Requirements for a Wearable Alarm Distribution System in Intensive Care Units

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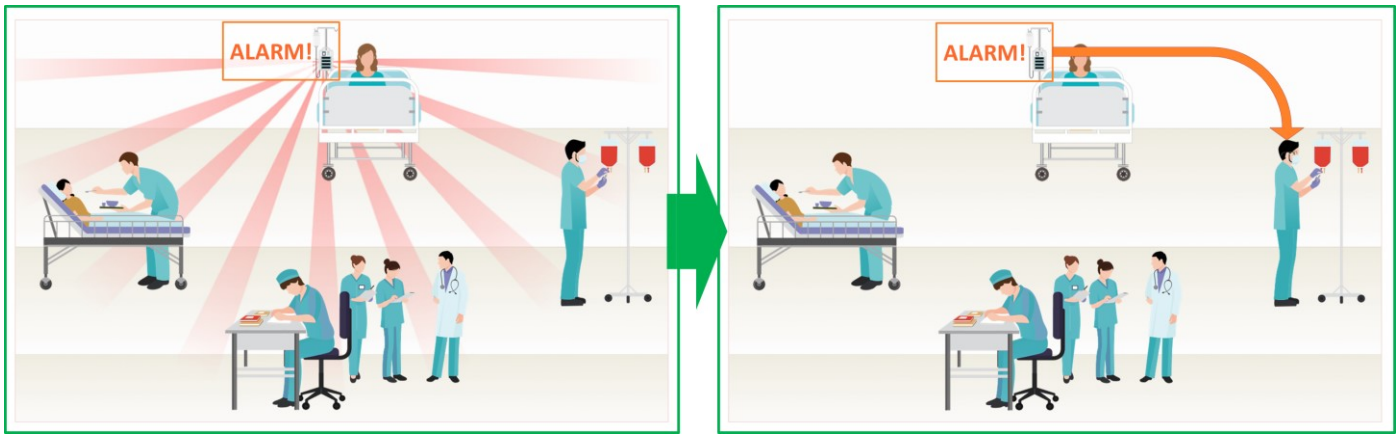

Abstract— Alarm fatigue is a well-known and widely spread condition which occurs when one is desensitized by the exposure to excessive alarm signals. It causes a delayed or inadequate response to alarms and affects in particular people working in safety critical environments, such as in an intensive care unit (ICU). With up to 350 alarms per patient a day, there is a high alarm load on healthcare professionals which has also severe effects on the patients. In cooperation with healthcare professionals, we develop solutions to reduce the number of acoustic alarms in ICUs. This paper presents requirements for a wearable alarm distribution system that aims to forward patient alarms to the responsible healthcare professional. Moreover, we propose a multimodal alarm design, which conveys three different urgency levels with bone-conductive sound, light and vibration.

Keywords— Multimodal, Critical Care, Alarm Fatigue, Alarm Distribution, User-centered Design

I. Introduction

The amount of alarms and the noise level of alarms in Intensive care units (ICU) has a severe effect on the work conditions of a critical care nurse [1]. Critical care nurses might miss an alarm which in the end leads to a critical, potentially fatal, situation for a patient. In addition to the tragedy for the patients themselves, this causes a severe second victim effect for the care takers. In our research, we aim (1) to minimize the amount of alarms which are delivered to each healthcare provider by a personalized alerting, and (2) to explore whether the personalized alarms can be delivered by other sensory modalities by wearable technology to reduce the acoustic stress for the nurses. In cooperation with healthcare professionals, we designed a new alarm distribution system. For this, we carried out semi-structured interviews in expert groups with 3 and 4 healthcare professionals with different levels of experience from two different hospitals to design a wearable system to distribute alarms. As a result, each nurse should receive the alarms of their own patients and the physicians should get critical alarms for their patients. The device should alert the nurse with three different alarm priorities to distinguish between technical, uncritical and critical alarms, whereas technical and uncritical alarms should represent a similar urgency. Alarms should be clearly perceptible and easily identifiable, so the care taker can respond appropriately to any

threatening situation for the patient. If there is no response to an alarm, the alarm should be forwarded automatically after a certain time to ensure an appropriate reaction time. Generally, the nurse should be able to unsubscribe for alarms, so the alarm will be forwarded directly to a second nurse. The alarm distribution also introduces additional functions to call for an emergency and functions to acknowledge alarm while still being in care of a patient. To implement the alarm distribution, we explore suitable alarm representations as well as body positions for peripheral light cues, bone-conductive sound and vibrotactile cues to deliver the different alarm categories e.g., by a novel head mounted display [2].

II. Background

Nowadays, ICUs are equipped with a number of multiple highly sophisticated technical systems and devices which measure the patient's vital data continuously to ensure an uninterrupted monitoring. This led to a critical increase of alarms on ICUs with up to 350 alarms per bed and day [1].

Since each alarm can be triggered by a critical situation or a technical problem, it must be evaluated and acknowledged by an intensive care nurse or a physician. To simplify the identification of each alarm, they are commonly divided into critical (life threatening), and noncritical alarms. The noncritical alarms can also be distinguished by low priority alarms, which indicate that a value crosses a predefined threshold, and technical alarms which means, that a monitor cannot measure or detect alarm conditions reliably (e.g., due to a displaced sensor). Each alarm has an individual sound, which pitch and frequency of the beeps increases with the priority of the alarm.

Since most intensive care units foster a ubiquitously audible alarm distribution, the patient alarms of every patient sound from a central working and monitoring station and, depending on the local alarm policy within the hospital, also from the concerned patient room -- audible for every person in the ICU. Due to the huge number of patient alarms, healthcare professionals, especially nurses who are mainly responsible for the alarm management, get desensitized by alarms. This leads to a slow reaction time or even missing alarms. This condition is called alarm fatigue.

There are several successful approaches in research which aim to reduce alarm fatigue by decreasing the number of alarms with specific algorithms, smart alarm delays or changes in the alarm policy [3]. Even though there were significant differences in the number of alarms, the remaining alarms are still audible, obtrusive and distracting from nursing tasks.

In 2014, Maria Cvach et al. [4] counteract that issue by introducing a new alarm escalation algorithm for a personalized alerting. The algorithm distinguishes between crisis and non-crisis condition of high priority alarms. Both conditions run over two escalation steps. If the first nurse does not react to an alarm in a certain period of time, a second nurse will receive the alarm. If he or she does not react within 60 seconds, the charge nurse will be notified. For a non-crisis alarm, the algorithm starts delayed with a longer time period for the first escalation step.

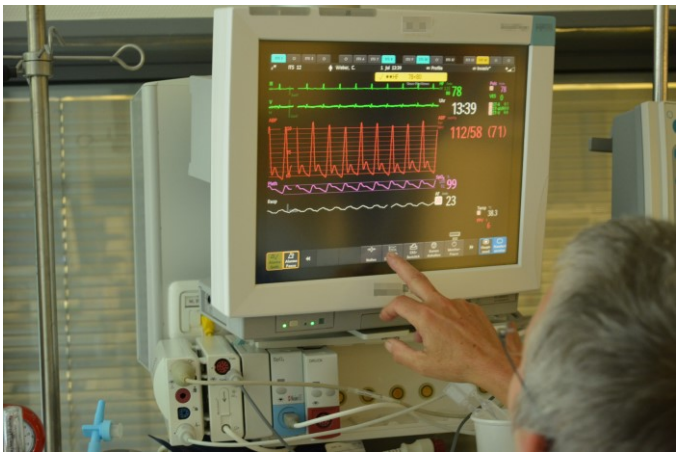

Figure 1: Insights from the shadowing session.

Cvach et al. evaluated this algorithm on two ICUs using pagers. Their approach decreased the mean alarm frequency and duration on the participating units significantly and shows the importance of a distributed alerting.

However, although portable devices like pagers can improve the distribution of alarms in hospitals, they have the disadvantage that they have to be put inside pockets. Besides hygienic issues due to the constantly required hand contact with the device, the vibrotactile signal of a pager may go undetected, as nursing tasks are often stressful and physically demanding [5].
Therefore, we explore wearable alarm systems (WAS). Embedded into a wearable device, the majority of the audible alarms can be replaced by other stimuli, such as bone-conductive sound, vibration, or light to alert healthcare providers unobtrusively but perceivable. Contrary to common alarm systems, this enables less obtrusive but perceivable personalized alerting.
In a user-centered approach, we adapted the alarm distribution algorithm and derived requirements for a WAS.

III. Requirements for a WADS

A. Methodology

Our requirements analysis consists mainly of two parts. To get a first impression, we did a 4h shadowing session in a surgical ICU with 13 beds (see Figure 1). Notes were made using pen and paper. We started at 10.00am and left after the shift handover at 02.00pm.

As a second step, we did two group discussions with 4 and 3 participants from two different hospitals (from different federal states) with different levels of experience. The first group consisted of two physicians, a charge nurse and a medical engineer; the second group consisted of a charge nurse, a nursing instructor and a nurse. Each session took about two hours. Key questions for the sessions were 1. who of the care takers in the ICU should get which alarms and 2. how they can be acknowledged or forwarded. As a further question, we asked how they would like to.

For collecting answers, we provided cards and pencils. Moreover, we recorded the discussion for an additional analysis.

B. Results

1) Shadowing

From the shadowing session, we could learn that nursing tasks are physically very demanding. Due to the local nursing crisis [7] a nurse has to care for around 3 patients during her shift, which requires moving frequently between patient rooms and other locations coupled with physically demanding tasks (like mobilizing patients). After entering or leaving a patient room, the healthcare professionals disinfected their hands.

Besides the high alarm load, there are several other disruptive noises (i.a., other medical devices that are not connected to the monitoring system, telephones, clanking glass containers, conversations) which make an ICU a very loud environment. The perceived alarms were mostly low priority alarms. Due to the yellow highlighting of the relevant vital parameter which caused the alarm on the patient monitoring display, they were called "yellow alarms". Analogously, technical alarms were called "blue alarms" and critical ones "red alarms".

Regarding the alarm management policy, we could observe that most of the time, the first step was to acknowledge or silence an alarm in the relevant patient room. However, the relevant alarm information could also be seen on the monitoring display in other patient rooms. This means, to acknowledge an alarm the nurses had to interrupt their current task, go to the respective patient, acknowledge the alarm and after the appropriate action (e.g., change the alarm threshold) they could return to their former task.

2) Expert Discussion

Due to their awareness of the relevance of the issue, participants in both sessions were communicative and motivated from the beginning.

All participants agreed that a patient's alarm should be forwarded to the responsible nurse, first. However, the physicians added that they also want to receive critical alarms for their patients. In both sessions, it was remarked to alert a second nurse from the appropriate care sector as a first escalation level. The remaining nurses will be alerted only as the last escalation level. All participants agreed that in case of critical alarms, the first escalation level will be skipped and the alarm should be directly forwarded to the whole shift.

We asked in both sessions, in which situations a device should not alert the healthcare professional. One participant of the first group noted directly that alarms should alert the user in every situation. After a short discussion, the group concluded that there should be no alarms in specific rooms, as e.g., the break room. Moreover, alarms should be generally not audible for patients. The second group proposed that the device should enable the possibility to sign off from alarms. When we led the participants to the alarm categories, one participant of the first session proposed to forward technical alarms just to the nursing station. This led to the discussion that a missed technical alarm could hide a critical alarm, what makes it "as urgent as a yellow one". Consequently, the participants agreed to forward all alarm types "that refer somehow to patients".

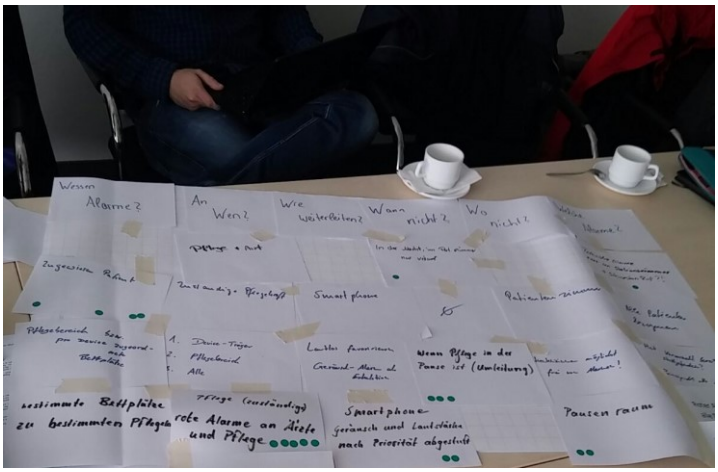

Figure 2: Results from an expert discussion.

The technical alarms were also a discussion point in the second session. One participant mentioned that this frequent "beep" of the technical alarm is just a background noise which is acoustically not prominent. However, the participants of the second session agreed, that they consider the alarm division in three stages as useful.

When we asked, how they should receive an alarm, the first answer of the first group was "a Smartphone". However, there were concerns of all participants that there should not be another phone in their pockets. After we asked them to go more into detail, one participant confessed that they are in general not aware "what is possible with the today's technology". Afterwards they agreed in some device which alerts preferably silent, e.g., vibrating or blinking. One participant stated: "Well, the noncritical alarms could blink somehow. Somewhere. But I have no idea how this should be possible". Alternatively, the alarm loudness should increase with the priority and alarms with a high priority should generally remain audible. The second group focused directly on vibration. In their opinion, the most important factor for a WAS was the size. Additionally to the general safety and hygienic regularities, the device should be as small as possible. For that reason they rejected their idea of a vibrotactile belt and came up with a personal mount (e.g., an armlet or leg band) on which the "technical parts" can be attached. Finally, it should withstand the frequent patient contact "with all associated factors" (e.g., contact with body fluids).

Regarding the functionality of the system, the participants of both sessions agreed, that the device should not differ too much from the current monitoring system. Therefore, the wearer should be able to acknowledge and silence an alarm with the device. Moreover, it should forward alarms after a certain time automatically. The second group proposed also an "emergency button", which acts like a red alarm and calls for help.

C. Summary

From the results, we could identify special issues and differences to Cvach's algorithm. Finally, we could derive the following alarm distribution and escalation model (see Figure 3):

- Low priority and technical alarms will be forwarded to the responsible nurse with a 60 sec. delay
- If there is no reaction within 60 sec., the alarm will be forwarded to a second nurse.
- If the second nurse does not react within 60 sec., the alarm will be forwarded to the remaining nurses (see Figure 3: top).
- High priority alarms will be forwarded to the responsible nurse and the responsible physician immediately (see Figure 3: bottom).
- If there is no reaction within 60 sec., the alarm will be forwarded to the remaining nurses.
- The responsible nurse has the option to acknowledge, to silent or to forward the alarm; to call for assistance and for an emergency call.
- An emergency call behaves like the high priority alarm and will be forwarded to the remaining nurses and the responsible physician

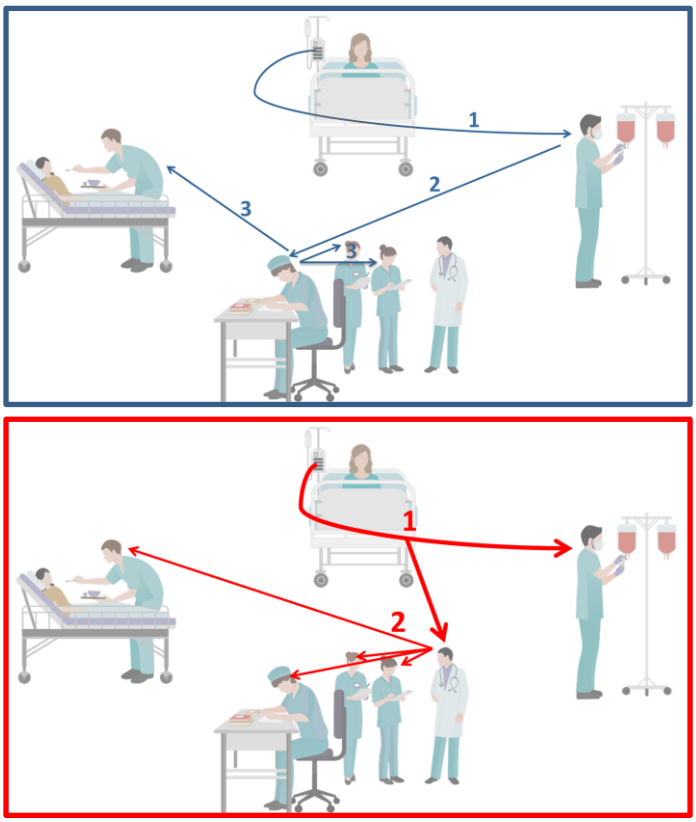

Figure 3: Alarm distribution model (top: uncritical alarms, bottom critical alarms)

A device that implements this algorithm should fulfill the following requirements to be integrable into the ICU workflow:

The WAS must not be applied to the hands or forearms to comply with applicable hygiene and clothing standards. It should be shock and water resistant to withstand various circumstances in intensive care units. The nurse should able to clean and especially to wipe-disinfect the surface of the device to prevent germs or viruses from being transferred from one patient to another.
It should be made of allergy-free and breathable material to avoid sweating while wearing it. For cost-saving reasons, the hardware components should be easy to detach, so they can be used by multiple intensive care nurses.
The system should be easily applicable and moreover, resizable to fit different intensive care nurses. In addition, it should sit tight to the body so that it does not slip or get lost during work.
The size of the device should be as small as possible.

The WAS should alert reliably with three levels of urgency to distinguish between high priority, low priority and technical alarms.
The high priority alarms should be delivered acoustically. Technical alarms should be differentiated according to their cause.
The alarms must be easily and quickly identifiable.

Healthcare professionals must be able to forward or silence an alarm, call for emergency and sign on/off from alarms.

Finally, the device must be easily integrable into the nursing workflow without having negative influence on the quality of nursing.

D. Discussion

Both expert groups highlighted the relevance of a personalized alarm distribution.

Even if they did work in the same federal state, both groups developed a similar solution to distribute alarms with similar differences to the algorithm of Cvach [4]. We assume that this is caused by national differences in the alarm policy.

Also regarding the alerting, all participants agreed that there is a need for a non-acoustic alerting system. However, the lack of awareness regarding new technologies might have restricted the creativity of the first group, which kept them from creating further ideas of a multimodal alerting. The second group focused only on vibrotactile alerting.

Distinguishing reliably between alarms is an important requirement for alarms in safety critical environments [6]. Therefore, we consider delivering alarms via the following multimodal stimuli.

1. Sound via bone-conductive speakers. One advantage of bone-conductive speakers is that sounds can be delivered to the user almost inaudibly for surroundings. Additionally, the audio channels are kept free for air-transmitted noises like conversations. Another advantage is that commonly known tones can be used to convey alarms. Since we want to reduce acoustic alarms, we suggest using this stimulus for the critical alarms only.

2. Light. Former research showed that light is a suitable stimulus to represent information reliably and even to notify users within ambient systems [9]. We believe that light is also suitable to display several alarms to nurses. There is a huge design space for light patterns that we currently explore to convey different levels of urgency. Therefore, we are doing participatory design sessions. However, the colors which are already mapped to the different alarm categories (e.g., red, yellow and blue) have to be considered in the design process.

3. Vibration. In contrast to light, vibrotactile feedback is already established and well known for mobile notifications in everyday life. Nonetheless, it may cause a condition called phantom vibration syndrome. This means, the user perceives that a device is vibrating, when, in fact, it is not [8]. For that reason, we propose to use that stimulus rarely. Since the results indicated that there is a need to distinguish between important and uncritical technical alarms, we propose to use simply a light pattern for the uncritical technical alarm and another light pattern in combination with vibrotactile cues to increase the urgency for critical technical alarms.
The resulting multimodal alarm design can be seen in Figure 4.

	High Priority	Low Priority	Technical
Audio	✓		
Light	✓	✓	✓
Vibration			(✓)

Figure 4: Multimodal alarm signaling concept

However, our results are limited in some points. First of all, we presuppose that there is a reliable alarm classification, which divides between high priority, low priority, critical technical and simple technical alarms. Additionally, we regard only alarms that originate from patient monitoring systems. A reliable reduction of acoustic alarms in hospitals would also require a standardized interface between medical devices and patient monitoring systems to integrate the alarms of all devices.

Moreover, with two expert groups, our results are still preliminary and need to be evaluated with healthcare professionals of hospitals from several federal states. Due to several safety regularities based on the medical products law, we are only allowed to test this in a lab setting, not in the field.

There are several ways to implement the derived requirements for a multimodal WAS. For now, we developed a multimodal head-mounted display (HMD) [2]. In the future, we want to evaluate the usability and acceptance of the HMD as well as the accuracy of its alerting. The study will take place in a lab setting with nurses during tasks that mimic common loads of nursing tasks like physical load, cognitive load and hand-eye coordination.

IV. Conclusion

In this paper, we described the user-centered development of requirements for a wearable alarm distribution system. Our results build on two expert group discussions with healthcare professionals of different hospitals from two federal states. We found differences from a former alarm distribution algorithm implemented on pagers and adapted this algorithm. The derived requirements include context-specific demands for a wearable device that should alert healthcare professionals with three different levels of urgency with mainly non-acoustic alarms. Moreover, we proposed an exemplary multimodal concept to implement these alarms on a wearable alarm system.

However, our study results are limited, since they were not evaluated, thus far. In future, we aim to evaluate our distribution algorithm as well as our requirements using an HMD. There are several safety regulations which keep us from testing in the field. Therefore, we are planning to conduct further experiments in intensive care simulation labs.

There are multiple ways to implement the requirements and our findings may support researchers to develop a wearable alarm system to distribute alarms in ICUs.

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