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Alarm Fatigue: Using Alarm Data from a Patient Data Monitoring System on an Intensive Care Unit to Improve the Alarm Management

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Abstract. Excessive numbers of clinical alarms reduce the awareness of caregivers. Frequent alarms, many of which are non-actionable, can lead to cognitive overload, stress, and desensitization to alarms, called "Alarm Fatigue", which can severely impact patient safety. Due to the multifactorial nature of excessive alarming quantitative data about many facets of alarm generation and management are required in order to tackle the problem efficiently and effectively. Since there is no system available which would provide said data, we set out to develop one in the form of a data warehouse based on a thorough understanding of clinicians' needs. The developed system answers the users' needs in terms of readily providing them information on a daily basis, but also serves as a data source for further research. Further work is needed to include alarm sources from outside the patient monitoring infrastructure.

Keywords. Alarm fatigue; Clinical Alarms; Clinical Alarms: organization and administration; Sociotechnical System; Critical Care; Patient Safety

1. Introduction

1.1. Background

The problem of medical device alarms is well-known on intensive care units (ICUs). Oftentimes, these alarms are neither clinically nor technically actionable with rates as high as 80%-99% [6] and with up to 350 alarms per day and patient occurring [1; 7]. The workload and mental stress from handling that many alarms and the fact that the majority of these alarms have no consequences [1] is often regarded as leading to a condition called *Alarm Fatigue* [8], characterized by inadequate responses to alarms, seriously impacting patient safety. The causes of alarm fatigue are multifactorial and stem from diverse sources like device infrastructure, floor layout, consumables, configuration, training and education, quality of processes, and staff habits and attitudes [10]. All sources need to be analyzed in order to define targeted interventions for improving the alarm management, the success of which must in turn be measurable.

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In general, this requirement poses two problems. The technical problem lies in getting access to alarm-related data in an analyzable form in the first place [1]. The methodical problem is posed by the absence of validated, or at least broadly accepted, metrics which indicate specific problems in the overall alarm system [9]. There is as of today an utter lack of metrics and corresponding benchmark data to either assess the effects of excessive alarms, like prolonged response times or inadequate reactions, or to indicate possible root causes, such as improper electrode placement, missing adaptation of thresholds to patient status or training deficits. Since both the root causes and the consequences of excessive alarms are highly diverse and can vary from unit to unit, any improvement effort in this regard, but also the ongoing management of the alarm system requires quantitative measurements factors contributing to, and effects resulting from, the dysfunctional state of the alarm system. It must be noted that said improvement efforts can vary broadly in scope, from a broad project targeting the entire unit's alarm management to an ad-hoc effort to understand and mitigate a problem with too many alarms from the patient in bed XYZ over the last hours. **The aim of this project** is to develop a self-service business intelligence tool to enable healthcare workers on an ICU to assess and manage the quality of their alarm system. To meet this aim, the tool should provide actionable and easy-to-understand information which enables healthcare staff to identify problems and select appropriate measures to address them.

1.2. Needs

Literature review and the expert interviews enabled us to identify the following user-goals for particular use cases [12]:

- Handover: As a charge nurse/shift nurse during handover, in order to spot problems that I have to address immediately, I need a quick overview of the alarm management quality during the last shift on a patient-level.
- Quality review: As a team member interested in maintaining or improving alarm system quality, I need access to alarm quality data for the entire unit over a selectable time span (up to several months). I need to be able to benchmark the unit against prior performance or comparable other units.
- Deep dive: As a healthcare professional tasked with analyzing a particular problem in alarm management, in order to get a comprehensive understanding of the problem, I need to perform exploratory data analyses on alarm quality data for selected beds, timespans, and metrics.

The above use cases (*Handover*, *Quality review* and *Deep Dive*) place a few rather evident non-functional constraints on the solution, i.e.:

- The handling of the tool should not require significant training efforts.
- The visualizations should be intuitive for healthcare workers.

One important insight, already published [10], was that causes of excessive alarms can be rather diverse and their effects can range from operational inefficiencies to impaired staff health to lower patient safety.

This, together with analysis of the above use cases, led to the identification of the following needs:

- The healthcare worker should have access to alarm data analyses on a self-service basis in order to spot problems in the alarm management [2].
- The healthcare worker should have access to current data (latency not more than several minutes) in order to support ad-hoc analyses.
- Healthcare workers need information in the form of aggregate metrics in order to understand measurable effects and probable causes of (i.e. typical factors which can contribute to) excessive alarms.
- Healthcare workers in their daily routine as well as consultants, process experts, and researchers must have access to data during analysis in varying levels of detail and analytical sophistication.

2. State of the art

For the technical problem described above, i.e. near real-time access to alarm-related data in an easy to analyse way, there are currently no off-the-shelf solutions available. Existing vendor-provided features in this area allow for a log export which is highly vendor proprietary, or an HL7 Version 2.x data stream, the semantics of which are also vendor proprietary. Both features are not comprehensive and typically require heavy pre-processing. The methodical problem mentioned above, i.e. the lack of metrics to quantify the performance of alarm generation and management, is even graver, as it has been frequently observed [5; 9].

Currently, metrics mentioned in the literature are the following:

- Alarms per monitored bed/day (AMBD) [8]
- Response times to alarms (ART) [3]
- Alarm positive predictive values (APPV) [4]

AMBD can be calculated in a straightforward manner, provided one has access to alarm data at all. However, despite the fact that it is arguably the most commonly used measure, its value is extremely limited. AMBD cannot be used for benchmarking or making pre-post-comparisons. For example, is a reduction from 180 to 140 AMBD really an improvement, if the proportion of red alarms has been tripled? Alarm bursts, i.e. clusters of more than e.g. 30 alarms from a single patient within one hour, evidently add disproportionally to cognitive overload and desensitization, but will not add much to the total AMBD count. Most likely the most severe drawback of the AMBD metric is that it does not provide any indication of the possible root causes of excessive alarming. Healthcare workers cannot derive any actionable insight from the fact that there are more alarms per patient than specified in an alarm account limit.

A similar thing can be said about ART: It does not discriminate between types (clinical, technical) or severities of alarms. It does not indicate possible root causes and it cannot be used for benchmarking between units as there are too many confounding factors like the units' floor layouts or specific policies, for instance whether acknowledgment of an alarm from the central station is admissible.

Finally, the APPV metric, while it offers some kind of information about the reasons for a possible desensitization, it cannot be routinely measured, because it requires either a healthcare worker's assessment on the spot plus some form of documentation or a retrospective analysis by humans, based on recorded signals, physiological values and/or video recordings.

As we intend to enable healthcare workers to improve their alarm management, the only viable solution is a set of routinely measurable metrics providing actionable insights into the root causes and possible effects of excessive alarming. The used metrics have been described in [13].

Interventions for improving the alarm situation and alarm fatigue are well described in literature. Many publications reported experiences from improvement projects. However, in how far these results can be replicated at other units remains questionable due to the vast number of possible root causes of non-actionable alarms. As units may differ with respect to the degree in which various root causes contribute to the problem, and from anecdotal evidence in past projects, one should be prepared to accept that they differ considerably. A simple transfer of the proposed measures to a specific unit may be inefficient or even not effective at all. Thus, the use case *Quality review* requires a radically new set of metrics to design and select a set of interventions which are targeted at the actual status quo. Likewise, when short-term problems with alarm management need to be found and addressed (Use case: *Handover*), just knowing how many alarms there were in a particular time frame for a particular patient will not provide much help.

A system that enables healthcare workers in real-time to get a comprehensive overview of the alarm situation alarms and to identify problematic causes as well as effects of alarm fatigue on a self-service basis is not known to the authors. A system for preprocessing and exporting alarm data for clinical studies is not known to the authors.

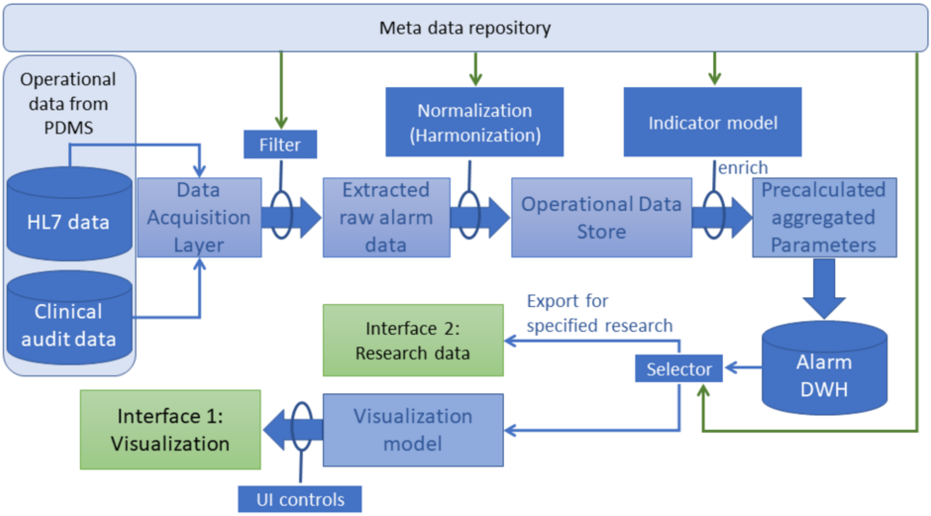

Figure 1. Processing pipeline of the alarm-related data from the Patient Data Monitoring System (PDMS), DWH = Data Warehouse.

3. Concept

In order to enable healthcare workers to investigate on the alarm situation on their ICU, we started to connect to the clinical patient data monitoring system. Using this connection, we can gather the required data for the healthcare workers. This data need to be pre-processed (Figure 1) until it can be used for the self-service platform. The processing pipeline is configured according to the rules and indicators from the meta data repository. This repository needs to be adapted for each participating unit. The processing includes the filtering for data privacy and data avoidance as described in the General Data Protection Regulation (GDPR). The next step is the normalization and harmonization for standardizing the operational data store (ODS) and the alarm data warehouse. On the basis of the ODS data, the analysis layer calculates the indicators for the alarm situation on the ICU. The data is then saved in a data warehouse. For accessing the data, two user groups need to be considered. On the one hand researchers should be enabled to do clinical studies in order to improve the general alarm situation and develop guideline to handle alarm fatigue. On the other hand the healthcare workers need to be enabled to investigate for their very specific situations.

A requirements elicitation was performed in order to identify the information needs for the healthcare workers. Based on the information needs, specific views were implemented providing the adequate information. The next step was an elicitation testing the views with both user groups, nurses and clinicians. For enabling clinical research, a requirements elicitation with clinicians needs to be done. This included a workshop with clinicians, nurses, and medical device manufacturers of the data providing systems. The implemented system required a validation by the user groups.

We have gathered the requirements by conducting a total of 15 interviews, each 90 minutes, with nurses from two intensive care units and a workshop with clinicians. Our main goal was to identify the information needs for an adequate alarm management. Following the identified informational needs, specific analytic views for alarm data analysis were implemented. These views were integrated in a self-service analytical information system for clinicians. A workshop with clinicians was conducted to evaluate the prototype and gather information for further improvement. An ethical vote was obtained for this study. (Medizinische Ethik-Kommission Oldenburg, Nr. 052/2016, Chair: Prof. Dr. F. Griesinger/Ethik Kommission des FB Medizin, Nr. 139/16, Chair: Prof. Dr. H. Tillmanns)

4. Implementation

For gathering test data, the alarm data from two surgical ICUs from different sites were included. The data were gathered for 24 hours over 7 days on both ICUs. A data interface of the patient data monitoring system was used. The interface provided data in a HL7 format. For privacy, only the message header (MSH) and the observation result (OBX) segment was processed. The OBX segment was used to gather the alarm related information. As a second data source and for additional information an audit log from the patient data monitoring system was used. Both data sources were combined as a data basis for the data warehouse. The data warehouse was implemented using a standard SQL data base (PostgreSQL). The data warehouse was connected to a customized self-service business intelligence platform.

Bedlabel	Alarm count
Total	**3574**
Bed1	102
Bed2	382
Bed3	162
Bed4	208
Bed5	119
Bed6	228
Bed7	387
Bed8	284
Bed9	104
Bed10	100
Bed11	435
Bed12	143
Bed13	120
Bed14	318
Bed15	284
Bed16	198

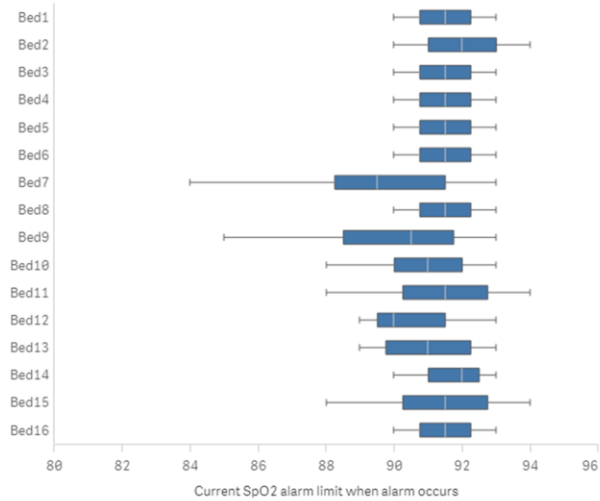

Figure 2. Self-Service interface for investigating on the alarm situation of SpO2 alarms on the unit. This view represents a simplified version with artificial data of 24 hours.

The HL7 data interface of the patient data monitoring system and the data from the clinical audit log were the data basis for the developed alarm data warehouse. The combination of both data sources resulted in information about the alarm data, alarm pausing and acknowledgement, alarm setting changes, and physiological values in the moment of an occurring alarm condition. For providing a platform to enable explorative data analysis, a data warehouse was set up and the messages were transformed into a multidimensional model. When extracting the operational data and transforming it, we needed to filter and normalize the data. Because we got two different sites the data needed to be harmonized in the next step to correct syntactically or semantically varying data. In this step, we also added metadata describing the setting like *language* and *number of beds per unit*. A complete overview of the processing pipeline is presented in Figure 1.

A Tool was implemented that supports the nurses in their alarm management by giving them useful information in a specially adapted view. There are specific views implemented for the different identified needs of the healthcare workers. For further information, the healthcare worker can configure the views. The healthcare workers can interact with the system in a self-service way.

An example of this kind of view is provided in Figure. For a specific unit, this view presents the alarm count per bed on the left and the alarm limits at the time the alarms occur on the right side of the last 24 hours for the charge nurse. In this artificial data set *Bed7* has a high amount of alarms and a wide range of alarm limits exceeded. A head nurse can use this data and evaluate the situation on the unit in the last 24 hours and consider a detailed discussion during handover. (Use case: *Handover*) If this condition persists a *Deep Dive* could be performed.

The system is based on two different data sources. The HL7 interface provides real-time data for the alarms and the physiologic values of the patients. The clinical audit trails need to be exported every 90 days and can afterwards be imported into the data warehouse system. The trail has additional information about the pause/acknowledgement of alarms at the bedside and the alarming/acknowledgement on the central station. As described in the processing pipeline in Figure 1, KPIs of the indicator model are precalculated for the data warehouse. The developed tool offers a way to export the customized data for further research into a statistical tool, i.a. R or SPSS.

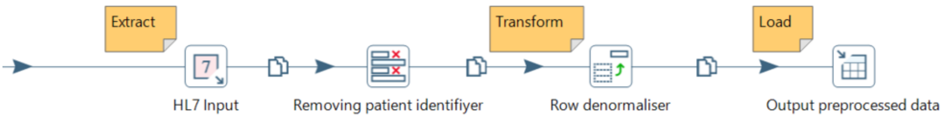

Figure 3. Simplified representation of the structured processing view in Pentaho Data Integration.

The processing pipeline was implemented using Pentaho Data Integration Suite (PDI) and Java. The output of the pipeline can be reproduced this way and the data flow can be monitored. PDI offers a structured view (Figure 3) of the processing pipeline that enable clinicians to retrace the processing.

We tested the implemented platform in a workshop with clinicians of the AlarmRedux-project. The feedback from them was used for further development of the platform. The export for research data was adapted according to the given comments.

5. Lessons learned (Discussion)

We developed a system that enables the users to investigate the alarm situation on their unit on a self-service basis. The evaluation of the system has only been done during a workshop with the project team. For developing the system further and leaving the alpha status, a full validation of the system with a bigger user group should be addressed. A new beta validation study, with more users from different hospitals, should be conducted.

The system is able to give the users the identified information needs in real-time. But we are dependent on the interface from the patient data monitoring system. Having a medical device manufacturer in the project helped a lot during implementation. The availability of documentation and support for difficult decisions from the manufacturer was a main driver for fast development and a secure system.

We provided an interface for clinicians to export alarm data for further clinical studies. The very close relation to the clinicians in the project supported an adequate data representation for clinical research.

Some limitations apply to the developed system. Currently the system is only based on the data from the patient data monitoring system. Healthcare workers already demand more data sources like alarms from ventilators. This data would improve the quality of the measurements for the alarm management on the unit. Also, the clinical audit log needs to be manually exported by a clinician from the patient data monitoring system every 90 days and then be transferred to a folder on a server. That server recognizes the change and triggers the processing automatically. The HL7 data is populated automatically.

Our system provides benefits on two different levels. On the operative level the system provides information that should support improving the knowledge of the healthcare workers on their alarm situation and problematic fields. On the strategic level it supports accelerating clinical research for alarm fatigue resulting in guidance to improve the alarm situation.

Healthcare workers have various benefits from the system. At present, there is no system enabling them to get objective insight into their alarm management. In literature, the need for objective measurements giving insights into the alarm situation is already described [11]. Enabling healthcare workers to base decisions on data improves the ability to choose adequate interventions and to measure the effects of the intervention. Many interventions were already developed and are well described but choosing the adequate one is a big challenge if data is not available. One possible intervention to improve the alarm management of a unit is conducting trainings. These trainings need to be adopted for the specific unit and their alarm situation. The system enables the healthcare worker to gather data on their unit and do trainings based on this data. As an example, the healthcare worker could identify that the 'electrode off' alarms are continuously rising, so they decide to train their staff on proper skin preparation and handling the electrodes the right way.

6. Conclusion

We successfully integrated the identified requirements in the system. The alarm data from two ICUs was transferred into a data warehouse and the data is ready for explorative data analysis. During the workshop we identified the need for more specific view for several special use cases. We are also currently working on more advanced indicators describing the alarm situation on the unit. Based on these advanced indicators, a group of the AlarmRedux project is working on a specific overview of the alarm situation on unit. With this view the healthcare worker should be able to identify problematic fields in the unit in seconds with all the needed information. Currently, clinicians are unable to do research on the alarm data of their units. As a validation test for the research export of the data warehouse, a clinical study will be conducted based on the alarm data warehouse with the clinicians and nurses from the AlarmRedux project.

Conflict of Interest

Dirk Hüske-Kraus is working at Philips Healthcare. The other authors state that they have no conflict of interests.

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