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Implementing an Intelligent Alarm System in Intensive Care Units

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Abstract

Today's intensive care units monitor patients through the use of various medical devices, which generate a high ratio of false positive alarms due to a low alarm specificity. The false alarms have resulted in a stressful working environment for healthcare professionals that are getting more desensitized to triggered alarms and causing alarm fatigue. The patient safety is also compromised by having high noise levels in the patient room, which disturbs their sleep. This thesis has developed an intelligent alarm system with an improved alarm management and the use of 23 intelligent algorithms to minimize the number of false positive alarms. The suggested system is capable of improving the alarm situation and increasing the patient safety in critical care. The algorithms were modeled with fuzzy logics consisting of delays and multi parameter validation. The results were iteratively developed by having focus groups with various experts.

Keywords: ICU, false alarms, alarm fatigue, intelligent alarm, smart alarm, fuzzy logic, delay, cross-check

Sammanfattning

Dagens intensivvårdsavdelningar övervakar patienter med hjälp av flera medicintekniska apparater som genererar en stor mängd falska larm på grund av larmens låga specificitet. Det här har resulterat i en stressig arbetsmiljö för sjukvårdspersonal som dessutom blir allt mer okänsliga för larm, vilket har orsakat en ökad larmtrötthet. Den förhöjda ljudnivån i patientrummet sätter patientsäkerheten på spel och stör deras sömn. Detta examensarbete har utvecklat ett intelligent larmsystem med en förbättrad larmhantering och 23 intelligenta algoritmer för att minimera antalet falska larm. Algoritmerna utformades med fuzzy logik som innehåller tidsförskjutningar och valideringar av flera parametrar. Resultaten utvecklades iterativt genom fokusgrupper med ett flertal experter. Det rekommenderade systemet skulle kunna förbättra larmsituationen och öka patientsäkerheten i intensivvården.

Nyckelord: ICU, false alarms, alarm fatigue, intelligent alarm, smart alarm, fuzzy logic, delay, cross-check

Contents

List of Abbreviations

ABP Arterial Blood Pressure
CIVA Central Intensive Care Unit Karolinska University Hospital
ECG Electrocardiography
$etCO_2$ End-Tidal Carbon Dioxide
FPA False Positive Alarms
GUI Graphical User Interface
HIVA Heart Intensive Care Unit Karolinska University Hospital
HL7 Health Level Seven
HR Heart Rate
ICU Intensive Care Unit
IPS Indoor Positioning System
LAN Local Network Area
MV Minute Volume
PC Personal Computer
PDMS Patient Data Management System
RR Respiratory Rate
SIVA Södertälje Hospital Intensive Care Unit
SpO_2 Blood Saturation
TPA True Positive Alarms
WLAN Wireless Network Area

1 Introduction

Achieving a high patient safety level in hospitals requires an adequate monitoring of the patient status through the use of several medical devices. Most of these devices have an alarm system to alert the healthcare professionals; usually when a parameter value has crossed a predefined threshold range or when a technical issue occurs [1].

A high sensitivity and specificity in these alarm systems are essential for critically ill patients during anesthesia, surgery and intensive care. However, the current alarm systems specificity has been reduced in favor of a higher sensitivity in order to register all critical events [2]. An alarm being triggered every 1.2 minutes during intraoperative care has shown to be a direct result of this trade-off relationship [3]. Another outcome has been that 85 percent of all the triggered alarms are false positive, especially those generated from mechanical ventilators, patient monitors and infusion pumps [4][5].

Alarm fatigue is a direct consequence of the high alarm rate, which results in healthcare professionals responding later to alarms and falsely silencing them due to alarm desensitization [6]. Moreover, the excessive quantity of alarms affects the sympathetic nervous system and has led to a noisy alarm environment that constantly disturbs the patient's sleep quality [7][8].

Several studies have looked into how intelligent alarms could solve the specificity issue and as stated in Appendix A, most have concluded that either general enhancements, signal processing or artificial intelligence could be a possible solution. An intelligent alarm system should be effective in reducing artifacts, accurate in generating an alarm and applied in real-time measuring [9]. A reoccurring problem faced in these studies has been with the difficulty in transmitting data from medical devices due to the lack of interoperability [10].

The aim of this master thesis was to develop a system architecture for an intelligent alarm system in an ICU milieu, which would include an improved alarm management process and intelligent alarm algorithms. Moreover, another aim was to implement a functional prototype of the intelligent alarm algorithms.

This thesis was a pre-study for Maquet Critical Care and will be used to build a demonstrator based on the system architecture. The theoretical background used in this thesis is presented in Appendix A.

2 Method

An intelligent alarm management system was developed using an applied qualitative research method beginning with a pre-study. The pre-study consisted of a direct, undisguised and unstructured observation at CIVA as well as semi-structured interviews at CIVA, HIVA and SIVA.

2.1 System Functionality

A list of which sensors that could be part of the system was constructed based on their clinical relevance in an ICU and their availability on the market. Additionally, the devices that would be procured for the new Karolinska Hospital were considered. The procured devices were listed after a meeting with a project manager at Stockholm County Council.

A research into the functionality of these devices was conducted with the focus on their alarm management and communication capabilities, which were analyzed by reading each device's functional description. Subsequently, a decision was made on which data network to use for the selected devices. The communication methods in the system were illustrated in a network infrastructure. User needs and requirements for an intelligent alarm management system were gathered from the pre-study. Functions that satisfy these needs were developed and described with a wireframe as well as a representing GUI.

The network infrastructure, GUI and wireframe were improved after iterative focus group discussions with network specialists, a GUI expert, a market analysis and system architectures at Maquet Critical Care. The final results from these focus groups were then used in developing the system architecture.

2.2 Intelligent Alarms

Relationships between vital parameters and different intelligent algorithms were studied in order to create intelligent alarms and implement them in a functional prototype.

2.2.1 Fundamentals

The most frequent FPA from each chosen medical devices were determined from available literature. The exact name of these alarms, their priority and the sensor that triggered them were retrieved from respective product specification. Moreover, the relationship between the parameters that triggered these alarms and other monitored parameters were established from medical literature.

2.2.2 Algorithms

Intelligent algorithms based on fuzzy logics were put together according to Figure 1. The logics consisted of fuzzy sets, which concluded whether a triggered alarm was false positive or not by using predefined if-and-then rules. The fuzzy rules consisted of time delays and various cross-checks of related parameters. Phase dependent intelligent algorithms were also constructed to be part of the intelligent alarm management system.

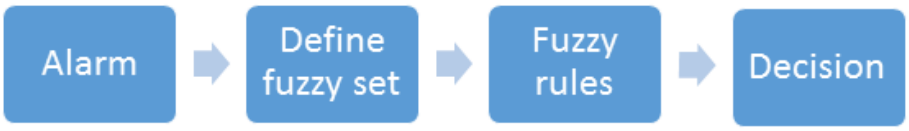

Figure 1: The method used for implementing fuzzy logics when developing intelligent alarms. The decision concludes whether the alarm is true or false positive.

To corroborate the intelligent algorithms after their development, two medical directors for ventilation and anesthesia at Maquet Critical Care were consulted in three focus group meetings. The resulting algorithms were then illustrated with flow charts by using Lucidchart 2015 (Lucidchart Software Inc., South Jordan, UT, USA).

2.2.3 Functional Prototype

A functional prototype of the intelligent alarms was implemented in Mathworks MATLAB R2016a (The Mathworks Inc., Natick, MA, USA) that validated whether alarms were false or not. Before coding, a database with three tables was constructed in Microsoft SQL format. The first and second table stored original alarms from medical devices and parameter values, respectively. These tables provided the inputs that were used in the Matlab code, which consisted of the intelligent algorithms. Lastely, the third table saved the validated alarms from the algorithms.

3 Results

The result of this thesis was a system architecture for an improved alarm management system, called ALMAS, that includes 23 intelligent algorithms for reducing the amount of FPA. These algorithms have been implemented in a Matlab-based application for validating whether the alarms are FPA or TPA. A detailed description of the system architecture is presented in Appendix B.

3.1 Chosen ICU Situation

The solution is suited for an adult patient in an ICU, where each patient has an own room and a central station for remote monitoring. The patient in question is monitored with the use of ECG leads, an invasive arterial catheter, a pulse oximetry and a capnography through a Philips Healthcare's IntelliVue MP70 patient monitor. The patient is also connected to a stand-alone Nonin WristOx2 pulse oximetry and a B. Braun SpaceStation infusion pump. Moreover, the patient is intubated with an endotracheal tube connected to a Maquet Critical Care SERVO-U mechanical ventilator, which is set to only monitor and assist the patient's breathing.

3.2 System Infrastructure

The data communication of metrics and alarms from the chosen medical devices is presented in Table 1. The end point of the communication is a PC which functions as a gateway, $PC_{Gateway}$, located in the patient room. The room is identified with a unique identification code provided by the gateway which in turn transports data through LAN to another PC, called PC_{Main}. Figure 2 illustrates the network infrastructure and communication in the system, which includes a mobile solution called Alarm Mobile and a screen called Alarm Monitor.

The PC_{Main} is located in a central station and functions as the main processer for the entire system. Its primary functions include an intelligent alarm application as well as the GUI for the Alarm Mobile and Alarm Monitor. The PC_{Main} also functions as a server that stores the database with the saved metrics and alarms. The Alarm Monitor presents these metrics in real-time and generates intelligent alarms in the central station. The monitor, which can monitor up to four patients at the same time, presents these alarms audibly and visually. Healthcare professionals are also able to monitor selected patients through the Alarm Mobile, which instead notifies them visually and through vibration.

Table 1: A list of the chosen medical devices and their data communication methods with the $PC_{Gateway}$.

Name	Medical Device	Data Communication
IntelliVue MP70	Patient monitor	LAN
Nonin WristOx2	Pulse oximetry	Bluetooth
SpaceMaster	Infusion pump	LAN
SERVO-U	Mechanical ventilator	Serial port

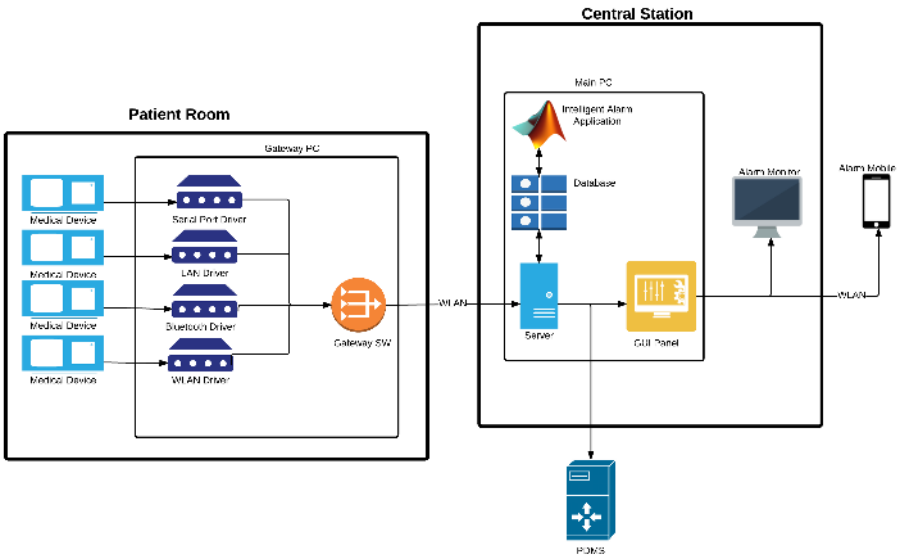

Figure 2: The network infrastructure of the intelligent alarm management system. The $PC_{Gateway}$, in the patient room, receives data through serial ports, LAN, Bluetooth and WLAN. The data is then sent to the PC_{Main} in a central station, which contains a database and the Intelligent Alarm application. The PC_{Main} also contains the GUI software for the Alarm Monitor. All data could be saved in a PDMS.

3.3 System Functions

In this section the results of the GUI illustrations and the system functionalities are specified.

3.3.1 GUI

Figure 3, Figure 4 and Figure 5 illustrates the results from the wireframe of the Alarm Monitor as well as the GUI for the Alarm Monitor and the Alarm Mobile.

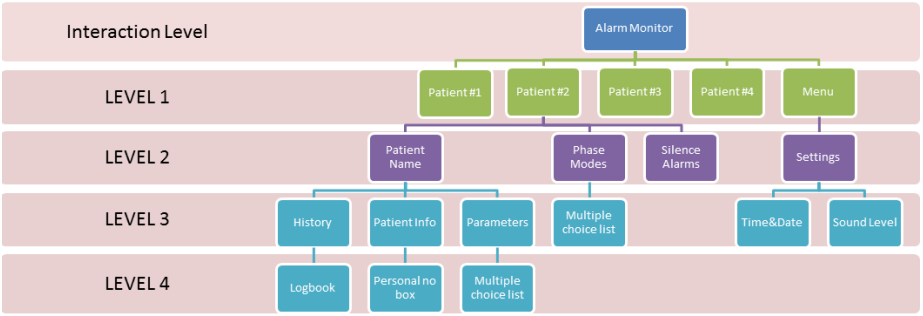

Figure 3: The wireframe of the GUI for the Alarm Monitor displaying all four interaction levels for Patient 2. Level 2-4 are the same for Patient 1, 3 and 4.

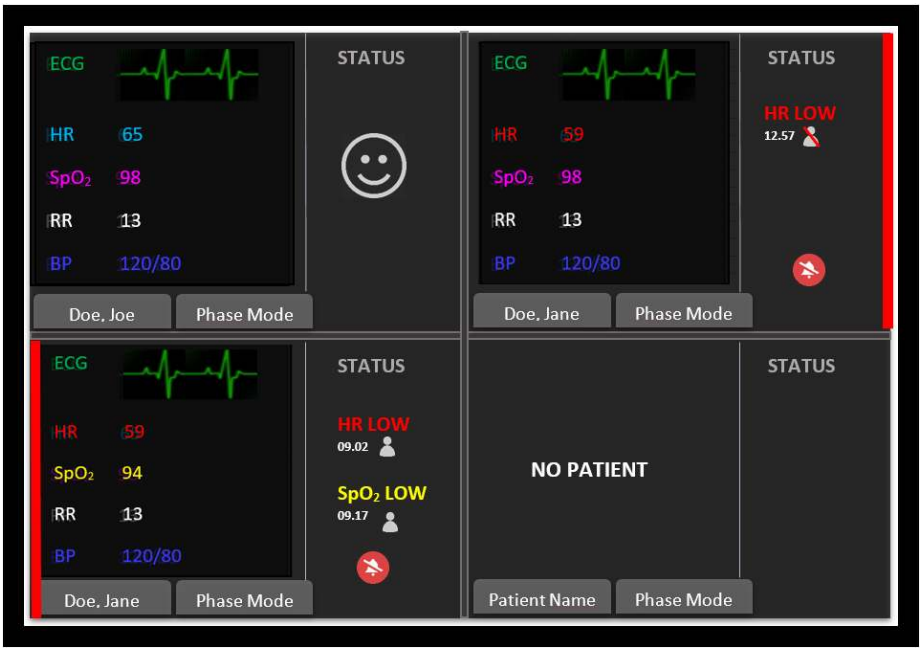

Figure 4: The home page of the Alarm Monitor with three of four connected patients. The GUI also shows how different alarms are displayed and the user icon shows if there is a user in the patient room or not.

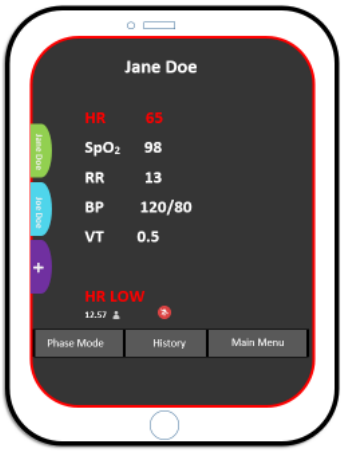

Figure 5: The GUI of the Alarm Mobile showing the home page for the patient Jane Doe where one alarm is triggered.

3.3.2 Alarm Management

Healthcare professionals have the option to silence intelligent alarms once they are presented on the Alarm Monitor or the Alarm Mobile within two minutes. If the alarms are not silenced within this time, the alarms are presented audibly in the patient room. Once an intelligent alarm has been silenced, the user still has to acknowledge the alarm in the patient room within a certain time depending on the priority of the alarm.

3.3.3 Phase Dependent Settings

ALMAS has two different phase dependent settings that adjust the behavior of alarms from the medical devices in the patient room. One more setting modifies the function of the Alarm Mobile. These settings are listed below:

Nursing Mode
When clinical interventions are to be performed, Nursing Mode can be activated to silence low and medium priority alarms. These alarms are instead presented only visually on the respective medical device.

Family Mode
The Family Mode setting can be activated to create a friendlier display when the patient has visitors. The displays on the devices show minimal presentation of metrics and curves. Another function of this mode is to give the visitors the option to play instrumental music from a pre-selected list.

Fika Mode
Healthcare professionals can activate the Fika Mode during their breaks, which would silence all alarms from the Alarm Mobile. However, in case of emergency the alarms would bypass the Fika Mode filter.

3.3.4 IPS

The Alarm Mobile has an IPS function that presents whether a healthcare professional is inside a patient room with a user icon. This function can also be used to turn on or off the displays on bedside medical devices when healthcare professionals are inside or outside the room.

3.4 Intelligent Alarms

23 intelligent algorithms were developed based on fuzzy logics. Flow charts for each algorithm are shown in Appendix C.

3.4.1 Respiratory

RR, SpO_2, MV and $etCO_2$ had a strong relationship amongst the vital parameters in the respiratory system. RR was inversely proportional to $etCO_2$ and directly proportional to SpO_2 as well as MV, which meant that if RR increased, $etCO_2$ decreased and the other two increased. Twelve algorithms where developed for eleven respiratory alarms triggered from the before mentioned parameters. These alarms, their priority and the source are presented in Table 2.

An intelligent algorithm validates an apnea alarm as TPA if the same alarm is also raised from the ventilator. Otherwise, it is regarded as a FPA and clinically irrelevant for healthcare professionals. If a low $etCO_2$ alarm is triggered, a 15 seconds delay is implemented before checking if the RR value has increased. In that case, the alarm is labeled as TPA and otherwise FPA. For a high $etCO_2$ alarm, the algorithm instead checks if the RR value has decreased.

Table 2: All original alarms from each device are categorized in respiratory and hemodynamic alarms, respectively. There are three priorities: High (***), medium (**) and low (*).

	Alarm Name	Priority	Device	Sensor
Respiratory Alarms	Apnea	***	IntelliVue MP70	-
	Low $etCO_2$	**	IntelliVue MP70	Capnography
	High $etCO_2$	**	IntelliVue MP70	Capnography
	Low SpO_2	**	IntelliVue MP70	Pulse oximetry
	Low SpO_2	**	Nonin WristOx_2	-
	Low MV	***	SERVO-U	-
	High MV	**	SERVO-U	-
	Low RR	**	SERVO-U	-
	High RR	**	SERVO-U	-
	Low RR	**	IntelliVue MP70	ECG
	High RR	**	IntelliVue MP70	ECG
Hemodynamic Alarms	Ventricular Tachycardia	***	IntelliVue MP70	ECG
	Ventricular Fibrillation	***	IntelliVue MP70	ECG
	Low pulse rate	**	IntelliVue MP70	Pulse oximetry
	High pulse rate	**	IntelliVue MP70	Pulse oximetry
	Low HR	**	IntelliVue MP70	ECG
	High HR	**	IntelliVue MP70	ECG
	Low HR	**	IntelliVue MP70	Pulse oximetry
	High HR	**	IntelliVue MP70	Pulse oximetry
	Low HR	**	IntelliVue MP70	ABP
	High HR	**	IntelliVue MP70	ABP

The intelligent algorithm that validates if a low SpO_2 alarm from the patient monitor as TPA is presented in Figure 6. A similar algorithm is used for validating a low SpO_2 alarm from a stand-alone pulse oximetry. If the patient is only monitored with a dependent pulse oximetry, a third algorithm validates the low SpO_2 alarm according to Figure 7.

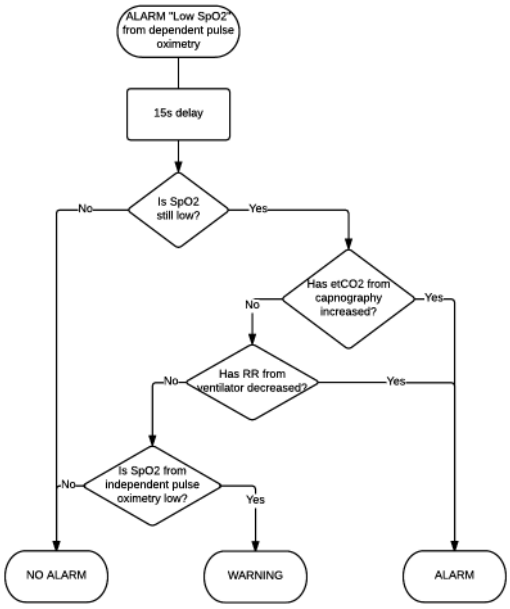

Figure 6: The flow chart presents the developed intelligent algorithm for a "Low SpO_2" alarm from a dependent pulse oximetry.

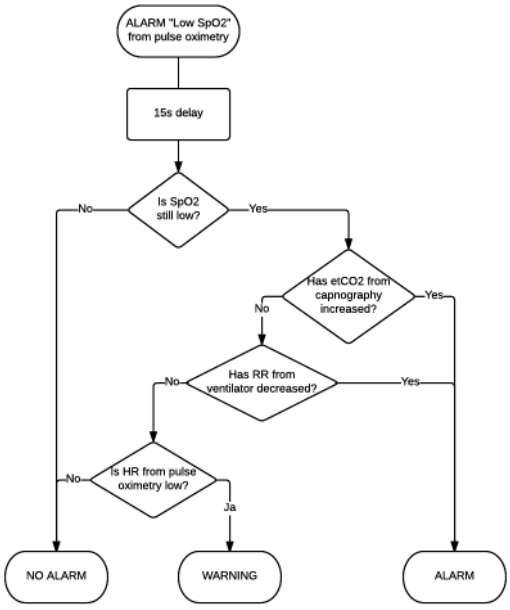

Figure 7: This algorithm explains the procedure when a "Low SpO_2" alarm is generated from only one pulse oximetry.

Figure 8 illustrates the algorithm for low MV alarm from a mechanical ventilator. For high MV alarms, the algorithm instead controls if the SpO_2 and $etCO_2$ have increased and decreased, respectively.

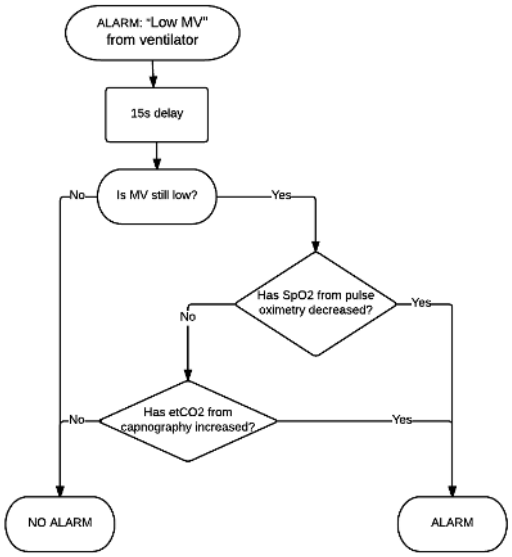

Figure 8: The flow chart describes the algorithm for a "Low MV" alarm from a ventilator.

A low RR alarm from a ventilator is validated with the algorithm in Figure 9, which is the same for a high RR alarm but is instead a TPA if the SpO_2 has decreased and the $etCO_2$ value has increased. On the other hand, a low RR alarm from ECG is validated as in Figure 10 and is similar for high RR alarms.

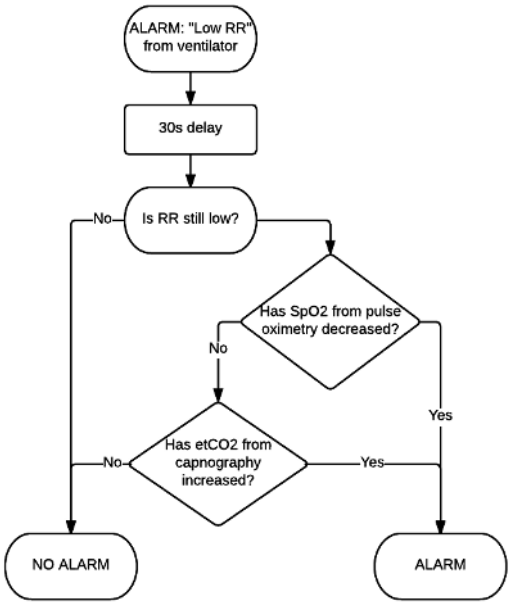

Figure 9: The original "Low RR" alarm is validated, whether it is TPA or FPA, through this algorithm.

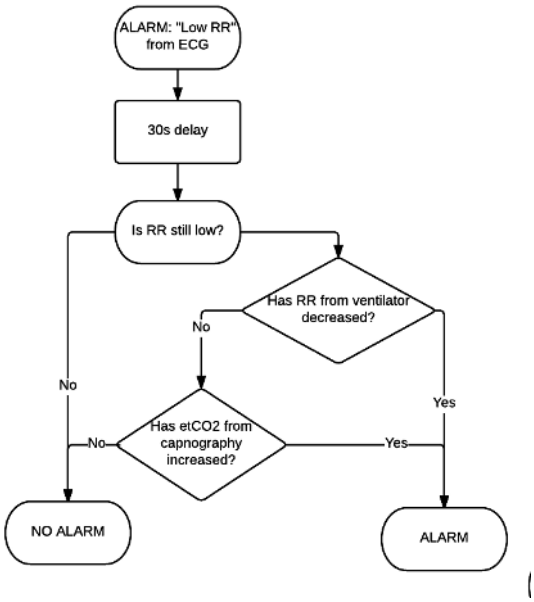

Figure 10: If the "Low RR" alarm is instead triggered from the ECG, the validation procedure will look like this.

3.4.2 Hemodynamic

Ten algorithms where developed for ten hemodynamic alarms triggered from ECG, pulse oximetry and ABP catheter. These alarms, their priority and the source are presented in Table 2 as previously presented in section 3.3.1.

Ventricular tachycardia and fibrillation alarms are declared as TPA if and only if the ABP has decreased or increased. A low pulse rate alarm from a pulse oximetry is validated with the algorithm in Figure 11. For high pulse rate alarm, the same cross-checking is made.

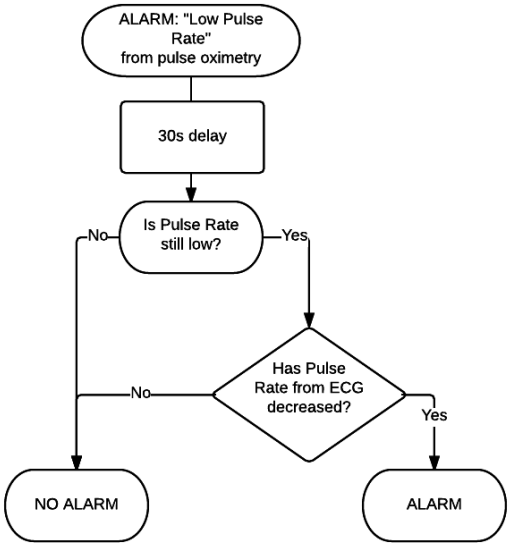

Figure 11: The flow chart presents the algorithm for "Low Pulse Rate" from a pulse oximetry.

A low HR alarm from ECG and pulse oximetry are presented in Figure 12 and Figure 13, respectively. If a high HR alarm is triggered instead, the same algorithms will be applied expect that it will check for increased HR values from the different devices. If low and high HR alarms are generated from an ABP catheter, the algorithm checks whether the HR value from ECG and pulse oximetry have decreased or increased.

3.4.3 Internal Milieu

When the nutrients and medication content in an infusion pump needs to be refilled, the healthcare professionals are alerted through continuous warnings that updates every two minutes instead of triggering a high priority alarm. However, if the content level reaches below 5 percent, an audible alarm is raised from the infusion pump.

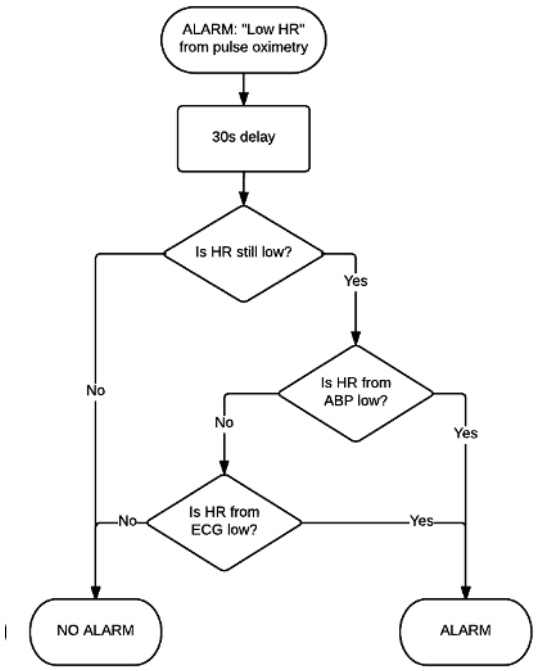

Figure 12: An original "Low HR" alarm from ECG is validated as TPA if it also result in an alarm through the above flow chart.

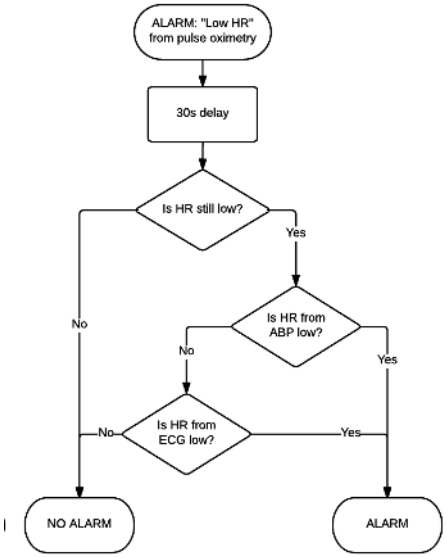

Figure 13: The intelligent algorithm for an "Low HR" alarm is presented in the flow chart.

3.5 Functional Prototype

The result of the functional prototype is a Intelligent Alarm Application consisting of 28 classes, Figure 14. The main class is called AlarmFetch, which reads the database and searches for original alarms that have not been validated. These alarms are then sent to AlarmSort that distribute the alarms to the corresponding intelligent algorithm. If the original alarm is TPA, it is written in the TableIntelligentAlarms class as either an alarm or a warning. 18 of the total 23 intelligent algorithms were implemented. The alarms that were not implemented in the functional prototype were: Ventricular Tachycardia, Ventricular Fibrillation, Apnea, low SpO_2 from a stand-alone pulse oximetry and low content alarms from infusion pumps.

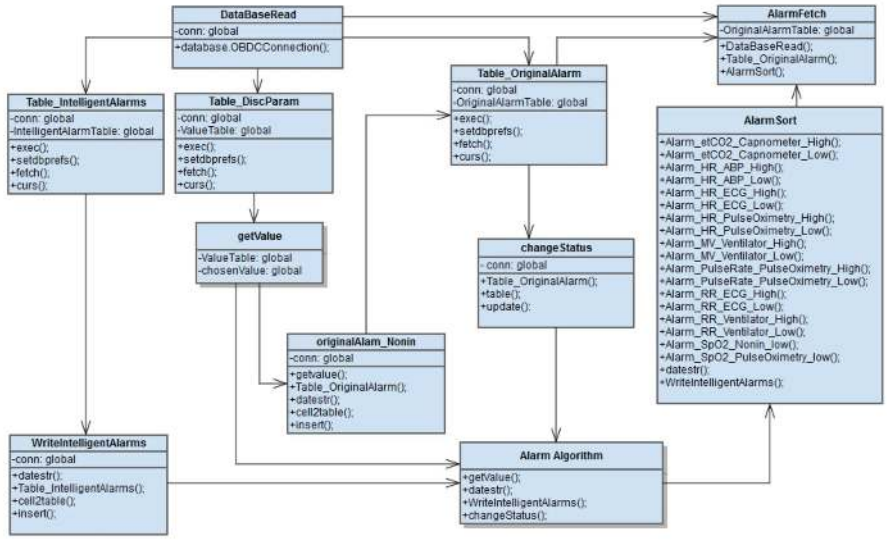

Figure 14: An UML diagram of the Matlab-based Intelligent Alarm Application showing the relationship between the classes. The class Alarm Algorithm is a generalization of the 18 intelligent alarm classes.

4 Discussion

Our choice of method has shown to be effective in reaching the aim of the thesis, which was to develop a system architecture for an intelligent alarm system in an ICU milieu. Through the observation and interviews with the healthcare professionals, a better understanding of the problematic situation and specification of the system requirements were accomplished. The iterative process of having several focus groups with experts has shown to be optimal and proficient in improving the developed ideas.

4.1 Hardware Functionalities

The wireframe of the system was illustrated with the focus to simplify the user interactions in the Alarm Monitor's GUI. The monitor was designed to display only four patients per monitor in order to create a clear and simple GUI, where the healthcare professionals are capable of receiving adequate information about these four patients. An initial idea was to only present alarms in the Alarm Monitor without presenting any parameters. However, the interviewed healthcare professionals indicated that they required having parameters included. In our opinion, the current design would be ergonomic, aesthetic and efficient for functioning in an ICU environment.

Having a mobile solution that is capable of alerting healthcare professionals and presenting monitored parameters was received with mixed reactions. The interviewees expressed their concerns regarding being disturbed during their unpaid lunch breaks, which was taken into consideration when developing Fika Mode. The GUI of Alarm Mobile was designed to be consistent and familiar to the Alarm Monitor. From a hygienic view, a mobile was chosen over other portable solutions such as wristbands.

The motivation for having a $PC_{Gateway}$ in each patient room was to be able to localize the rooms in the system, give a unique identification for each patient and identify which devices are used for treating and monitoring of the patient.

4.2 Alarm Management

A reoccurring insight was that patients themselves are not capable of addressing alarms and thus should not hear them. Silencing alarms and only presenting them visually in the patient room would minimize the stimulation of sympathetic nervous system in patients, which would result in an overall decreased heart and breathing rate during their stay at the ICU. A more silent environment would improve their sleep quality, which has shown to improve their treatment.

To create the silent environment, alarms were chosen to be distributed to the central station and Alarm Mobile. Alerting through vibration instead of audibly in the Alarm Mobile further decreases the noise levels. However, the vibration has to be strong enough to grab the attention of the healthcare professionals.

Currently, the provided care is aimed to be patient-centered in order to increase the safety of admitted patients. The suggested alarm management system fulfills this aim by requiring that even if the alarms are silenced outside the patient room, the healthcare professionals still have to acknowledge them in the bedside device that generated them within two minutes.

4.3 Algorithms

An insight from the observation was that, during clinical interventions, several false alarms were generated. These alarms were generally of low and medium priority, which the nurses disregarded during interventions, such as brushing the patient's teeth and repositioning them. Therefore, having Nursing Mode would reduce the FPA rate and unnecessary disruptions in their work. Another phase dependent setting was Family Mode that would create a better environment for the patients' visitors and ease their worries. Having the option of playing music, which is offered in Family Mode, would improve the patient treatment [11]. Both of these modes were well-received amongst the interviewed specialists and nurses.

The motivation for only using fuzzy logics from the artificial intelligence algorithms was due to the lack of efficient metadata containing monitored metrics and classifications of alarms. Additionally, algorithms based on fuzzy logics and sets could be made with scarce information about complex nonlinear processes, such as patient status. Our fuzzy models were developed for those parameters and devices that produced the most FPA in the ICU.

The multi parameter cross-checking sets were chosen based on the robustness and strength of the relationship between the parameters. These sets would study how a related parameter would change during a given time in regards to the parameter that generated an alarm. The underlining motive when developing them was that several parameters would deteriorate in case of a TPA and that it was unlikely that a serious condition would be indicated by a single parameter. Moreover, delays were implemented in order to minimize artefacts and clinically irrelevant events.

From the observation at CIVA, we noticed that several noisy alarms were triggered from infusion pumps when a content's volume was low. These alarms were low priority for healthcare professionals and created unnecessary disruptions. The purpose of our infusion pump algorithm was to alert them in a more silent and intelligent way without jeopardizing the patient safety.

4.4 Patient Safety

To increase patient safety, alarms and metrics have to arrive as fast as possible. Real-time communication is necessary for presenting continuous curves, such as ECG. The $\mathrm{PC}_{\mathrm{Gateway}}$ must ensure that data from the medical devices is received correctly and disruptions in the communication are noticed by watchdogs. These watchdogs start reacting when no signal is received within a certain time. The same procedure is used for the communication between the $\mathrm{PC}_{\mathrm{Gateway}}$ and $\mathrm{PC}_{\mathrm{Main}}$.

According to our results, a few medical devices communicate wirelessly and for this purpose authentication together with encryption is necessary. Additionally, devices outside our system must not disrupt the hospital network and therefore the importance lies in dividing the network between the medical devices.

Another aspect of the patient safety is the sensitivity and specificity of the intelligent alarms. The sensitivity needs to be 100 percent to identify every life threating situations and consequently the specificity of current commercial products has diminished. The purpose of our intelligent alarms is to increase the specificity through the resulted 23 algorithms. These algorithms have been developed and validated iteratively with clinicians to ensure that the patient safety is not compromised. Using delays is also a safety focus that have been guaranteed by previous studies without exposing the patient to threats.

4.5 Market Aspect

Currently, there are mobile solutions that distribute alarms as well as various patient monitors that gather parameters and alarms on a single display. The use of intelligent alarms is currently uncommon but a solution by Covidien employs averaging of parameters from pulse oximetries and capnographies, see Appendix A. Even though current products utilize delays, they are short in comparison with ours. Previous studies have been implementing intelligent algorithms, but most have been limited to a single device. Although a single device usually measures several parameters, it is not enough to reduce the rate of FPAs in comparison with our integrated system of several different devices.

Our solution regarding a more silent ICU would improve the ergonomic aspect for both patients and healthcare professionals by reducing the level of noise. Moreover, the workflow would be more efficient since TPAs are distributed to the right person and FPAs are reduced. A reduction in FPAs would also minimize the interruption of clinical work, which is positive because of the existing personnel shortage in Swedish healthcare. Economically, this is also important due to the increasing population age in Sweden. Additionally, the IPS function in the Alarm Mobile has an environmental advantage in that it switches off the bedside displays when healthcare professional leaves the patient room.

On one hand, an integrated solution is not available today because it would force competitors to cooperate with each other and implement interoperability standards such as HL7. On the other hand, companies might also not accept a remote system to silence their alarms even though it is allowed by the standard IEC 60601-1-8. Before entering the market, the regulatory aspect of our results should be studied and the responsibilities should be clearly specified.

4.6 Future Work

The developed intelligent algorithms have to be clinically evaluated and tested if they are capable of reducing FPA in a sufficient percentage. These algorithms needs further to be investigated whether they suppress any TPA, which would compromise the patient safety. The algorithms were intended to be validated with an online questionnaire aimed for Swedish nurses and physicians currently working in ICUs. However, having a questionnaire was deemed to be too complicated and ineffective after a discussion with a clinical expert at Maquet Critical Care.

For a better feedback about how to improve the algorithms, these clinicians should first be included in iterative focus groups. After which, a more clinical evaluation should be performed by gathering metadata during a long time period and classifying all the triggered alarms with the help of the healthcare professionals on duty. The data should then be processed by the intelligent alarm algorithms and the resulted alarms should be compared with their classification.

The developed alarm management system will be prototyped and technically tested internally at Maquet Critical Care that will include our Matlab application. The reason behind only using 18 of the 23 algorithms is due to limitations in the future prototype as it would not include all of the chosen sensors.

The resulted system architecture is currently limited to an adult patient in an ICU but with slight modifications, it could be applied to other areas such as neonatal care, anesthesia and surgery. The integrated system could include more devices and intelligent alarms for additional parameters.

5 Conclusion

The intelligent alarm system developed in this thesis improves the patient safety through creating a more silent ICU environment by distributing alarms. Thus creating a better work environment for healthcare professionals and minimizing the negative effect of alarm fatigue. Bedside medical devices are also more than capable of being integrated in a single system using different communication methods. Due to the complex and nonlinear nature of human processes, fuzzy logics has shown to be useful in modeling the algorithms. By using the 23 developed algorithms, the rate of FPAs could be diminished. However, they should be clinically and technically evaluated and tested in greater detail.

In conclusion, our solution can be used to improve monitoring of an adult patient in an ICU and increase the specificity of alarms. The solution can also be applied to other critical care units and include more medical devices.

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Appendix A: State of the Art

Contents

List of Abbreviations

ABP Arterial Blood Pressure
ANN Artificial Neural Network
BP Blood Pressure
CO Cardiac Output
CVP Central Venous Pressure
dB Decibels
DBN Dynamic Bayesian Network
ECG Electrocardiography
etCO_2 End-Tidal Carbon Dioxide
FDA Food and Drug Administration
FiO_2 Fraction of Inspired Oxygen
FNA False Negative Alarms
FPA False Positive Alarms
HL7 Health Level Seven
HR Heart Rate
ICU Intensive Care Unit
LAN Local Network Area
MAP Mean Arterial Pressure
PAP Pulmonary Arterial Pressure
PAW Airway Pressure
PEEP Positive End Expiratory Pressure
PIP Peak Inspiratory Pressure
P_{CO_2} Partial Pressure of Carbon Dioxide
P_{O_2} Partial Pressure of Oxygen
QoS Quality of Service
RF Radio Frequency
RR Respiratory Rate
SpO_2 Blood Saturation
TNA True Negative Alarms
TPA True Positive Alarms
VT Tidal Volume
MV Minute Volume
WHO World Health Organization
WLAN Wireless Network Area
4G Fourth Generation Mobile Communication

1 Introduction

This State of the Art studies how clinical alarms are generated from various medical devices and how these alarms are managed by healthcare professionals in intensive care units. The classification and amount of each alarm have also been described, as well as the impact of the current alarm system on patient safety and work environment. The main focus has been how the current alarm system could be improved by implementing intelligent alarm algorithms and increasing the interoperability of these medical devices.

2 Medical Devices

Healthcare professionals have to interpret and monitor physiological vital parameters in respiratory system, hemodynamics, consciousness and internal milieu [1].

2.1 Respiratory System Monitoring

To assist a patient incapable of maintaining a functioning respiratory system, a *mechanical ventilator* is often used in intensive care [1]. The parameters monitored by ventilators include: RR, VT, MV, PAW, PEEP, FiO_2, PIP, and apnea. *Pulse oximetry* is widely used for monitoring patient's SpO_2 and HR [2][3]. Moreover, *capnography* is utilized to measure the values of the RR and $etCO_2$ [4][5].

2.2 Hemodynamics Monitoring

ECG is a noninvasive monitoring device for measuring the cardiac potentials by placing electrodes on the patient [1]. With this method HR can be measured, which is an important vital parameter in intensive care [6]. *Arterial catheter* and *central venous catheter* are two general tools utilized for monitoring cardiovascular pressure. An arterial catheter measures BP, MAP, HR, P_{O_2}, P_{CO_2} and pulse pressure whereas a venous catheter measures CVP and respiratory variations [3][1]. Another catheter that is inserted into the patient is *pulmonary arterial pressure* which measures PAP and CVP [7]. Furthermore, CO monitoring can be performed through several methods such as *thermodilution* [3].

2.3 Internal Milieu and Consciousness Monitoring

The most reliable way of examining consciousness is to check the patient's ability to move, response to physical stimuli, pupil's reaction to light and lastly mental capability to answer questions. The patient's metabolism, temperature, fluid balance, electrolyte balance and acid-base homeostasis fall together under the term internal milieu [1]. The temperature can be taken with *pulmonary artery thermistor* and different *temperature probes* [8]. For providing patients with nutrition and medication, various types of *infusion pumps* are used that administer fluids in a controlled amount either intravenously, subcutaneous, arterial or epidural [1]. The need for *dialysis* sometimes arises in ICUs when the renal function has been reduced in order to adjust the electrolyte balance and remove toxins as well as excessive fluids [9].

2.4 Patient Monitoring Overview

Generally, the monitored parameters from these medical devices are presented on separate monitors using the single-sensor-single-indicator method. This implies that the numerical values and graphical waveforms from each sensor are presented separately and without any form of integration [10]. In addition to these monitors, a bedside *patient monitor* has been used in ICUs as a standard since the 1970s. Their popularity has been due to their capability of connecting to several other supported medical devices and presenting them in a single

monitor [11]. The supported devices differ from one manufacture to another, but the most common usually include electrocardiogram sensors, various blood pressure catheters, pulse oximetry and ventilators [12].

In addition to bedside patient monitors, a *remote monitoring system* is sometimes equipped in ICUs. The system presents the parameters in a central monitor that is usually located at the nurses' workstation or on a mobile device. The purpose of such a system is not to replace the bedside care but to increase the efficiency of the care and to distribute the workload [13].

3 Alarm Systems

Should the patient status get gradually worse, an alarm would be generated from the medical devices to aware of the need for immediate attention or intervention [14].

3.1 Functionality

The alarm system in most medical devices is based on setting a threshold value for each parameter that is monitored. Alarms are then subsequently triggered whenever the value from the measured parameter is outside the specified interval [15]. It is probable that multiple alarms from the same medical device could be triggered simultaneously. In that occasion, the medical device would present either the first alarm or the one with the highest prioritization. Moreover, another function that has been implemented in some medical devices is short delays before triggering an alarm, which is due to possible artifacts [16].

When a threshold is reached, the triggered alarms could be presented audibly, visually and through vibration in a mobile device. The audible and visual alarms are structured differently and even the sound level varies in each device [16][17]. Research has been conducted in increasing the interoperability of these devices through Plug-and-Play modules in order to present the different alarms in a single system [18].

3.2 Classification

Alarms can be distinguished as either clinical or technical depending on what caused them [16]. According to Burgess et al. [19], clinical alarms could be categorized based on their sensitivity and specificity into the following four cases:

- True positive alarms, which are correctly triggered alarms
- True negative alarms, which are correctly non-triggered alarms
- False positive alarms, which are incorrectly triggered alarms
- False negative alarms, which are incorrectly non-triggered alarms

These alarms could further be divided depending on their clinical value to the healthcare professionals. TPAs and FNAs are considered clinically relevant whereas TNAs and FPAs are considered clinically irrelevant [20]. The specificity of these alarm systems diminishes in the expense of a high sensitivity in a trade-off relation to ensure that no critical event has been oversighted [21][22][23].

The reasons behind a triggered FPA are several, which include sensor misplacement, clinical interventions and patient movements [16][24]. Furthermore, Drews [10] stated that healthcare professionals had difficulties setting thresholds due to complex menus in existing medical devices. Selecting an incorrect threshold range could result in an artifact that eventually would trigger an FPA [25]. The amount of FPAs has been reported to be frequent in several studies, which have shown that these alarms make up between 85-99 percent of all triggered alarms [26][27][28].

Görges et al. [24] conducted a 200 hour long observation of alarms in an ICU and found that the most common alarms were VT and MV but the most ineffective and ignored alarms were SpO2 and HR. A part of their findings is summarized in Table 1. Cho et al. [29] collected alarm data during a 48 hour long observation in 5 different ICUs and concluded that out of all the alarms, the patient monitor, ventilator and infusion pump generated 81.9, 8.3 and 9.6 percent respectively.

Table 1: A statistical summary presenting the total amount of generated alarms and the ineffectiveness of these alarms; meaning that the alarm did not lead to a clinical intervention or were ignored.

Alarm	Amount	Ineffective and Ignored
VT	247	88.7%
MV	197	83.7%
SpO_2	188	95.2%
Infusion pumps	147	17.1%
HR	134	91.0%
BP	127	80.3%
RR	75	82.6%

3.3 Outcome of Excessive Alarms

Drew et al. [30] observed during a recent study that over 2.5 million audible and inaudible alarms were produced from 461 ICU patients over a 31-days period, which would correspond to an average of 187 audible alarms per patient per day. In a similar study by Schmidt et al. [31], an alarm on average was triggered every 1.2 minutes during intraoperative care.

The high amount of alarms contributes to a work environment where healthcare professionals are overwhelmed by alarms, which in turn results in alarm fatigue [32]. Consequently, alarm fatigue leads to longer response time [33][34], alarm desensitization [35][36], falsely silencing the alarms [37] and workaround behavior [38]. Another effect of alarm fatigue has led healthcare professionals to extend the range of thresholds without considering the patient's safety [32].

How fast healthcare professionals respond to an alarm situation depend on the patient status, the workload and the reliability of the alarm system [39]. Jones [40] described that alarm fatigue has a negative effect on differentiating diverse alarms and thus also affects the reaction time. Several investigations performed by FDA have indicated that alarm fatigue has been the main cause of more than 560 patient deaths during the period 2005-2008 [41].

The current level of noise has been breaking WHO's recommendations, 35 dB during the night and 40 dB during the day [42]. It has been concluded that the sound level was roughly 56 dB in a nine-bedded intensive care unit with a

maximum of 80 dB [43]. Similarly, Schmidt et al. [17] observed that the sound level were frequently around 70 dB and would even reach 90 dB.

The high noise levels have been affecting the stimulation of the sympathetic nervous system of healthcare professionals [44], which causes physiological stress [45], poor attention and delayed response time for triggered alarms [33]. Other effects of the sympathetic nervous system stimulation that occurs when a sudden alarm has been generated is an increased heart and breathing rate, which can be experienced by the patients as well [46]. Moreover, studies have shown that a noisy hospital environment has a negative consequence in the patient's sleep quality by disturbing their sleep [30][47].

4 Regulatory Framework

The main requirements of an alarm system are to identify every occurring critical threat and to generate an alarm or a warning in those cases [48]. Beside these alerts, these systems need to provide a clinical message about the triggered alarm [49].

The requirements of an intelligent alarm system are defined in the standard IEC 60601-1-8, which also includes the requirements for general alarm systems [50]. The standard is used as the regulatory framework in Europe and USA [51] and defines [50] intelligent alarm systems as an:

> "Alarm System that makes logical decisions based on monitored information without operator [...] Intelligent Alarm system can use one or more variables or patterns of variable or variables to make decisions that determine the presence or absence of an alarm condition and its priority."

Moreover, it defines the presentation, distribution and the characteristics of alarms in such systems. It also outlines that intelligent alarm systems must fulfill the requirements set by IEC 606001-1-6 to be confirmed as usable systems [50].

5 Intelligent Algorithms

An intelligent alarm system should be effective in reducing artifacts, accurate in generating an alarm and applied in real-time measuring [49]. The logical architecture behind such a system could consist of methods that provide general enhancements, signal processing and artificial methods [48].

5.1 General Enhancements

A study has inquired how re-prioritizing and distributing alarms from monitoring devices could raise better response by the healthcare professionals [52]. Moreover, implementing a CDS system, which is a computer-based information system that assists healthcare professionals with decision making [53], could also have the same outcome [54]. Other general enhancements that would have the same previous effect are mentioned below.

5.1.1 Delay

There are generally two types of delays, ON- and OFF-delays, that can be implemented to reduce FPAs in an intelligent alarm system. The ON-delay could be used to prevent alarms from being triggered in the first place by stating that a condition has to remain deteriorated longer than a specified time before generating an alarm. OFF-delays are meant for reducing repetitive alarms by combining them to one single alarm and thus reducing FPAs [55].

Görges et al. [24] supported the ON-delay by concluding that using an ON-delay of 15 seconds would generally reduce FPAs with 50 percent while 19 seconds ON-delay would minimize the amount of false alarms with 67 percent. More specifically, a 19 seconds alarm delay in mechanical ventilators would reduce false positive tidal volume alarms by 18 percent and minute volume alarms by 37 percent without threatening the patient's safety. Moreover, a delay between 6-19 seconds on SpO_2 would reduce the alarms by 50-52 percent, which is supported by two other studies [56][57].

5.1.2 Phase Dependent Settings

The type of alarm and the FPA rate are dependent on the clinical intervention that caused it and in each case the reaction from the healthcare providers varies. The different characteristics in the specific intervention should be considered when implementing new methods for reducing the amount of alarms in intensive care units [17]. Phase dependent settings has also been suggested in another study by Seagull and Sanderson [58] who concluded that during some phases of a surgery, low priority alarms should be turned off. It has also been concluded that several FPA emerged during special clinical interventions, such as oral care and washing [24].

5.1.3 Multi Parameter Validation

A prominent method for reducing FPAs is to create a form of cross checking algorithm that considers several vital parameters before sounding an alarm. Aboukhalil and his colleagues [59] developed such an algorithm that cross checked

ECG alarms with ABP and HR values, which was able to reduce false arrhythmia-related alarms from 42.7 to 17.2 percent. However, their system failed in detecting 9.4 percent of true positive ventricular fibrillation alarms.

5.2 Signal Processing Methods

Signal processing methods could be implemented to develop an intelligent alarm system in intensive care units.

5.2.1 Kalman Filter

The Kalman filter is a computerized solution for removing noise from data streams over discrete time. Even if the nature of the modeled system is unknown, the Kalman filter can estimate the state of the model in the past, present and future and has proven to be the best linear estimator of any system regardless of distribution [60]. Several studies have implemented Kalman filters in acquired signals to reduce the amount of FPA by improving the signal-to-noise ratio, such as the study by Li et al. [61] that used the filter to several vital parameters and were able to minimize the amount of noise in each signal which has been supported by another study as well [62].

5.2.2 Median Filter

A statistical approach to reduce FPAs is to use median filters, which is a non-linear method that is mainly applied in signal processing to improve the signal-to-noise ratio by determining the median value over several time periods [63]. Yang et al. [64] in their study applied a hybrid median filter that combined HR values from two different sensors, which resulted in reduced artifacts and noise in the signal.

5.2.3 Autoregressive Model

The autoregressive model is a linear process which consists of a finite amount of elements that are represented with both a time dependent deterministic part and a stochastic part [65]. Lehman et al. [66] used autoregressive processing in order to monitor changes in HR, MAP and BP in ICU patients. They concluded that their algorithm could improve monitoring of patients and raising predictive alarms. A similar study by Choi et al. [67] applied multivariate autoregressive model to minimize the amount of FPAs by detecting faults in measurements. Scalar and multivariable autoregressive models were used in another study to predict acute respiratory failure by detecting deviations in the electroencephalography signal [68].

5.3 Artifical Methods

Another approach is to take the advantage of artificial intelligence such as trend analysis and rule-based algorithms.

5.3.1 Artificial Neural Network

ANN is similar to biological neural networks in how it processes information, which occurs in several basic components called artificial neurons. These neurons act as processing units in the network and are linked together with different connections [69]. Further, these units receive one or more inputs from other neurons but always produce one single output that could be sent to more than one neuron. There are possibilities for ANN to be trained and subsequently be used to calculate particular patient outcomes [70].

It has been proven by Zhou et al. [71] that implementing ANN could help in predicting acute hypotension in ICU patients. Another study has also applied ANN to predict how many days a patient suffering from trauma injury needed to stay in the intensive care unit and how high the survival probability was. The employed ANN in the mentioned study measured the vital parameters of test patients and predicted an outcome, which has shown to have a specificity of 96 percent and a sensitivity of 75 percent [72]. Another predictive ANN method was deployed to early detect brain death by observing several vital parameters in ICU and has been proven to be valuable to healthcare personals [73].

5.3.2 Dynamic Bayesian Network

A system that changes dynamically over time could be presented with a graphical model called DBN. The model would allow monitoring changes in a system over time and even predicting future behavior of the system. This would be preformed by observing the probability distribution on a set of stochastic variables over time [74]. DBN has been applied for monitoring several parameters to diagnose the probability that a specific condition occurs; conditions such as ventilator-associated pneumonia [75] and multi-organ dysfunction syndrome [76].

5.3.3 Fuzzy Logics

The absence of sufficient information about a specific process leads to difficulties in applying a precise mathematical model to describe the process and the elements within it. Such nonlinear processes can be described with a fuzzy model [77]. The theory behind fuzzy models was first described by Zadeh [78] and currently the theory is applied in different technical areas, mostly in control systems [49].

Sugeno and Yasukawa imply [79] that this model, consisting of fuzzy logics and sets, could portray various processes in humans. King et al. [80] have implemented a CDS system based on fuzzy logics that showed a 45 percent reduction in total alarms by combining four vital parameters, namely HR, BP, SpO_2 and RR. A different study used data from the MIMIC database, a free database containing real-time clinical data, and fuzzy logic algorithms to decrease the amount of FPA for arterial blood pressure. The algorithms combined arterial blood pressure data with ECG and it caused an elimination of FPA from 28.6 to 0.4 percent [81]. Leite and colleagues [82] developed a fuzzy model that monitored several cardiac parameters and sent the data to an alarm system, which resulted in an accuracy of 96 percent.

6 Data Communication in ICU

The data generated by different monitoring devices is transmitted either through wire or wirelessly. All these types of communication differ in what transport interfaces and protocols they use [83].

6.1 Data Communication

There exists several standards for increasing interoperability in the healthcare, such as HL7, which is the most commonly used interoperability standard worldwide and especially in American hospitals [84]. The HL7 standard defines how data is packaged, transported and integrated to provide a smooth transition in healthcare networks [85]. The ISO 11073-10101 standard defines the nomenculature for communication between medical devices [86]. The standard also defines the relationship between the architecture of the system and the elements in it.

The acquired data from the different monitored parameters is usually stored in a database server for future analysis and processing. The data format could be either as a raw data dump of all the underlying values for subsequent analysis or real-time values for immediate processing [87].

6.2 Comparison of Wireless Communication

The most commonly used forms of wireless communication are: RF, WLAN, Bluetooth, 4G and ZigBee [83][88]. A comparison of these different technologies is presented in Table 2, except for RF module due to being very different depending on manufacturer [88].

Table 2: A comparison of Bluetooth, ZigBee, WLAN and 4G module over the used standard protocols, data rate, communication range, communication frequency and power consumption.

	Bluetooth [89]	ZigBee [90]	WLAN [91][92]	4G module [93]
Protocols	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.111	LTE
Data rate [Mbps]	1	0.02 to 0.25	1-100	1.5
Range [m]	10-100	10-100	up to 100	over 1000
Frequency [GHz]	2.4	0.868, 0.915, 2.4	2.5, 5.0	2.6
Power consumption	Low	Very Low	High	High

6.3 Security and Quality

Most of these wireless communications have both encryption and authentication mechanisms to increase security in their data transfer [83]. However, the difference lies in which security protocols are applied in the process. Comparing these different protocols, the most secure one is the protocols used by 4G module, followed by ZigBee and the lowest ones are those of WLAN and Bluetooth [93] [94].

A data communication network has to fulfill several requirements in order to have a high QoS, such as how long it will take data to reach its destination, how much data fails to reach its destination and how much data a network can send and receive [95]. It is especially important to have a high QoS in real-time ICU networks in order not to jeopardize the patient's health [96].

7 Market Research

There are currently several patient monitors that are available on the market, such as the Intellivue series by Philips Healthcare [97][98], Carescape series by GE Healthcare [99][100], PulsioFlex from Pulsion Medical Systems [101] and BeneVision series by Mindray [102]. According to the previously mentioned manufacture specifications, all latest solutions in respective series have the possibility of connecting to a remote monitor in a central station and are capable of communicating data through serial ports, WLAN and LAN. Moreover, the specifications indicate that all of these solutions are HL7 compatible either directly or through the use of a specialized gateway.

The Efficia CMS200 remote monitoring solution from Philips Healthcare stood out from the other manufacturers in that it could silence the alarms from the bedside Philips patient monitors [103]. Additionally, several bedside patient monitor solutions have support to communicate their data and alarms to mobile solutions such as Ascom's Myco [104].

A few of the mechanical ventilators currently being used in ICUs are the SERVO series from Maquet Critical Care [105],[106] and PulmoVista 500 from Dräger Medical [107]. These manufacturer specifications indicate that both solution communicate their data through serial ports and only the SERVO series are HL7 compatible through the use of Maquet's MSync gateway. Further, both solutions are capable of communicating their data to a patient monitor.

B. Braun's SpaceStation [108] and Caesarea Medical Electronics' BodyGuard [109] are commonly used infusion pumps in ICUs. As stated in the specifications, the SpaceStation is capable of transporting medical data through LAN, serial ports and optionally WLAN whereas BodyGaurd can only communicate through LAN and serial port. Both manufacturers lack a solution for HL7 interoperability but support communication with bedside patient monitors.

Pulse oximetries can be divided into stand-alone solutions, such as Nonin Medical's WristOx2 3150 [110], and dependent, such as Nellcore's OxiMax N-600x [111] and Masimo's Rad-8 [112]. The manufacturer's specifications show that the dependent pulse oximetries communicate through serial ports to supportive patient monitors and the stand-alone pulse oximetry communicates only through Bluetooth. Moreover, the documents show that none of these devices have alarm algorithms but are defined in the supported patient monitors or received computer respectively.

There is limited use of intelligent algorithms to reduce FPAs in the previously mentioned solutions. However, several of the mechanical ventilator solutions and patient monitors use a short delay before triggering alarm to remove noise [113]. A solution that stood out from the rest in this aspect was Covidien's Smart Alarm Management which consists of different intelligent algorithms that can be used with Nellcor's pulse oximetry and Microstream's capnometers to reduce FPAs through implementing delays and averaging respectively [114].

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Appendix B: System Architecture

Contents

List of Abbreviations

GUI Graphical User Interface
HDMI High-Definition Multimedia Interface
ICU Intensive Care Unit
IPS Indoor Positioning System
LAN Local Access Network
PC Personal Computer
PDMS Patient Data Management System
WLAN Wireless Local Access Network

List of Definitions

Acknowledge
Acknowledging an alarm indicates that the user has taken the responsibility to investigate the cause of the alarm.
Central Station
The designated area in an ICU where healthcare professionals work administratively and not in direct contact with their patients.
Classical Mode
None of the medical devices and their alarms will be included in the intelligent alarm system. The alarms will be presented on the medical device in the patient room that triggered the specific alarm.
Intelligent alarms
Original alarms that have been validated through the Intelligent Alarm Application.
Medical Devices
Bedside devices deployed in the patient room that provide life support and patient monitoring.
Original Alarm
Alarms triggered from the bedside medical devices in the patient room.
Patient Room
The location where the patient is placed in the ICU for treatment.
Silence
Silencing an alarm turns off the audible functionality of the alarm for a given time.
User
Healthcare professionals working in ICUs.

1 Introduction

This system architecture is intended for lowering the level of noise in the patient room and the ICU by distributing the relevant alarms to the responsible health-care professional. Moreover, it is constructed with the intention to minimize the rate of false positive alarms without jeopardizing the patient safety.

The proposed system consists of several Gateway PCs, a minimum of one Main PC, one database, an Intelligent Alarm Application, a minimum of one Alarm Monitor and several Alarm Mobiles. This system architecture defines how the network infrastructure should be set up and gives GUI illustrations for the Alarm Mobiles and Alarm Monitors. Furthermore, the functionality of each part of the system is described. Lastly, a few user cases and the testability of the system are mentioned.

2 Functional Description

In this chapter, the network infrastructure and the functionality of the complete system is specified.

2.1 Network Infrastructure

Figure B. 1 shows the network infrastructure of the complete system, which consists of different medical devices that are connected to a $PC_{Gateway}$ in a patient room. These devices communicate with the $PC_{Gateway}$ through LAN, WLAN or Bluetooth. The $PC_{Gateway}$ is then connected through LAN to the PC_{Main}, which contains a database and an Intelligent Alarm Application. The PC_{Main}, which is located in the central station, is then connected via an HDMI cable to a touchscreen Alarm Monitor and through WLAN to an android based mobile, called the Alarm Mobile. For more information about each part of the system, see the specified sections below.

Figure B. 2 shows how several $PC_{Gateway}$ in different patient rooms connect to one or more PC_{Main} through LAN and additionally to a PDMS. The PC_{Main} could be located in the same or in different central stations. The network uses multiple handshaking to make sure that the data communicated from a medical device to a $PC_{Gateway}$ arrives to the destination and that the $PC_{Gateway}$ delivers the data to the PC_{Main}.

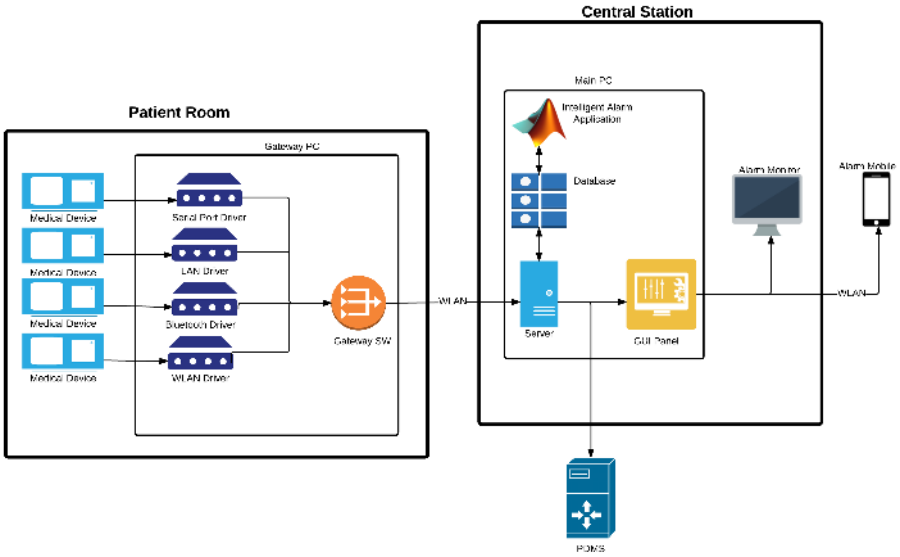


Figure B. 1 – Network infrastructure of the hardware in the proposed system. The system is set-up of several medical devices connected to a PC Gateway, a database and the Intelligent Alarm Application in a Main PC, an Alarm Monitor and an Alarm Mobile.

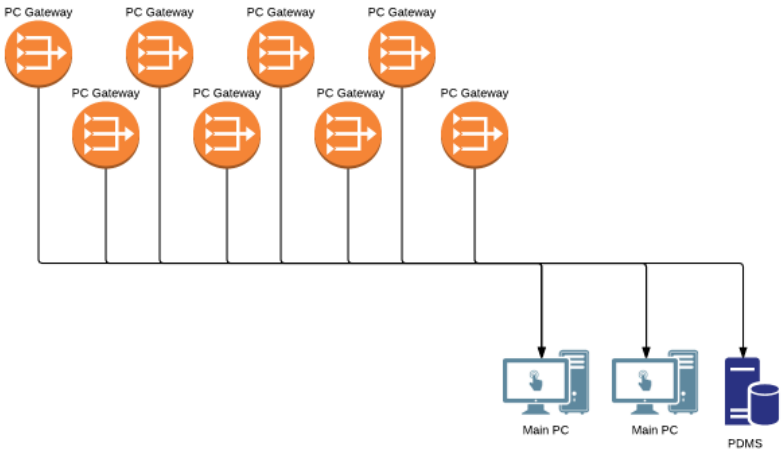


Figure B. 2 – Network infrastructure of the connection between several PC Gateways and one or more Main PCs.

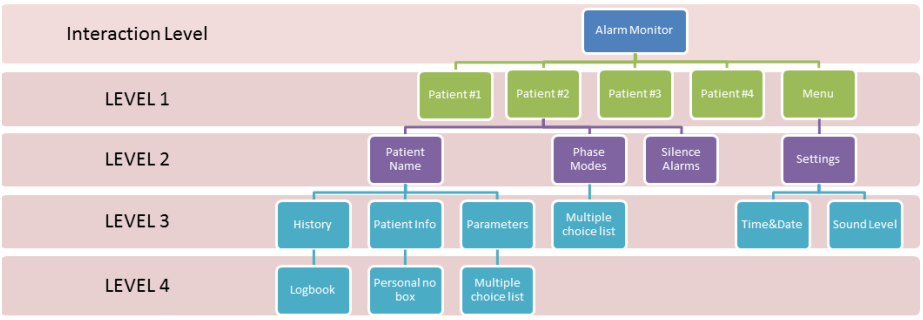


Figure B. 3 – The wireframe of the GUI for the Alarm Monitor displaying all four interaction levels for Patient 2. Level 2-4 are the same for Patient 1, 3 and 4.

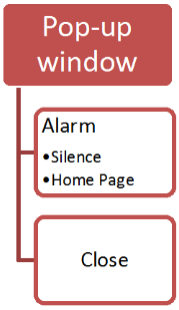


Figure B. 4 – The wireframe of the GUI for the Alarm Monitor displaying all four interaction levels.

2.2 GUI

This part of the system architecture includes a wireframe interface.

2.2.1 Wireframe Interface

Figure B. 3 presents an interaction scheme of the GUI for the Alarm Monitor, where each box represents an actionable button. In this scheme, there are four interaction levels that visualizes the user experience in the whole system. Figure B. 4 presents a pop-up window that could be produced in level 2, 3 and 4.

Level 1
This is the home page of the Alarm Monitor. A maximum of four patients can be displayed per each Alarm Monitor where the physiological and alarm status of each connected patient is presented. From this view, the user can access the main menu and silence alarms from an intended button.

Level 2-4
The user can access a button with the patient name, which includes alarm history, patient information, parameters. Additionally, the user has the ability to

change the phase mode and different settings in the main menu. See section 2.5 for more information about each function. Within these levels an alarm pop-up window would appear on the screen if an alarm is triggered. From this window, the user has the capability to silence the alarm or go back to the home page. Lastly, the user can always go back to the previous interaction level by clicking on a close button.

2.2.2 GUI illustrations

Figures B. 5, B. 6 and B. 7 are presented below as the proposed GUI illustrations of the Alarm Monitor and the Alarm Mobile.

2.3 Main PC

In addition to containing the main application for the network infrastructure and the GUI, each PC_{Main} contains a database and a MATLAB-based Intelligent Alarm Application. The intended location of the PC_{Main} is in the central station.

2.3.1 Database

This Microsoft SQL database consists of three tables containing the monitored physiological parameters, original alarms generated from the medical devices and intelligent alarms produced from the Intelligent Alarm Application.

2.3.2 Intelligent Alarm Application

The main purpose of this program is to minimize the amount of false positive alarms among the original alarms from the medical devices. This program will validate the original alarms in the database and store the true alarms in a separate table in the database. All of the stored true alarms are defined as intelligent alarms. Subsequently, these alarms are presented in the Alarm Monitor and the Alarm Mobile.

The Intelligent Alarm Application uses 23 intelligent algorithms, which are presented in Appendix C together with a list of original alarms that are validated in this system.

2.4 Gateway PC

The PC acts as a gateway allowing medical devices to connect to a PC_{Main} and should be located in each patient room. The $PC_{Gateway}$ supports the data communication from medical devices through LAN, WLAN or Bluetooth but connects to the PC_{Main} through LAN only. This computer also gives a unique identification to each patient room for easier medical device recognition by the PC_{Main}.

2.5 Alarm Monitor

The system contains at least one Alarm Monitor that will present true alarms in the central station but if needed, several Alarm Monitors could be used depending on the size of the ward.

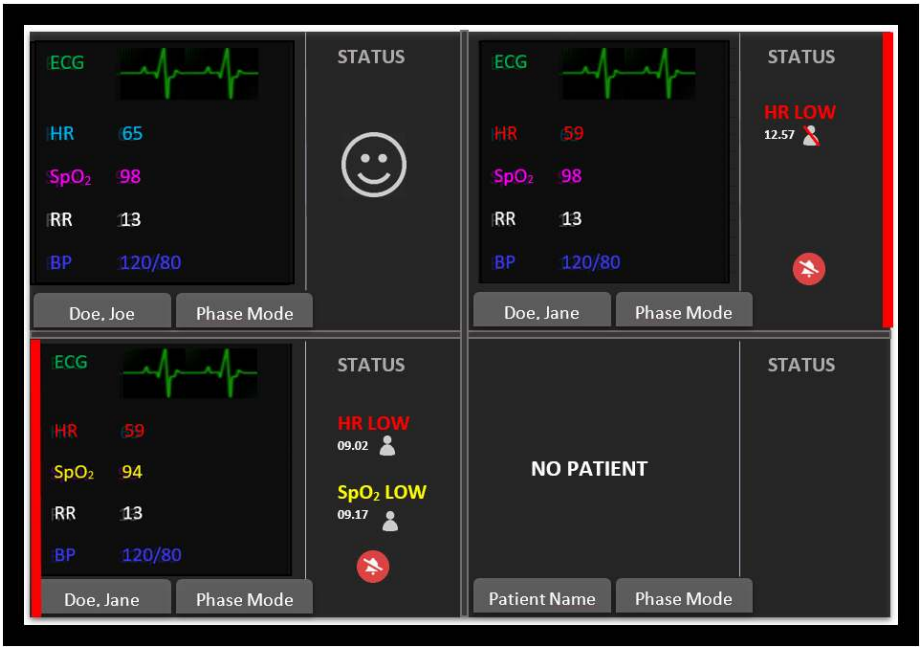


Figure B. 5 – The home page of the Alarm Monitor with three of four connected patients. The GUI also shows how different alarms are displayed and the user icon shows if there is a user in the patient room or not.

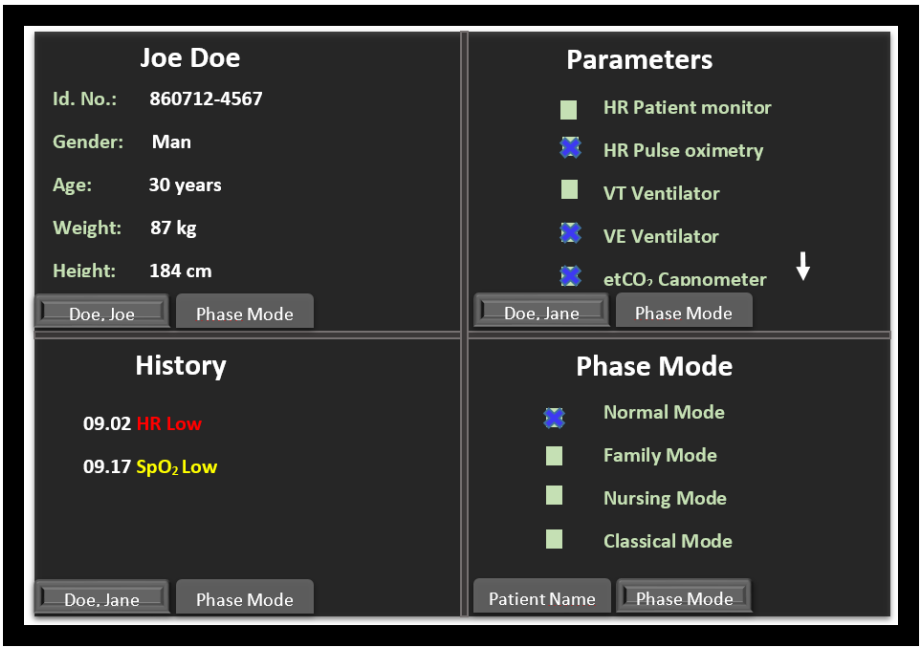


Figure B. 6 – The GUI of the main functionalities of the Alarm Monitor such as patient name, parameters, history and phase mode.

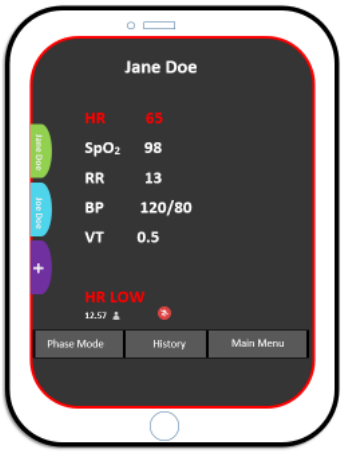


Figure B. 7 – The GUI of the Alarm Mobile showing the home page for the patient Jane Doe where one alarm is triggered.

2.5.1 Alarm Functionality

The touchscreen Alarm Monitor is connected to a PC_{Main} via an HDMI cable and is also intended to be located in a central station. A triggered original alarm, whether false or true, will only be presented visually on the medical device that generated it. Only the true ones, the intelligent alarms, will be presented on the Alarm Monitor. A pop-up window containing the intelligent alarm will also appear on Maquet Critical Care's SERVO-U mechanical ventilator in the patient room.

There are possibilities for an ICU to have several Alarm Monitors depending on the size of the ICU but one Alarm Monitor manages up to only four patients. In addition to the presentation of the alarms, the Alarm Monitor will also present the patient's vital parameters.

If a healthcare professional is located in the patient room, the intelligent alarm would be presented both visually and audibly at the SERVO-U ventilator window but only visually at the central station. However, the opposite would occur if there are no healthcare professionals in the patient room. This implies that the intelligent alarm would be presented both visually and audibly at the central station but only visually at the SERVO-U ventilator window. In Table 1, a summary of the intelligent alarm presentation is shown.

The user has two minutes to silence an intelligent alarm once it is presented on the Alarm Monitor before the system returns to Classical Mode and the medical device in question presents an audible alarm in the patient room, see section 2.5.6. Once an intelligent alarm has been silenced, the user still has to acknowledge the alarm in the patient room within a certain time depending on the priority of the alarm: three minutes for low priority alarms, two minutes for medium priority alarms and one minute for high priority alarms. The acknowledgment of an intelligent alarm has to occur in the patient room by pressing the

intended button on the GUI of the medical device that originated the alarm.

Table 1 – A table showing how the intelligent alarms will be presented in the patient room and in the central station depending on the location of users, in this case healthcare professionals.

User in the patient room	Patient Room	Central Station
True	Visually and audibly on a pop-up window in the ventilator	Visually on the Alarm Monitor
False	Visually on a pop-up window in the ventilator	Visually and audibly on the Alarm Monitor

2.5.2 Patient Name

Through this button, the user is able to fill out the patient information and assign the room in which the patient is placed. The Alarm Monitor can also be connected to a PDMS in order to receive the patient information automatically by only filling out the patient's ID. However, it is possible for the user to manually fill out patient information such as name, age, weight etc.

2.5.3 Parameters

This function is used to select what vital parameters to show on the Alarm Monitor with a maximum of five parameters. The Alarm Monitor will have these five parameters: HR, etCO_2, SpO_2, RR and BP as standard but the user can choose other parameters through this function. Depending on the physiological parameter, they could either be presented as numerical values or graphical waveforms.

2.5.4 History

The Alarm Monitor will save all of the generated intelligent alarms and the user can see these in an alarm logbook. Here the alarm name, priority, time and the medical device that triggered the alarm will be presented for the user.

2.5.5 Menu Settings

The users can modify the settings in the Alarm Monitor to adjust the sound level of the alarms, the local time and date etc. The Menu includes general settings for the monitor and the system as well.

2.5.6 Phase Modes

A phase mode is a function that allows users to modify how the medical devices in the patient room will behave. Different phase modes can be selected in the Alarm Monitor and as a standard, the phase is chosen to be Normal Mode, which is always on until another mode is selected. The other selectable modes are: Nursing, Family and Classical Modes.

Figure B. 8 – The Family Mode in SERVO-n ventilator from Maquet Critical Care.

These modes are selected by the user on the Alarm Monitor manually and have to be deselected within a certain time or else a reminder pop-up will appear on the monitor with the possibility to extend the mode or return to Normal Mode. If ignored, the phase settings will return automatically to the Normal Mode after 2 minutes. The initial time period for each remainder pop-up varies depending on which mode that is activated, 15 minutes for the Nursing Mode and 1 hour for the Family Mode and the Classical Mode respectively. Each phase mode is specified below.

Nursing Mode
Can be selected when clinical interventions are to be performed on ICU patients. For instance, a clinical intervention could be when the healthcare professionals are changing the patient's position or when brushing their teeth. During the Nursing Mode, low priority and medium priority alarms are silenced audible and only presented visually.

Family Mode
The displays on the medical devices in the patient room can be changed to show a friendlier view in order to minimize the presented metrics and curves. This mode can only be implemented on supported devices. One example of a supported device is Maquet Critical Care's SERVO-n, see Figure B. 8. Another function of this mode is to give the visitors the option to play instrumental music from a pre-selected list.

Classical Mode
With this mode the alarm functionality will return to the original functions in each medical device, meaning that each device will present its own alarms. In this case, the Intelligent Alarm Application will not handle the alarm functionality at all.

2.6 Alarm Mobile

In addition to the Alarm Monitor a mobile solution will be implemented in the system in order to receive alarms directly and to distribute the alarms within the unit.

2.6.1 Alarm Functionality

This is an android-based mobile solution that will be available to each on-duty healthcare professional. With this solution, they will be able to connect their mobile to the patient that they are responsible for during their shift by filling out the patient ID. This will ensure that relevant alarms are distributed to the responsible healthcare professional(s). One patient can be divided between several users and one user can always add more patients to the mobile. When the responsible healthcare professional is too busy to acknowledge an alarm, he or she can call for help through the mobile. In that case, all of the healthcare professionals in the ward will receive the alarm as a pop-up window on their mobile screen. Through which they can either indicate that they will take care of the alarm or dismiss it.

The healthcare professionals in the ICU will each use the Alarm Mobile to be notified of intelligent alarms through vibration and visual indications on the screen. The vibration function should be strong enough to grab the attention of the user and varies depending on the priority of the alarm as does the visual indicator.

Once an alarm is triggered, it will also be presented on the Alarm Monitor in the central station and on the ventilator if the user is in the patient room, as mentioned in section 2.5. The users can only silence alarms through the mobile solution but has to acknowledge them in the patient room. The silencing and acknowledgment of alarms is the same as the one described in section 2.5.1.

2.6.2 Parameters

This function is used to select what vital parameters to be shown on the Alarm Mobile and is similar to the one described in section 2.5.3.

2.6.3 History

This function is used to see a logbook of alarms generating intelligent alarms and is similar to the one described in section 2.5.4.

2.6.4 Menu Settings

Similar to the menu function that is described in section 2.5.5. However, in this menu the users will be able to modify the vibration level of the alarms instead of sound level.

2.6.5 Phase Modes

The Alarm Mobile will also have the same phase mode settings as the Alarm Monitor, which is described in section 2.5.6. Moreover, there is an additional phase mode, called Fika Mode, for the mobile that is not included in the Alarm Monitor.

Fika Mode
This mode is chosen whenever the healthcare professional is on a break in order to not receive any alarms to the mobile. This function will only be activated for 30 minutes before the users has to either extend it or it will return to Normal Mode.

2.6.6 Indoor Positioning System

There is an IPS function in the mobile solution that will find the user's position in the ward with a good accuracy using the Bluetooth function in the Alarm Mobile and the Gateway PC. The intended purpose of the IPS is to note whether there is a healthcare professional in the patient room and if so, the intelligent alarms are presented audibly in the patient room instead of the central station as described in section 2.5.

Additionally, another function of the IPS is to turn on the display of monitors when the healthcare professionals enter the room and turn off the displays when they leave. Moreover, the IPS function will be used to indicate whether there is a healthcare professional with the patient or not. The indication is symbolized with a user icon on the Alarm Monitor and the Alarm Mobile, see Figure B-5 and Figure B-7.

2.7 User Cases

There are mainly three big user cases in which the system will behave differently depending on whether the healthcare professionals are in the central station, in the patient room or in another area.

2.7.1 Central Station

When the healthcare professionals are in the central station the alarms from the medical devices in the patient room are directly silenced. These alarms are validated through the Intelligent Alarm Application and then presented on the Alarm Monitor that is placed in the central station. The Alarm Monitor will present the alarms audibly and visually. The responsible healthcare professional(s) will also receive the alarm through vibration and visual indicator through the Alarm Mobile.

The alarms that are triggered in the Alarm Monitor and in the mobile device can be silenced but it is not a prerequisite. If the alarms in the Alarm Monitor are silenced, then the same alarms in the mobile solution will automatically be silenced and vice versa. However, after silencing the alarm, the healthcare professional(s) has to acknowledge it in the patient room within a certain time.

If the alarms in the Alarm Monitor or in the mobile solution is not silenced within 2 minutes, the alarm function will return to the Classical Mode in the patient room. This implies that the medical device which generated the original alarm will now present it without the intelligent alarm managing system.

When healthcare professionals are in the central station the display of the medical devices' monitors are turned off but the parameters are still presented on the Alarm Monitor and on the Alarm Mobile as well.

2.7.2 Patient Room

When the responsible healthcare professional(s) are in the patient room, the intelligent alarms will be presented on a window on the ventilator. Moreover, the alarms will be presented visually on the Alarm Monitor and on the Alarm Mobile.

The triggered alarms need to be both silenced and acknowledged in the patient room. The user silences the alarm on the ventilator but acknowledges them on each medical device that originally generated the alarm. When a healthcare professional is entering the patient room, the monitors of the medical devices are turned on instantly and off when leaving.

2.7.3 Other Areas

When healthcare professionals are in other areas in the ICU than the central station or the patient room, the alarms from the medical devices in the patient room are silenced as usual. The intelligent alarms are instead presented audibly and visually in the Alarm Monitor at the central station. The responsible healthcare professional(s) will also receive the alarm through vibration and visual indicator in the mobile solution.

The alarms that are triggered in the Alarm Monitor and in the mobile device can be silenced through the Alarm Mobile. However, after silencing the alarm, the healthcare professional must acknowledge the same alarm in the patient room within a certain time.

If the alarms in the Alarm Monitor or in the mobile solution is not silenced within 2 minutes, the alarm function will return to the Classical Mode in the patient room. This indicates that the medical device which generated the original alarm will now present it as usually without the intelligent alarm managing system.

When healthcare professionals are in other areas, the monitors of the medical devices in the patient room are turned off but will turn on once they enter the room.

Appendix C: Intelligent Algorithms

Contents

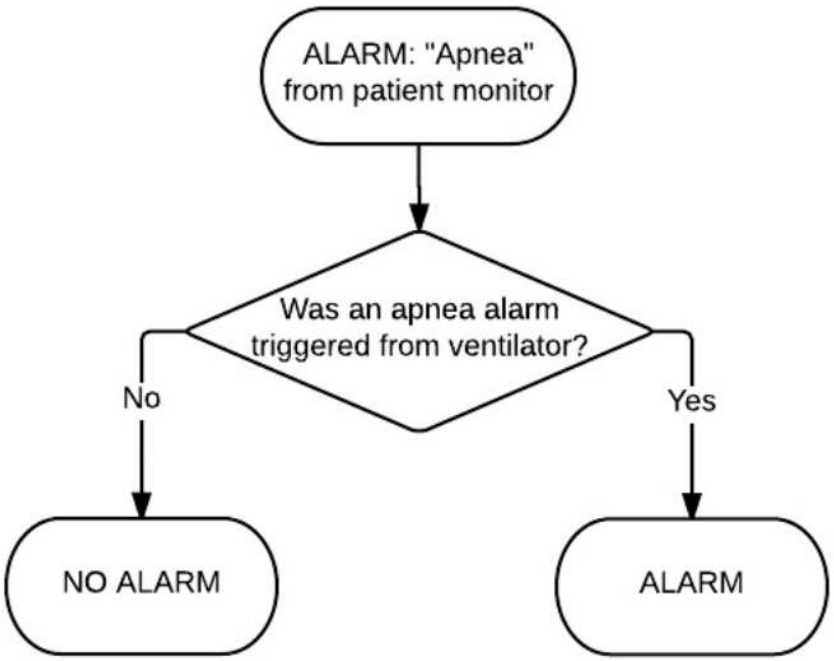
1 Original Alarms

Table 1 – All original alarms from each device are categorized in respiratory and hemodynamic alarms, respectively. There are three priorities: High (***), medium (**) and low (*).

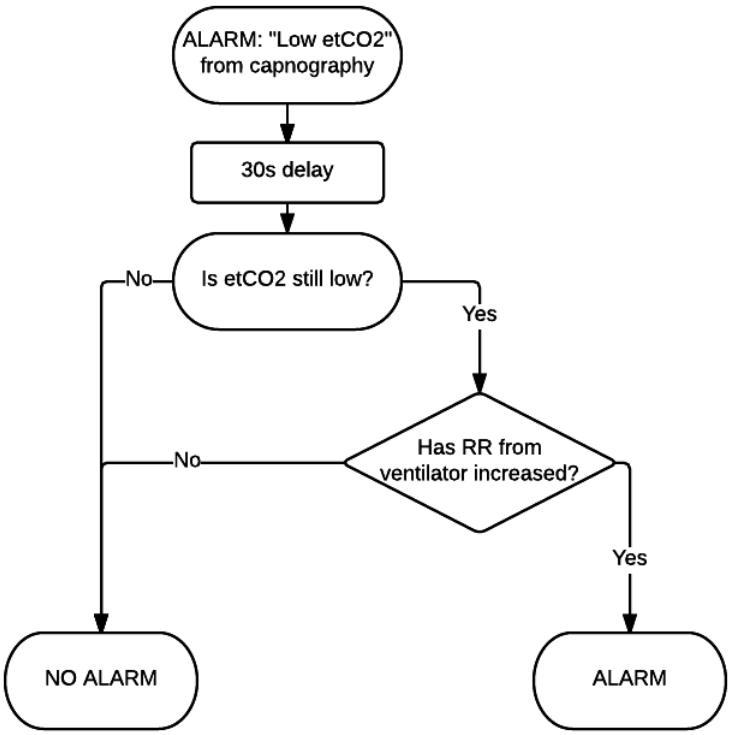
	Alarm Name	Priority	Device	Sensor
Respiratory Alarms	Apnea	***	IntelliVue MP70	-
	Low etCO2	**	IntelliVue MP70	Capnography
	High etCO2	**	IntelliVue MP70	Capnography
	Low SpO2	**	IntelliVue MP70	Pulse oximetry
	Low SpO2	**	Nonin WristOx2	-
	Low MV	***	SERVO-U	-
	High MV	**	SERVO-U	-
	Low RR	**	SERVO-U	-
	High RR	**	SERVO-U	-
	Low RR	**	IntelliVue MP70	ECG
	High RR	**	IntelliVue MP70	ECG
Hemodynamic Alarms	Ventricular Tachycardia	***	IntelliVue MP70	ECG
	Ventricular Fibrillation	***	IntelliVue MP70	ECG
	Low pulse rate	**	IntelliVue MP70	Pulse oximetry
	High pulse rate	**	IntelliVue MP70	Pulse oximetry
	Low HR	**	IntelliVue MP70	ECG
	High HR	**	IntelliVue MP70	ECG
	Low HR	**	IntelliVue MP70	Pulse oximetry
	High HR	**	IntelliVue MP70	Pulse oximetry
	Low HR	**	IntelliVue MP70	ABP
	High HR	**	IntelliVue MP70	ABP

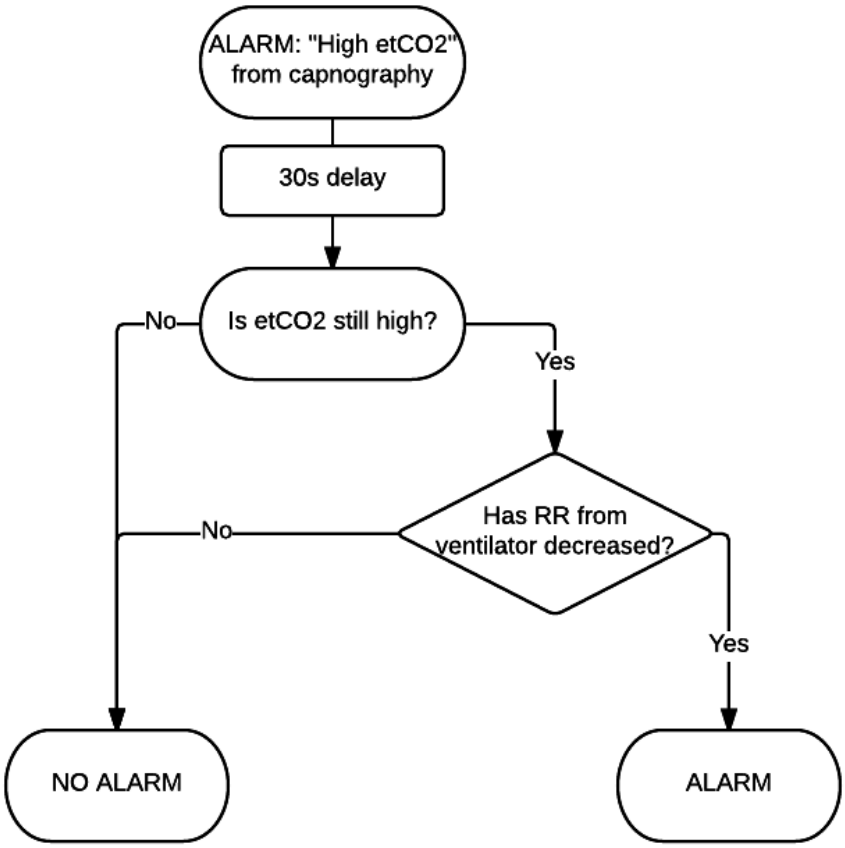
2 Respiratory Alarm Algorithms

2.1 Apnea



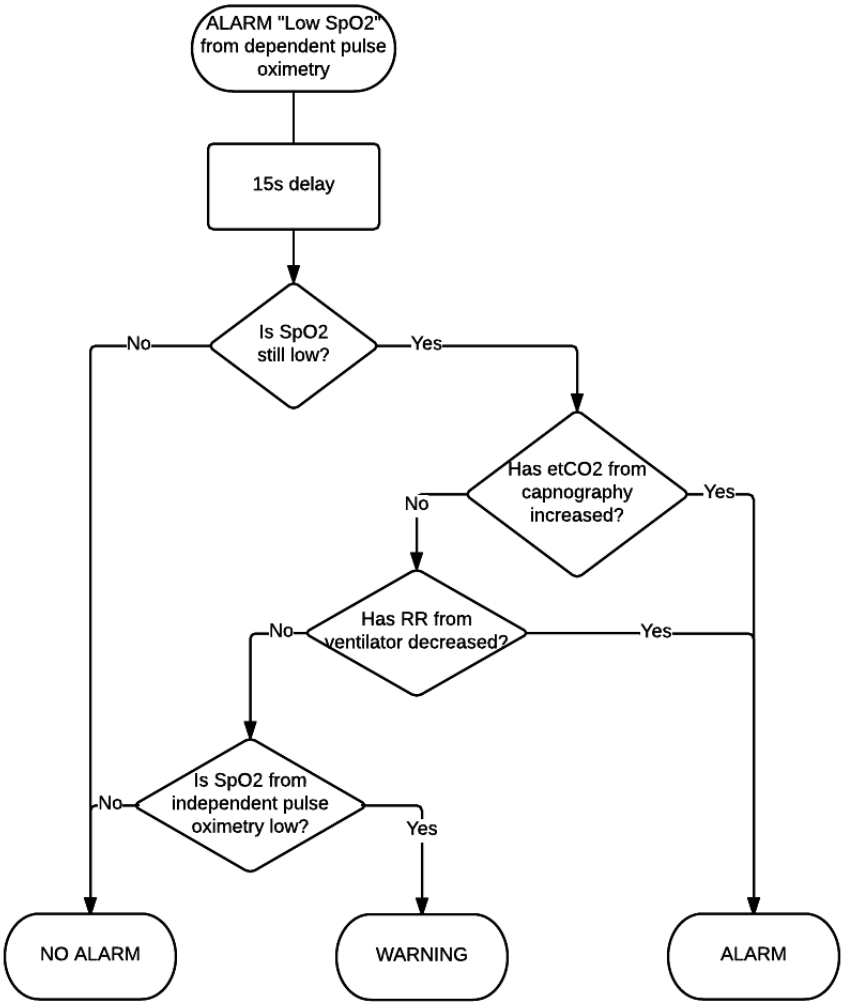
2.2 $etCO_2$


ALARM: "Low etCO2" from capnography
30s delay
Is etCO2 still low?
No
Yes
Has RR from ventilator increased?
No
Yes
NO ALARM
ALARM

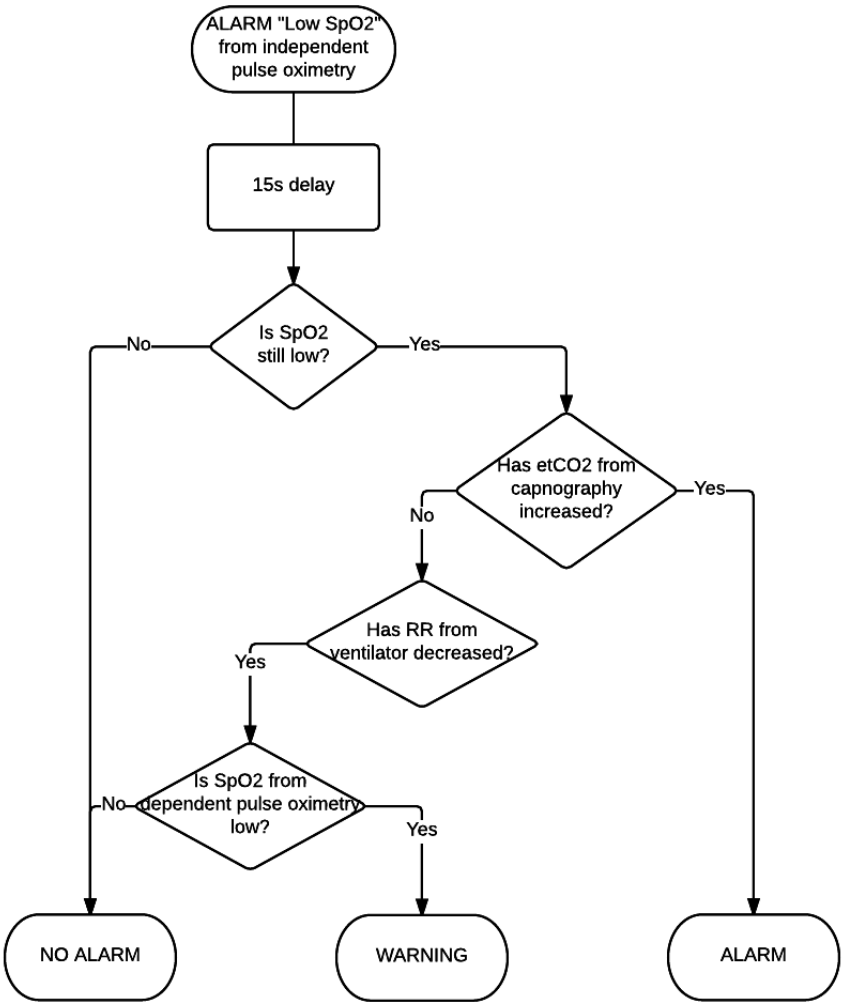

ALARM: "High etCO2" from capnography
30s delay
Is etCO2 still high?
No
Yes
Has RR from ventilator decreased?
No
Yes
NO ALARM
ALARM

2.3 SpO_2

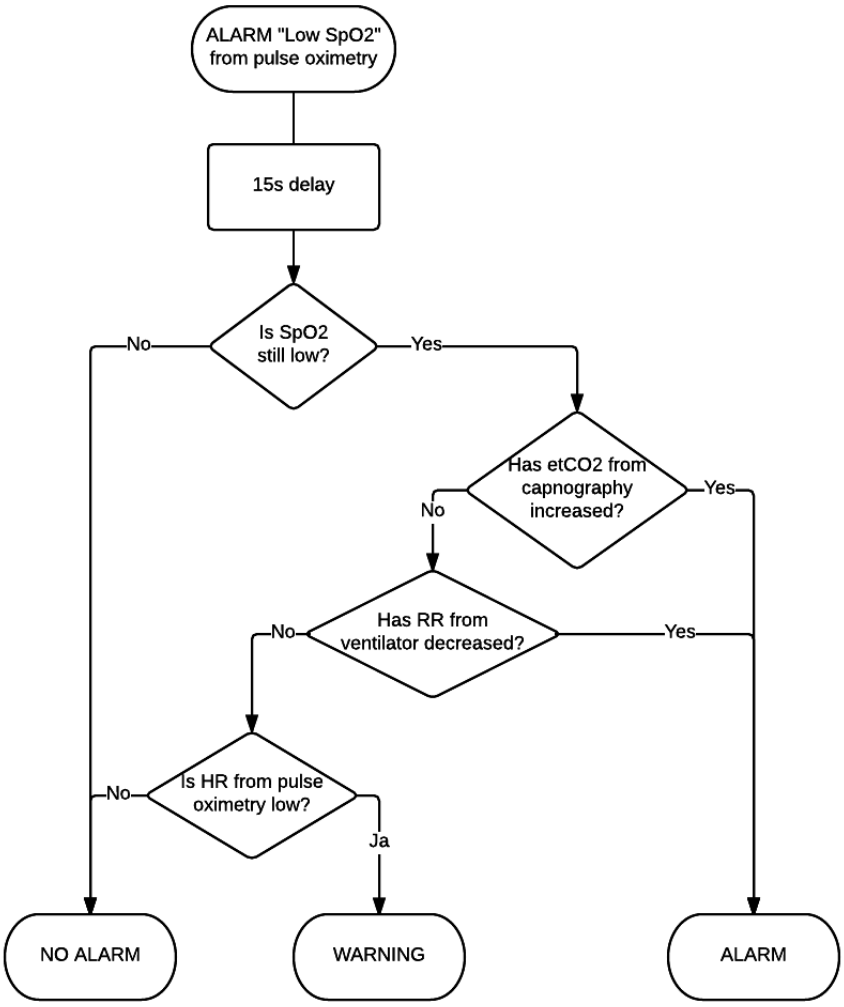
2.3.1 Dependent Pulse Oximetry



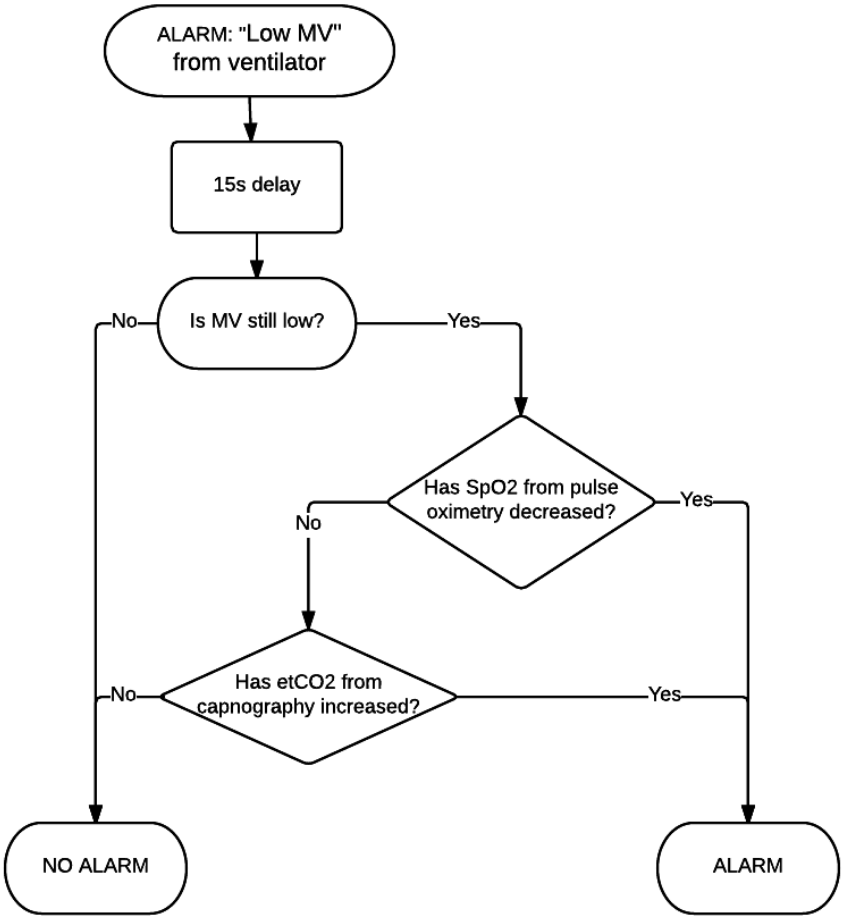
2.3.2 Independent Pulse Oximetry

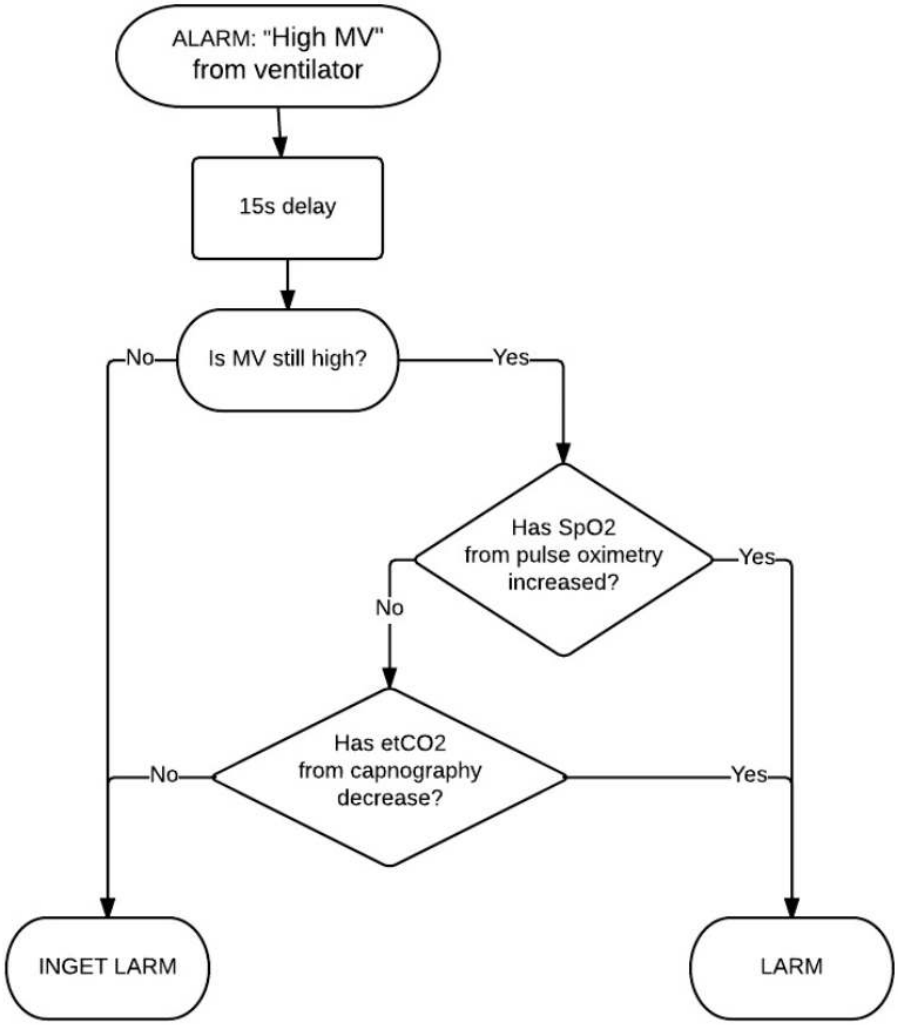


2.3.3 Single Pulse Oximetry



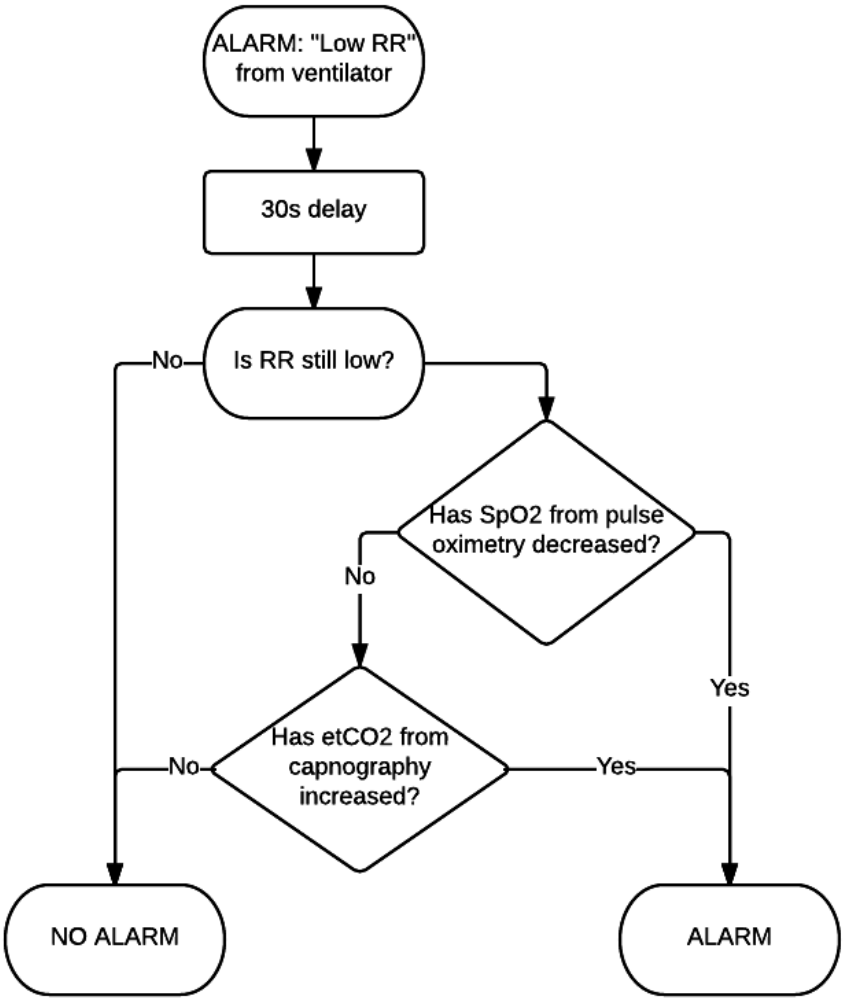
2.4 MV

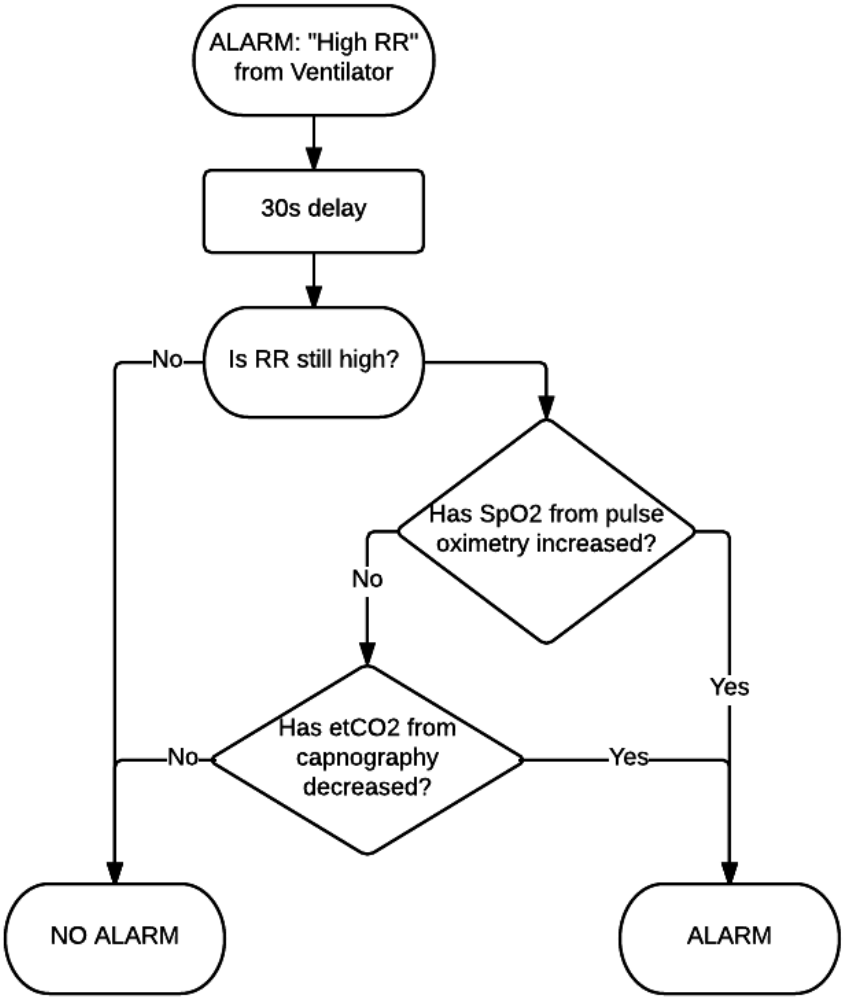

ALARM: "Low MV" from ventilator
15s delay
Is MV still low?
No
Yes
Has SpO2 from pulse oximetry decreased?
No
Yes
Has etCO2 from capnography increased?
No
Yes
NO ALARM
ALARM


ALARM: "High MV"
from ventilator
15s delay
Is MV still high?
No
Yes
Has SpO2
from pulse oximetry
increased?
Yes
No
Has etCO2
from capnography
decrease?
No
Yes
INGET LARM
LARM

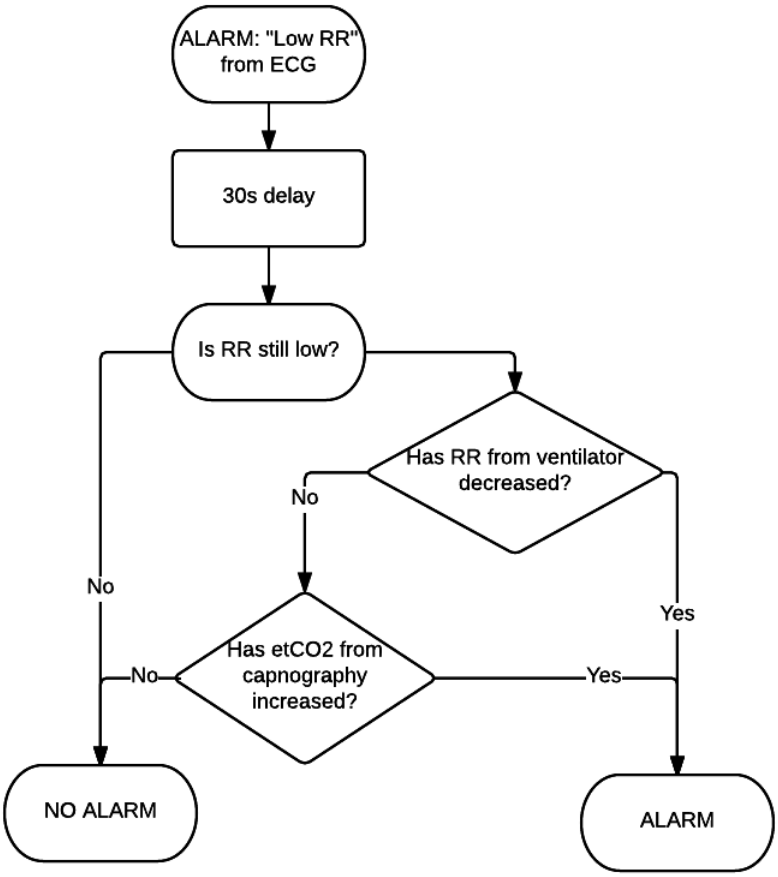
2.5 RR

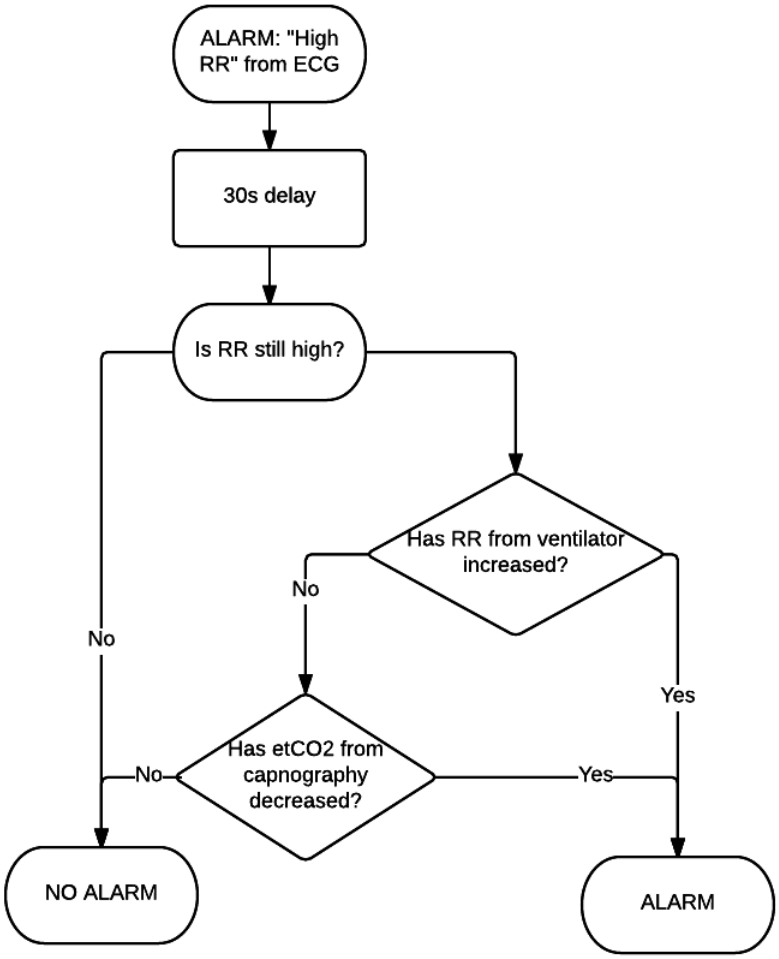
2.5.1 Ventilator




ALARM: "High RR" from Ventilator
30s delay
Is RR still high?
No
Has SpO2 from pulse oximetry increased?
No
Yes
Has etCO2 from capnography decreased?
No
Yes
NO ALARM
ALARM

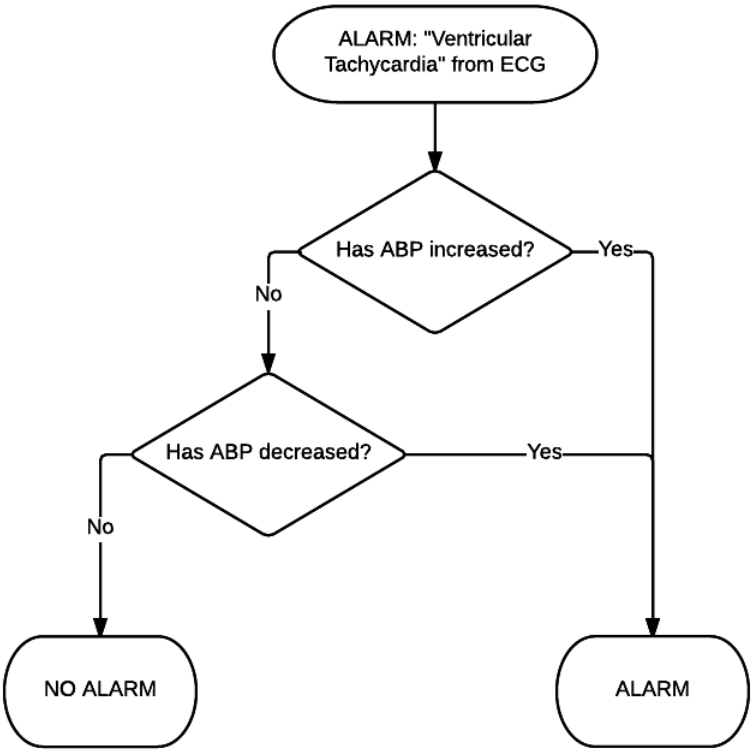
2.5.2 ECG


ALARM: "Low RR" from ECG
30s delay
Is RR still low?
No
Has RR from ventilator decreased?
No
Yes
No
Has etCO2 from capnography increased?
No
Yes
NO ALARM
ALARM

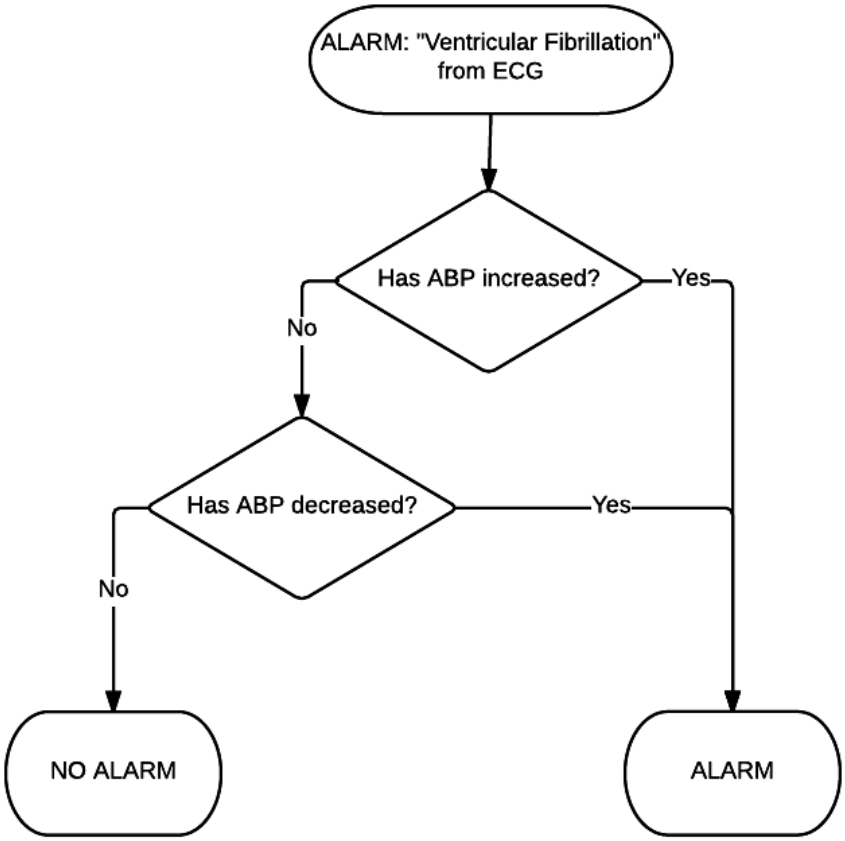

ALARM: "High RR" from ECG
30s delay
Is RR still high?
No
Has RR from ventilator increased?
No
Yes
Has etCO2 from capnography decreased?
No
Yes
NO ALARM
ALARM

3 Hemodynamic Alarm Algorithms

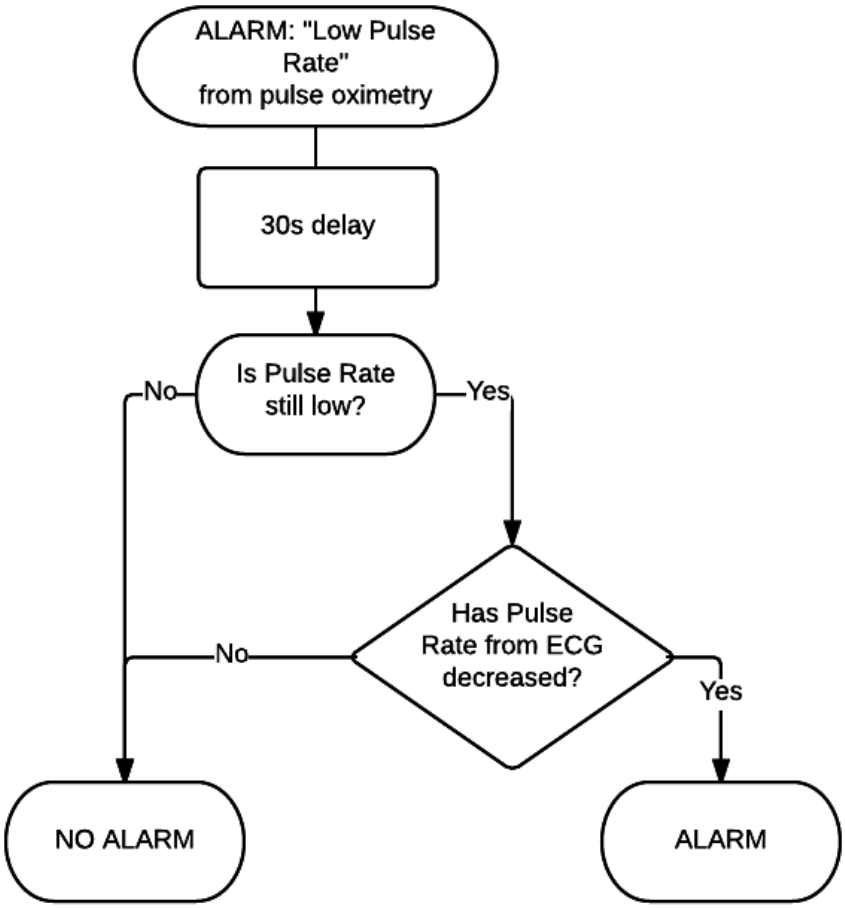
3.1 Venticular Tachycardia

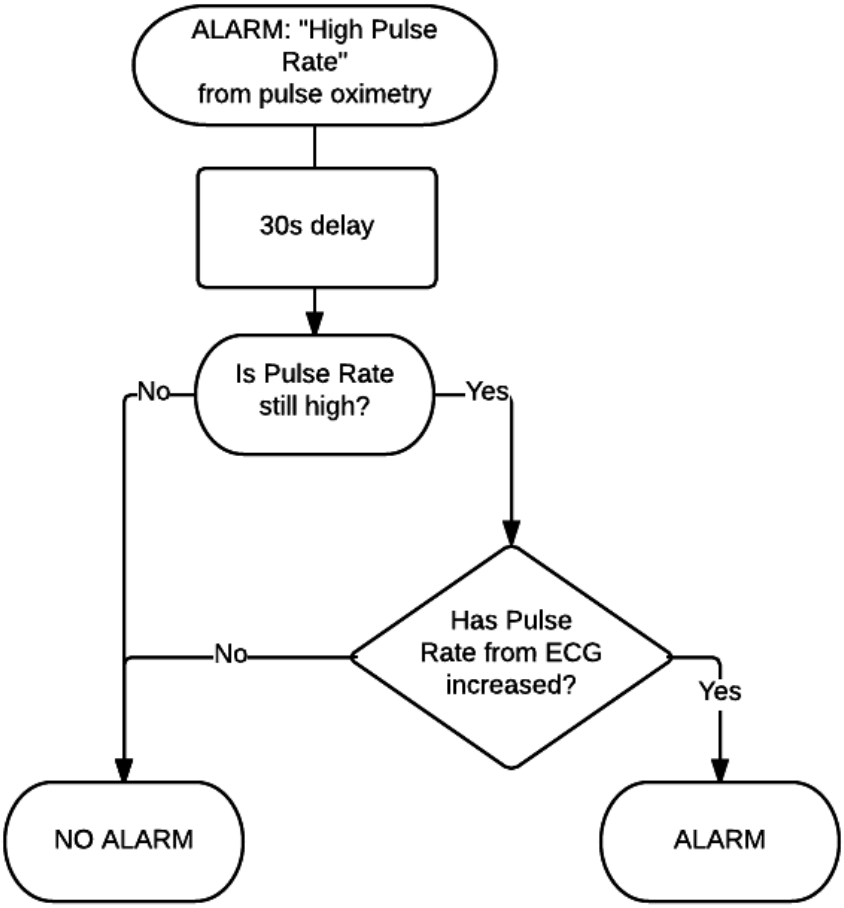


3.2 Venticular Fibrillation



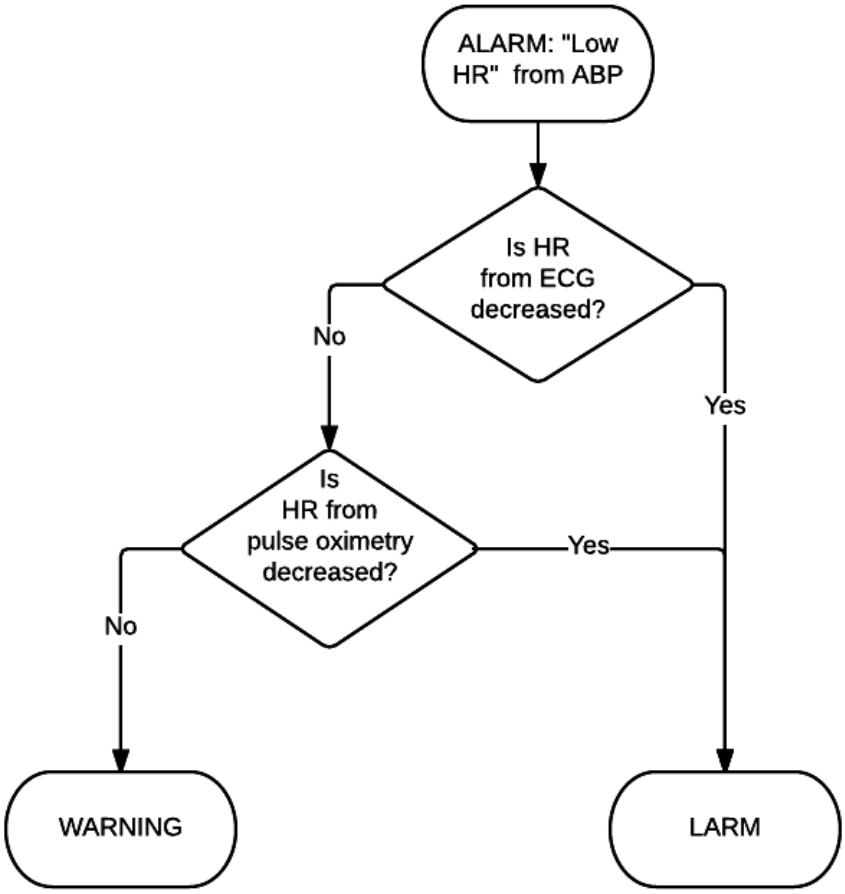
3.3 Pulse Rate

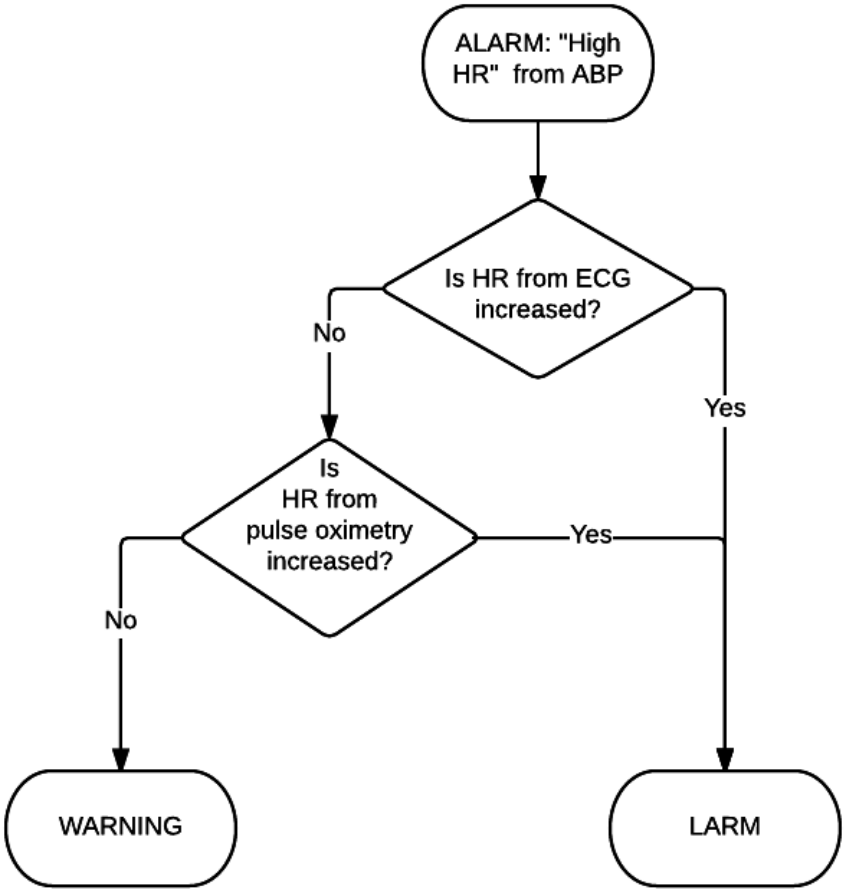



ALARM: "High Pulse Rate"
from pulse oximetry
30s delay
Is Pulse Rate still high?
No
Yes
Has Pulse Rate from ECG increased?
No
Yes
NO ALARM
ALARM

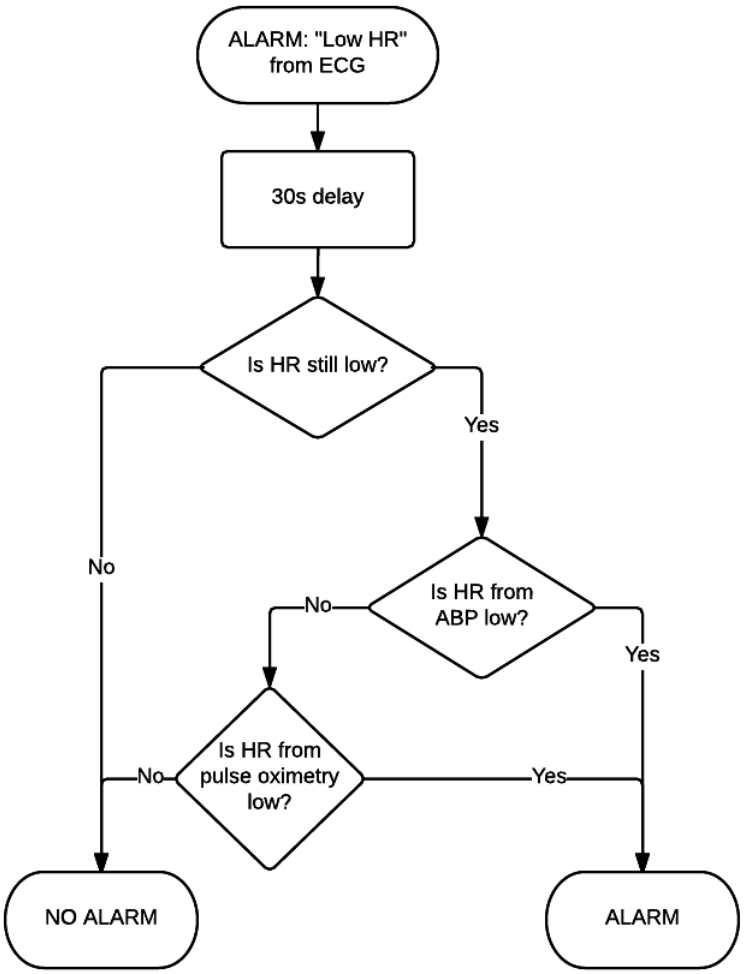
3.4 HR

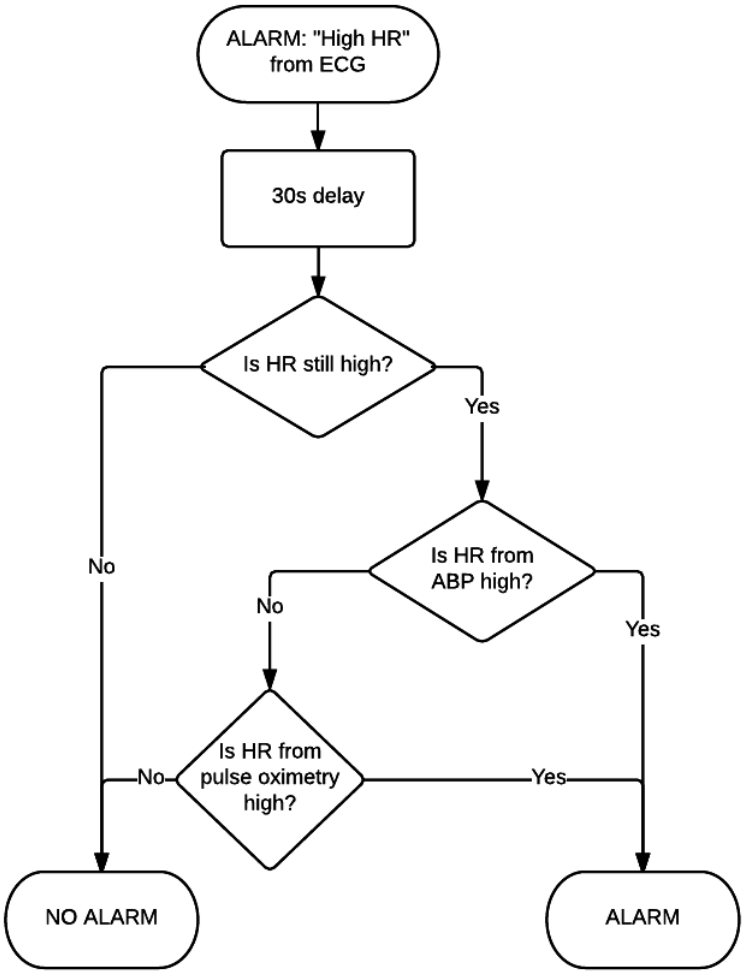
3.4.1 ABP


ALARM: "Low HR" from ABP
Is HR from ECG decreased?
No
Yes
Is HR from pulse oximetry decreased?
Yes
No
WARNING
LARM

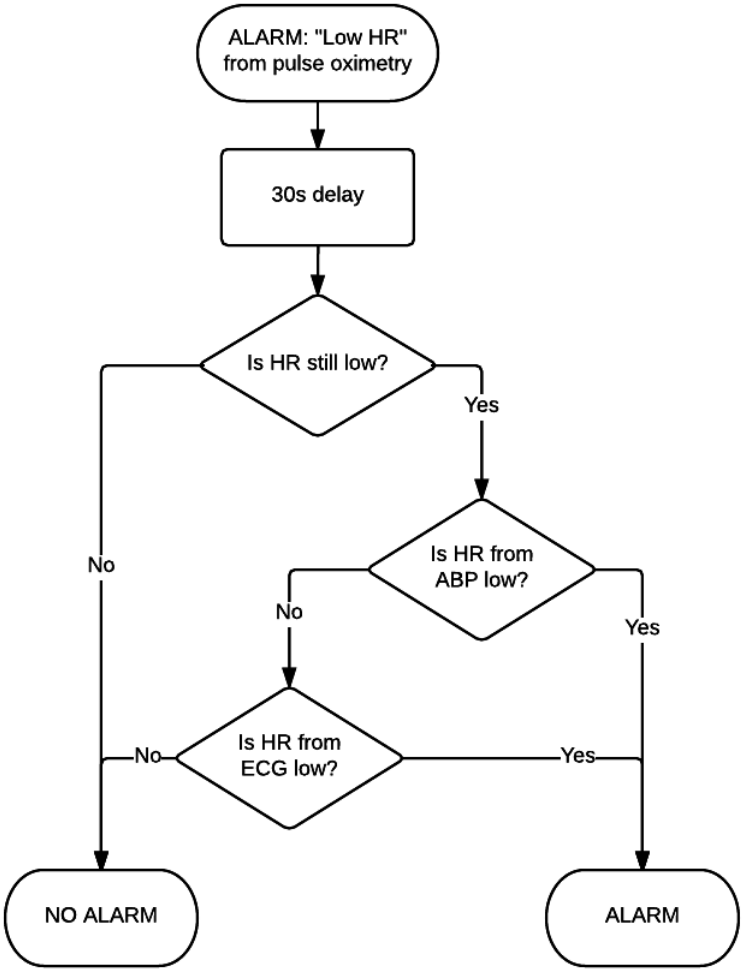

ALARM: "High HR" from ABP
Is HR from ECG increased?
No
Yes
Is HR from pulse oximetry increased?
Yes
No
WARNING
LARM

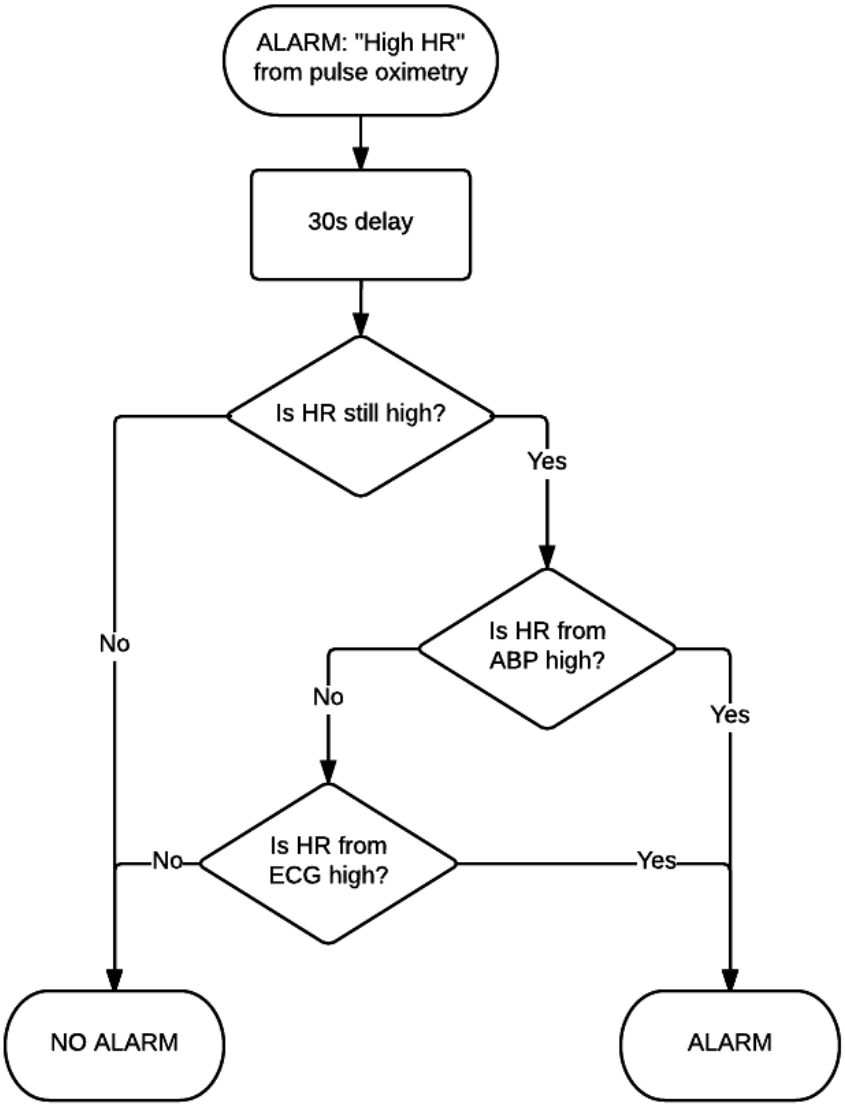
3.4.2 ECG


ALARM: "Low HR" from ECG
30s delay
Is HR still low?
Yes
No
Is HR from ABP low?
No
Yes
Is HR from pulse oximetry low?
No
Yes
NO ALARM
ALARM

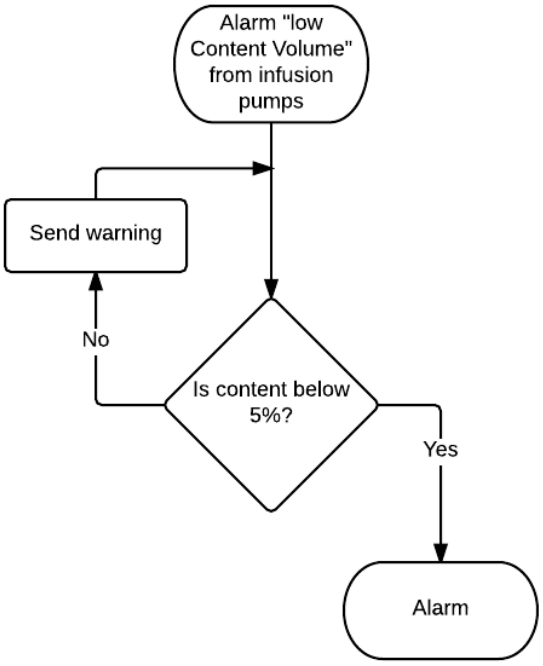

ALARM: "High HR" from ECG
30s delay
Is HR still high?
Yes
No
Is HR from ABP high?
No
Yes
Is HR from pulse oximetry high?
No
Yes
NO ALARM
ALARM

3.4.3 Pulse Oximetry




ALARM: "High HR" from pulse oximetry
30s delay
Is HR still high?
Yes
No
Is HR from ABP high?
No
Yes
Is HR from ECG high?
No
Yes
NO ALARM
ALARM

4 Internal Milieu Alarm Algorithms



Appendix D: The Matlab Script

Contents

1 Database Connection to the Application

The following is the Matlab script that was used to connect the database to the application.

1.1 DataBaseRead

```
function DataBaseRead()
global conn;
conn = database.ODBCConnection('SilentVentilation','
    SilentVentilation','sH32%p');
end
```

1.2 Table OriginalAlarm

```
function Table_OriginalAlarm()
global conn OriginalAlarmTable

curs = exec(conn,'select AlarmName, Device, LimitValue,
    InDate, Status from OriginalAlarm');%,'select Status
    from OriginalAlarm']);
setdbprefs('DataReturnFormat','cellarray');
curs = fetch(curs);
OriginalAlarmTable = curs.Data;
end
```

1.3 Table IntelligentAlarms

```
function Table_IntelligentAlarms()
global conn IntelligentAlarmTable

curs = exec(conn,['select AlarmName, Priority, Device,
    InDate, OutDate, Status from IntelligentAlarm']);
setdbprefs('DataReturnFormat','cellarray');
curs = fetch(curs);
IntelligentAlarmTable = curs.Data;

end
```

1.4 Table DiscParam

```
function Table_DiscParam
%Sets up Paramter table
global conn ValueTable

curs = exec(conn,['select ParamName, ParamValue, Device
    from DiscParam']);%,'select Status from OriginalAlarm
    ']);
setdbprefs('DataReturnFormat','cellarray');
curs = fetch(curs);
ValueTable = curs.Data;

end
```

2 Main classes

These classes were used to set-up the flow in the script by reading values from tables, writing in tables and sorting alarms.

2.1 Alarm Fetch

```
function AlarmFetch()
%Retrive AlarmName from OriginalAlarm

DataBaseRead();

global OriginalAlarmTable

Table_OriginalAlarm()

%Only new Alarms
max_size=size(OriginalAlarmTable,1);

for i=1:1:max_size
    if OriginalAlarmTable{i,5}==0
        AlarmName=OriginalAlarmTable{i,1};
        Device=OriginalAlarmTable{i,2};
        Threshold=OriginalAlarmTable{i,3};
        InDate=OriginalAlarmTable{i,4};
        AlarmSort(AlarmName,Device,Threshold,InDate);
    end
end
end
```

2.2 Alarm Sort

```
function AlarmSort(AlarmName,Device,Threshold,InDate)


%Sort Alarms to right validation algorithm

%Low SpO2 Alarms from Pulse Oximetry
if strcmp(AlarmName,'Low_SpO2')==1
    if strcmp(Device, 'Pulse Oximetry')==1
        Alarm_SpO2_PulseOximetry_Low(AlarmName, Device,
            Threshold, InDate);
    elseif strcmp(Device, 'Nonin')==1
        Alarm_SpO2_Nonin_Low(AlarmName, Device, Threshold
            , InDate);
    end

%Low HR Alarms from Pulse Oximetry, ECG, ABP
```

```
15  elseif strcmp(AlarmName,'Low_HR')==1
16        if strcmp(Device, 'Pulse Oximetry')==1
17           Alarm_HR_PulseOximetry_Low(AlarmName, Device,
                 Threshold,InDate);
18        elseif strcmp(Device, 'Arteriel Blood Pressure')==1
19           Alarm_HR_ABP_Low(AlarmName, Device, Threshold,
                 InDate);
20        elseif strcmp(Device, 'Electrocardiography')==1
21           Alarm_HR_ECG_Low(AlarmName, Device, Threshold,
                 InDate);
22        end
23
24  %High HR Alarms from Pulse Oximetry, ECG, ABP
25  elseif strcmp(AlarmName,'High_HR')==1
26        if strcmp(Device, 'Pulse Oximetry')==1
27           Alarm_HR_PulseOximetry_High(AlarmName,Device,
                 Threshold,InDate);
28        elseif strcmp(Device, 'Arteriel Blood Pressure')==1
29           Alarm_HR_ABP_High(AlarmName,Device,Threshold,
                 InDate);
30        elseif strcmp(Device, 'Electrocardiography')==1
31           Alarm_HR_ECG_High(AlarmName,Device,Threshold,
                 InDate);
32        end
33
34  %Low RR Alarms from Pulse ECG, Ventilator
35  elseif strcmp(AlarmName,'Low_RR')==1
36        if strcmp(Device, 'Ventilator')==1
37           Alarm_RR_Ventilator_Low(AlarmName,Device,
                 Threshold,InDate);
38        elseif strcmp(Device, 'Electrocardiography')==1
39           Alarm_RR_ECG_Low(AlarmName,Device,Threshold,
                 InDate);
40        end
41
42  %High RR Alarms from Pulse ECG, Ventilator
43  elseif strcmp(AlarmName,'High_RR')==1
44        if strcmp(Device, 'Ventilator')==1
45           Alarm_RR_Ventilator_High(AlarmName,Device,
                 Threshold,InDate);
46        elseif strcmp(Device, 'Electrocardiography')==1
47           Alarm_RR_ECG_High(AlarmName,Device,Threshold,
                 InDate);
48      end
49
50  %Low etCO2 Alarm from Capnometer
51  elseif strcmp(AlarmName,'Low_etCO2')==1
52      Alarm_etCO2_Capnometer_Low(AlarmName,Device,Threshold
            ,InDate);
53
```

```
%High etCO2 Alarm from Capnometer
elseif strcmp(AlarmName,'High_etCO2')==1
    Alarm_etCO2_Capnometer_High(AlarmName,Device,
        Threshold,InDate);

%Low MV Alarm from Ventilator
elseif strcmp(AlarmName,'Low_MV')==1
    Alarm_MV_Ventilator_Low(AlarmName,Device,Threshold,
        InDate);

%High MV Alarm from Ventilator
elseif strcmp(AlarmName,'High_MV')==1
    Alarm_MV_Ventilator_Low(AlarmName,Device,Threshold,
        InDate);

%Low Pulse Rate Alarm from Pulse Oximetry
elseif strcmp(AlarmName,'Low_PulseRate')==1
    Alarm_PulseRate_PulseOximetry_Low(AlarmName,Device,
        Threshold,InDate);

%High Pulse Rate Alarm from Pulse Oximetry
elseif strcmp(AlarmName,'High_PulseRate')==1
    Alarm_PulseRate_PulseOximetry_High(AlarmName,Device,
        Threshold,InDate);
else
    %%%%%%% Alarms Not Included in Script
    OutDate=datestr(now,31);
    DataStream={AlarmName,3,Device,InDate, OutDate, 0};
    WriteIntelligentAlarms(DataStream);

end
```

2.3 changeStatus

```
function changeStatus(data, whereClause)
global conn

Table_OriginalAlarm()
colNames = {'Status'};
tableName='OriginalAlarm';
dataStream = table(data,'VariableNames',{'Status'});


update(conn,tableName,colNames,dataStream,whereClause);

end
```

2.4 WriteIntelligentAlarms

```
function WriteIntelligentAlarms(AlarmName, Priority,
    Device, InDate)
global conn

OutDate=datestr(now,31);
Status=0;

DataStream={AlarmName,Priority,Device, InDate, OutDate,
    Status};

Table_IntelligentAlarms();
colnames={'AlarmName','Priority','Device','InDate','
    OutDate','Status'};
tablename = 'IntelligentAlarm';

DataFormat = cell2table(DataStream,'VariableNames',
    colnames);
insert(conn,tablename,colnames,DataFormat);

end
```

2.5 getValue

```
function getValue(ParamName,Device)
global ValueTable chosenValue
Table_DiscParam;

max_size=size(ValueTable,1);

for i=1:1:max_size
    if strcmp(ValueTable{i,1},ParamName)==1
        if strcmp(ValueTable{i,3},Device)==1
            chosenValue=ValueTable{i,2};
        end
    end
    i=i+1;
end
end
```

3 Alarms

These are the function classes that were used to create and validate alarms.

3.1 Original Nonin Alarm

```
function originalAlarm_Nonin()
global conn

Nonin_Value=getValue('SpO2','Nonin');

if Nonin_Value<95
    orgStatus=1;
else
    orgStatus=0;
end

%Write in OriginalTable

if orgStatus==1
    AlarmName='Low SpO2';
    LimitValue=95;
    Device='Nonin';
    InDate=datestr(now,31);
    Status=0;

    DataStream={AlarmName,Device,LimitValue, InDate,
        Status};
    Table_OriginalAlarm();
    colnames={'AlarmName','Priority','Device','InDate','
        Status'};
    tablename = 'OriginalAlarm';

    DataFormat = cell2table(DataStream,'VariableNames',
        colnames);
    insert(conn,tablename,colnames,DataFormat);
end

end
```

3.2 High etCO2 Alarm from Capnography

```
function Alarm_etCO2_Capnometer_High(Threshold, InDate)

first_RR_Ventilator_Value= getValue('RR','Ventilator');

%Delay
pause(30);
```

```
7
8  %Values after Delay
9  second_RR_Ventilator_Value= getValue('RR','Ventilator');
10 second_etCO2_Capnometer_Value= getValue('etCO2','
       Capnometer');
11
12 %Check Validity
13 if second_etCO2_Capnometer_Value>=Threshold
14      if second_RR_Ventilator_Value<=
            first_RR_Ventilator_Value
15          AlarmValid=1;
16      else
17          AlarmValid=0;
18      end
19 else
20      AlarmValid=0;
21 end
22
23 %Write & Update
24 OutDate=datestr(now,31);
25
26 if AlarmValid==1
27      DataStream={'High_RR',3,'Capnometer', InDate, OutDate
            , 0};
28      WriteIntelligentAlarms(DataStream);
29 end
30 whereClause={'Where AlarmName =''High_etCO2'''};
31 changeStatus({1}, whereClause);
32 end
```

3.3 Low etCO2 Alarm from Capnography

```
1  function Alarm_etCO2_Capnometer_Low(Threshold, InDate)
2
3  first_RR_Ventilator_Value= getValue('RR','Ventilator');
4
5  %Delay
6  pause(30);
7
8  %Values after Delay
9  second_RR_Ventilator_Value= getValue('RR','Ventilator');
10 second_etCO2_Capnometer_Value= getValue('etCO2','
       Capnometer');
11
12 %Check Validity
13 if second_etCO2_Capnometer_Value<=Threshold
14      if second_RR_Ventilator_Value>=
            first_RR_Ventilator_Value
15          AlarmValid=1;
```

```
    else
        AlarmValid=0;
    end
else
    AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'Low_etCO2',3,'Capnometer', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''Low_etCO2'''};
changeStatus({1}, whereClause);
end
```

3.4 High HR Alarm from ABP

```
function Alarm_HR_ABP_High(Threshold, InDate)
%Values upon arrival
second_HR_ECG_Value=getValue('HR','Electrocardiography');
second_HR_PulseOximetry_Value=getValue('HR','Pulse
    Oximetry');


%Check Validity
if second_HR_ECG_Value>=Threshold ||
    second_HR_PulseOximetry_Value>=Threshold
        AlarmValid=1;
else
        AlarmValid=2;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'High_HR',3,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
    changeStatus({1});
elseif AlarmValid ==2
    DataStream={'High_HR',0,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
```

```
whereClause={'Where AlarmName =''High_HR'''};
changeStatus({1}, whereClause);
end
```

3.5 High HR Alarm from ABP

```
function Alarm_HR_ABP_Low(Threshold, InDate)

%Values upon arrival
second_HR_ECG_Value=getValue('HR','Electrocardiography');
second_HR_PulseOximetry_Value=getValue('HR','Pulse
    Oximetry');

%Check Validity
if second_HR_ECG_Value<=Threshold ||
    second_HR_PulseOximetry_Value<=Threshold
        AlarmValid=1;
else
        AlarmValid=2;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'High_HR',3,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
    changeStatus({1});
elseif AlarmValid ==2
    DataStream={'High_HR',0,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''Low_HR'''};
changeStatus({1}, whereClause);
end
```

3.6 Low HR Alarm from ECG

```
function Alarm_HR_ECG_Low(Threshold, InDate)

%Delay
pause(30);

%Values after Delay
second_HR_ABP_Value=getValue('HR','Arteriel Blood
    Pressure');
```

```
second_HR_ECG_Value=getValue('HR','Electrocardiography');
second_HR_PulseOximetry_Value=getValue('HR','Pulse
    Oximetry');

%Check Validity
if second_HR_ECG_Value<=Threshold
    if second_HR_ABP_Value<=Threshold ||
        second_HR_PulseOximetry_Value<=Threshold
        AlarmValid=1;
    else
        AlarmValid=0;
    end
else
    AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'Low_HR',3,'Electrocardiography', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''Low_HR'''};
changeStatus({1}, whereClause);
end
```

3.7 High HR Alarm from ECG

```
function Alarm_HR_ECG_High(Threshold, InDate)
%Delay
pause(30);

%Values after Delay
second_HR_ABP_Value=getValue('HR','Arteriel Blood
    Pressure');
second_HR_ECG_Value=getValue('HR','Electrocardiography');
second_HR_PulseOximetry_Value=getValue('HR','Pulse
    Oximetry');

%Check Validity
if second_HR_ECG_Value>=Threshold
    if second_HR_ABP_Value>=Threshold ||
        second_HR_PulseOximetry_Value>=Threshold
        AlarmValid=1;
    else
        AlarmValid=0;
    end
```

```
else
    AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'High_HR',3,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''High_HR'''};
changeStatus({1}, whereClause);
end
```

3.8 Low HR Alarm from Pulse oximerty

```
function Alarm_HR_PulseOximetry_Low(Threshold, InDate)

%Delay
pause(30);

%Values after Delay
second_HR_ABP_Value=getValue('HR','Arteriel Blood
    Pressure');
second_HR_ECG_Value=getValue('HR','Electrocardiography');
second_HR_PulseOximetry_Value=getValue('HR','Pulse
    Oximetry');

%Check Validity
if second_HR_PulseOximetry_Value<=Threshold
    if second_HR_ABP_Value<=Threshold ||
        second_HR_ECG_Value<=Threshold
        AlarmValid=1;
    else
        AlarmValid=0;
    end
else
    AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'Low_HR',3,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
```

```
end

whereClause={'Where AlarmName =''Low_HR'''};
changeStatus({1}, whereClause);

end
```

3.9 High HR Alarm from Pulse oximerty

```
function Alarm_HR_PulseOximetry_High(Threshold, InDate)

%Delay
pause(30);

%Values after Delay
second_HR_ABP_Value=getValue('HR','Arteriel Blood
    Pressure');
second_HR_ECG_Value=getValue('HR','Electrocardiography');
second_HR_PulseOximetry_Value=getValue('HR','Pulse
    Oximetry');

%Check Validity
if second_HR_PulseOximetry_Value>=Threshold
    if second_HR_ABP_Value>=Threshold ||
        second_HR_ECG_Value>=Threshold
        AlarmValid=1;
    else
        AlarmValid=0;
    end
else
    AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'High_HR',3,'Pulse Oximetry', InDate,
        OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''High_HR'''};
changeStatus({1}, whereClause);
end
```

3.10 Low MV Alarm from Ventilator

```
function Alarm_MV_Ventilator_low(Threshold, InDate)

first_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
    Oximetry');
first_etCO2_Capnometer_Value=getValue('etCO2','Capnometer
    ');

%Delay
pause(30);

%Values after Delay
second_MV_Ventilator_Value=getValue('VM','Ventilator');
second_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
    Oximetry');
second_etCO2_Capnometer_Value= getValue('etCO2','
    Capnometer');


%Check Validity
if second_MV_Ventilator_Value<=Threshold
     if second_SpO2_PulseOximetry_Value<=
         first_SpO2_PulseOximetry_Value ||
         second_etCO2_Capnometer_Value>=
         first_etCO2_Capnometer_Value
          AlarmValid=1;
     else
          AlarmValid=0;
     end
else
     AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
     DataStream={'Low_MV',3,'Ventilator', InDate, OutDate,
          0};
     WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''Low_MV'''};
changeStatus({1}, whereClause);
end
```

3.11 High MV Alarm from Ventilator

```
function Alarm_MV_Ventilator_High(Threshold, InDate)

first_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
    Oximetry');
first_etCO2_Capnometer_Value=getValue('etCO2','Capnometer
    ');

%Delay
pause(30);

%Values after Delay
second_MV_Ventilator_Value=getValue('VM','Ventilator');
second_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
    Oximetry');
second_etCO2_Capnometer_Value= getValue('etCO2','
    Capnometer');


%Check Validity
if second_MV_Ventilator_Value>=Threshold
     if second_SpO2_PulseOximetry_Value>=
         first_SpO2_PulseOximetry_Value ||
         second_etCO2_Capnometer_Value<=
         first_etCO2_Capnometer_Value
          AlarmValid=1;
     else
          AlarmValid=0;
     end
else
     AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
     DataStream={'High_MV',3,'Ventilator', InDate, OutDate
         , 0};
     WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''High_MV'''};
changeStatus({1}, whereClause);
end
```

3.12 Low Pulse Rate Alarm from Pulse Oximetry

```
function Alarm_PulseRate_PulseOximetry_Low(Threshold,
    InDate)

pause(30);

%Values upon arrival
second_PulseRate_ECG_Value=getValue('Pulse Rate','ECG');
second_PulseRate_PulseOximetry_Value= getValue('Pulse
    Rate','Pulse Oximetry');


%Check Validity
if second_PulseRate_PulseOximetry_Value<=Threshold &&
    second_PulseRate_ECG_Value<=Threshold
     AlarmValid=1;
else
     AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
     DataStream={'Low_PulseRate',3,'Pulse Oximetry',
         InDate, OutDate, 0};
     WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''Low_PulseRate'''};
changeStatus({1}, whereClause);
end
```

3.13 High Pulse Rate Alarm from Pulse Oximetry

```
function Alarm_PulseRate_PulseOximetry_High(Threshold,
    InDate)

pause(30);

%Values upon arrival
second_PulseRate_ECG_Value=getValue('Pulse Rate','ECG');
second_PulseRate_PulseOximetry_Value= getValue('Pulse
    Rate','Pulse Oximetry');


%Check Validity
if second_PulseRate_PulseOximetry_Value>=Threshold &&
    second_PulseRate_ECG_Value>=Threshold
```

```
12      AlarmValid=1;
13  else
14      AlarmValid=0;
15  end
16
17  %Write & Update
18  OutDate=datestr(now,31);
19
20  if AlarmValid==1
21      DataStream={'High_PulseRate',3,'Pulse Oximetry',
            InDate, OutDate, 0};
22      WriteIntelligentAlarms(DataStream);
23  end
24  whereClause={'Where AlarmName =''High_PulseRate'''};
25  changeStatus({1}, whereClause);
26  end
```

3.14 Low RR Alarm from Ventilator

```
1   function Alarm_RR_Ventilator_low(Threshold, InDate)
2
3   first_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
        Oximetry');
4   first_etCO2_Capnometer_Value= getValue('etCO2','
        Capnometer');
5
6   %Delay
7   pause(30);
8
9   %Values after Delay
10  second_RR_Ventilator_Value=getValue('RR','Ventilator');
11  second_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
        Oximetry');
12  second_etCO2_Capnometer_Value= getValue('etCO2','
        Capnometer');
13
14
15  %Check Validity
16  if second_RR_Ventilator_Value<=Threshold
17      if second_SpO2_PulseOximetry_Value<=
            first_SpO2_PulseOximetry_Value ||
            second_etCO2_Capnometer_Value>=
            first_etCO2_Capnometer_Value
18              AlarmValid=1;
19      else
20              AlarmValid=0;
21      end
22  else
23      AlarmValid=0;
```

```
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
     DataStream={'Low_RR',3,'Ventilator', InDate, OutDate,
          0};
     WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''Low_RR'''};
changeStatus({1}, whereClause);
end
```

3.15 High RR Alarm from Ventilator

```
function Alarm_RR_Ventilator_High(Threshold, InDate)

first_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
    Oximetry');
first_etCO2_Capnometer_Value= getValue('etCO2','
    Capnometer');

%Delay
pause(30);

%Values after Delay
second_RR_Ventilator_Value=getValue('RR','Ventilator');
second_SpO2_PulseOximetry_Value=getValue('SpO2','Pulse
    Oximetry');
second_etCO2_Capnometer_Value= getValue('etCO2','
    Capnometer');

%Check Validity
if second_RR_Ventilator_Value>=Threshold
     if second_SpO2_PulseOximetry_Value>=
          first_SpO2_PulseOximetry_Value ||
          second_etCO2_Capnometer_Value<=
          first_etCO2_Capnometer_Value
           AlarmValid=1;
     else
          AlarmValid=0;
     end
else
     AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);
```

```
27
28 if AlarmValid==1
29     DataStream={'High_RR',3,'Ventilator', InDate, OutDate
           , 0};
30     WriteIntelligentAlarms(DataStream);
31 end
32 whereClause={'Where AlarmName =''High_RR'''};
33 changeStatus({1}, whereClause);
34 end
```

3.16 Low RR Alarm from ECG

```
1  function Alarm_RR_ECG_low(Threshold, InDate)
2
3  first_RR_Ventilator_Value=getValue('RR','Ventilator');
4  first_etCO2_Capnometer_Value= getValue('etCO2','
       Capnometer');
5
6  %Delay
7  pause(30);
8
9  %Values after Delay
10 second_RR_Ventilator_Value=getValue('RR','Ventilator');
11 second_RR_ECG_Value=getValue('RR','Electrocardiography');
12 second_etCO2_Capnometer_Value= getValue('etCO2','
       Capnometer');
13
14
15 %Check Validity
16 if second_RR_ECG_Value<=Threshold
17     if second_RR_Ventilator_Value<=
           first_RR_Ventilator_Value ||
           second_etCO2_Capnometer_Value>=
           first_etCO2_Capnometer_Value
18          AlarmValid=1;
19     else
20          AlarmValid=0;
21     end
22 else
23     AlarmValid=0;
24 end
25
26 %Write & Update
27 OutDate=datestr(now,31);
28
29 if AlarmValid==1
30     DataStream={'Low_RR',3,'Electrocardiography', InDate,
           OutDate, 0};
31     WriteIntelligentAlarms(DataStream);
```

```
end
whereClause={'Where AlarmName =''Low_RR'''};
changeStatus({1}, whereClause);
end
```

3.17 High RR Alarm from ECG

```
function Alarm_RR_ECG_High(Threshold, InDate)

first_RR_Ventilator_Value=getValue('RR','Ventilator');
first_etCO2_Capnometer_Value= getValue('etCO2','
    Capnometer');

%Delay
pause(30);

%Values after Delay
second_RR_Ventilator_Value=getValue('RR','Ventilator');
second_RR_ECG_Value=getValue('RR','Electrocardiography');
second_etCO2_Capnometer_Value= getValue('etCO2','
    Capnometer');


%Check Validity
if second_RR_ECG_Value>=Threshold
    if second_RR_Ventilator_Value>=
        first_RR_Ventilator_Value ||
        second_etCO2_Capnometer_Value<=
        first_etCO2_Capnometer_Value
        AlarmValid=1;
    else
        AlarmValid=0;
    end
else
    AlarmValid=0;
end

%Write & Update
OutDate=datestr(now,31);

if AlarmValid==1
    DataStream={'High_RR',3,'Electrocardiography', InDate
        , OutDate, 0};
    WriteIntelligentAlarms(DataStream);
end
whereClause={'Where AlarmName =''High_RR'''};
changeStatus({1}, whereClause);
end
```

3.18 Low SpO2 Alarm from Intellivue Pulse Oximetry

```
function Alarm_SpO2_PulseOximetry_Low(AlarmName, Device,
    Threshold, InDate)

%Values upon Alarm Arrival
first_etCO2_Capnometer_Value=getValue('etCO2','Capnometer
    ');
first_RR_Ventilator_Value=getValue('RR','Ventilator');

%Delay
pause(30);

%Values after Delay
second_SpO2_Pulsoximetry_Value=getValue('SpO2','Pulse
    Oximetry');
second_etCO2_Capnometer_Value=getValue('etCO2','
    Capnometer');
second_RR_Ventilator_Value=getValue('RR','Ventilator');


%Check Validity
if second_SpO2_Pulsoximetry_Value<=Threshold
     if second_RR_Ventilator_Value <
         first_RR_Ventilator_Value ||
         second_etCO2_Capnometer_Value<
         first_etCO2_Capnometer_Value
          AlarmValid=1;
     else
          AlarmValid=2;
     end
else
     AlarmValid=0;
end

%Write & Update
if AlarmValid==1
     Priority=3;
     WriteIntelligentAlarms(AlarmName, Priority, Device,
         InDate);
elseif AlarmValid==2
          Priority=0;
          WriteIntelligentAlarms(AlarmName, Priority,
              Device, InDate);
end
%%%%
whereClause={'Where AlarmName =''Low_SpO2'''};
changeStatus({1}, whereClause);
end
```

3.19 Low SpO2 Alarm from Nonin Pulse Oximetry

```
function Alarm_SpO2_Nonin_Low(AlarmName, Device,
    Threshold, InDate)

%Values upon Alarm Arrival
first_etCO2_Capnometer_Value=getValue('etCO2','Capnometer
    ');
first_RR_Ventilator_Value=getValue('RR','Ventilator');

%Delay
pause(30);

%Values after Delay
second_SpO2_Nonin_Value=getValue('SpO2','Nonin');
second_etCO2_Capnometer_Value=getValue('etCO2','
    Capnometer');
second_RR_Ventilator_Value=getValue('RR','Ventilator');


%Check Validity
if second_SpO2_Nonin_Value<=Threshold
    if second_RR_Ventilator_Value <
        first_RR_Ventilator_Value ||
        second_etCO2_Capnometer_Value<
        first_etCO2_Capnometer_Value
         AlarmValid=1;
    else
        AlarmValid=2;
    end
else
    AlarmValid=0;
end

%Write & Update
if AlarmValid==1
    Priority=3;
    WriteIntelligentAlarms(AlarmName, Priority, Device,
        InDate);
elseif AlarmValid==2
         Priority=0;
         WriteIntelligentAlarms(AlarmName, Priority,
             Device, InDate);
end

%%%%
whereClause={'Where AlarmName =''Low_SpO2'''};
changeStatus({1}, whereClause);
end
```

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