INTENS CRIT CAR E NUR xxx (xxxx) xx x

Contents lists available at ScienceDirect

Intensive & Critical Care Nursing

journal homepage: www.sciencedirect.com/journal/intensive-and-critical-care-nursing

Research Article

Improving alarm management to reduce alarm fatigue in critical care: a mixed-methods study

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ARTICLEINFO

Keywords:
Alarm fatigue
Health personnel
Critical care nursing Patient safety
Intensive care units

ABSTRACT

Background: The excessive number of false alarms in the intensive care unit (ICU) environment constitutes a significant clinical issue, contributing to alarm fatigue among medical staff. Effective alarm management is crucial for reducing the incidence of false alarms and enhancing patient safety in the critical care setting. This study aimed to conduct a quantitative analysis of alarms generated by cardiac monitors, assess ICU staff attitudes toward the alarm system, and implement and evaluate the effectiveness of an intervention designed to improve alarm management in an anaesthesiology and intensive care unit.

Methods: The project employed an action research methodology. It incorporated pre- and post-intervention analysis of alarm data retrieved from patient monitoring systems, participant observation, a questionnairebased survey, and root cause analysis (RCA). The intervention consisted of educational initiatives and technical adjustments.

Results: A total of 119,158 alarms were recorded in the pre-intervention phase and 151,840 in the postintervention phase (a 47.4% increase). Despite the overall increase in alarm volume, improvements were observed in the structure and classification of alarm. The number of red technical alarms decreased by 61.1%, while the number of short yellow alarms dropped by 2.3%. Participant observation revealed high noise levels, selective staff responsiveness to alarms, and varied proficiency in monitor operation. The staff confirmed that alarms were burdensome, caused fatigue, and had a negative impact on patient care. RCA analysis revealed the absence of a comfort profile for palliative patients and identified issues with device configuration and technical artefacts.

Conclusion: Despite an overall increase in alarm frequency, the intervention led to an improvement in alarm quality. ICU staff experience alarm fatigue, necessitating ongoing monitoring and support. The lack of standardized alarm management protocols highlights the need for threshold standardization and a clear delineation of responsibilities. Interventions combining staff education with technical optimization are the most effective. *Implications for clinical practice:* Alarm management should be regarded as an interdisciplinary task, involving nursing staff, physicians, clinical engineers, and representatives from medical device manufacturers.

Background

The average number of alarms per patient that nurses respond to during a single shift ranges from 150 to 400 [1,2], with the vast majority being false or clinicaly insignificant [3]. Nursing staff, who spend the most time with patients, monitoring their condition 24 h a day, are particularly vulnerable to alarm fatigue. Their excess can cause irritation resulting from annoying and false alarms, which naturally leads to muting or completely disabling them. This, in turn, increases the risk of missing clinically significant alarms that require timely intervention. Such sensory overload associated with alarm excess may result in delayed response or even complete disregard of alarm signals [4]. Notably, the high frequency of false alarms reduces medical staff's trust in patient monitoring systems [5], thereby compromising patient safety [6]. As it turns out, Up to 3–40% of nurses report having never received training on the basic functions of patient monitors, and this lack of training has no measurable effect on alarm fatigue or patient safety outcomes Through regular training, medical staff will be able to use monitoring devices safely and experience less sensory overload. A response to this problem may be joint action by the clinical team and the representative of the medical device manufacturer, especially of cardiac monitors, to optimally set alarm thresholds, delay alarm functions, and optimize workflow related to device operation [8]. A comprehensive alarm management optimization program, targeted at a previously defined problem, is a possible response to the complex issue of alarm fatigue [7].

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Received 4 August 2025; Received in revised form 29 September 2025; Accepted 3 October 2025
Available online 15 October 2025

Aim

This study aimed to conduct a quantitative analysis of alarms generated by cardiac monitors, assess ICU staff attitudes toward the alarm system, and implement and evaluate the effectiveness of an intervention designed to improve alarm management in an anaesthesiology and intensive care unit.

The following questions were also posed:

What types and categories of alarms occurred most frequently before and after the technical and educational intervention? Do monitoring device alarms contribute to fatigue among staff? Is alarm management carried out by medical staff in daily clinical practice?

What organizational and technical factors contribute to improper alarm management?

Which competencies should be strengthened in educational programs?

Methods

Study design

The project employed both observational and action research methodologies. The study was conducted in the intensive care unit of a university hospital in northern Poland, spanning from January to December 2023. The researchers followed the guidelines of the STROBE Statement [9].

ICU setting

The ICU unit in which the study was conducted is a tertiary-level (Level III) referral unit, characterized by a 1:1 nurse-to-patient ratio. The unit has an open architectural layout. In the main room, there are 10 patient beds. In the rear section of the unit, there are two single-bed isolation rooms. The central monitoring station is located in the center of the main room, adjacent to the nursing observation area. Patient stations are separated by curtains.

Alarm characteristics

Physiological parameter alarms are categorized into two types: red and yellow alarms. A red alarm indicates a high-priority alarm, typically associated with a life-threatening condition (e.g., asystole). A yellow alarm signifies a lower-priority physiological parameter alarm (e.g., exceeding the respiratory rate alarm threshold). Additionally, shortduration yellow alarms are available, the majority of which indicate the occurrence of specific arrhythmias (for example, ventricular bigeminy). Blue technical alarms indicate that the monitoring device is unable to measure or detect alarm conditions reliably. If a technical alarm causes interruption of monitoring and detection of alarm conditions (for example, lead disconnection), the numerical reading is replaced by a question mark in the sector and Patient Window, and an audible signal sounds. Technical alarms without the described sound signal indicate that the data may be unreliable; however, monitoring continues uninterrupted.

Color description: Red alarms indicate high priority; yellow alarms indicate medium priority; blue alarms indicate low priority (Table 1).

The abbreviation Tech denotes technical alarms related to measurement issues. The absence of this abbreviation indicates a physiological alarm signaling the patient's condition. A distinct category is the Short Yellow alarms, which signal ongoing arrhythmias.

Alarm types refer to specific messages transmitted by the cardiac monitor. Additionally, alarm types are marked with an asterisk (*) for physiological alarms and an exclamation mark (!) for technical alarms. The number of symbols reflects the urgency of the alarm.

Study participants

Medical staff working in the ICU were involved in participant observation, a survey, and interviews. The staff were informed about the ongoing project and gave their consent to participate in the study. During the project, 40 nurses were employed in the unit. The study in the ICU was conducted by a clinical consultant from Philips, who was introduced to the staff before the start of the study. Patients in the unit were not participants in the study. All data obtained from the cardiac monitors were fully anonymized.

Study procedure

The study was conducted in a 12-bed ICU after obtaining approval from the ICU Head and the Hospital Management. The process consisted of six stages [Fig. 1].

The first stage of the study involved collecting quantitative alarm data extracted from the monitoring system. The data obtained from the system included the total number of alarms, broken down by type and classification, as well as the alarm burden (alarms per bed per day). Quantitative alarm data were collected directly from the ICU's patient monitoring system. The measurement covered two 40-day periods (before the technical and educational intervention, and two months after the completion of the project). All alarms generated by the cardiac monitors in the 12-bed ICU were recorded continuously (24/7). The extracted data included the following categories: number of alarms, alarm types (technical and physiological), alarm classifications (what the alarms communicated), and the types of alarms per bed per day.

The second stage involved participant observation. Direct observation of an anaesthesia nurse's work amounted to a total of 40 h, including 4 h during a night shift. Nursing staff were informed of the researcher's presence. The study employed participant observation conducted at selected ICU care stations, which allowed for capturing the actual workflow of the medical staff and their interactions with the monitoring systems. During the observation, the following elements were taken into account: types of alarms (technical, physiological), staff responses, situational context (e.g. whether the alarm occurred during a procedure or when no intervention followed), team communication, preventive actions (electrode checks, personalized settings, parameter control), use of monitor functions (pause, muting), and technical aspects of equipment operation (software control).

The third stage of the study consisted of a questionnaire-based survey conducted among members of the clinical team, aimed at assessing the subjective level of alarm overload, the perceived usefulness of alarms, and their impact on occupational stress and work quality. Completion of the questionnaire was voluntary. The questionnaire was completed by 17 nurses out of the 40 employed. The questionnaire distributed among the staff included 11 questions, allowing for responses using a nominal scale or in the form of yes/no/don't know answers. The tool enabled the identification of opinions and experiences related to the impact of alarms on patient comfort, quality of care, work organization, and staff attitudes toward the functioning of monitoring systems.

Table 1
Alarm characteristics.

Color	Alarm type	Priority	Type
	Red	**High**	**Physiological (*)**
	Red Tech	**High**	**Technical (!)**
	Yellow	**Medium**	**Physiological (*)**
	Short Yellow	**Medium**	**Rhythm disturbances, episodic arrhythmias (*)**
	Yellow Tech	**Low**	**Technical (!)**
	Blue Tech	**Low**	**Technical (!)**

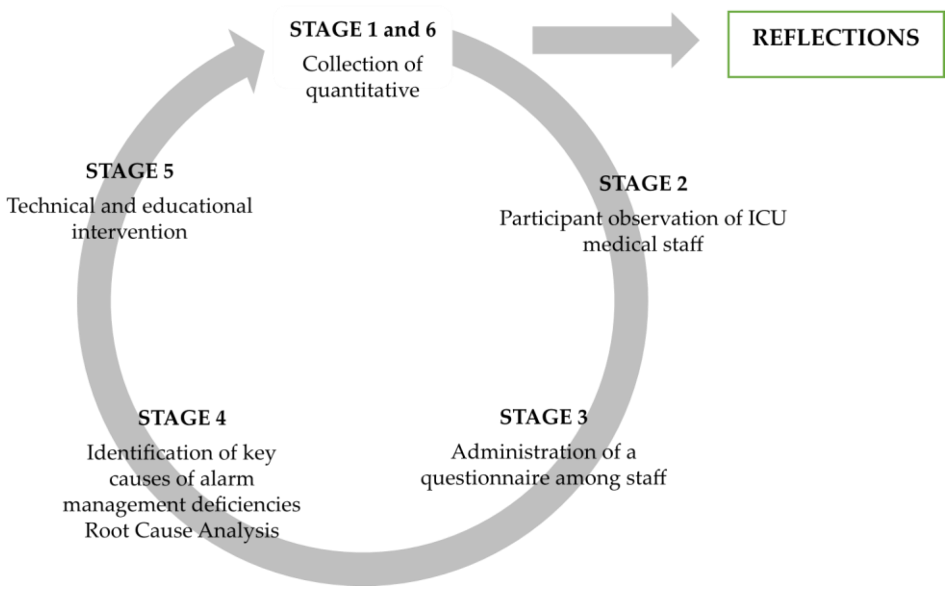

Fig. 1. Action research cycle with study stages.

During the **fourthstage**, a Root Cause Analysis (RCA) wasconducted to identify the primary causes of irregularities in the alarm management process. An extended version of RCA was used in this study, serving not only to evaluate incidents retrospectively but also to identify underlying organizational, procedural, and psychological mechanisms that influence the functioning of the alarm system in the intensive care setting. Unlike traditional incident-oriented RCA, the analysis in this study included:

- Review of system data related to alarms (alarm logs)
- Participant observation of staff during actual clinical shifts
- Unstructured interviews with medical staff (nurses, physicians, technicians)
- Identification of behavioral patterns, habits, and informal practices used in response to alarm burden
- Analysis of organizational and environmental factors (e.g., alarm policies, staffing levels, shift scheduling).

During the **fifth stage**, a technical and educational intervention was implemented based on the collected data (Table 2). The technical intervention involved changes to the monitor configuration, which are described in more detail in the results section. The educational intervention targeted nursing staff, focusing on increasing their knowledge and awareness of the importance of effective alarm management. The training was designed as targeted education, based on the initial analysis of competency gaps related to the use of cardiac monitors. The program included two key components: Bedside training – conducted directly in the intensive care unit using real monitoring stations. Due to the high workload and the necessity of maintaining continuous patient care, sessions were held in small groups (1:1 or 1:2), allowing for the tailoring

Table 2
Integrated summary of technical and educational interventions implemented.

Technical Interventions	Educational Intervention

Objective and Rationale: The technical interventions were fully targeted at the identified root causes of alarms.	**Objective and Rationale:** The training program was designed as targeted education, based on an initial analysis of competency gaps related to the operation of cardiac monitors.
System Configuration Changes: ▪ Activation of the Smart Alarm Delay function for the oxygen saturation parameter, with a medium delay setting. ▪ Implementation of the Alarm Advisor application, which continuously analyzes yellow alarms and provides recommendations for adjusting alarm threshold settings. ▪ Deactivation of yellow alarms for the following arrhythmias: Pair PVC, Multiform PVC, PVC/min, and PVC runs.	**Bedside Training:** Conducted in the clinical environment using actual monitoring stations. The training sessions lasted approximately 30 min.
Enhancement of Monitor Functionality: ▪ Introduction of a Full Alarm Pause option with a duration of 5 min, intended exclusively for use during nursing procedures (with the possibility of immediate cancellation at any time). ▪ Creation of a Comfort Care profile to allow for appropriate adjustment of monitoring settings for patients in whom futile therapy has been discontinued.	**Online Training Sessions:** Remote training was conducted via the Microsoft Teams platform and lasted approximately 30 min. Recordings from the bedside monitor, using a test patient setup, were made available and demonstrated each configuration change step by step.
Technical Review: The analysis revealed that at least three devices generated recurring technical alarms, including issues related to battery performance and X3 module compatibility, which were subsequently addressed in the service plan.	**Training Program:** 1. The phenomenon of alarm fatigue and its impact on patient and staff safety. 2. Appropriate use of age-specific monitoring profiles. 3. Adjustment of alarm thresholds to meet individual patient needs. 4. Correct connection of monitoring equipment (selection of appropriate pulse oximetry sensors and proper electrode placement). 5. Explanation of visual indicators. 6. Safe use of the alarm pause function. 7. Overview of the implemented monitor configuration changes. 8. Demonstration of the application of newly introduced functions.

of content to participants' skill levels and enhancing the effectiveness of the training.

Remote training – to accommodate staff working in shifts, two online sessions were organized via the Microsoft Teams platform. These meetings were open and targeted at staff working night or weekend shifts, for whom access to on-site training was limited.

The **finalstage** involved reevaluating the process through a repeated quantitative analysis of the alarm database after the project's completion.

Bioethics committee

The study was conducted following the guidelines of the Declaration of Helsinki and was approved by the Bioethics Committee of the Medical University of Gdansk (NKBBN/777-371/2023).´

Data analysis

Data analysis was conducted using a mixed-methods approach, integrating both quantitative and qualitative methodologies. For the quantitative component, descriptive statistical tools available in Microsoft Excel 365 were utilized. For the qualitative data, a thematic qualitative analysis was conducted, employing manual open coding and grouping of data into analytical categories.

Participant observation was analyzed following the principles of qualitative content analysis. The data was initially segmented into meaningful units (incidents, statements, behaviors), which were then assigned to analytical categories. An inductive approach was employed, allowing for the direct identification of themes from the data without relying on pre-established frameworks.

As part of the root cause identification process, Root Cause Analysis (RCA) was conducted using the „5 Whys" technique, enabling the mapping of incident sequences and identification of both immediate errors (e.g., delayed response) and contributing factors (e.g., sensory overload, lack of monitor setting personalization, insufficient training on alarm hierarchy). The results of the analyses were compiled in a manner that allowed for the triangulation of quantitative and qualitative findings and the development of practical recommendations.

Results

Stage 1 and 6 Alarm quantity

The number of alarms occurring in the ICU environment is shown in Table 3. First observation: During the initial 40-day period, a total of 119,158 alarms were recorded. The distribution of alarm types during this period was as follows: red alarms – 4,083 (3.4 %), red technical alarms – 2,133 (1.8 %), yellow alarms – 22,663 (19 %), yellow technical alarms – 1,382 (1.2 %), short yellow alarms – 16,930 (14.2 %), blue technical alarms – 71,967 (60.4 %). Second observation: During the second 40-day period, a total of 151,840 alarms were recorded. The distribution of alarm types during this period was: red alarms – 4,057 (2.7 %), red technical alarms – 829 (0.5 %), yellow alarms – 25,038 (16.5 %), yellow technical alarms – 1,397 (0.9 %), short yellow alarms – 16,549 (10.9 %), blue technical alarms – 103,970 (68.5 %).

Alarm frequency and type per monitoring station

Table 4 presents the 30 most frequently occurring alarm types per ICU bed per day, recorded during the first observation period, along with the corresponding results from the second observation. For each alarm type, the percentage change was calculated, representing the process outcome. A decrease in the number of occurrences was observed in 16 out of the 30 analyzed alarm types (53.3 %). The most significant reductions were observed in the following cases: Tskin NoTransduc. – a decrease of 92.6 % (54 to 4), C5 Lead Off – a decrease of 91.7 % (12 to 1), * Missed beat – a decrease of 54.5 % (11 to 5), SpO_2 Pulse? – a decrease of 23.5 % (17 to 13). An increased number of alarms was observed in 13 incidents (43.3 %), with the most significant one for: ** CPP Noisy Signal – an increase of 440 % (10 to 54), **HR – an increase of 314.3 % (21 to 87), ABP – an increase of 291.7 % (12 to 47), * PVC/min – an

Table 3

Number of alarms by priority in the study and the process outcome.

Alarm type	First observation	Second observation	Outcome
Red	4083	4057	− 0.6 %
Red Tech	2133	829	− 61.1 %
Yellow	22,663	25,038	+10.5 %
Short Yellow	16,930	16,549	− 2.3 %
Yellow Tech	1382	1397	+1.1 %
Blue Tech	71,967	103,970	+44.5 %
TOTAL	119,158	151,840	+27.4 %

Alarm type	First observation	Second observation	Process outcome
Tskin NoTransduc.	54	4	− 92.6 %
SpO_2 No Pulse	40	55	37.5 %
ART Noisy Signal	40	40	0.0 %
ART No Pulse	36	38	5.6 %
CCO Bad Signal	23	23	0.0 %
**ABPs	22	21	− 4.5 %
**HR	21	87	314.3 %
**ARTs	21	21	0.0 %
**ICPm	20	17	− 15.0 %
* HR	19	22	15.8 %
ABP No Pulse	18	40	122.2 %
**SpO_2	17	15	− 11.8 %

SpO_2 Pulse?	17	13	−23.5 %
**CCO	14	22	57.1 %
**RR	14	19	35.7 %
* AFIB	14	16	14.3 %
* Multiform PVC	14	14	0.0 %
* Pair PVC	14	12	− 14.3 %
ABP	12	47	291.7 %
SpO_2 Unplugged	12	13	8.3 %
C5 Lead Off	12	1	− 91.7 %
Cannot Analyze ECG	11	10	− 9.1 %
* Missed Beat	11	5	− 54.5 %
**CPP Noisy Signal	10	54	440.0 %
CCO PulseOverrange	9	13	44.4 %
CCO PressOverrange	9	10	11.1 %
SpO_2 Poor Signal	9	6	−33.3 %
* PVC/min	8	22	175.0 %
CCO ABP Invalid	8	10	25.0 %
CCO/Tbld NoTransduc.	8	5	− 37.5 %

Table 4

Types of alarms per ICU bed per day and the process outcome.

increase of 175.0 % (8 to 22). In 4 incidents (13.3 %), the number of alarms remained the same.

Stage 2 and 3

The results of the participant observation

The unit operates as an open-space ICU, without physical barriers between patient beds, which significantly contributes to high noise levels. In addition to alarms generated by cardiac monitors, alarms are also emitted by other medical devices (e.g., infusion pumps) as well as non-medical sources such as trash cans with automatic lids, pneumatic tube systems, and telephones. Observations indicated that the noise level was high, contributing to a distinct auditory chaos that potentially affected staff comfort and focus. Notably, medical staff demonstrated a high tolerance, or even desensitization, to lower-priority alarm sounds while remaining appropriately responsive to clinically significant alarms. In informal discussions, the issue of "alarm fatigue" was repeatedly mentioned. During observations, significant differences in the level of knowledge and skill in operating cardiac monitors were noted. The team included both highly experienced users capable of using advanced monitor functions, as well as newly employed staff who demonstrated strong engagement and a willingness to develop their competencies.

The data collected from questionnaires administered to ICU staff are presented in Table 5. A total of 17 fully-completed forms were obtained (response rate 42.5 %). It is worth noting that respondents were generally unable to clearly state whether alarm management policies and procedures were in place in the unit or whether actions could be taken to improve the current situation related to alarm burden. All participants agreed that alarms negatively affect patient comfort, interfere with the delivery of care, and are exhausting and burdensome for the staff.

Stage 4 and 5

The results of Stage IV are presented in Table 6. Based on the Root Cause Analysis (RCA), seven key issues were identified. Technological and equipment-related problems included excessive sensitivity of SpO2 sensors, motion artifacts, and too short alarm pauses. Organizational and systemic issues involved: the lack of a palliative care profile and the shared use of a central access to both infusion and CVP measurement. Clinical decision-making challenges included a high number of ventricular arrhythmias. The described recommendations for solutions were incorporated into the technical and educational interventions during Stage V.

Table 5

Questionnaire results.

QUESTION	YES	NO	I DON'T KNOW
Do you believe that the current level of alarm burden negatively impacts patient comfort?	17 (100.0)	0 (0.0)	0 (0.0)
Do you feel fatigued or burdened by nuisance alarms?	17 (100.0)	0 (0.0)	0 (0.0)
Do nuisance alarms frequently interfere with patient care?	17 (100.0)	0 (0.0)	0 (0.0)
Do false/unnecessary alarms reduce your trust in alarms and lead you to silence them?	8 (47.0)	9 (53.0)	0 (0.0)
Can you configure/change alarm settings on your own?	17 (100.0)	0 (0.0)	0 (0.0)
Does your unit have alarm management policies and procedures in place, and are they followed?	12 (71.0)	5 (29.0)	0 (0.0)
Are the alarms used in my unit adequate to alert staff to potential or actual changes in the patient's condition?	16 (94.0)	1 (6.0)	0 (0.0)
Do you think that you and your colleagues are sensitive to alarms and respond promptly?	17 (100.0)	0 (0.0)	0 (0.0)
Have there been frequent instances where alarms were not audible and were missed?	3 (30.0)	14 (70.0)	0 (0.0)
Do the surrounding sounds often affect your ability to recognize alarms?	5 (29.0)	12 (71.0)	0 (0.0)
Is there anything you think could improve the situation regarding alarm burden?	12 (71.0)	0 (0.0)	5 (29.0)

Discussion

The present project is the first study in Poland to address the issue of alarm management in the ICU environment. The findings confirm that excessive alarm burden in the ICU represents a significant clinical problem, affecting both patient safety and the comfort and efficiency of medical staff. Referring to Stages 1 and 6, the educational and technical intervention did not lead to a reduction in the overall number of alarms; in fact, a 27.4 % increase was observed. However, a clear improvement was noted in the structure and classification of alarm types. RedTech alarms decreased by as much as 61.1 %, indicating a prioritization of patient safety, as well as the effectiveness of technical tuning of monitoring systems and staff education in their operation. The significant increase in Yellow (+10.5 %) and BlueTech (+44.5 %) alarms is associated with the technical aspects of patient care and reflects a major portion of false alarms. SpO_2 "No Pulse", ABP "No Pulse", and ABP "Signal Artifact" alarms may suggest issues with the device or transducer, although the patient's clinical condition may also influence their frequency. A high number of clinically insignificant alarms may result from the use of default factory monitor settings and a lack of customization of monitoring profiles to match the patient's clinical condition [8]. In their study, Gross et al. emphasized the importance of classifying alarms based on clinical relevance rather than simply by quantity [10]. However, the high volume of technical alarms may contribute to the development of alarm fatigue among ICU staff and promote

Table 6 (*continued*)

Problem	Cause	Recommendation for a solution
Excessive reactivity of SpO_2 sensors	SpO_2 sensors exhibit excessive sensitivity to physiological fluctuations in oxygen saturation, particularly in critically ill patients, where natural variations in saturation are frequent and do not always necessitate intervention. As a result, numerous alarms of low clinical value are generated.	It is advisable to consider the use of alternative sensors for patients with unstable peripheral perfusion, as well as to implement algorithms that account for artifacts related to centralization of circulation. Recommendations should be developed to guide users in selecting the most suitable sensor types based on the patient's specific clinical condition.
Use of non-original SpO_2 sensors	Hospital procurement policy	The manufacturer assumes no responsibility for the accuracy of measurements obtained using unvalidated accessories, which may result in false alarms or failure to trigger alarms. Such situations pose a risk of both false alarms and delayed detection of actual clinical deterioration.
Excessive alarms related to ventricular arrhythmias	The monitoring system generates a high number of alarms in response to ventricular rhythm disturbances (e.g., PVCs, PVCs/min, runs of PVCs), which may lack clinical significance in the context of the patient's condition, particularly when such arrhythmias are secondary to ongoing treatment or underlying disease.	Monitor settings should be adjusted through the implementation of an intelligent algorithm that assesses not only the presence of arrhythmia but also its clinical relevance. Medical staff should receive training on the interpretation of arrhythmias and the function of algorithms that delay alarm activation in low-risk cases.
Simultaneous use of central venous access for infusion and hemodynamic monitoring (CVP)	Central venous access is used simultaneously for infusion and central venous pressure (CVP) measurement, which can result in periodic disturbances to the measurement line. This leads to incorrect readings, frequent alarms, and interruptions in monitoring.	Situations should be identified where the temporary suspension of CVP analysis during active infusion is feasible, to prevent false alarms.
Motion artifacts generated during nursing care	Nursing activities (such as repositioning, hygiene procedures, or limb manipulation) generate short-term artifacts that are misinterpreted by the monitoring system as pathological changes, resulting in false alarms.	Improvement of motion detection and artifact correction algorithms based on contextual data is recommended. Staff education should include guidance on alarm muting during nursing procedures and effective reactivation afterward.
Insufficient duration of system pause on the cardiac monitor — frequent use by staff	A 3-minute pause duration is insufficient. During patient care activities, pressing the pause button every 3 min is burdensome and distracting from the task at hand.	It is recommended to modify the cardiac monitor configuration to provide users with an option for an extended alarm pause. Staff education should focus on the correct use of alarm pauses, including training on how to activate and deactivate alarm blocking.
Lack of a dedicated system option for patients with discontinued futile therapy	Monitoring systems generate alarms regardless of the patient's clinical context, interpreting all deviations from normal parameters as potentially actionable. In the case of patients in the dying phase, this results in repeated and unnecessary audible alarms. These signals are interpreted by the system as requiring intervention, even when medical intervention is no longer appropriate.	It is recommended to introduce the possibility of configuring monitoring settings for patients in whom futile therapy has been discontinued—for example, by creating a special monitoring mode or patient profile aimed at ensuring comfort. This mode should allow for: • Complete silencing of non-essential physiological alarms while maintaining technical oversight; • Clear marking of the patient's status on the monitor (e.g., through color coding or iconography); • Secured access to this function, so that the decision to activate it is made consciously and is clinically justified. At the same time, staff training should be implemented regarding the correct use of alarm pause, alarm blocking and unblocking, as well as the ethical and practical aspects of caring for dying patients.

Results presented as absolute numbers (percentages).

desensitization to alarm signals [11]. In the present project, no data were collected regarding patient load per workstation or the clinical status of individual patients, both of which may significantly influence the number of alarms generated. A 2024 study suggests that the number of alarms is an unreliable indicator of nurses' alarm management skills. It also confirms the impact of patient volume and nurse staffing levels per shift on alarm burden [12].

During participant observation (Stage 2), significant noise was noted within the unit, which may impair communication and increase stress levels among staff [13]. Additionally, the excessive number of devicegenerated sounds contributes to sensory overload during attempts to assess the clinical relevance of a given alarm, potentially leading to nurse fatigue as well as irritation and anxiety associated with the acoustic characteristics of alarm sounds [14,15]. Alarm fatigue was reported in both questionnaire responses (Stage 3) and during conversations with staff. A 2021 study confirmed that the level of alarm fatigue among Polish nurses is moderate [16]. However, it was found that even a well-executed alarm management project, which successfully reduced the number of alarms, did not result in a corresponding decrease in staff fatigue. This issue poses a threat to patient safety and highlights the need to raise staff awareness [17,18]. It is noteworthy that 29 % of study participants were unsure whether alarm management procedures were in place in their unit. This may indicate insufficient internal communication, a lack of standardization, or unclear alarm protocols. These findings are consistent with Cvach's observations, who emphasized that effective alarm management requires both systemic support (procedures and protocols) and clearly communicated operational frameworks [11].

An important element of the project was the qualitative analysis performed in the form of Root Cause Analysis (Stage 4). The RCA showed key organizational issues. The alarm pause was found to be too short, which may contribute to excessive interruption of clinical tasks and, consequently, to the ignoring of repeated alarm signals [19]. From a patient safety perspective, an extended alarm pause must be automatically deactivated once the procedure is completed [1,20]. Device overreactivity to motion artifacts was also identified. During nursing procedures, the extended alarm pause mentioned above may serve as a solution [20]. Furthermore, the lack of a dedicated patient profile for those under limitation of futile therapy represents a systemic issue, resulting in repeated alarms for patients in whom clinical intervention is no longer indicated. This forces staff to manually silence alarms, disrupts medical procedures, and leads to alarm fatigue [21]. Clearly defined and effectively communicated alarm management protocols can address many of the uncertainties faced by ICU staff [22,23].

The training program (Stage 5) on the use of cardiac monitors, delivered both at the bedside and remotely, proved to be an effective and flexible way to improve the skills of the medical staff. However, the educational intervention was not ongoing and did not include all staff members of the unit, which may have led to less awareness about strategies for managing alarm burden. A 2019 project conducted in China implemented a 12-week cyclical training program for nursing staff. Thanks to regular educational interventions, the study achieved a significant reduction in both perceived alarm fatigue and the number of alarms in the clinical environment [24]. In a 2023 U.S.-based study, researchers reported a 16.92 % reduction in Red Alarms through staff education and improved team communication. A 2023 review emphasized the role of training as an integral component of alarm management, emphasizing the importance of developing educational programs that promote staff awareness and responsibility for alarm fatigue [25].

In summary, the findings of the project indicate the need for a comprehensive approach to alarm management in the ICU—one that integrates technological, organizational, and educational interventions [26]. The implementation of technology alone is insufficient without accompanying staff training and systemic decision-making support. The optimization of monitoring systems should involve not only IT specialists and biomedical engineers, but also the active participation of nursing staff, who possess the most accurate understanding of the actual clinical needs and limitations [27–29]. The absence of a continuous alarm management process contributes to the intensification of alarm fatigue, which may negatively affect both the quality of care and patient safety [30]. From a methodological standpoint, it is worth highlighting the effectiveness of the action research approach applied in this project. This method allowed not only for the identification and description of the existing problem, but also for the implementation of practical changes and assessment of their effectiveness. The iterative nature of the intervention enabled flexible adaptation to the dynamically evolving needs of staff and the conditions within the unit. The final stage of reflective analysis enabled the researchers to critically evaluate the project's limitations and to optimize alarm management practices for future implementation.

Conclusion

1. The most frequent type of alarms, both before and after the intervention, was BlueTech. Despite the overall increase in the number of alarms post-intervention, an improvement in their qualitative structure was observed, indicating more effective filtering of clinically insignificant signals.
2. ICU staff reported experiencing alarm fatigue, highlighting the need for regular assessment of fatigue levels and its inclusion in both educational and technical interventions.
3. Study participants could not definitively confirm whether alarm management protocols were implemented in the unit; however, in daily practice, staff responded appropriately to high-priority alarms.
4. To minimize improper alarm management, it is essential to standardize the rules for modifying alarm thresholds through the development of procedures and defined responsibilities among staff.
5. Combining educational initiatives with technological optimization proves to be a more effective alarm management strategy than implementing either type of intervention in isolation.

Implications for practice

- There is no one-size-fits-all method for alarm management, even within a single hospital. It is a process that considers the care environment, the needs of staff and patients, and the team's readiness for change.
- Alarm management is a continuous process that requires cyclical technical, educational, and systemic interventions.
- Alarm management should be regarded as an interdisciplinary task, involving nursing staff, physicians, clinical engineers, and representatives from medical device manufacturers.

Study limitations

Completion of the questionnaires was voluntary, with researchers primarily focusing on the assessment of the environment and technical aspects of monitoring. In the future, before any alarm management projects are conducted, it is necessary to evaluate both environmental factors and actively engage the entire unit staff in the study. Additionally, assessment of alarm fatigue was not mandatory and was not conducted post-study; instead, the evaluation concentrated on quantitative data as a measure of the process. An additional limitation is that the questionnaire was not formally psychometrically validated (e.g., construct validity, reliability testing). The instrument was developed and provided by an external technical consultant with expertise in alarm management and medical device configuration, and its content was reviewed by two senior ICU nurses and one ICU physician to ensure clinical relevance and content validity. As the questionnaire was designed as a context-specific tool tailored to our ICU setting, no additional psychometric validation was undertaken, which should be considered when interpreting the findings. Considering that the ICU environment may continue to contribute to the persistence of alarm fatigue even after the intervention, it is essential to regularly assess the level of fatigue among staff. In future studies, alarm fatigue should be included as one of the key indicators for evaluating the effectiveness of the intervention [31]. This study did not account for patient load or their clinical conditions within the unit. These variables could significantly contribute to the quantitative analysis of alarms and the reasons for their increase. Furthermore, only alarms generated by monitoring devices were evaluated. In the ICU environment, numerous devices generate alarms that may also contribute to the phenomenon of alarm fatigue.

CRediT authorship contribution statement

Katarzyna Lewandowska: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Wioletta Mędrzycka-Dąbrowska:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Magdalena Mikłas:** Formal analysis, Data curation. **Magdalena Wujtewicz:** Writing – review & editing, Supervision.

Declaration of competing interest

Magdalena Mikłas is an employee of Philips Polska Sp. z o.o. Based on the obtained results, a report will be prepared by Philips Polska sp. z o.o., describing the first project in Poland on alarm management of monitoring devices (cardiac monitors and central monitors), including the project results and other detailed data and information related to the project, taking into account applicable legal regulations. Philips Polska sp. z o.o. may, without any additional consents or fees, indefinitely use, quote, distribute, modify, adapt, translate into foreign languages, and utilize the aforementioned report — in whole or in part — for its purposes, in particular for research, business, marketing, promotional, and other purposes, as well as transfer the report — in whole or in part — to companies belonging to the Philips Royal Group. Philips Polska sp. z o.o. and the companies belonging to the Philips Royal Group are obliged to indicate the name of the unit where the aforementioned project was conducted.

Acknowledgments

The authors would like to sincerely thank Nurse Anna Cieminska for´ her invaluable support during this study. Her dedication, kindness, and assistance in organizing the data collection process had a significant impact on the smooth execution of the project and enabled its successful completion.

Funding

This research received no external funding.

Ethical statement

The study was conducted following the guidelines of the Declaration of Helsinki and was approved by the Bioethics Committee of the Medical University of Gdansk (NKBBN/777-371/2023).´

Data statement

The data on which our review is based are available in the manuscripts of the included articles and the appendix.

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