alarms (208 hours versus 75 hours; $p = 0.001$). Accelerated ventricular rhythm was the most common alarm (37%), followed by ventricular tachycardia (31%). **Conclusion:** We found that 15% of ICU patients have both true and false alarms and the vast majority are false. Further research is needed to build and test improved ECG arrhythmia algorithms that adjust for clinical and ECG characteristics associated with false alarms. Nurses' awareness of these characteristics may help

them identify patients at risk for excessive alarms and aid in developing unit specific solutions to decrease alarm fatigue.

TABLE OF CONTENTS

INTRODUCTION 1

Alarm fatigue 1

Cry Wolf Phenomenon 2

Case study 2

Purpose 3

METHODS 3

Design/setting/sample 3

Physiological bedside monitors 4

Electrocardiographic data 4

Electrocardiographic alarm annotation 4

RESULTS 5

Frequency of patients with true and false alarms and alarm types 5

Patient, clinical, ECG characteristics 6

Proportion of true versus false alarms 6

DISCUSSION 7

LIMITATIONS AND CONCLUSION 11

REFERENCES 13

APPENDICES 18

Appendix A. False ventricular tachycardia 18

Appendix B. True ventricular tachycardia 19

Appendix C. Monitoring infrastructure 20

Appendix D. Alarm default settings 21

Appendix E. Alarm types 22

Appendix F. Patient, clinical, and ECG characteristics 23

Appendix G. Proportion of true versus false alarms (all patients) 24

Appendix H. Proportion of true versus false alarms (Quartiles 1,2,3,4) 25

Introduction

Alarms are built into nearly every piece of equipment and monitoring device in the acute care setting with the intent to alert busy nurses to changes in a patient's condition that may require attention. Research indicates that the vast majority of alarms are false or do not require a change in patient care and are therefore nuisance alarms[1-3]. Excessive alarms can lead to alarm fatigue. Alarm fatigue is used to describe the phenomenon of desensitization to alarms caused by excessive alarm stimuli. As a result of alarm fatigue, nurses often resort to turning off alarm features, changing alarm parameters, and/or silencing alarms altogether[4-6]. Alarm fatigue poses a threat to patient safety when there is a delay to a true alarm or a true alarm is missed entirely because alarms were turned off. After a number of reported sentinel events due to missed true alarms, the Joint Commission[7] established alarm safety as a National Patient Safety Goal in 2013, requiring accredited hospitals to develop strategies for the management of alarm systems. Emergency Care Research Institute's[8] (ECRI) Heath Devices Group have also listed alarm hazards as a "Top 10 Health Technology Safety Hazard" since 2011.

Alarms are categorized as being either true or false. A true alarm correctly identifies an event (i.e., arrhythmia), whereas, a false alarm either incorrectly identifies an event (i.e., noise, inaccurate arrhythmia alarm) or is a true alarm which does not require a clinical action[9]. Electrographic (ECG) algorithms are designed for high sensitivity to ensure lethal arrhythmias (e.g., asystole, ventricular fibrillation/tachycardia) are not missed. Unfortunately, this high sensitivity is paired with very poor specificity, with the latter resulting in high numbers of false-positive alarms. In 2013, our team identified over 2.5 million individual alarms (audible and inaudible) during a 31-day study period in five adult intensive care units (ICU). We determined

that 88.8% of the 12,671 annotated ECG arrhythmia alarms were false alarms. This is the largest study to date illustrating the extent of the alarm fatigue problem in consecutive ICU patients[10].

With the premise of Aesop's fable "The Boy Who Cried Wolf", psychologists studied the "cry-wolf" phenomenon in relation to different types of warning systems. Psychologist Shlomo Breznitz[11] found that false threats reduced the physiological fear of subsequent threat(s) and therefore significantly decreased its credibility. Bliss et al. [12] used this phenomenon to study response rates to different reliabilities of alarms and found that 90% of the participants responded to alarms according to the perceived probability that the alarm would be true, also referred to as probability matching. Several studies applied this theoretical model to healthcare and found that nurses use probability matching when they respond to physiological alarms from bedside monitors[13-15]. When probability matching is applied, nurses are less likely to respond when they are exposed to excessive false alarms, which means the true alarms might be missed. This phenomenon poses a threat to patient safety and is particularly problematic in patients with both true and false alarms.

The following is an example of how the "cry- wolf" phenomenon can affect warning systems in the acute care setting: C.C. is a 68-year old male admitted to the ICU for severe sepsis related to pneumonia. On the first day of admission, the bedside monitor alarmed for a crisis alarm, indicating ventricular tachycardia (VT) (Appendix A). The nurse responded to the VT alarm to find the patient resting in bed with vital signs unchanged. The nurse notified the provider, but no actions were taken because it was determined that the rhythm was a wide complex tachycardia due to an underlying right bundle branch block and was not true VT. Over the next 17 days, C.C. had 1,119 similar false VT alarms. However, on day 17, the patient had three true VT alarms (Appendix B). In addition to the true and false VT alarms, this patient also

has several other ECG arrhythmia alarm types including: (1) asystole n = 5; 3 true, 2 false, (2) ventricular fibrillation n = 2; 1 true, 1 false, (3) accelerated ventricular rhythm n = 41; 2 true, 39 false, (4) pause n = 21; 21 true, 0 false, and (5) ventricular bradycardia n = 14; 0 true, 14 false. Only 2% of the total alarms were true, while 98% were false. As his condition worsened, the patient went on to receive comfort care and eventually passed away. However, this case illustrates the substantial challenge nurses face in caring for patients with both true and false alarms.

While numerous descriptive studies have explored the problem of alarm fatigue[15-17] and tested potential solutions[18-20], no studies have reported on the unique problem of patients with both true and false alarms. With this in mind, the purpose of this secondary analysis was to examine patients with both true and false arrhythmia alarms in the ICU. Specifically, we determine: (1) frequency of patients with true and false arrhythmia alarms in a sample of 461 ICU patients, (2) patient, clinical, and ECG characteristics associated with both true and false alarms, and (3) the number and types of true and false arrhythmia alarms (e.g., asystole, ventricular fibrillation, VT, accelerated ventricular rhythm, pause, and ventricular bradycardia).

Methods

Design/Setting/Sample

This secondary analysis utilized data from the UCSF Alarm Study, a prospective observational study conducted within a large urban tertiary-quaternary medical center. The detailed methods of the original study have been previously described[10]. Briefly, data were collected from the medical center's five adult ICUs (total of 77 beds) during a 31-day period in March 2013. The five ICUs consist of two medical-surgical ICUs, two neurological ICUs, and

one cardiac ICU. The study was approved by UCSF Committee on Human Research with waiver of informed consent because this was an observational study only and all ICU patients require physiologic monitoring as a part of their routine care. As a result, all consecutive patients that were treated in the five ICUs during the one-month data collection period were included in the study. A total of 461 patients were enrolled in the study.

Physiological Bedside Monitors

All physiologic waveforms (e.g., ECG, arterial blood pressure, pulse oximetry, and respirations), numeric vital signs measurements, alarm parameter settings, and alarms both audible and inaudible (e.g., arrhythmia, parameter, and technical) were collected from each of the 77 bedside monitors using a sophisticated research infrastructure (Appendix C). Each ICU bed was equipped with a Solar 8000i bedside monitor (version 5.4 software, GE Healthcare, Milwaukee, WI), all of which were connected to a central monitoring station via a closed network. A research version of CARESCAPE Gateway (GE Healthcare, Milwaukee, WI) was specially designed to access study data from the network and directed into an external server for off-line analysis. The data was captured and stored using BedMasterEx software (Excel Medical Electronics, Inc, Jupiter, FL) and then accessed using applications and analytics program (e.g., LabChart Reader, Matlab).

Electrocardiographic Data

A Mason-Likar 5-electrode ECG lead configuration was used to monitor ICU patients. Seven ECG leads (I, II, III, aVR, aVL, aVF, and one V lead [V1]) were captured for analysis. Alarm default settings from the bedside monitoring manufacturer and those selected by UCSF for monitoring are displayed in Appendix D.

Electrocardiographic Alarm Annotation

Six ECG arrhythmia alarms were annotated (e.g., asystole, ventricular fibrillation, VT, accelerated ventricular rhythm, pause, and ventricular bradycardia). These ECG arrhythmias were selected because all were configured as audible alarms; hence contribute to alarm fatigue. Four nurse scientists used a standardized protocol to analyze cardiac rhythms that triggered any of the six arrhythmia alarms. Each alarm was determined to be true or false. All of the PhD trained annotators completed a 10-week course in clinical electrocardiography and a 3-hour alarm annotation certification course taught by the principal investigator of the Alarm Study. The inter-rater reliability of alarm annotation showed 95% agreement in true or false positive alarms between the annotators (Cohen's Kappa score of 0.86).

Results

Frequency of Patients with True and False Alarms and Alarm Types

Appendix E illustrates the distribution of alarms in the 461 patients. Of the total sample of 461 ICU patients, 211 (46%) had no arrhythmia alarms, 12 (3%) had only true alarms, 167 (36%) had only false alarms, and 71 (15%) had both true and false alarms.

As illustrated in Appendix E, among the sample of 71 patients with both true and false alarms there were a total of 10,699 arrhythmias alarms: 1,348 (13%) were true and 9,351 (87%) were false. The 10,699 alarms were categorized into the six arrhythmia types and further separated as to whether they were true or false alarms. Of the 10,699 alarms, the greatest proportion of arrhythmia alarm was for accelerated ventricular rhythm (3,974; 37%); with 220 (6%) true alarms and 3,754 (94%) false alarms. The second most common arrhythmia alarm was for VT (3,362; 31%); with 460 (14%) true, 2,902 (86%) false. This was followed by pause (1,394; 13%); with 267 (19%) true, 1,127 (81%) false, then ventricular bradycardia (1,246; 12%); with 39 (3%) true alarms, 1,207 (97%) false alarms. The fewest number of alarms were

for ventricular fibrillation (152; 1%); with 107 (70%) true alarms, 45 (30%) false alarms, followed by asystole (571; 5%); with 255 (45%) true alarms, 316 (55%) false alarms.

Patient, Clinical, and ECG Characteristics

Appendix F shows patient demographics, common confounders (e.g., ECG, patient factors), hospital unit, and length of ICU stay by three categories including: (1) the entire sample, (2) patients without both true and false alarms, and (3) patients with both true and false alarms. When comparing the subset of patients with both true and false alarms to those without both true and false, there were no differences by gender, age, body mass index, race, or ethnicity. There were differences between the two groups based on known confounders associated with false alarms. Specifically, the presence of ventricular pacemaker, bundle branch block (BBB), altered mental status, mechanical ventilation, and left ventricular assist device (LVAD) were associated with the presence of both true and false alarms. However, tremor was not. There was a difference in the hospital unit comparisons with the overall p-value of 0.001. Post hoc analysis showed that a higher proportion of cardiac ICU patients had both true and false alarms (37% versus 15%; $p = 0.001$; Bonferroni correction 0.0083). The other unit comparisons were not different. Length of ICU stay was longer in patients with both true and false alarms as compared to those without both true and false alarms (208 hours versus 75 hours; $p = 0.001$).

Proportion of True versus False Alarms

Of the 10,699 total alarms among the patients with both true and false alarms, 1,348 (13%) were true alarms and 9,351 (87%) were false alarms. Appendix G illustrates the proportion of true versus false alarms in each of the 71 patients. As seen in Appendix G, the distribution of true versus false alarms by patients varied widely, with a small group of patients contributing high numbers of alarms, making visualization of individual patient data challenging.

Therefore, we use Appendix H to further illustrate the distribution of true and false alarms among the 71 patients by placing patients into quartiles using the total number of alarms as the unit of analysis. The first quartile represents patients with the lowest total alarm count, whereas the fourth quartile, represents the one patient with the highest total alarm count.

Quartile one illustrates the alarms for patients 1 to 62, who had a range of 2 to 148 alarms. As seen on the right side of the bar chart, patients with higher number of alarms had a higher distribution of false alarms versus true alarms. Quartile two included six patients (63 to 68) whose alarms total ranged from 167 to 429 alarms. Of the six patients in this quartile, four patients had predominately false alarms, and two had predominantly true alarms. Quartile three shows two patients (69 and 70) who had 509 and 1,205 alarms, respectively. Patient 69 had mostly true alarms while patient 70 had mostly false alarms. Of note, patient 69 had VT storm. Quartile four shows one patient (71) who had 53% of all of the alarms (5,712 of total 10,699 alarms). This patient had 34 (0.6%) true alarms; hence 99.4% were false. As illustrated in these bar charts in Appendix H (B-D), nine patients from quartile two, three, and four produced the vast majority of total alarms (9,062 of 10,699; 85%).

Discussion

In our sample of 461 ICU patients, we found that 71 (15%) patients had at least one true and one false arrhythmia alarm(s) during continuous ECG monitoring. This subset of patients produced a total of 10,699 arrhythmia alarms, 1,348 (13%) were true arrhythmia alarms and 9,351 (87%) were false arrhythmia alarms. The rational for conducting this study was to examine this unique subset of patients with both true and false ECG arrhythmia alarms, with the hypothesis that they could potentially illustrate the “cry wolf” phenomenon described by alarm fatigue. While we cannot directly measure alarm fatigue in nurses or determine whether true

arrhythmia events were missed from this retrospective analysis, our study illustrates a substantial clinical challenge faced by nurses. We further hypothesize this situation places ICU patients at risk for missed events when true alarms are buried amongst high rates of false alarms. To our knowledge, this is the first study to report on patients with both true and false arrhythmia alarms. Our study is unique in that the parent study annotated over 12,600 ECG arrhythmia alarms, which represents one of the largest datasets exploring this topic.

In examining the six different arrhythmia alarm types, we found that asystole and ventricular fibrillation alarms contributed the least number of alarms. More than half of the 571 asystole alarms were false (55%) and 30% of the 152 ventricular fibrillation alarms were false. These types of alarms trigger a crisis level alarm, which is configured as a latching alarm that continuously sounds until it is manually acknowledged by staff. In addition, crisis level alarms receive the fastest response by clinical staff[21] and thus have the potential to contribute to alarm fatigue. While these types of arrhythmia alarms had the lowest rate of false positive alarms as compared to the other arrhythmia types, the rate of false alarms caused by asystole and ventricular fibrillation is still unacceptably high.

Ventricular tachycardia, accelerated ventricular rhythm, pause, and ventricular bradycardia contributed the highest number of alarms in our sample of 461 ICU patients. In each of these four alarm types, there were considerably more false alarms as compared to true alarms. Accelerated ventricular rhythm was the highest contributor of alarms, with 94% of the 3,974 total alarms being false and only a small proportion true (220; 6%). Practice guidelines for VT state antiarrhythmic therapy is not indicated for accelerated ventricular rhythm[22]; thus, this type of true alarm is a nuisance alarm, (i.e., false-positive alarm and/or clinically irrelevant alarm)[3]. Funk et al.[4] in a survey of nurses, reported nuisance alarms are perceived to have untoward

effects on both nurses and patient care. They found that nuisance alarms occurred frequently, disrupted patient care, reduced trust in alarms, and led to silencing alarms, which could lead to missed true alarms. In fact, our hospital changed the alarm level for accelerated ventricular rhythm from warning to advisory based on data from the UCSF Alarm study. We are now exploring whether accelerated ventricular rhythm could be adjusted to a message level alarm or perhaps turned off all together. Adjusting this alarm type to inaudible alone, could reduce alarm burden by 37%; however, further study is needed to determine if making accelerated ventricular rhythm alarms an inaudible alarm is safe for patients. We are in the process of examining whether true accelerated ventricular rhythms lead to adverse patient outcomes, which will provide valuable insight about the potential clinical utility of this alarm.

In previous studies, our team identified several ECG confounders associated with an increased number of false alarms: presence of ventricular pacemaker, BBB, and LVAD[10,23]. In addition, we found clinical factors are associated with higher rates of false alarms including altered mental status and treatment with mechanical ventilation[23]. Our study builds upon this finding to show that patients with these confounding factors not only had higher rates of false alarms, but importantly also had true alarms.

Our finding shows that a higher proportion of patients with true and false alarms are in the cardiac ICU, which is not surprising since this population of cardiac patients are more likely to have ECG confounders as compared to neurological or medical-surgical ICUs. Care for patients with these clinical and ECG characteristics represent a substantial challenge for nurses. Most monitor algorithms do not automatically identify clinical and ECG confounders. For example, the “PaceMode” feature is available for patients with ventricular pacemakers, but it requires the nurse to identify a paced rhythm and then turn the feature ‘on’. Manufacturers of

bedside monitors should consider developing algorithms to automatically and correctly identify confounders such as BBB, mechanical ventilation, LVAD, and other patient factors known to cause false alarms.

Patients with both true and false alarms had a longer average ICU length of stay as compared to patients without both true and false (208 hours versus 75 hours; $p = 0.001$). One explanation for this may be that patients with both true and false alarms are more acutely ill and thus at higher risk for arrhythmias. In addition, longer length of ICU stay leads to longer monitoring times and thus, a higher potential for more alarms in general. This finding may suggest that patients with longer lengths of ICU stay are vulnerable because they may be more acutely ill, have more total alarms, and therefore, are at higher risk for missed true alarm events.

In a study by Rosman et al.[24], ECG alarms that occurred the day prior were reviewed to determine if true alarms had occurred. Of 1,769 total VT alarms in 86 pediatric patients, 17 (1%) VT alarms were true and were missed by the clinical staff. Of the missed VT alarms, treatment for two patients was significantly altered because the VT alarms led to a significant change in the patient's condition. These findings suggest that when nurses are exposed to high numbers of false alarms, it is likely that true alarms could be missed because they are lost in all of the "noise". While we did not explicitly examine missed true alarms in our study due to our retrospective analysis design, we hypothesize this problem exists in our study as well because like Rosman et al.'s study we had considerably higher numbers of false alarms as compared to true alarms.

We also identified nine outlier patients who generated a substantially greater number of total alarms, with a disproportionate number of false compared to true alarms. Specifically, six of the nine patients had significantly more false than true alarms. The patient with the most alarms,

contributed 5,712 (53%) of the 10,699 total alarms with only 34 (0.6%) true alarms and 5,678 (99.4%) false alarms. Our team[10,23] and others[25] have reported on the contribution of outlier patients to the problem of alarm fatigue. An overwhelmingly higher number of false alarms from outlier patients creates a risk not only for these patient, but for other patients on the unit because nurses are constantly being distracted by frequent alarms.

Our study highlights a significant problem that impacts bedside nurses and places ICU patients at risk for missed true events. Patients who have both true and false alarms are at risk of becoming a victim of the "cry wolf" phenomenon if a true and possibly actionable alarm is missed because it is mixed in with high numbers of false alarms. Studies find that responses to alarms by nurses' can be affected by several factors including; alarm priority (e.g., crisis, warning, advisory, message), the patient's alarm history, change of shift, hours into a nurse's shift, nurse's experience level, as well as their past experiences[21,26]. By appreciating and understanding clinical and ECG characteristics associated with both true and false alarms, nurses can play an important role in recognizing patients at risk for this problem, which may minimize the risk of missing true alarms. Nurses can help facilitate and problem solve unit specific strategies through quality improvement and research projects to change policies and procedures around bedside alarm customization and alarm management techniques. Quality improvement interventions have been shown to decrease alarm rates[9,20,27,28] and should be used to guide these initiatives to reduce false alarms without missing true alarms. While institutional efforts can focus on implementing methods to improve patient safety, future research is needed to examine new algorithms designed for customization of clinical and ECG characteristics known to cause false alarms.

Limitations

This was a retrospective analysis of patients with both true and false alarms and did not include an examination of alarm fatigue or missed events. Hence, we could not report on whether the true alarms were missed, clinical consequences to patients, or nurses' response to the alarms.

Conclusion

Of 461 patients in the UCSF alarm study, 71 (15%) patients had both true and false ECG arrhythmia alarms. This subset of patients has associated clinical and ECG characteristics including; ventricular pacemaker, BBB, altered mental status, mechanical ventilation, and LVAD. Patients admitted to the cardiac ICU are also more likely to experience both true and false ECG arrhythmia alarms. Patients with both true and false ECG arrhythmia alarms have a longer length of ICU stay. The highest proportion of ECG arrhythmia alarms were for accelerated ventricular rhythm, followed by VT. Only a few outlier patients contributed the majority of the alarms. There is a need for further research to develop dynamic algorithms that adjust to certain clinical and ECG characteristics that are associated with false alarms while maintaining the ability to identify true arrhythmias. Until these capabilities are available, nurses can play a role in recognizing patients with certain clinical and ECG characteristics responsible for excessive arrhythmia alarms and use quality improvement and research endeavors to develop unit specific solutions to decrease alarm fatigue.

References

1. Paine CW, Goel VV, Ely E, et al. Systematic review of physiologic monitor alarm characteristics and pragmatic interventions to reduce alarm frequency. *Journal of Hospital Medicine*. 2016;11(2):136-144. doi:10.1002/jhm.2520
2. Cvach M. Monitor alarm fatigue: an integrative review. *Biomedical Instrumentation & Technology.* 2012;46(4):268-277. doi:10.2345/0899-8205-46.4.268
3. Cvach MS, Dang D, Foster J, Irechukwu J. Clinical alarms and the impact on patient safety. *Initiatives in Safe Patient Care.* date unknown;1-8. http://www.premiersafetyinstitute.org/wp-content/uploads/Initiatives-in-Safe-Pt-Care-Alarm-safety.pdf Accessed April 2,2018
4. Funk M, Clark JT, Bauld TJ, Ott JC, Coss P. Attitudes and practices related to clinical alarms. *American Journal of Critical Care*. 2014;23(3):e9-e18. doi: 10.4037/ajcc2014315
5. Healthcare Technology Foundation. National Clinical Alarms Survey: Perceptions, Issues, Improvements, and Priorities of Healthcare Professionals. 2011. http://www.thehtf.org/documents/2011_HTFAlarmsSurveyOverallResults.pdf Accessed April 2, 2018
6. Healthcare Technology Foundation. HTF Update: 2016 National Clinical Alarm Survey Results. 2016. http://thehtf.org/documents/2016%20National%20Clinical%20Alarms%20Survey%20Results.pdf Accessed April 2, 2018
7. The Joint Commission. The Joint Commission announces 2014 National Patient Safety Goal. *Joint Commission Perspectives*. 2013;33(7):1-4.

https://www.jointcommission.org/assets/1/18/JCP0713_Announce_New_NSPG.pdf Accessed April 2, 2018

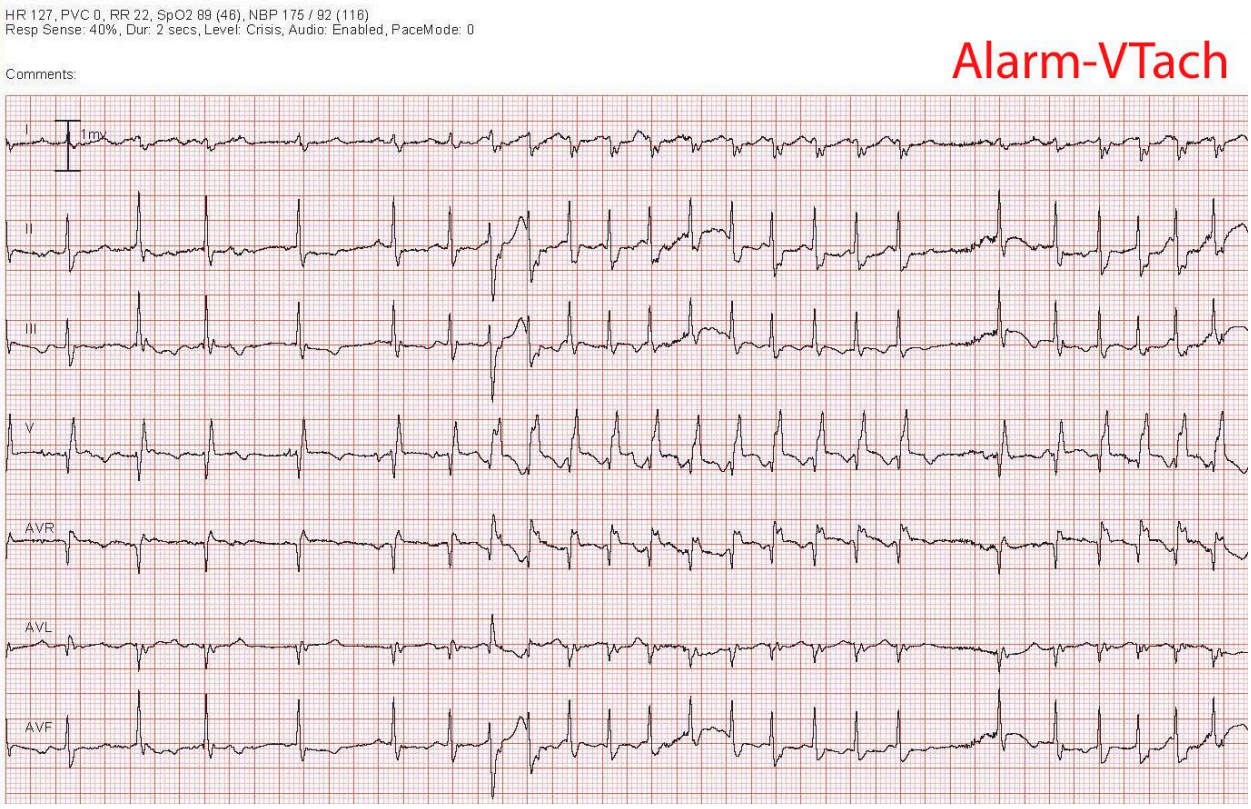
8. ECRI Institute. Top 10 health technology hazards. *Health Devices*. https://www.ecri.org/Pages/2018-Hazards.aspx
9. Winters BD, Cvach MM, Bonafide CP, et al. Technological distractions (Part 2): a summary of approaches to manage clinical alarms with intent to reduce alarm fatigue. *Critical Care Medicine.* 2018;46(1):130-137. doi: 10.1097/CCM.0000000000002803
10. Drew BJ, Harris P, Zègre-Hemsey JK, Mammone T, 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.g002
11. Breznitz ST. *Cry Wolf: The Psychology of False Alarms.* Hillsdale, New Jersey: Lawrence Erlbaum Associates; 1984.
12. Bliss JP, Gilson RD, Deaton JE. Human probability matching behaviour in response to alarms of varying reliability. *Ergonomics.* 1995;38(11):2300-2312. doi:10.1080/00140139508925269
13. Bailey JM. The implications of probability matching for clinician response to vital sign alarms: a theoretical study of alarm fatigue. *Ergonomics*. 2015;58(9):1487-1495. doi:10.1080/00140139.2015.1021861
14. Bitan Y, Meyer J, Shinar D, Zmora E. Nurses' reactions to alarms in a neonatal intensive care unit. *Cognition, Technology & Work.* 2004;6(4):239-246. doi:10.1007/s10111-004-0162-2

15. Bonafide CP, Lin R, Zander M, et al. Association between exposure to nonactionable physiologic monitor alarms and response time in a children's hospital. *Journal of Hospital Medicine.* 2015;10(6):345-51. doi:10.1002/jhm.2331
16. Siebig S, Kuhls S, Imhoff M, Gather U, Schölmerich J, Wrede, CE. Intensive care unit alarms--how many do we need? *Critical Care Medicine.* 2010;38(2):451-456. doi:10.1097/CCM.0b013e3181cb0888
17. Voepel-Lewis T, Parker ML, Burke CN, et al. Pulse oximetry desaturation alarms on a general postoperative adult unit: a prospective observational study of nurse response time. *International Journal of Nursing Studies.* 2013;50(10):1351-1358. doi:10.1016/j.ijnurstu.2013.02.006
18. Albert NM, Murray T, Bena JF, et al. (2015). Differences in alarm events between disposable and reusable electrocardiography lead wires. *American Journal of Critical Care.* 2015;24(1):67-73. doi:10.4037/ajcc2015663
19. Cvach MM, Biggs M, Rothwell KJ, Charles-Hudson C. Daily electrode change and effect on cardiac monitor alarms: an evidence-based practice approach. *Journal of Nursing Care Quality. 2013*;28(3):265-271. doi: 10.1097/NCQ.0b013e31827993bc
20. Whalen DA, Covelle PM, Piepenbrink JC, Villanova KL, Cuneo CL, Awtry EH. Novel approach to cardiac alarm management on telemetry units. *Journal of Cardiovascular Nursing.* 2014;29(5):E13-22. doi:10.1097/JCN.0000000000000114
21. Bonafide CP, Localio AR, Holmes JH, et al. Video analysis of factors associated with response time to physiologic monitor alarms in a children's hospital. *JAMA Pediatrics.* 2017;171(6):524-531. doi:10.1001/jamapediatrics.2016.5123

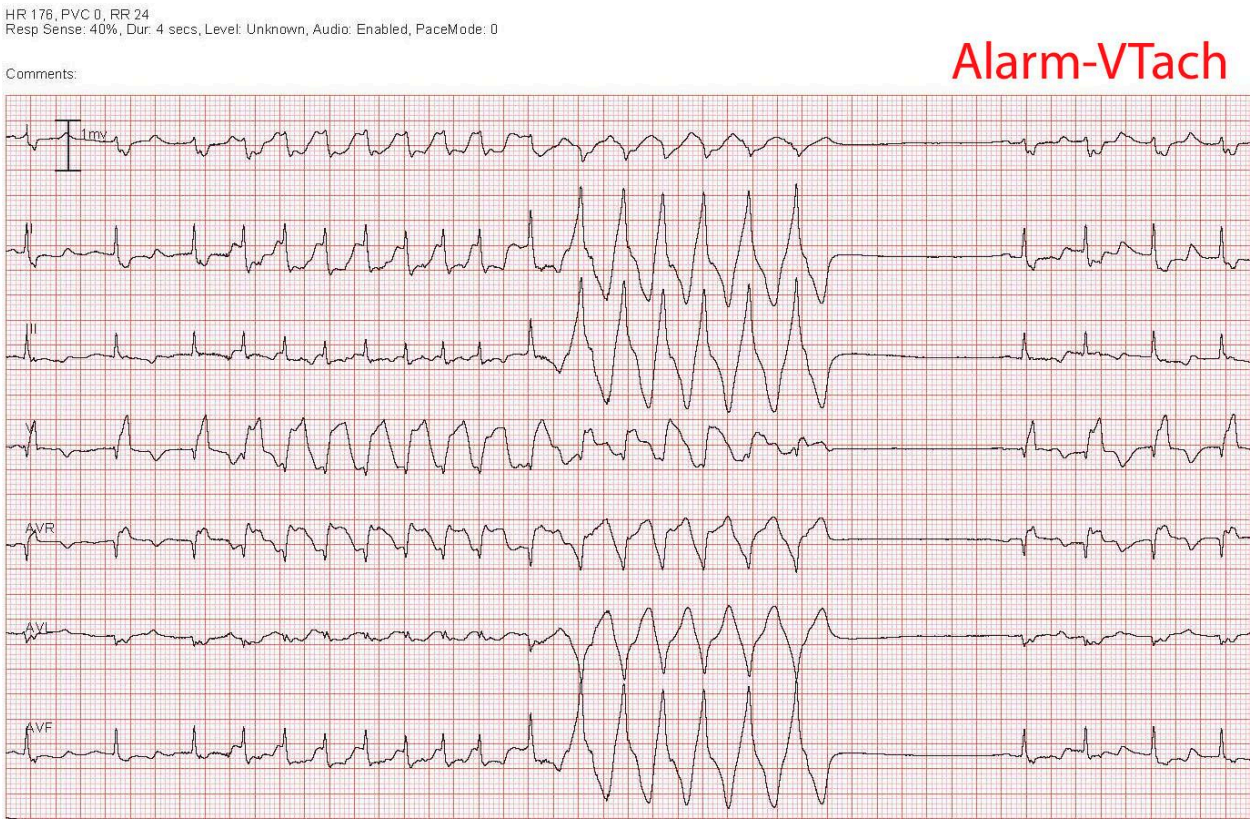
22. Al-Khatib SM, Stevenson WG, Ackerman MJ, et al. AHA/ACC/HRS guideline for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines and the Heart Rhythm Society. *Circulation.* 2017. http://circ.ahajournals.org/content/early/2017/10/30/CIR.0000000000000548 Accessed April 2, 2018
23. Harris PR, Zègre-Hemsey JK, Schindler D, Bai Y, Pelter MM, Hu X. Patient characteristics associated with false arrhythmia alarms in intensive care. *Therapeutics and Clinical Risk Management.* 2017;13:499-513. doi:10.2147/TCRM.S126191
24. Rosman EC, Blaufox AD, Menco A, Trope R, Seiden HS. What are we missing? Arrhythmia detection in the pediatric intensive care unit. *The Journal of Pediatrics*. 2013;163(2):511-514. doi:10.1016/j.jpeds.2013.01.053
25. Cvach M, Kitchens M, Smith K, Harris P, Flack MN. Customizing alarm limits based on specific needs of patients. *Biomedical instrumentation & technology*. 2017;51(3):227-234. doi:10.2345/0899-8205-51.3.227
26. Gazarian PK, Carrier N, Cohen R, Schram H, Shiromani S. A description of nurses' decision-making in managing electrocardiographic monitor alarms. *Journal of Clinical Nursing*. 2015;24(1-2):151-159. doi:10.1111/jocn.12625
27. Allan SH, Doyle PA, Sapirstein A, Cvach M. Data-driven implementation of alarm reduction interventions in a cardiovascular surgical ICU. *Joint Commission Journal on Quality and Patient Safety*. 2017;43(2):62-70. doi:10.1016/j.jcjq.2016.11.004

28. Dandoy CE, Davies SM, Flesch L, et al. A team-based approach to reducing cardiac monitor alarms. *Pediatrics*. 2014;134(6):e1686-e1694. doi:10.1542/peds.2014-1162

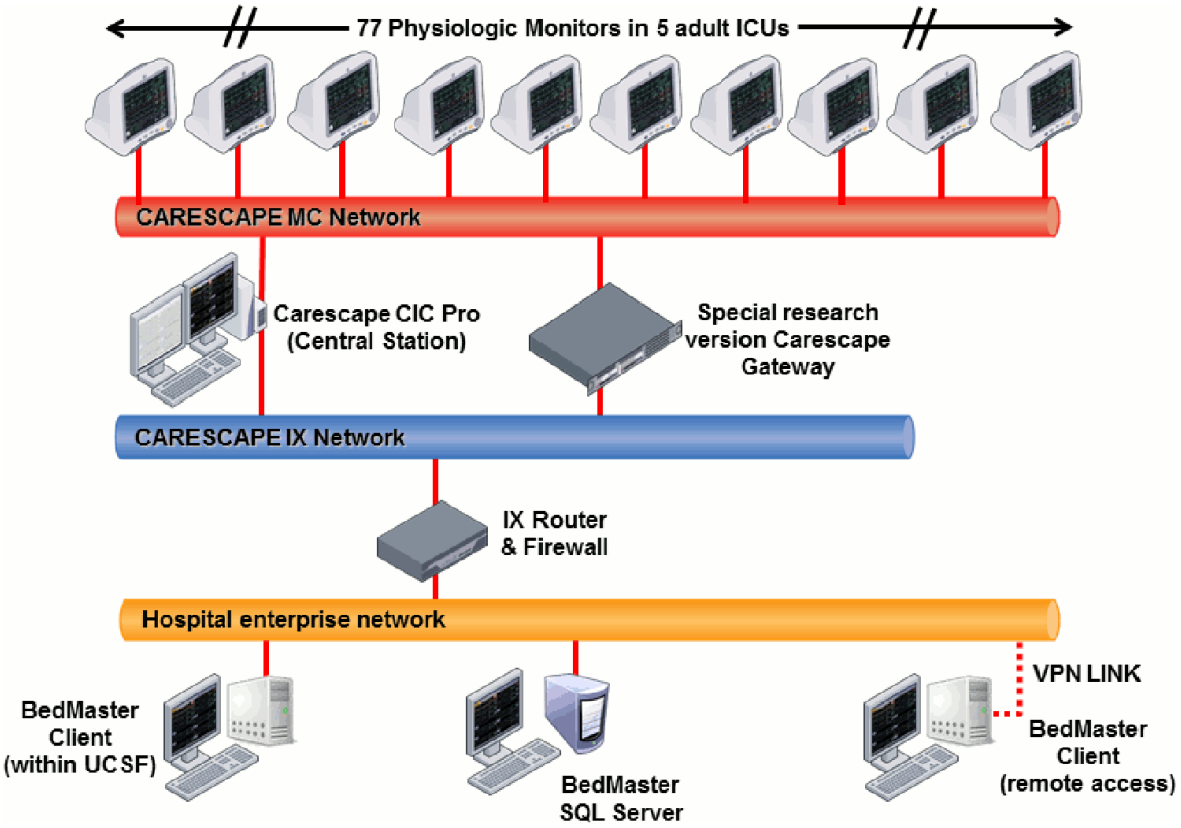
Appendix A. False ventricular tachycardia alarm in a patient with a total of 1,119 similar alarms. Shown are leads I, II, III, V (V1 is the hospital default), aVR, aVL, and aVF. Note the rhythm prior to the wide complex tachycardia is atrial fibrillation with right bundle branch block. The wide complex tachycardia maintains an irregular pattern at a rate of ~ 225 beats per minute with a taller right QRS peak suggestive of supraventricular tachycardia with aberrancy and not ventricular tachycardia.



Appendix B. True ventricular tachycardia (VT) alarm in a patient with both true and false VT alarms.



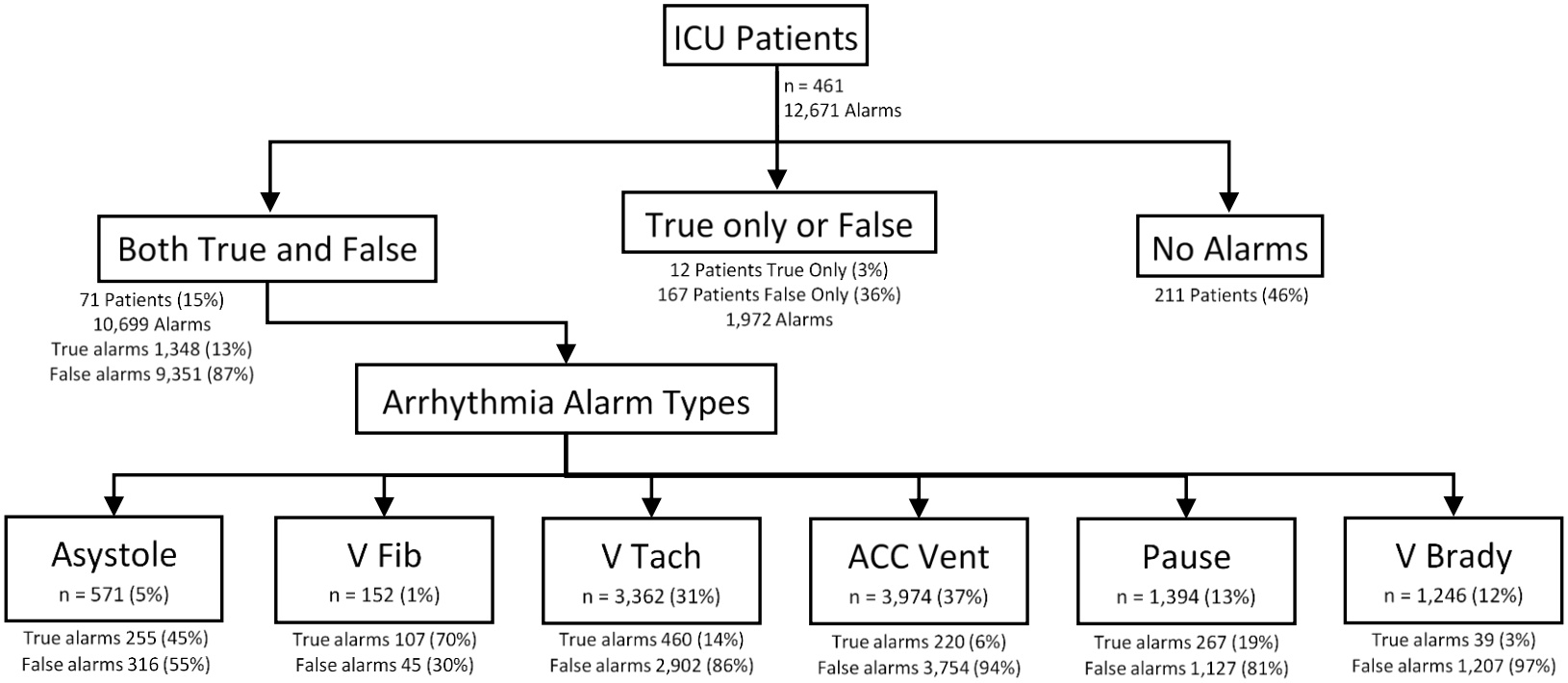
Appendix C. Monitoring infrastructure to store all alarm data collected from bedside physiologic monitors in five adults intensive care units.



Appendix D. Alarm default setting during study period separated by factory default settings and UCSF default settings.

Alarm Default Settings for Adult ICUs during Study Period		
Alarm Sounds: Crisis, 3 beeps continually; Warning, 2 beeps; Message, inaudible text		
Arrhythmia Alarms	**Factory Default**	**UCSF Default**
Asystole	Crisis	Crisis
Ventricular Fibrillation	Crisis	Crisis
Ventricular Tachycardia	Crisis	Crisis
Accelerated Ventricular Rhythm	Message	Warning
Pause	Message	Warning
Ventricular Bradycardia	Crisis	Warning

Appendix E. All 461 ICU patients divided into patients with both true and false alarms, true only or false only alarms, and no alarms. Arrhythmia alarms produced by patients with both true and false alarms are categorized by alarm type. Each arrhythmia alarm type is further separated into true and false (note individual patients could have more than one arrhythmia type).
V fib = ventricular fibrillation; V tach = ventricular tachycardia; ACC vent = accelerated ventricular rhythm; V brady = ventricular bradycardia

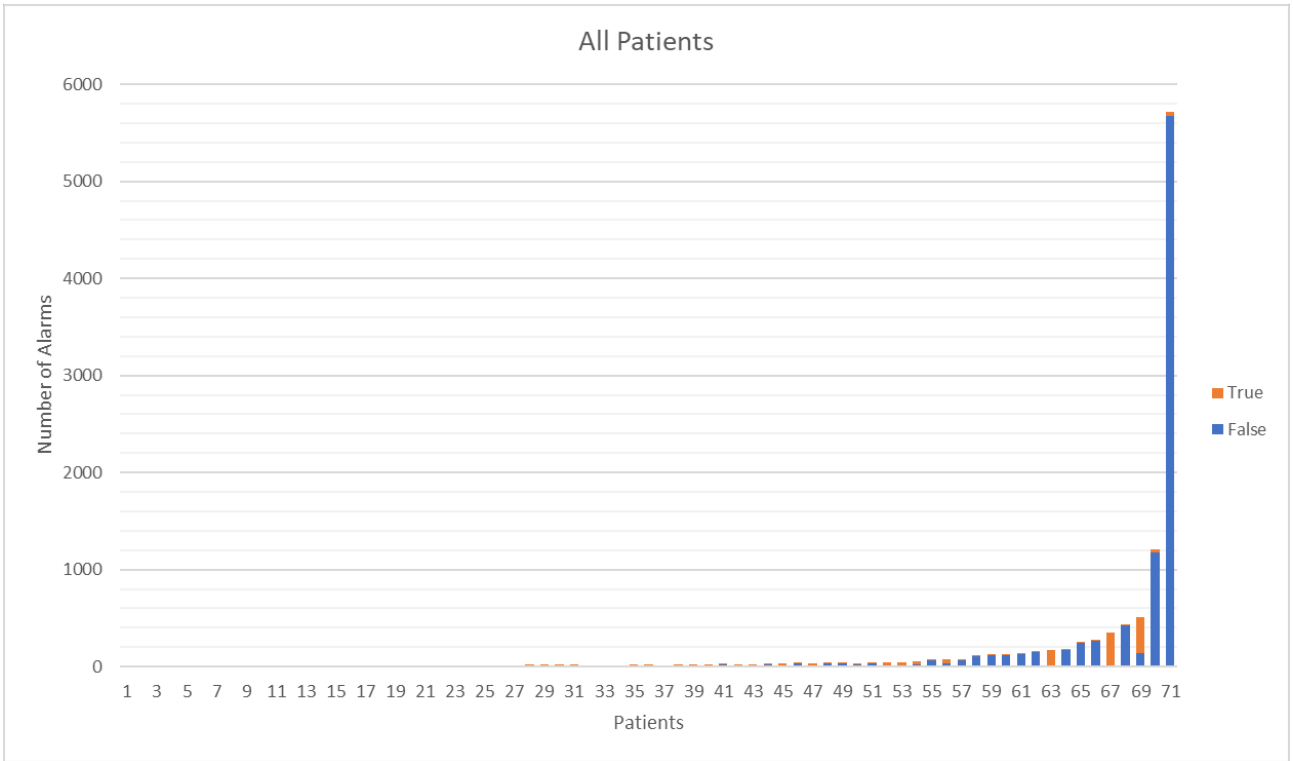


Appendix F. Demographics, common confounders, hospital unit and length of ICU stay in 461 total patients separated by patients without both true and false alarms versus those with both true and false alarms.

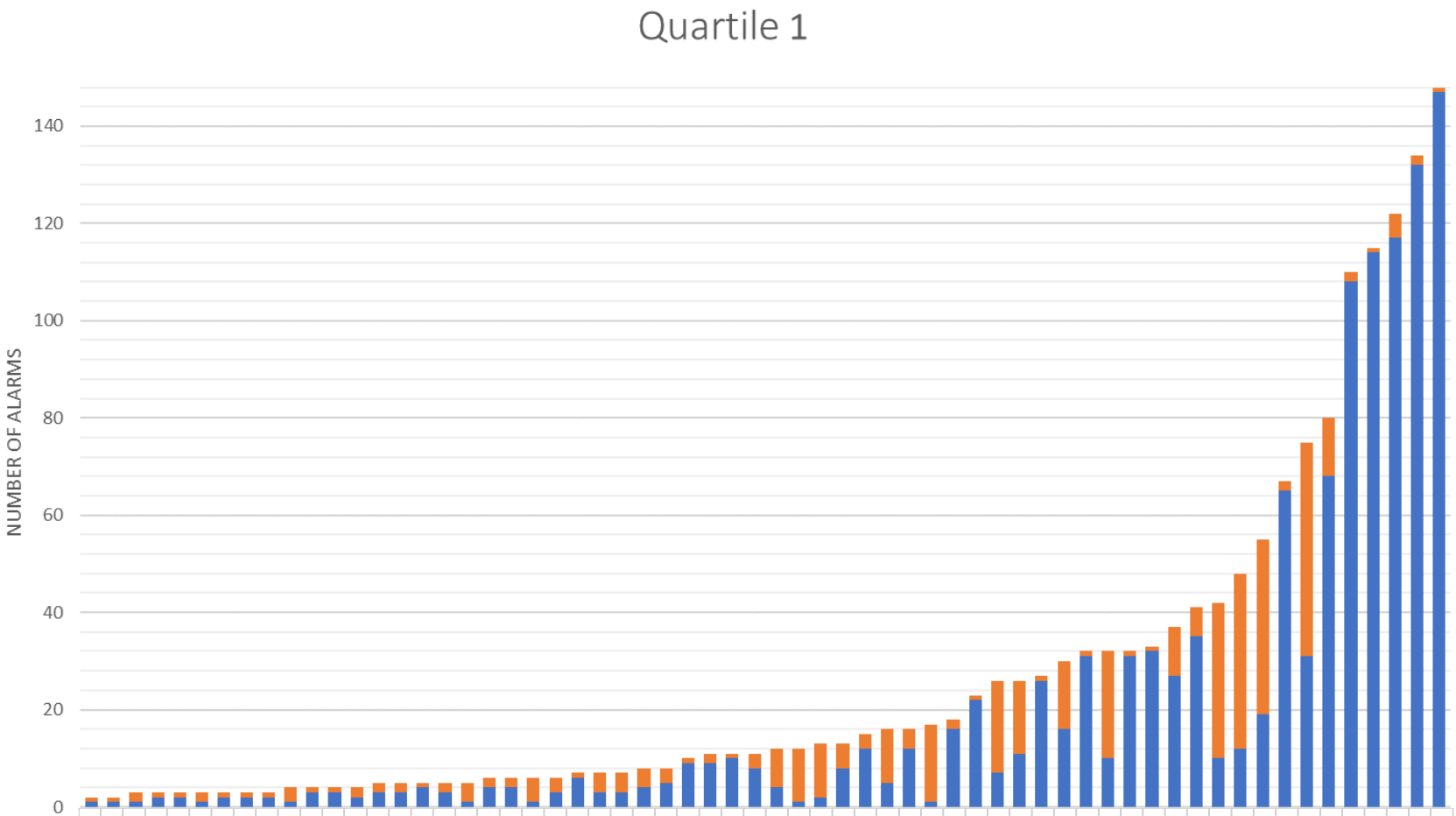
Variables	Total Sample n = 461 n (%)	Patients without True & False Alarms n = 390 (85%) n (%)	Patients with True & False Alarms n = 71 (15%) n (%)	P-value without True & False vs with True & False
Gender				
- Male	250 (54)	207 (53)	43 (61)	0.244
- Female	211 (46)	183 (47)	28 (39)	
Age year Mean (SD)	60 ± 17	60 ± 17	59 ± 17	0.715
Body Mass Index	28 ± 8	28 ± 8	29 ± 9	0.438
Race				
- Asian	76 (17)	65 (17)	11 (16)	
- Black or African American	35 (8)	27 (7)	8 (11)	
- Native Hawaiian, Pacific Islander	8 (2)	7(2)	1 (1)	0.052
- White	281 (61)	232 (60)	49 (69)	
- Unknown, decline to state	61 (13)	59 (15)	2 (3)	
Ethnicity				
- Not Hispanic or Latino	401 (87)	337 (86)	64 (90)	
- Hispanic or Latino	52 (11)	45 (12)	7 (10)	0.427
- Unknown, decline to state	8 (2)	8 (2)	0 (0)	
Confounders causing false alarms				
- Ventricular Pacemaker	17 (4)	**10 (3)**	**7 (10)**	**0.003**
- BBB (right or left)	12 (3)	**7 (2)**	**5 (7)**	**0.011**
- Tremor	36 (8)	31 (8)	5 (7)	0.793
- Altered Mental Status	198 (43)	**152 (39)**	**46 (65)**	**0.001**
- Mechanical Ventilation	164 (36)	**117 (30)**	**47 (66)**	**0.001**
- LVAD	3 (1)	**0 (0)**	**3 (4)**	**0.004***
Hospital Unit (ICU)				
- Medical-surgical	183 (40)	**160 (41)**	**23 (32)**	
- Neurological	195 (42)	**173 (44)**	**22 (31)**	**0.001**
- Cardiac	83 (18)	**57 (15)**	**26 (37)¥**	
Length of ICU stay (hours)	95 ± 178	**75 ± 121**	**208 ± 333**	**0.001^**

BBB = bundle branch block; LVAD = left ventricular assist device; ICU = intensive care unit
* Fishers Exact Test used due to small sample size; ^ Levene's Test < 0.05 equal variances not assumed; ¥ Unit analysis, overall p value significant, post-hoc analysis of chi-square test with Bonferroni correction ($p < 0.0083$) shows cardiac ICU is only unit where there is a statistical difference

Appendix G. Distribution of true and false alarms among the 71 patients. Given that there were outlier patients (right side of figure) it is difficult to see the distribution of true and fasle alarms in each patient; hence, the sample was divided into quatiles using the total number of alarms (n = 10,699 alarms) to better appreciate the distribution of true and false alarms in the 71 patients.

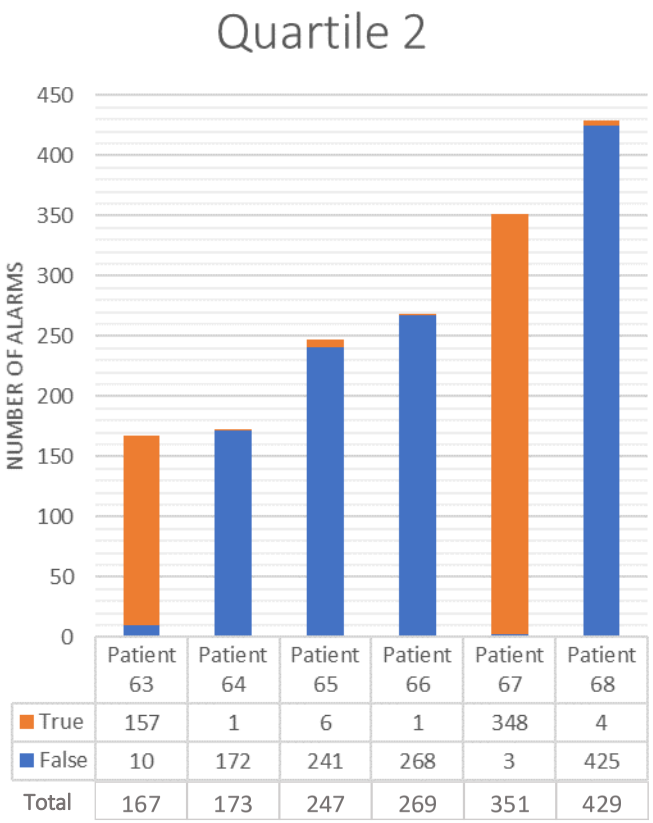


Appendix H. (A to D) A. 62 patients in Quartile 1 (n = 1,637 alarms) **B.** Six patients in Quartile 2 (n = 1,636 alarms) **C.** Two patients in Quartile 3 (n = 1,714 alarms) **D.** One patient in Quartile 4 (n = 5712 alarms)

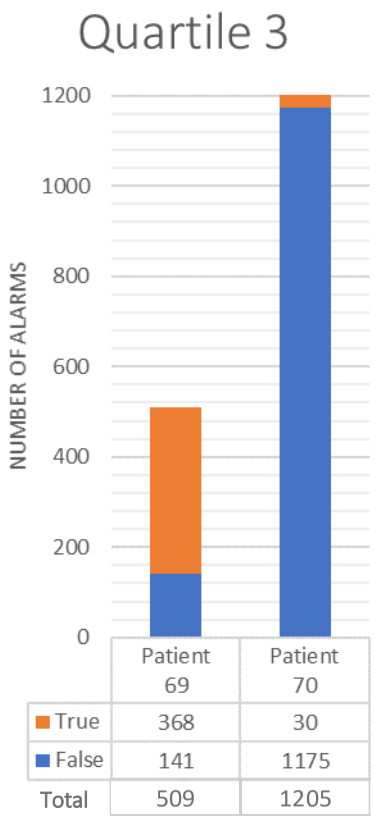


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
True	1	1	2	1	1	2	1	1	1	3	1	1	2	2	2	1	2	4	2	2	5	3	1	4	4	4	3	1	2	1	3	8	11	11	5	3	11	4	16	2	1	19	15	1	14	1	22	1	1	10	6	32	36	36	2	44	12	2	1	5	2	1
False	1	1	1	2	2	1	2	2	2	1	3	3	2	3	3	4	3	1	4	4	1	3	6	3	3	4	5	9	9	10	8	4	1	2	8	12	5	12	1	16	22	7	11	26	16	31	10	31	32	27	35	10	12	19	65	31	68	108	114	117	132	147
Total	2	2	3	3	3	3	3	3	3	4	4	4	4	5	5	5	5	5	6	6	6	6	7	7	7	8	8	10	11	11	11	12	12	13	13	15	16	16	17	18	23	26	26	27	30	32	32	32	33	37	41	42	48	55	67	75	80	110	115	122	134	148

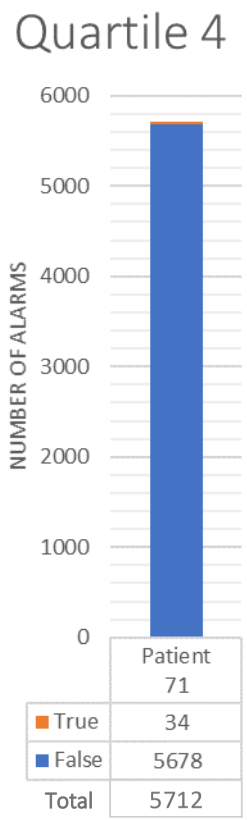
A. Illustrates 62 patients in Quartile 1 (n= 1,637 alarms)



B. Illustrates six patients in Quartile 2 (n = 1,636 alarms)



C. Illustrates two patients in Quartile 3 (n = 1,714 alarms)

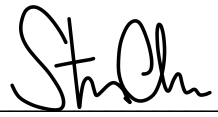


D. Illustrates one patient in Quartile 4 (n = 5712 alarms)

Publishing Agreement

It is the policy of the University to encourage the distribution of all theses, dissertations, and manuscripts. Copies of all UCSF theses, dissertations, and manuscripts will be routed to the library via the Graduate Division. The library will make all theses, dissertations, and manuscripts accessible to the public and will preserve these to the best of their abilities, in perpetuity.

I hereby grant permission to the Graduate Division of the University of California, San Francisco to release copies of my thesis, dissertation, or manuscript to the Campus Library to provide access and preservation, in whole or in part, in perpetuity.



Author Signature

5/14/2018

Date