Time series evaluation of improvement interventions to reduce alarm notifications in a paediatric hospital

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ABSTRACT

Background10 The Joint Commission identified inpatient alarm reduction as an opportunity to improve patient safety; enhance patient, family and nursing satisfaction; and optimise workflow. We used quality improvement (QI) methods to safely decrease non-actionable alarm notifications to bedside providers.

Methods In a paediatric tertiary care centre, we convened a multidisciplinary team to address alarm notifications in our acute care cardiology unit. Alarm notification was defined as any alert to bedside providers for each patient-triggered monitor alarm. Our aim was to decrease alarm notifications per monitored bed per day by 60%. Plan-Do-Study-Act testing cycles included updating notification technology, establishing alarm logic and modifying bedside workflow processes, including silencing the volume on all bedside monitors. Our secondary outcome measure was nursing satisfaction. Balancing safety measures included floor to intensive care unit transfers and patient acuity level.

Results At baseline, there was an average of 71 initial alarm notifications per monitored bed per day. Over a 3.5-year improvement period (2014–2017), the rate decreased by 68% to 22 initial alarm notifications per monitored bed per day. The proportion of initial to total alarm notifications remained stable, decreasing slightly from 51% to 40%. There was a significant improvement in subjective nursing satisfaction. At baseline, 32% of nurses agreed they were able to respond to alarms appropriately and quickly. Following interventions, agreement increased to 76% (p<0.001). We sustained these improvements over a year without a change in monitored balancing measures.

Conclusion We successfully reduced alarm notifications while preserving patient safety over a 4-year period in a complex paediatric patient population using technological advances and QI methodology. Continued efforts are needed to further optimise monitor use across paediatric hospital units.

INTRODUCTION

Hospital-based healthcare providers rely on continuous vital sign monitoring, including pulse oximetry and electrocardiographic-based cardiorespiratory monitors, to alert them to changes in patients' clinical conditions. However, continuous monitors can generate a large volume of nuisance alarm notifications that do not represent a meaningful change in clinical status. This may lead to alarm fatigue, or alarm desensitisation, which can lead to providers not responding to alarms.[1] Alarm fatigue has become a patient safety priority,[2–4] and the Joint Commission highlighted alarm fatigue as the most common contributing factor to alarm-related sentinel events.[5 6] Since 2014, their annual National Patient Safety Goals have required all institutions to implement measures to improve alarm management.

Initial studies identified alarm fatigue to be directly related to the number of alarms per patient per day, with some patients experiencing up to 350 physiological monitor alarms daily.[7] On a paediatric ward, up to 99% of alarms are non-actionable, either not accurately reflecting the clinical status of the patient or not requiring intervention.[1 8 9] Furthermore, nursing response time to alarms increases as exposure to non-actionable alarms increases.[10] Response times may pose a risk to patient safety when an alarm notification indicating a true decline in clinical condition is not addressed rapidly. On our acute care cardiology unit (ACCU) prior to 2014, nurses experienced greater than 100 alarm notifications per patient-day. Initial hospital-wide alarm reduction work focused on broadening the range for acceptable respiratory rates (set to 10–200 breaths per minute, as a high respiratory rate without other vital sign abnormalities is often a non-actionable alarm[11]) and using the alarm

system's intentional delay before alarms sounded (5 s). Despite these efforts, the ACCU alarm burden had not measurably improved, and the nursing staff, patients and families remained consistently interrupted by alarm notifications. Decreasing the number of non-actionable alarms became crucial to ensure that providers respond promptly to actionable alarms. Removing unnecessary alarm notification redundancy, such as audible alarm tones from the patient room monitors, also became an objective for the improvement team.

In order to address these concerns within the ACCU, we aimed to reduce the frequency of initial alarm notifications (defined as the primary alert to a handheld device carried by a bedside provider notifying them of a patient-triggered monitor alarm) per monitored bed per patient-day by 60% over a 3-year period. Furthermore, we sought to assess the impact of our interventions on patient safety and nurse experience.

METHODS

Context

Our institution is a large, urban academic medical centre. The ACCU contained 17 beds during the improvement work, and is similar in surgical volume, patient acuity and provider workforce to analogous units at other large paediatric institutions in the USA.[12] Patients admitted to the ACCU include those preparing for and recovering from cardiac surgery (including transplantation and mechanical circulatory support) and invasive procedures (including cardiac catheterisation), those with heart failure or arrhythmia and those with significant underlying heart disease but admitted for general paediatric indications. ACCU patients are cared for by a team of paediatric nurses, nurse practitioners, residents, cardiology fellows and attendings. Each patient room can provide continuous monitoring with 5-lead electrocardiography (ECG) telemetry, respiratory rate and oxygen saturations. Prior to the study period, our monitors visually and audibly alarmed in patient rooms and at the nurses' station, and audibly to nursing pagers (Statview; General Electric Healthcare, Chicago, IL). Every monitor alarm resulted in multiple immediate and quickly repeated communications, or 'alarm notifications', to the primary and charge nurse. Alarm fatigue had been identified as an institution-wide problem, resulting in the formation of a Monitor Oversight Committee.[8]

Interventions

In 2014, we created a multidisciplinary team to address alarm notifications in the ACCU. Team members included the ACCU director, nursing staff, nurse practitioners, nursing leadership and representatives from information services. We identified key drivers including (1) staff, unit leadership and patient/family engagement in alarm management, (2) standardised, reliable processes for patient-specific monitor use, and (3) clearly defined roles, responsibilities and accountability for the alarm process. Using the Model of Improvement from the Institute of Healthcare Improvement, we used frequent, small tests of change and Plan-Do-Study-Act (PDSA) cycles to work towards our goal.[13]

Over a 3.5-year period during 2014–2017, we implemented a variety of interventions, many occurring concurrently. The various alarm system technologies that were used are demonstrated in figure 1. This process map demonstrates how the different alarm systems (GE and Philips; General Electric Healthcare, Chicago, IL, and Philips, Amsterdam, Netherlands), middleware platforms (Statview and Connexall; GlobeStar Systems, Toronto, Ontario, Canada) and nurse-held devices (Statview pager and Voalte phones; Voalte, Sarasota, FL) helped modify and deliver alarm notifications to the nursing staff. Table 1 details the overall chronology of our work, and the major components are outlined in the sections below.

New technology

We began with three technology interventions: (1) transitioning from pagers to a smartphone-based application for nursing alarm notification, (2) integrating a new middleware platform, capable of alarm customisation, which communicated between monitors and smartphones (Connexall), and (3) adopting new software to facilitate the transmission of waveforms to nurses through smartphones (AirStrip; AirStrip Technologies, San Antonio, TX). After testing, nurses reported not using the waveform technology due to the presence of hallway/alcove monitors throughout the ACCU, so this intervention was abandoned in 2016. Ultimately, we incorporated a new bedside monitor system also capable of alarm logic customisation (Philips).

Alarm logic

We took a graduated approach to building logic into our alarm management to ensure patient safety was maintained. To understand the baseline prevalence of non-actionable alarm notifications, we enlisted night shift nurses to record all alarm notifications received during their shifts, noting those that required clinical action (eg, increasing supplemental oxygen). Night shift was chosen for feasibility, as daytime included rounding and other clinical tasks. After a 2-month observation period, we had a better understanding that many alarm notifications were commonly non-actionable and thus could be targeted for alarm logic PDSAs.

Testing began with middleware-mediated intentional alarm delays from the bedside monitor to the nurse's phone (figure 1, generation 1). An alarm delay required that the alarm threshold be exceeded for a prespecified amount of time (the 'delay') before sending the alarm notification to the bedside provider. Delays allow for

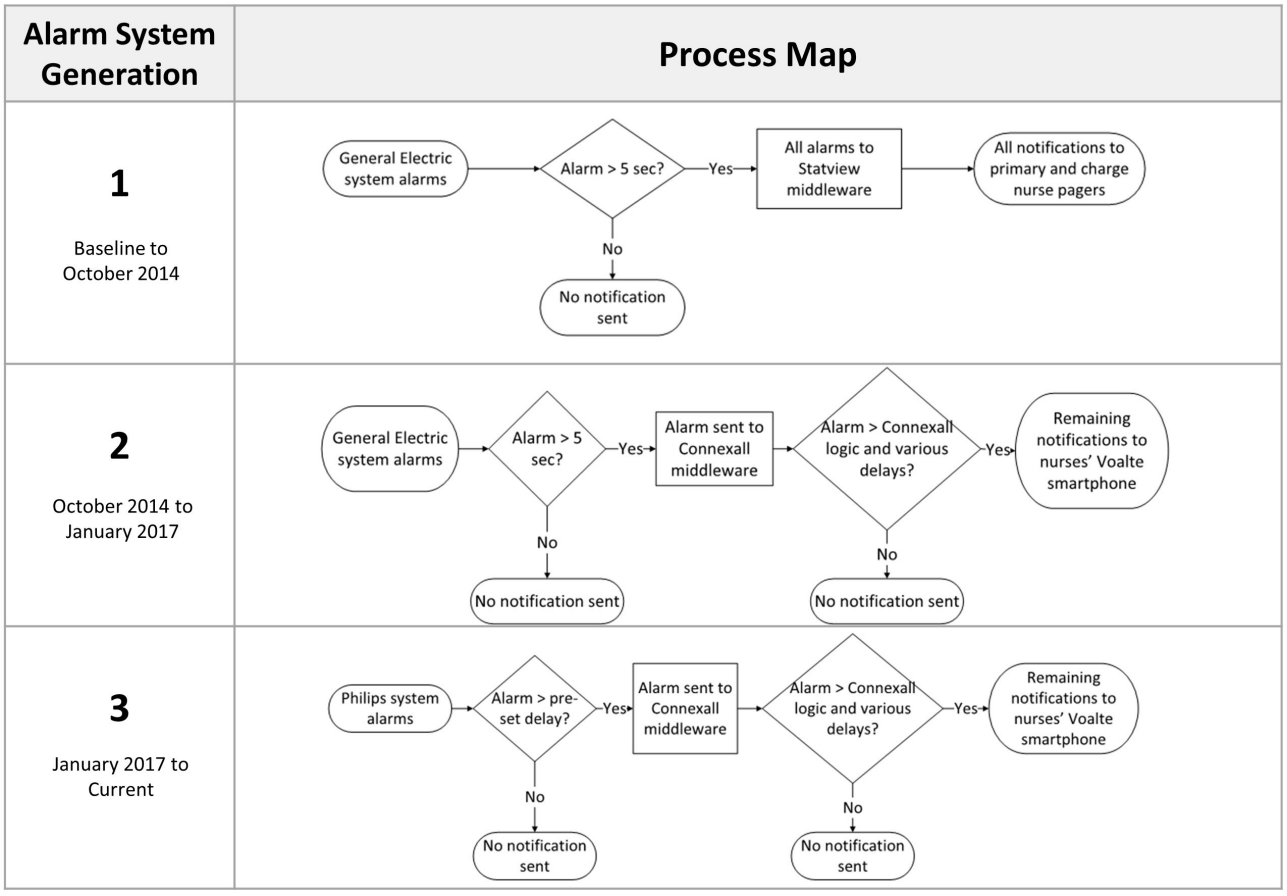

Figure 1 Alarm system generations and associated process map. In generation 1, after a 5 s delay, the General Electric monitor system sends all alarms to Statview middleware, which sends all notifications without delay to primary and charge nurse pagers. The generation 2 alarm system included Connexall middleware, which implemented alarm logic and varying delays before sending notifications to nurses' Voalte smartphone. Finally, in generation 3, the General Electronic monitor system was replaced by a Philips monitor system, which implemented additional alarm logic and varying delays. All subsequent notifications were sent through the Connexall middleware then directly to nurses' Voalte smartphone.

filtering out alarms that were false or not felt to be significant; if an alarm outlasted the delay, it was more likely not to be artefactual. After rigorous testing with safety surveillance, and the subsequent adoption of a new monitor system, the delay algorithms transitioned from middleware-mediated logic to a combination of logic from the middleware and the bedside monitor (figure 1, generation 3).

We tested delay times and also the vital sign thresholds needed to trigger an alarm notification for a variety of parameters: oxygen saturation (SpO_2), heart rate, ECG couplets per minute and the number of premature ventricular contractions (PVC) per minute. We began with conservative measures and gradually liberalised our approach as our learning developed. For example, for alarms related to high SpO_2 above a set threshold, we started with an alarm notification delay of 1 min; this was eventually increased to 5 min. The alarm notification delays for low SpO_2 readings were adjusted based on the severity of hypoxia. After progressive rounds of testing over years the following alarm notification delays were adopted: (1) SpO_2 less than 60%, no delay, (2) SpO_2 between 60% and 69%, a 15 s delay, (3) SpO_2 between 70% and 79%, a 30 s delay, and (4) SpO_2 between 80% and 89%, a 60 s delay (online supplementary table 1). Fifteen-second delays were adopted for high and low heart rates, and low respiratory rates.

Finally, we deactivated 20 non-actionable system-level default alarms that originated from mechanical or technical issues, such as alarms for respiratory rate lead detachment or poor SpO_2 signal connectivity (online supplementary table 2). Building on the system alarm learnings, similar non-actionable system alarms were deactivated in generation 3 (online supplementary table 3), with a 120 s delay added to the actionable system alarms such as ECG leads off (online supplementary table 4).

The approach to these parameters was incremental and included ongoing, careful review of safety process measures. Importantly, alarm logic interventions affected only the alarm notifications, with the visual monitor displays continuing to reflect current patient parameters.

Process changes

We prioritised process changes restructuring who receives alarm notifications and when, particularly for

Table 1 Specific interventions, alarm system generation and timing for each intervention

Category of intervention	Specific interventions	Alarm system generation	Timing
New technology	Voalte implementation with Connexall integration	2	October 2014
	Airstrip go-live	2	December 2014
	New monitor system go-live	3	January 2017
	Airstrip discontinuation	3	January 2017
Alarm logic	Progressive increase of low SpO_2 alarm delays		
	► Step 1 delay: +5 s for all alarms except SpO_2<60%	2	October 2015
	► Step 2 additional delay: +15 s for 80%<SpO_2<100% +10 s for 70%<SpO_2<79% +5 s for 60%<SpO_2<69%	2	April 2016
	► **Step 3 additional delay:** **+40 s for 80%<SpO_2<100%** **+15 s for 70%<SpO_2<79%** **+5 s for 60%<SpO_2<69%**	3	February 2017
	Progressive increase of high SpO_2 alarm delays, if parameter set		
	► Step 1 delay: +60 s for SpO_2>90%	2	June 2015
	► Step 2 delay: +300 s for SpO_2>90%	2	April 2016
	Progressive increase in amount of ventricular ectopy per minute needed to trigger alarm		
	► Ventricular couplets >5 per minute	2	January 2015
	► PVCs >30 per minute	3	February 2017
	Deactivation of 20 system-level alarms	2	February 2015
	Addition of high heart rate alarm delay (if rate <220 bpm), +15 s	2	April 2016
	Addition of low heart rate and respiratory rate alarm delay, +15 s	3	February 2017
	Delay of remaining system-level alarms, +120 s	3	February 2017
Process changes	Decrease initial and secondary notifications of alarms to nursing via escalation algorithms		
	► Algorithm 1: Secondary notifications resent to primary and charge nurse after 20 s delay	2	March 2015
	► Algorithm 2: +40 s to delay for secondary notification; charge nurse removed from initial notifications for low and medium acuity alarms, buddy nurse added to initial and secondary notification for medium acuity alarms and instead of charge nurse for secondary notification of low-acuity alarms; all staff received secondary notification of high-acuity alarms; tertiary notification to all staff added for low and medium-acuity alarms after additional 60 s delay	2	June 2016
	► **Algorithm 3: Only primary nurse receives initial notification for low and medium-acuity alarms, only primary nurse and buddy nurse receive secondary notifications; tertiary notifications sent to specific staff based on acuity**	3	March 2017
	Turn off in-room alarm volume	2	November 2015
	Improve per cent of leads changed every 24 hours to >80%	2	January 2016
	Condition-specific vital sign alarm parameters	3	January 2017

Bold indicates key interventions annotated on statistical process control charts.
PVC, premature ventricular contraction; SpO_2, pulse oxygenation level.

charge nurses who received a large burden of alarm notifications. We developed an algorithm of staged alarm notifications, with an initial alarm notification sent to specific nurse recipients, removing the charge nurse from receiving these notifications if it was not a high-acuity alarm such as ventricular tachycardia. If the alarm continued after a specified amount of time, a 'secondary' alarm notification would be resent to the initial recipients, with additional nurses added. We assigned 'buddy' bedside nurses to receive all secondary alarm notifications along with the primary bedside nurse, further relieving the charge nurse. We began with a specified 20 s delay between the initial and secondary alarm notifications. After careful consideration and patient safety monitoring, we increased the delay to 60 s before resending secondary alarm notifications. A 'tertiary' alarm notification was also added with a specified 60 s delay before resending alarm notifications to designated recipients. The final registered nurse (RN) escalation algorithm is shown in online supplementary figure 1.

Additional process changes included incorporating team discussions of patient-specific vital sign parameters and the need for continuous versus spot-check SpO_2 and telemetry into daily rounds. We implemented a manual process to track and improve the frequency of electrode lead replacement every 24 hours, due to evidence that this reduces the number of alarms without affecting safety parameters.[11 14] Interventions to this process included real-time follow-up for lead change failures, sending emails to bedside providers assessing barriers to lead change, adding lead replacement to the evening bathing routine and nursing reminders.

Patient- and family-targeted interventions

In order to decrease the burden of non-actionable alarms on families, we silenced all alarms in patient rooms starting November 2015. This intervention developed as a result of PDSA cycles and continued attention to patient safety and comfort. It was tested only after alarm logic had been safely incorporated into daily practice and nursing consistently received all intended alarm notifications. Of note, the alarm system retained the following intentionally redundant mechanisms: (1) silent visual displays on bedside monitors, (2) audible and tactile alarm notifications on smartphones, (3) audible alarm notifications at the nurses' station, and (4) a hard-wired and hospital-wide audible and visual hallway system for code and other emergency use. The testing that drove silencing in-room alarm volume required substantial communication and buy-in among nursing staff, ancillary staff members, physicians and patient families.

Measures

The primary outcome measure was the reduction of initial alarm notifications per monitored bed per day averaged by month. Following the introduction of middleware, we also followed the proportion of initial alarm notifications relative to the total alarm notifications per month as a process measure. This measure monitored the impact of changes to the alarm notification strategy on the overall burden of alarm notifications to bedside providers. We extracted the number of alarms and alarm notifications directly from the monitors and middleware platforms.

Our secondary outcome measure was nursing satisfaction as assessed by an internal, non-validated survey. We conducted the survey in October 2015 and February 2016, around the time of the low SpO_2 delay testing. The email-distributed online survey contained three questions with categorical responses including 'strongly agree, agree, disagree, strongly disagree', and one question with categorical responses including 'rarely or never, once per month, once per week, once per shift, multiple instances per shift'.

Safety process measures included an internal, non-validated patient acuity scoring system (Safety Assessment and Focused Evaluation; SAFE) to monitor patient status as a balancing measure. The SAFE score is similar to Paediatric Early Warning Score but with modifications specific to a cardiac population,[15] and its use since 2011 predates the alarm reduction quality improvement (QI) work (online supplementary table 5). We used this tool as a safety balancing measure because we believe that a change in patient acuity, reflected by an increased score, may reflect unrecognised clinical decompensation due to decreased alarms on the unit. The monthly proportion of SAFE scores that were 4 or greater (the level at which a provider must be notified) for every 10 patients was monitored. Additional safety balancing measures included rates of medical emergency team (MET) activation and transfers to the cardiac intensive care unit (CICU),[16] each measured per 1000 patient-days. We also tracked readmission rates to the ACCU less than 7 days after discharge and monitored adverse events such as codes on the unit from the electronic health record.

Analysis

We used statistical process control charts to monitor the following measures: initial alarm notifications (XMR chart), proportion of initial to total alarm notifications (P chart), per cent of patients with leads changed every 24 hours (P chart), MET activations and CICU transfers (XMR chart) and proportion of SAFE scores greater than or equal to 4 (P chart). We used established rules to determine if observed changes were common cause variation or due to special cause variation.[17]

For the purposes of this project, we created two categories for the survey results including 'strongly agree or agree' and 'strongly disagree or disagree' for the first three questions and 'once per month or less' and 'once per week or more' for the fourth question. We analysed the nurse survey data with χ^2 and Fisher's exact test as indicated to assess categorical measures.

RESULTS

Alarm notifications

Average initial alarm notifications improved, as evidenced by special cause variation, after implementation of two early interventions: increasing the number of PVCs needed to trigger an alarm and deactivating system alarms. Over 6 months between October 2014 and March 2015, alarm notifications decreased from 71.0 to 37.1 initial alarm notifications per monitored bed per day (figure 2). After an additional 2 years of testing (approximately March 2015 to March 2017), including high and low SpO_2 alarm delays, modifying the RN escalation algorithms and introducing a new alarm system, special cause reduction was again seen, with the average initial alarm notifications decreasing to 22.4 per monitored bed per day. This represented a total reduction of 68% over the intervention period.

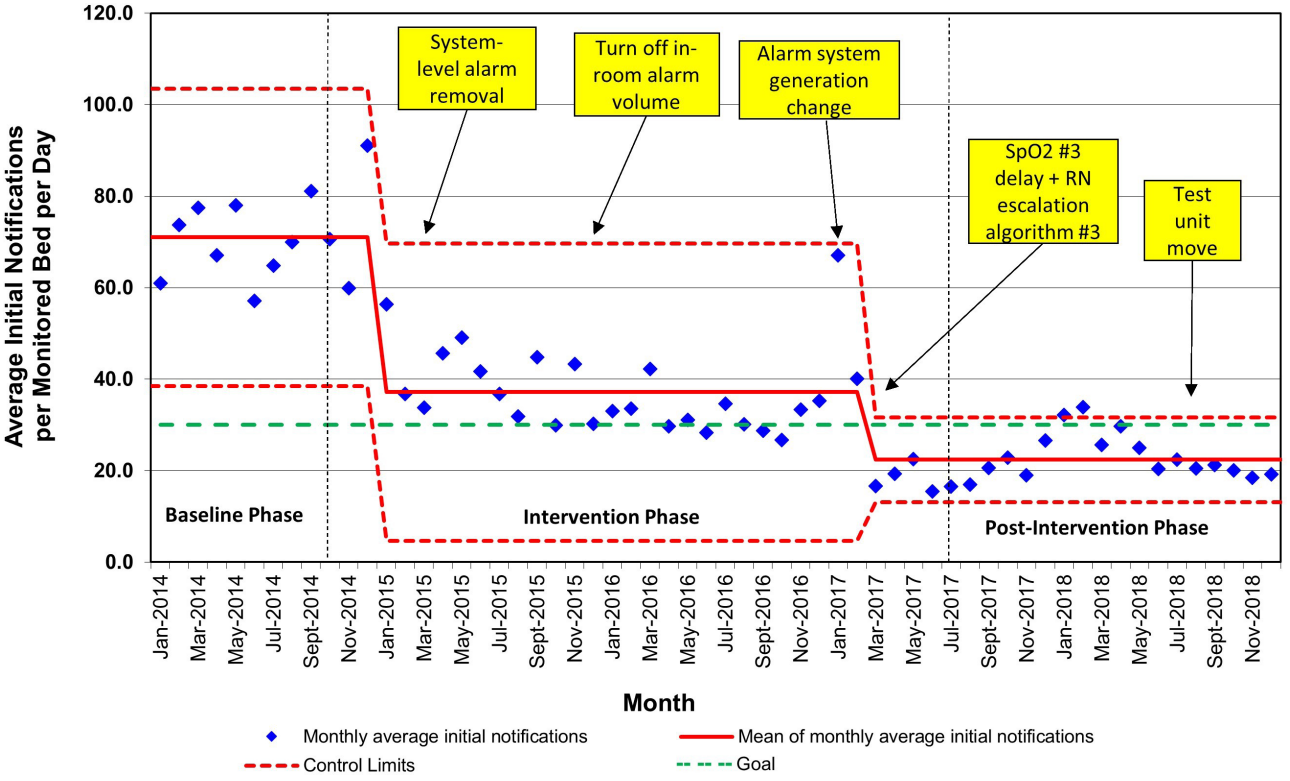

Figure 2 Average initial notifications per monitored bed per day, by month. RN, registered nurse.

These improvements have been sustained for greater than 18 months.

Special cause variation was seen in the average initial alarm notifications per monitored bed per day in January and February 2018 (figure 2) and number of MET calls and CICU transfers at that time, occurring concurrently with an increase in patient acuity due to seasonal illnesses. On review, there was no evidence of root cause within the alarm management strategy. Of note, no special cause variation was seen at the time of the ACCU moving its physical location within the hospital (August/September 2018), expanding from 17 to 24 beds.

Nursing satisfaction

Thirty-eight nurses participated in the survey prior to testing low SpO_2 interventions, and 25 nurses participated following the testing (table 2). Prior to this testing, 92% of nurses surveyed from the ACCU (n=35 of 38) either strongly agreed or agreed that 'nuisance

Table 2 Nursing satisfaction scores at baseline and 3 months after initial testing with low SpO_2 alarm delay

	October 2015 n=38		February 2016 n=25		
Survey question	Strongly agree or agree	Strongly disagree or disagree	Strongly agree or agree	Strongly disagree or disagree	P value
The majority of the time SpO_2 alarms are 'nuisance alarms' and do not require any action from the bedside nurse.	35 (92%)	3 (8%)	11 (44%)	14 (56%)	**<0.001**
SpO_2 alarms on the ACCU are adequate to alert bedside nursing staff to all clinically important oxygen saturation changes in the patient's condition.	32 (84%)	6 (16%)	23 (92%)	2 (8%)	0.46
The current frequency of alarms is at such a level that the bedside nurse is able to receive and respond to every alarm appropriately and quickly.	12 (32%)	26 (68%)	19 (76%)	6 (24%)	**<0.001**
	Once per month or less	Once per week or more	Once per month or less	Once per week or more	
When you provide bedside care, at what rate do you estimate that clinical SpO_2 alarms are missed and/or your response to a patient's clinical oxygenation is delayed?	16 (42%)	22 (58%)	18 (72%)	7 (28%)	**0.02**

Bold indicates statistical significance, p <0.05.

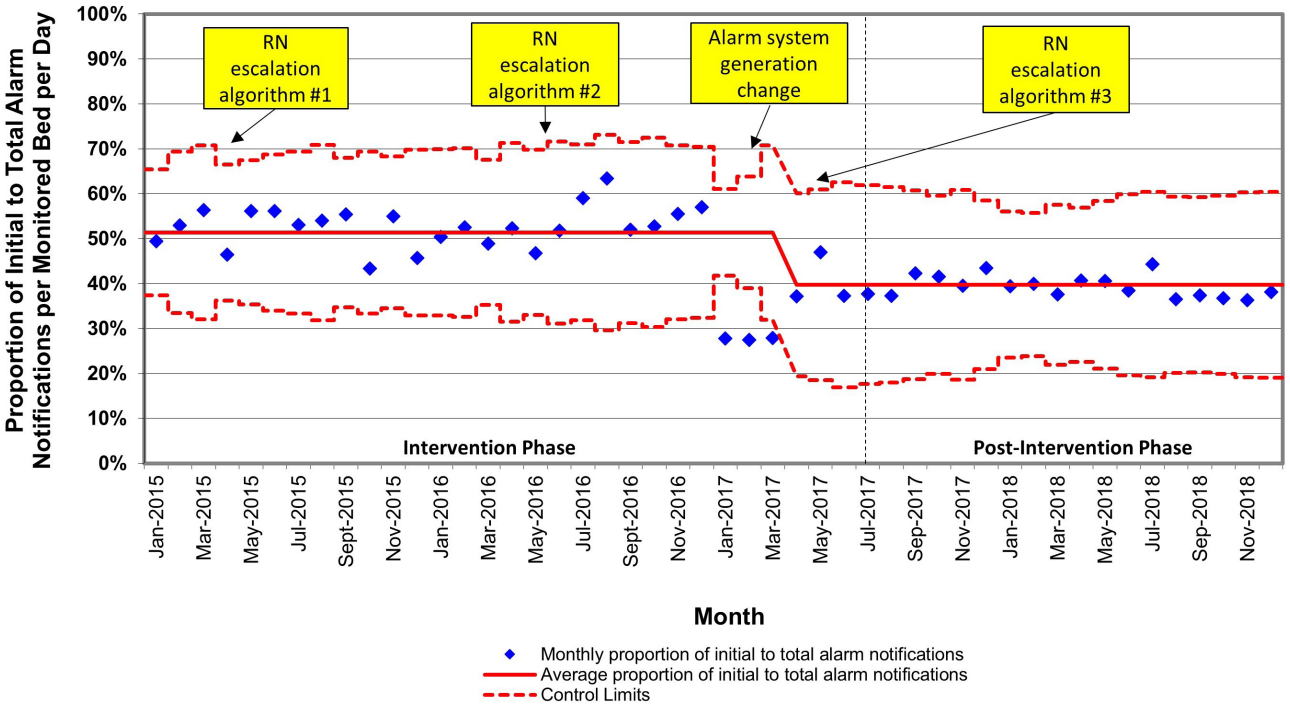

Figure 3 Proportion of initial alarm notifications to total alarm notifications per monitored bed per day, by month. RN, registered nurse.

alarms occur frequently', compared with only 44% after (n=11 of 25; p<0.001). Similarly, prior to testing, 68% of nurses (n=26 of 38) either strongly disagreed or disagreed that 'the bedside nurse is able to receive and respond to every alarm appropriately and quickly' compared with only 24% of nurses after (n=6 of 25; p<0.001). Additionally, prior to testing, the majority of nurses 'estimate that clinical SpO_2 alarms are missed and/or your response to a patient's clinical oxygenation is delayed' once per week or more (58%, n=22 of 38). On follow-up assessment, nurses felt that these events occurred once a month or less (72%, n=18 of 25, p=0.02).

Process and safety measures

The proportion of average initial alarm notifications to total alarm notifications did not change during early testing (figure 3, baseline 51%). Special cause variation was seen after the introduction of alarm system generation 3 and the third RN escalation algorithm, with a decrease to 40%. This reduction was felt to be an appropriate baseline for the new system. Baseline compliance with lead changes every 24 hours was 60%, and ultimately reached 85% (online supplementary figure 2).

With regard to balancing measures, the per cent of SAFE scores greater than or equal to 4, per 10 patients, did not vary greatly (online supplementary figure 3). At baseline, 5% of patients received a SAFE score greater than or equal to 4. In January 2015, prior to any major interventions in alarm reduction, special cause variation was seen with an increase to 10% that was reflective of ACCU patient acuity changes not associated with this QI effort (including an increased use of mechanical circulatory support and inotropic agents). Importantly, there was not an associated increase in METs and floor to intensive care unit transfers. The per cent of patients who received a SAFE score of greater than or equal to 4 remained stable at 10% throughout the testing period, until special cause variation was again seen with a decrease to 7.5% in January 2017.

The rate of METs and CICU transfers per 1000 patient-days remained stable at an average of 2.8 METs and 2.5 CICU transfers per 1000 patient-days (online supplementary figure 4). Similar to the special cause variation seen in the average initial alarm notifications per monitored bed per day, special cause variation was seen in the rate of METs per 1000 patient-days in January to February 2018 and again in January to February 2019, concurrent with seasonal changes in patient acuity. There was no change in the rate of less-than-7-day readmission during the study period (approximately 6.8% throughout).

DISCUSSION

We safely reduced the number of alarm notifications by 68% on a single paediatric ACCU over a 3.5-year period using QI methodology. The evidence-driven and novel interventions included high-reliability changes such as integrating new technology, implementing alarm logic and changing the nursing staff alarm notification process, including silencing the in-room monitor. The combination of these interventions enabled sustained improvements in initial alarm notifications for 18 months while monitoring overall

alarm burden. Coincident with alarm reduction, nursing experience improved. Indicators of patient safety, including SAFE scores, rates of METs and CICU transfers, and readmissions remained stable during the intervention phase, demonstrating common cause variation.

Likely, this work was successful because of the multifaceted nature, addressing the human, organisational and technical factors needed to improve alarm systems within a hospital setting.[18] Partnering with stakeholders such as clinical leadership, bedside providers and technical staff was critical. Our approach incorporated many evidence-based interventions previously shown to reduce alarm notifications,[19] such as implementing alarm delays,[20] changing ECG electrodes daily[11] and generating algorithms for alarm notification.[21 22] Previously, these strategies successfully decreased the number of alarms per patient-day over fourfold without compromising patient safety.[11 23] This work builds on these examples, but uniquely includes the first detailed use of alarm logic in a paediatric population and the first described systematic approach to silencing alarms within patient rooms.

Customisation of alarm logic is increasingly recognised as an effective solution to reduce alarms.[18 24 25] Graduated algorithms mean that for time-sensitive changes, the correct bedside providers are quickly notified and are able to respond appropriately, and for less time-sensitive changes, are not interrupted too early or too often. We capitalised on the ability to customise alarm logic, particularly with the low SpO_2 alarm notification delays. Many paediatric low SpO_2 alarms are artefact due to child movement, or transient and not representative of an actionable clinical change. The SpO_2 delays achieved using QI methodology are greater than predicted at the outset of this work, but the measured safety data strongly support the value of these parameters. Opportunity likely remains for additional delays and refinement.

Nursing staff satisfaction was prioritised as an outcome given evidence that reducing non-actionable alarm frequency is associated with improved nursing satisfaction and morale.[22] A decrease in alarm notifications can also help reduce nursing's perceived workload and improve work environment satisfaction.[26 27] Following interventions, ACCU nursing staff felt that they were more sensitive to alarms, that alarm notifications were more likely to alert them to important changes in the patient's condition and that alarms were less likely to be a nuisance. Subsequent efforts to measure the correlation between nursing staff retention and the unit alarm environment would be warranted.

Guidance on alarm management is available,[28] but evidence-based 'best practice' alarm utilisation guidelines do not yet exist in paediatric populations,[29] so our improvement team was empowered to challenge typical alarm conventions. Current alarm systems like ours employ a number of visual and auditory redundancies under the premise that more alarms are better. Therefore, silencing the in-room alarm volume was one of our most notable challenges to typical alarm management. The QI and nursing team observed that once alarms were consistently delivered to the individual and targeted provider, in-room audible signals seemed overly redundant, and served to awake/irritate/traumatise patients and families. Patients and caregivers desire that alarms are not heard in the patient room,[30] but testing this idea has not been previously reported. Assessing this intervention's effect on patient and family experience is ongoing, but first-hand reports continue to support its utility. The practice required significant change management and partnership with all key stakeholder services. However, it has been one of the most popular changes among the staff and families. Importantly, a wireless network outage demonstrated that the intervention is easily reversible if needed, simply by turning the alarm monitor volume back on.

Limitations

Given the lack of 'best-practice' evidence, we employed a conservative approach to testing. The safety balancing measures were monitored carefully for special cause variation, and the improvement team remained sensitive for sentinel patient events that could be associated with delayed alarm recognition (such as ACCU codes or patient deaths, of which there were none). However, this study was not powered specifically to detect differences in patient safety outcomes.

Two areas of limited measurement include the clinical activity of the nursing team and the patient/family experience. Night shift nursing documentation of clinically actionable alarms was comprehensive, but was dependent on subject participation and was not monitored throughout the study period. Assessing the rate of current non-actionable alarms in a more rigorous fashion may be an important next step for future studies, such as with the use of video-assisted tracking.[10 31] Such tracking could assist in an improved understanding of the optimal initial to total alarm notification ratio, as we believe a proportion of 40% represents a reasonable amount of actionable initial notifications, but the ideal amount is unknown. Similarly, patient/family experience was not optimally measured over the course of this work. Anecdotal experience suggests that the alarm notification reduction has a positive impact on patients and families, as has been previously described,[27] but there is not quantifiable evidence to support this aspect of the work.

The interventions described may be challenging to implement at institutions without technical support, the capability to measure alarms and notifications and familiarity with QI methodology. The results may also have been influenced by secular trends or other unmeasured factors. Additionally, this was a single-unit

study with a specific patient population, and the findings may not generalise to other populations or institutions. However, the ACCU population is a complex and fragile patient group, and given the absence of negative impacts on patient safety, these findings can be suggested to apply fairly to other patient populations.

CONCLUSIONS

Alarm notifications were reduced successfully, with a correlating improvement in nursing satisfaction and without a negative impact to patient safety, using a multidisciplinary approach and QI methodology. The learnings and results, from a tertiary care unit with medically fragile patients, could be considered for testing within other inpatient populations with similar or less complexity. Currently, these practice changes are spreading to all units across our hospital system. In addition, the team is pursing active partnership with other paediatric institutions to examine the results of spread. Tailoring the alarm interventions presented here to other populations may improve the quality of care for hospitalised children and the inpatient experience for our patients, families and staff, while maintaining the highest standards for patient safety.

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SUPPLEMENTAL TABLES/FIGURES

Supplemental Table 1: Current version of high (>92%) and low SpO2 delays used in alarm logic

Saturation (%)	Monitor Alarm Delay (sec)	Middleware Delay (sec)	Total Delay (sec)	Alarm Acuity
> 92	300	0	300	Medium
80-100	60	0	60	Medium
70-79	30	0	30	Medium
60-69	15	0	15	Medium
<60	0	0	0	High

"High" acuity refer to critical alarms requiring immediate attention, such as ventricular tachycardia.
"Medium" acuity refer to warning alarms requiring prompt attention, such as elevated heart rates.
"Low" acuity refers to advisory alarms, such as low ability to sense SpO2 or lead detachment.

Supplemental Table 2: Generation 2 non-alerting General Electric system alarms filtered by Connexall

ACC VENT	NBP MAX TIME	NURSE CALL	SENSOR
ARTIFACT	NBP MODULE	PVC	SPO2 ARTIFACT
BIGEMINY	NBP OVER PRES	R ON T	SPO2 PROBE
CONNECT PROBE	NO BREATH	RR LEADS FAIL	SPO2 SENSOR
NBP FAIL	NO ECG	RSP HI	SPO2M LO

Supplemental Table 3: Generation 3 non-alerting Philips system alarms filtered via Connexall

!!Check Patient ID	AO No Transducer	ARTs xx > yy	CPP HI
3D Desat Idx 6	AO Noisy Signal	awRR xx < yy	CPP Interrupted
3D Desat Idx 7	AO Overrange	awRR xx > yy	CPP LOW
A Lead Off	AO Unplugged	Batt Empty	CPP Measure Failed
ABP Artifact	AO Zero+Check Cal	Batt Incompat	CPP No Pulse
ABP Change Scale	AoD HI	Batt Low	CPP No Transducer
ABP Chk Sources	AoD LOW	Batt Malfunction	CPP Noisy Signal
ABP Cuff Overpress	AoD xx < yy	Brady/P LO	CPP Overrange
ABP Deactivated	AoD xx > yy	Brady/P xx < yy	CPP Unplugged
ABP Disconnect	AoM HI	Cannot Analyze ECG	CPP xx < yy
ABP Equip Malf	AoM LOW	Cannot Analyze QT	CPP xx > yy
ABP Interrupted	AoM xx < yy	Cannot Analyze ST	CPP Zero+Check Cal
ABP Measure Failed	AoM xx > yy	Cannot Analyze STE	Cuff Not Deflated
ABP No Pulse	AoS HI	Charger Malfunct	CVP Artifact
ABP No Transducer	AoS LOW	Check ECG Source	CVP Change Scale
ABP Noisy Signal	AoS xx < yy	Check Equipment	CVP Chk Sources
ABP Overrange	AoS xx > yy	Check Keyboard	CVP Cuff Overpress
ABP Unplugged	ART Artifact	Check Patient ID	CVP Deactivated

Supplemental File 1

ABP Zero+Check Cal	ART Change Scale	Check Settings	CVP Disconnect
ABPd HI	ART Chk Sources	Check Touch Input	CVP Equip Malf
ABPd LOW	ART Cuff Overpress	Check Touchscreen	CVP Interrupted
ABPd xx < yy	ART Deactivated	Check Watertrap	CVP Measure Failed
ABPd xx > yy	ART Disconnect	Chk ECG Settings	CVP No Pulse
ABPm HI	ART Equip Malf	Chk ECG Sync Cable	CVP No Transducer
ABPm LOW	ART Interrupted	Chk MSL Connection	CVP Noisy Signal
ABPm xx < yy	ART Measure Failed	Chk SyncOut Cable	CVP Overrange
ABPm xx > yy	ART No Pulse	CO2 Auto Zero	CVP Unplugged
ABPs HI	ART No Transducer	CO2 Change Scale	CVP Zero+Check Cal
ABPs LOW	ART Noisy Signal	CO2 Deactivated	CVPd HI
ABPs xx < yy	ART Overrange	CO2 Equip Malf	CVPd LOW
ABPs xx > yy	ART Unplugged	CO2 No Tubing	CVPd xx < yy
Agent Mixture	ART Zero+Check Cal	CO2 Occlusion	CVPd xx > yy
Align Watertrap	ARTd HI	CO2 Overrange	CVPm HI
AO Artifact	ARTd LOW	CO2 Pump Off	CVPm LOW
AO Change Scale	ARTd xx < yy	CO2 Purging	CVPm xx < yy
AO Chk Sources	ARTd xx > yy	CO2 Sens Warmup	CVPm xx > yy
AO Cuff Overpress	ARTm HI	CPP Artifact	CVPs HI
AO Deactivated	ARTm LOW	CPP Change Scale	CVPs LOW
AO Disconnect	ARTm xx < yy	CPP Chk Sources	CVPs xx < yy
AO Equip Malf	ARTm xx > yy	CPP Cuff Overpress	CVPs xx > yy
AO Interrupted	ARTs HI	CPP Deactivated	dSpO2 Chk Sources
AO Measure Failed	ARTs LOW	CPP Disconnect	E Lead Off
AO No Pulse	ARTs xx < yy	CPP Equip Malf	ECG Check Cable
ECG Noisy Elec LA	ICPm xx > yy	Meas, Deactivated	No Data T-Mon
ECG Noisy Elec LL	ICPs HI	Missed Beat	Non-Sustain VT
ECG Noisy Elec RA	ICPs LOW	MMS Ext, Unplugged	P Unplugged
ECG Noisy Elec V	ICPs xx < yy	MMS Ext, Unpowered	P Artifact
ECG NoisySignal	ICPs xx > yy	MMS Ext,Equip Malf	P Change Scale
ECG Out Equip Malf	imCO2 xx < yy	MMS Extension Malf	P Chk Sources
ECG/Arrh AlarmsOff	imCO2 xx > yy	MMS Malf	P Cuff Overpress
EcgRsp Deactivated	Insert Battery	MMS Msmt Malf	P Deactivated
Event:Sat LOW	IPI Check Pat, Age	MMS Unplugged	P Disconnect
ExtBat Missing	IPI Check Sources	MMS Unsupported	P Equip Malf
FMS Unplugged	IPI xx < yy	MSL Power Overload	P Interrupted
FMS Unsupported	IPI xx > yy	Multiform PVCs	P Measure Failed
GM Alarm Suppress	Irregular HR	NBP Artifact	P No Pulse
GM Standby	LA Lead Off	NBP Change Scale	P No Transducer
GM Unplugged	LAP Artifact	NBP Chk Sources	P Noisy Signal
GM Warmup	LAP Change Scale	NBP Cuff Overpress	P Overrange
GM Zero Running	LAP Chk Sources	NBP Deactivated	P Zero+Check Cal
Grade ? Unknown	LAP Cuff Overpress	NBP Disconnect	Pacer Not Capt
HR High	LAP Deactivated	NBP Equip Malf	Pair PVCs
HR Low	LAP Disconnect	NBP Interrupted	PAP Artifact
I Lead Off	LAP Equip Malf	NBP Measure Failed	PAP Change Scale
ICP Artifact	LAP Interrupted	NBP No Pulse	PAP Chk Sources
ICP Change Scale	LAP Measure Failed	NBP No Transducer	PAP Cuff Overpress
ICP Chk Sources	LAP No Pulse	NBP Noisy Signal	PAP Deactivated
ICP Cuff Overpress	LAP No Transducer	NBP Overrange	PAP Disconnect
ICP Deactivated	LAP Noisy Signal	NBP Unplugged	PAP Equip Malf
ICP Disconnect	LAP Overrange	NBP Zero+Check Cal	PAP Interrupted
ICP Equip Malf	LAP Unplugged	NBPd High	PAP Measure Failed

Supplemental File 2

ICP Interrupted	LAP Zero+Check Cal	NBPd LOW	PAP No Pulse
ICP Measure Failed	LAPd HI	NBPd xx < yy	PAP No Transducer
ICP No Pulse	LAPd LOW	NBPd xx > yy	PAP Noisy Signal
ICP No Transducer	LAPd xx < yy	NBPm High	PAP Overrange
ICP Noisy Signal	LAPd xx > yy	NBPm LOW	PAP Unplugged
ICP Overrange	LAPm HI	NBPm xx < yy	PAP Zero+Check Cal
ICP Unplugged	LAPm LOW	NBPm xx > yy	PAPd HI
ICP Zero+Check Cal	LAPm xx < yy	NBPs High	PAPd LOW
ICPd HI	LAPm xx > yy	NBPs LOW	PAPd xx < yy
ICPd LOW	LAPs HI	NBPs xx < yy	PAPd xx > yy
ICPd xx < yy	LAPs LOW	NBPs xx > yy	PAPm HI
ICPd xx > yy	LAPs xx < yy	No 3D Desat Index	PAPm LOW
ICPm HI	LAPs xx > yy	No Central Monit,	PAPm xx < yy
ICPm LOW	Leadset Unplugged	No Data Monitor	PAPm xx > yy
ICPm xx < yy	LL Lead Off	No Data Tele	PAPs HI
PAPs LOW	RAPd xx > yy	SpO2l ReplaceSensr	SpO2r Searching
PAPs xx < yy	RAPm HI	SpO2l Searching	SpO2r Sensor Malf
PAPs xx > yy	RAPm LOW	SpO2l Sensor Malf	SpO2r Unplugged
Pause	RAPm xx < yy	SpO2l Unplugged	SpO2r xx < yy
Pd xx < yy	RAPm xx > yy	SpO2l xx < yy	SpO2r xx > yy
Pd xx > yy	RAPs HI	SpO2l xx > yy	ST High
Perf High	RAPs LOW	SpO2po Chk Sensor	ST Low
Perf Low	RAPs xx < yy	SpO2po Chk Sources	ST Multi aVF,I
Perf xx < yy	RAPs xx > yy	SpO2po Equip Malf	ST Multi aVF,II
Perf xx > yy	Repl, Tele Batt	SpO2po Low	ST Multi aVF,III
Perfl xx < yy	Resp Leads Off	SpO2po Low Perf	ST Multi aVL,I
Perfl xx > yy	RL Lead Off	SpO2po No Pulse	ST Multi aVL,II
PerfPo xx < yy	R-on-T PVCs	SpO2po Poor Signal	ST Multi aVL,III
PerfPo xx > yy	RR High	SpO2po ReplaceSensr	ST Multi aVR,I
PerfPr xx < yy	RR Low	SpO2po Searching	ST Multi aVR,II
PerfPr xx > yy	RR xx > yy	SpO2po Sensor Malf	ST Multi aVR,III
PPV bad ART Signal	Run PVCs High	SpO2po Unplugged	ST Multi I ,aVL
PPV Chk Sources	S Lead Off	SpO2po xx < yy	ST Multi I ,aVR
Pulse High	Some ECG AlarmsOff	SpO2po xx > yy	ST Multi II ,aVF
Pulse Low	Speaker Malfunct	SpO2poInterference	ST Multi II ,aVR
Pulse xx < yy	SpO2 Chk Sensor	SpO2pr Chk Sensor	ST Multi III,aVF
Pulse xx > yy	SpO2 Chk Sources	SpO2pr Chk Sources	ST Multi III,aVR
QT High	SpO2 Equip Malf	SpO2pr Equip Malf	ST Multi V3 ,V4
QT Low	SpO2 High	SpO2pr Low	STE aVF ,I
RA Lead Off	SpO2 Interference	SpO2pr Low Perf	STE aVF ,II
RAP Artifact	SpO2 Low	SpO2pr No Pulse	STE aVF ,III
RAP Change Scale	SpO2 Low Perf	SpO2pr Poor Signal	STE aVL ,I
RAP Chk Sources	SpO2 No Pulse	SpO2pr ReplaceSensr	STE aVL ,II
RAP Cuff Overpress	SpO2 Poor Signal	SpO2pr Searching	STE aVL ,III
RAP Deactivated	SpO2 ReplaceSensr	SpO2pr Sensor Malf	STE aVR ,I
RAP Disconnect	SpO2 Searching	SpO2pr Unplugged	STE aVR ,II
RAP Equip Malf	SpO2 Sensor Malf	SpO2pr xx < yy	STE aVR ,III
RAP Interrupted	SpO2 Unplugged	SpO2pr xx > yy	STE I ,aVF
RAP Measure Failed	SpO2 xx < yy	SpO2prInterference	STE I ,aVL
RAP No Pulse	SpO2 xx > yy	SpO2r Chk Sensor	STE I ,aVR
RAP No Transducer	SpO2l Chk Sensor	SpO2r Chk Sources	STE II ,aVF
RAP Noisy Signal	SpO2l Chk Sources	SpO2r Equip Malf	STE II ,aVL
RAP Overrange	SpO2l Equip Malf	SpO2r Interference	STE II ,aVR

Supplemental File 3

RAP Unplugged	SpO2l Interference	SpO2r Low	STE III ,aVF
RAP Zero+Check Cal	SpO2l Low	SpO2r Low Perf	STE III ,aVL
RAPd HI	SpO2l Low Perf	SpO2r No Pulse	STE III ,aVR
RAPd LOW	SpO2l No Pulse	SpO2r Poor Signal	ST-I xx < yy
RAPd xx < yy	SpO2l Poor Signal	SpO2r ReplaceSensr	ST-I xx > yy
ST-II xx < yy	Tesoph xx > yy	UAP No Pulse	UVPs LOW
ST-II xx > yy	TesophNoTransducer	UAP No Transducer	UVPs xx < yy
ST-III xx < yy	Tnaso Deactivated	UAP Noisy Signal	UVPs xx > yy
ST-III xx > yy	Tnaso Equip Malf	UAP Overrange	V Lead Off
ST-MCL xx < yy	Tnaso High	UAP Unplugged	V1 Lead Off
ST-MCL xx > yy	Tnaso Low	UAP Zero+Check Cal	V2 Lead Off
ST-V xx < yy	Tnaso NoTransducer	UAPd HI	V3 Lead Off
ST-V xx > yy	Tnaso Overrange	UAPd LOW	V4 Lead Off
SyncOut Equip Malf	Tnaso xx < yy	UAPd xx < yy	V5 Lead Off
Tachy/p High	Tnaso xx > yy	UAPd xx > yy	V6 Lead Off
Tachy/p xx > yy	Trect Deactivated	UAPm HI	Vent Bigeminy
Tart Deactivated	Trect Equip Malf	UAPm LOW	
Tart Equip Malf	Trect High	UAPm xx < yy	
Tart High	Trect Low	UAPm xx > yy	
Tart Low	Trect NoTransducer	UAPs HI	
Tart NoTransducer	Trect Overrange	UAPs LOW	
Tart Overrange	Trect xx < yy	UAPs xx < yy	
Tart xx < yy	Trect xx > yy	UAPs xx > yy	
Tart xx > yy	Tskin Deactivated	Unsupported LAN	
Tcore Deactivated	Tskin Equip Malf	UVP Artifact	
Tcore Equip Malf	Tskin High	UVP Change Scale	
Tcore High	Tskin Low	UVP Chk Sources	
Tcore Low	Tskin NoTransducer	UVP Cuff Overpress	
Tcore NoTransducer	Tskin Overrange	UVP Deactivated	
Tcore Overrange	Tskin xx < yy	UVP Disconnect	
Tcore xx < yy	Tskin xx > yy	UVP Equip Malf	
Tcore xx > yy	Tven Deactivated	UVP Interrupted	
Tele Battery Low	Tven Equip Malf	UVP Measure Failed	
TELE Weak Signal	Tven High	UVP No Pulse	
Temp Deactivated	Tven Low	UVP No Transducer	
Temp Equip Malf	Tven NoTransducer	UVP Noisy Signal	
Temp High	Tven Overrange	UVP Overrange	
Temp Low	Tven xx < yy	UVP Unplugged	
Temp NoTransducer	Tven xx > yy	UVP Zero+Check Cal	
Temp Overrange	UAP Artifact	UVPd HI	
Temp xx < yy	UAP Change Scale	UVPd LOW	
Temp xx > yy	UAP Chk Sources	UVPd xx < yy	
Tesoph Deactivated	UAP Cuff Overpress	UVPd xx > yy	
Tesoph Equip Malf	UAP Deactivated	UVPm HI	
Tesoph High	UAP Disconnect	UVPm LOW	
Tesoph Low	UAP Equip Malf	UVPm xx < yy	
Tesoph Overrange	UAP Interrupted	UVPm xx > yy	
Tesoph xx < yy	UAP Measure Failed	UVPs HI	

Supplemental File 4

Supplemental Table 4: Generation 3 Philips system alarms that alert after a 120 second delay implemented by Connexall

ECG Leads Off	SpO2l No Sensor	SpO2po Sensor Off	SpO2r No Sensor
SPO2 PROBE OFF	SpO2l Sensor Off	SpO2pr No Sensor	SpO2r Sensor Off
SpO2 No Sensor	SpO2po No Sensor	SpO2pr Sensor Off	

Supplemental Table 5: SAFE scoring algorithm used as monitoring parameter and balancing measure

ACCU SAFE TOOL		**Patient Label**	
Date: Time:			
Room:			
Nurse's Last Name:			
Watcher: YES NO			
Circle: Watcher/High Risk Therapy/Communication Concern/Family Concern			
Circle: A. Single ventricle B. Post transplant			
C. Cardiomyopathy D. VAD			
E. Other cardiac F. non -cardiac G. cath pt	Rating		Rating
Heart Rate/Rhythm:		***Behavioral Level of Consciousness/NOT RELATED TO HOSPITAL ANXIETY***	
Sinus rhythm or baseline rhythm, HR WNL or parameters	0	Relaxed, content, resting appropriately	0
Arrhythmias with stable VS & perfusion (reviewed by Fellow-no concern)	1	Slightly anxious/slightly irritable	1
Persistent brady or tachy outside of baseline or ordered parameters	2	Reassured by occasional touching, hugging, talking to , distractible	
New/increased arrhythmias with fellow/RN heightened concerns	3	Anxious, irritable, decreased activity	2
Arrhythmias with unstable VS or perfusion	4	Increasingly difficult to distract or console or stay asleep	
		Very Anxious, Very irritable	3
		Unable to console, unable to rest, or increasing drowsiness	
Perfusion: (FOR VAD DEVICES)		Lethargic, confused	4
Pink and/or cap refill </= 2 seconds **(FILL or FLOW at BASELINE)**	0	Minimally responsive or unresponsive to pain	
Pale and/or cap refill 3 seconds	1		
Grey or cap refill > 4 seconds	2		
Gray/mottled or cap refill >5 sec **(DECR FILL OR FLOW, INCR POWER)**	3	**Concerns from pt., family *(R/T DETERIORATING MEDICAL STATUS)*:**	
Decreased peripheral pulses, cool to touch, cyanotic,	4	No Concerns or not present	0
		Slight Concerns and/or Family not engaged	1
		Family with increasing concerns	2
Respiratory Effort:		Family uncomfortable regarding concerns	3
Normal for age	0	Family very uncomfortable regarding concerns	4
Resp. Rate MILDLY INCREASED YET EASY	1		
Resp. Rate MODERATELY INCREASED YET EASY	2		
Resp. Rate increased with effort mild to moderately labored	3	**Nursing Concerns FOR DETERIORATING MEDICAL STATUS**	
Resp. Rate increased with effort moderate to severely labored	4	***Rate 0 for no concerns***	0
			1
			2
Current Oxygen Therapy			3
Room Air or stable on home oxygen dose	0	***Rate 4 for highly concerned***	4
Oxygen use is stable or in process of weaning	1		
Intermittent episodes of O2 usage	2	TOTAL SCORE	
New or Increased continuous oxygen requirement	3		
Unable to maintain ordered sats within reasonable O2 delivery	4		
		FOR PATIENTS SCORING 7 OR ABOVE:	
GI Concerns		***1. RESIDENT IS TO BE NOTIFIED that pt scored 7 or above each time scored and document that patient scored 7 or above and why in***	
No concerns, NPO for procedure, or tolerating PO/enteral feeds	0	***notification log***	
Tolerating feeds, but unable to progress feeds or Poor appetite	1	***2. RESIDENT IS TO EVALUATE PT.***	
Vomitting some of feeds and/or complaints of nausea	2	***3. FOCUSED Q2H Vital Signs-- and chart***	
Vomiting >/= half of feeds (fussy with feeds), n/v &/or abd. distention	3	***4. FOCUSED Q2H Assessments-- and chart***	
Increasing abdom distention, increasing nausea/emesis, blood in stool	4		

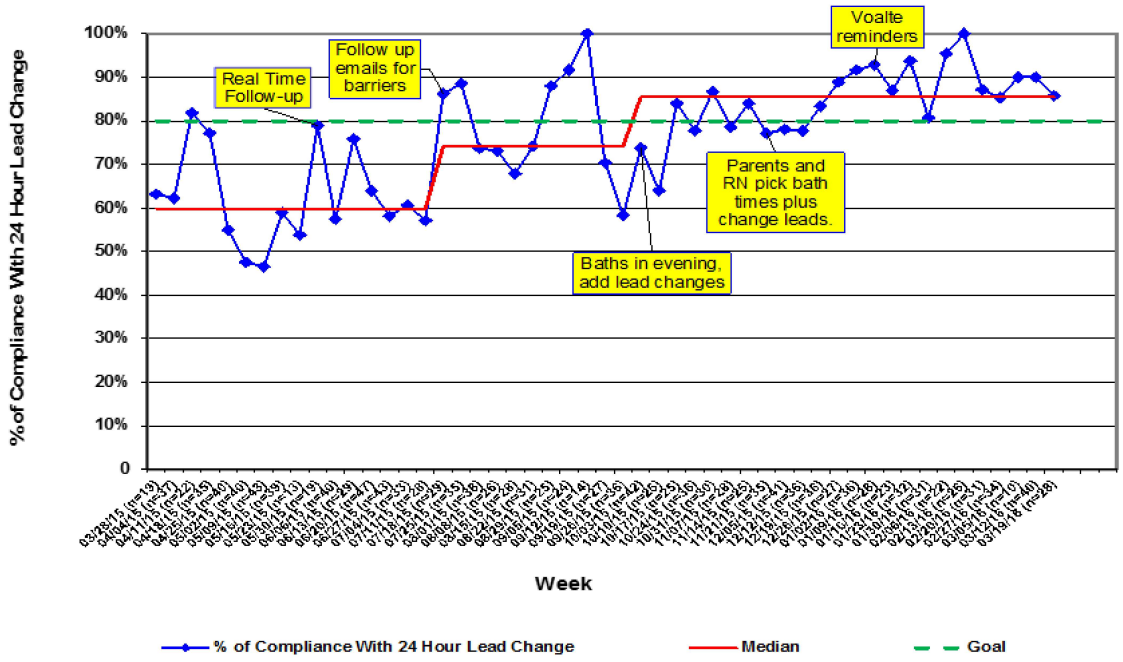
Supplemental File 5

Supplemental Figure 1: Current RN escalation algorithm

Alarm Acuity	Initial Notification Recipients	Secondary Notification Recipients	Tertiary Notification Recipients
High	Primary RN Charge RN	After 60 seconds → Primary RN Buddy RN	After 60 seconds → All staff
Medium	Primary RN	After 60 seconds → Primary RN Buddy RN	After 60 seconds → Primary RN Buddy RN Resource RN Charge RN
Low	Primary RN	After 60 seconds → Primary RN Buddy RN	After 60 seconds → Primary RN Buddy RN

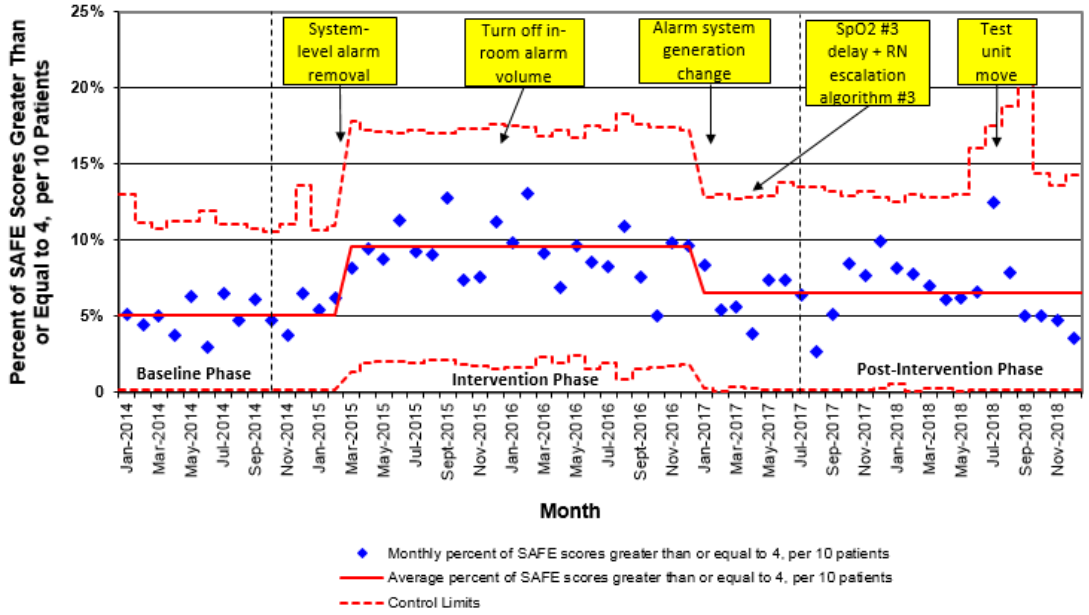
"High" acuity refer to critical alarms requiring immediate attention, such as ventricular tachycardia.
"Medium" acuity refer to warning alarms requiring prompt attention, such as elevated heart rates.
"Low" acuity refers to advisory alarms, such as low ability to sense SpO2 or lead detachment.

Supplemental Figure 2: Percentage of patients with ECG leads changed every 24 hours by week

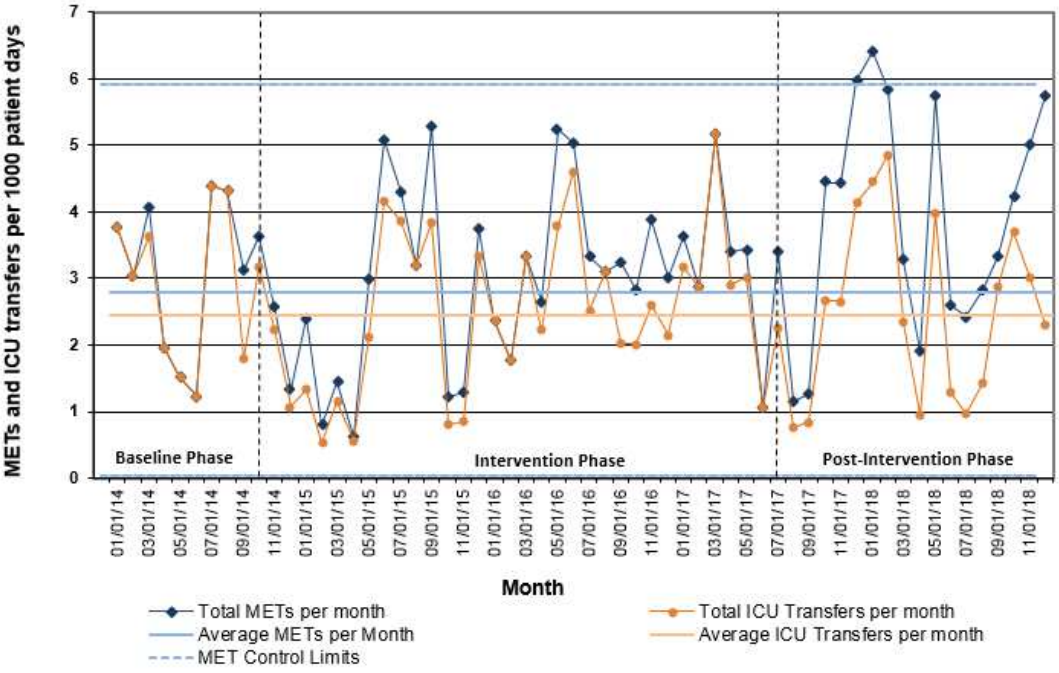


Supplemental File 6

Supplemental Figure 3: Percent of SAFE scores greater than or equal to 4, per 10 patients, by month.



Supplemental Figure 4: METs and floor-to-ICU transfers per 1000 patient days by month.



Supplemental File 7