Alarm management in provisional COVID-19 intensive care units: a retrospective analysis and recommendations for future pandemics

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Abstract

Background: In response to the high patient admission rates during the SARS-CoV-2 (COVID) pandemic, provisional intensive care units (ICUs) were set up, equipped with temporary monitoring and alarm systems. We aimed to find out whether the provisional ICU setting led to a greater alarm burden and more alarm fatigued staff.

Objective: We aimed to compare the alarm situation between provisional COVID ICUs non-COVID ICUs during the second Corona wave in Berlin, Germany. The study focused on measuring alarms per bed per day, identifying medical devices with higher alarm frequencies in COVID-19 settings, evaluating the median duration of alarms in both types of ICUs, and assessing the level of alarm fatigue experienced by healthcare staff.

Methods: Our approach involved a comparative analysis of alarm data from two provisional COVID-19 ICUs and two stationary non-COVID-19 ICUs. Through interviews with medical experts, we formulated hypotheses about potential differences in alarm load, alarm duration, alarm types, and staff alarm fatigue between the two ICU types. We analyzed alarm log data from the patient monitoring systems of all participating ICUs to inferentially check the differences. Additionally, we assessed staff's alarm fatigue with a questionnaire, aiming to comprehensively understand the impact of the alarm situation on healthcare personnel.

Results: COVID ICUs had significantly more alarms per bed per day than non-COVID ICUs and the majority of the staff lacked experience with the alarm system. The overall median alarm duration was similar in both ICU types. We found no COVID-specific alarm type patterns. The alarm fatigue questionnaire results suggest that staff in both types of ICUs were alarm fatigued. However, physicians and nurses in COVID ICUs showed a significantly higher level of alarm fatigue.

Conclusions: Staff in COVID ICUs were exposed to a higher alarm load, and the majority lacked experience with alarm management and the alarm system. We recommend training and educating ICU staff in alarm management as part of the preparations emphasizing the importance of alarm management training for future pandemics.

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Conclusions: Staff in COVID ICUs were exposed to a higher alarm load, and the majority lacked experience with alarm management and the alarm system. We recommend training and educating ICU staff in alarm management as part of the preparations emphasizing the importance of alarm management training for future pandemics. However, the limitations of our study design and the specific pandemic conditions warrant further studies to confirm these findings and to explore effective alarm management strategies in different ICU settings.

Keywords: patient monitoring; intensive care unit; alarm fatigue; alarm management; patient safety; ICU; alarm system; alarm system quality; medical devices; clinical alarms; COVID

INTRODUCTION

Patients critically ill with coronavirus disease 2019 (COVID) frequently suffer from multiple organ failure and need life-sustaining measures such as continuous renal replacement therapy, mechanical ventilation or even extracorporeal membrane oxygenation (ECMO) [1]. Therefore, during major COVID outbreaks (e.g., in 2019 and 2020), ICUs all over the world saw an increase in admission rates of up to 300% [2]. Intensive care capacities became scarce; in some regions treatment places became exhausted [3]. Hospitals thus had to increase their intensive care capacities to cope with the proliferating number of COVID patients [4]. As a consequence, in many countries, provisional ICUs were set up [5–9].

In provisional COVID ICUs, akin to standard ICU settings, patients require continuous monitoring of their vital signs that include heart rate (HR), cardiac rhythm, and blood oxygen saturation via pulse oximetry (SpO2). If an abnormal situation occurs (e.g., a vital sign exceeds a preset limit), an alarm is issued to capture the attention of clinicians [10]. However, ICU staff today are often alarm fatigued [11], because of high rates of false positive or non-actionable alarms (e.g., Varisco et al., [12]). Alarm fatigue can be hazardous for patient safety, especially when critical alarms are missed [13,14]. The constant noise can cause high levels of stress among staff and disrupt patient sleep-wake-cycle, increasing the risk for delirium and potentially poorer recovery outcomes [15,16].

In COVID ICUs, the alarm situation might have been even worse: ICU staff, likely overworked due to an overwhelming patient load and a massive workload, had to cope with the psychological burden of the fear of infection and the distressing reality of witnessing numerous patient deaths. ICU staff suffered from poor mental health during the COVID Pandemic [17–19] and more errors in clinical settings occurred [20].

Moreover, the makeshift nature of the ICUs, eventually set up hastily to handle the surge in patients, likely exacerbated these problems. The often improvised and provisional nature of these units likely introduced additional operational complexities and stressors such as limited space and insufficient technical equipment, further taxing the already strained staff. All of this might have been topped (or caused) by a loud and potentially unreliable alarm system.

This study systematically assesses the alarm situation of two provisional COVID ICUs and two non-COVID ICUs, focusing on both the actual alarm rates and the extent of alarm fatigue experienced by ICU staff. By incorporating expert interviews with medical professionals who have worked in COVID ICUs, alongside quantitative analyses of alarm log data from the bedside monitors [21–23] and results from the alarm fatigue questionnaire [24], this investigation is following a multimodal approach.

METHODS

Study design

In this study, the alarm situation of two provisional COVID ICUs was compared with that of two non-COVID ICUs; all four ICUs were situated on the same campus at a German tertiary care university hospital in Berlin, Germany. A retrospective observational analytical study design was utilized, with the comparison being approached from three perspectives: (1) Hypotheses were derived and tested based on interviews with medical experts, exploring potential differences in alarm situations between COVID and non-COVID ICUs; (2) Alarm log data from both types of ICUs were analysed; (3) Results from an alarm fatigue questionnaire, which was administered as part of another study ([24]) during the same period were collected and analysed.

The non-COVID ICUs comprise an interdisciplinary ICU with patients who have recently undergone surgery or are perioperative (henceforth abbreviated as “Surgical”), and an ICU with a focus on on internal medicine (henceforth abbreviated as “Medical”) with the focus on internal medicine, in which patients suffering from severe infection, cardiac diseases, kidney failure, or other single or multiple-organ failures are treated.

The medical and surgical ICUs have single- and multi-bedrooms with a total of 20 and 21 beds. The COVID ICU was divided into two separate units: the COVID-A ICU had 16 beds in single-bedrooms and COVID-B ICU had single- and multi-bedrooms with a total of 24 beds.

Expert interviews for hypothesis design

To derive hypotheses about how the alarm situation might differ between COVID and non-COVID ICUs, five medical experts (two physicians and three nurses) were interviewed from July until December 2021. The interviews were semi-structured [25,26]. The foundational questions were grounded in our overarching research question: "What distinguishes the alarm situations in COVID ICUs from non-COVID ICUs?". A detailed list of these questions can be found in Supplementary Table 1.

Additionally, two job shadowings were conducted (on 01/10/2021 in the medical ICU and on 12/11/2021 at COVID-B). During the second session of job shadowing, an interview was conducted in COVID-B. The remaining four interviews were held online via Microsoft Teams [27]. The integral aspect was that beyond the structured questions, medical experts were proactively asked on potential hypotheses regarding the alarm situational differences between the ICU types.

Subsequent to the interviews, the collected data, including transcripts and notes, were meticulously examined. The hypotheses were derived through in-depth examination and collective discussion in an interdisciplinary team.

Statistical analysis

Data analysis

The alarm logs were processed and analyzed as previously described [22], using *R* [28] with *RStudio* [29] in combination with the following packages: *lubridate* [30], *ggplot2* [31], and *dplyr* [32]. The logs were extracted from the *Philips IntelliVue* patient monitoring system (in the surgical and medical ICU: *MX800*, software version “m”, in the COVID ICUs: *MX750*, software version “p”) as CSV files from non-COVID ICUs and XML files from the COVID ICUs. Alarm signals from mechanical ventilation devices were not correctly stored in the alarm log data due to transmission errors and therefore excluded from the analysis. The included alarm signals and the assignment to their medical device are listed in Supplementary Table 3. The logs range across 113 days (from 19/11/2020 to 11/3/2021).

Hypothesis testing

To test for statistical differences between COVID and non-COVID ICUs, the units were grouped accordingly. All tests were one-tailed with a significance level of $\alpha = 0.05$. P-values were adjusted with Bonferroni. The first hypothesis (H_1) was that the alarm load in COVID ICUs is higher than in non-COVID ICUs. This hypothesis was further subdivided in total alarm load, clinical red alarms, clinical yellow alarms, and technical alarms.

The second hypothesis (H_2) posited that more alarms are issued from specific medical devices, namely ECG and IBP, in COVID ICUs than in non-COVID ICUs. The alarms from these devices were further categorized based on their alarm color (potentially life-threatening events “red alert” or vital signs out of prespecified limits “yellow alert”).

Lastly, the third hypothesis (H_3) proposed that the alarm duration in COVID ICUs is longer than in non-COVID ICUs. For this hypothesis, the alarm durations from clinical alarms were subdivided into medical devices (Non invasive blood pressure (NIBP), Temperature, SpO2, ECG and IBP device) and alarm color (yellow and red alarms).

For H_1 and H_2, the alarm load was quantified in alarms per bed per day. Given that the distributions were skewed to the right and approximately gamma distributed, a dummy coded no-intercept model of Generalized Linear Models (GLM) with a log link function has been used. Simple unpaired Cohen's D was used as effect size and has been calculated with the package *effsize* from Torchiano [33].

For H_3, testing was conducted with median alarm durations. The distributions of alarm durations were highly skewed to the right and approximately exponentially distributed, therefore nonparametric bootstrapping with the *boot* package from Canty, Angelo and Ripley [34] was used with an a priori estimation of the difference in alarm duration with (1).

$$H_0 : \mu_1 - \mu_2 \leq 3 \qquad (1)$$

$$H_A : \mu_1 - \mu_2 > 3$$

Differences of 3 seconds were considered significant, while smaller effects that could already be significant due to the large sample were considered as not significant. A median based estimator for Cohen's D-type effect-size (2) with an estimation of variance (3) was used, where *k* is the number of units and *l* is the number of alarms.

$$D = \frac{x_{med,1} - x_{med,2}}{s_{med}} \qquad (2)$$

$$s_{med}^2 = \frac{1}{n-1} \sum_{i=0}^{k} \sum_{j=0}^{l} (x_{ij} - x_{med}) \qquad (3)$$

To test the difference of alarm fatigue experienced by ICU staff between COVID and non-COVID

ICUs (H_4), an unpaired t-test using Cohen's D as effect size has been conducted.

Exploratory data analysis

Metrics previously defined in our study [22] were utilized for the evaluation of the alarm situation in the ICUs: Alarms per bed per day, critical alarms (yellow, red, and blue), alarms per device, alarm flood conditions (10 or more alarms within 10 minutes), use of the alarm pause function per bed per day, proper pause to pause ratio, and concurrent alarm duration per bed per day. This latter metric was first introduced by Varisco et al [12] and is calculated by summing the number of active parallel alarms. Specifically, if two alarms sound simultaneously within a second, this is counted as one second of concurrent alarm duration, and if three alarms sound simultaneously within a second, two seconds are counted.

The metrics were related to bed occupancy and time period, to compare the results between different ICUs. Due to the absence of information about the cause of termination in the data, it was not possible to determine the alarm response time. Therefore, alarm duration was utilized instead.

In the calculations of alarm floods and concurrent alarm duration, only alarms with an auditory modality, specifically yellow and red alarms, were included. For the alarm duration used in calculating concurrent alarm duration, a cutoff was set at 1800 seconds. Alarm durations exceeding this limit were considered outliers and were therefore excluded from the analysis.

Alarm fatigue questionnaire

The questionnaire data was taken from a different study [24] that coincided with our data collection. The questionnaire, distributed as an online survey via *REDcap* [35] to ICU staff at the same German hospital between April and June 2021, provided responses from COVID-A, COVID-B, a third COVID ICU (COVID-C), and the two non-COVID ICUs (Medical, Surgical). The original questionnaire consisted of 27 items, yet only those aligning with the 9-item questionnaire, developed by Wunderlich et al [36], were included in this analysis. Each item was measured on a 5-point Likert scale, ranging from 'I strongly agree' to 'I strongly disagree'.

Demographic questions about work experience, place of work, and position (nurses, physicians and support staff i.e., students or nurses from general wards) were also part of the questionnaire. Only responses from participants who consented to data analysis were included in the study. Submissions with one or two missing items were imputed at random based on the predictive mean matching algorithm using one imputation with the *mice* package [37]. To calculate an alarm fatigue score, the items were scored from -2 (*I strongly disagree*) to 2 (*I strongly agree). I partly agree* was scored with 0. Four items were scored reversely. The sum of all Likert items results in the alarm fatigue score that ranges from -18 to 18. A score of -18 would indicate that the staff is not alarm fatigued at all, while 18 would mean that the staff is strongly fatigued, the midpoint is 0. We report the alarm fatigue in percent as recommended by [24] with (4).

$$Alarm\,fatigue\,of\;participant\,i = \frac{Score_i + 18}{36} \cdot 100 \qquad (4)$$

RESULTS

Beginning with insights from expert interviews to formulate our hypotheses, we proceeded to test them empirically using alarm log data and an alarm fatigue questionnaire, concluding with insights from our exploratory data analysis.

Expert interviews for hypothesis design

Two interviewees reported that only around one-third of the staff in COVID ICUs had experience in intensive care, while the remaining two-thirds consisted of nurses who until then had only worked on general wards, or individuals without specific experience, such as medical students, and even untrained personnel. The staff were assigned to different tasks depending on their qualifications. One physician suggested that staff were not trained on how to properly apply sensors, like electrocardiogram (ECG) electrodes, potentially leading to additional (medically not relevant) alarms. One nurse suggested that alongside the alarm burden, the high fatality rate among patients psychologically strains staff. According to the interviewees, the patient cohort in the COVID ICUs had a more or less homogeneous clinical picture with varying COVID severity. Many patients needed mechanical ventilation and underwent continuous renal replacement therapy with dialysis devices that cause very loud and unpleasant alarms. These alarms were however not recorded in the alarm logs.

One physician reported that patients with COVID often have multiple organ failure, a high length of stay and are therefore often equipped with seven or more perfusors for medication (e.g., antibiotics, catecholamines, sedatives, parental nutrition), which all trigger additional alarms that are also not recorded in the alarm logs. All three nurses reported a higher alarm burden compared to non-COVID ICUs. All interviewees described the removal and reattachment of all patient sensors during transition from prone to supine position or vice versa as a possible cause of false alarms if the alarm pause function isn't used. Based on this information, we hypothesized:

H_1: The alarm load in COVID ICUs is higher than in non-COVID ICUs.

Two of the three nurses reported that they perceived many patients to be multimorbid, overweight, and of older age, with many having a cardiac or pulmonary history and tachycardia. All interviewees reported that COVID patients’ circulation was extremely unstable, which lead us to hypothesize that medical devices related to blood circulation, i.e. the ECG, NIBP, or the invasive blood pressure (IBP) device issue more alarms in COVID ICUs:

H_2: More alarms are issued from ECG, NIBP, and IBP devices in COVID ICUs than in non-COVID ICUs.

Both COVID ICUs featured long corridors with inward-opening doors, which were usually closed to isolate infectious patients. The interviewees reported that the corridors, the dispensary room, and the physician’s room were not equipped with central monitoring, and the health care providers accordingly had no overview of the patients, which made it difficult to localize the origin of the auditory alarms. Only the nurses' room was equipped with central monitoring, but alarms could not be terminated remotely. According to the interviewees, temporary arrangements have been made by the staff to address this problem, such as leaving doors to patients' rooms slightly open, or placing speakers from the monitors in the hallway. However, to respond to or silence an alarm, staff had to enter the patient’s room. This required them to put on personal protective clothing (i.e., gloves, a protective hood, a polypropylene protective gown, and a face shield or goggles). Dressing took about 30 seconds, hindering medical staff from quickly changing from one room to another. All three nurses reported that the protective clothing did not interfere with the termination of the alarms, the usability of the monitor displays, or the adjustment of monitor settings. However, they all described it as strenuous and time-consuming. Accordingly, we derived the third hypothesis:

H_3: The alarm duration in COVID ICUs is higher than in non-COVID ICUs.

Patients in COVID ICUs often present with severe, complex medical conditions that require close monitoring and interventions. One nurse suggested that next to the alarms and heavy workload, patients’ high fatality rate could strain and distress staff psychologically. This mental and emotional strain could potentially affect staff performance and cognitive abilities, potentially hindering their response to alarms. Combining this information with our reasoning for the previous three hypotheses, we formulate the fourth as follows:

H_4: Staff’s alarm fatigue in COVID ICUs is higher than in non-COVID ICUs.

Having delineated the hypotheses informed by the expert interviews, we proceeded to empirically test each of them, starting with the alarm load in different ICU settings.

Hypothesis 1: The alarm load in COVID ICUs is higher than in non-COVID ICUs

Significant differences were observed in all four tests, which confirmed our hypothesis that the alarm load was higher in provisional COVID ICUs than in non-COVID ICUs (P<.001; Table 1). COVID ICUs experienced an average of 23% more alarms in total, 41% more red critical alarms, and 24% more yellow alarms compared to non-COVID ICUs. The alarm load caused by technical alarms was 109% higher in COVID ICUs. The alarm load results, subdivided by medical device and alarm color, are reported in Supplementary Figure 1. The technical alarm signal that resulted in the most alarms per bed per day was the ECG lead off, with mean values recorded as follows: Surgical at 3.42 (SD: 2.10), Medical at 3.84 (SD: 2.87), COVID-A at 7.22 (SD: 1.93), and COVID-B at 7.77 (SD: 2.41).

Table 1: Alarm load from all ICU and results from hypothesis testing of H_1.

	Surgical	Medical	COVID-A	COVID-B
Alarm Load	122.84 (SD 38.95)	122.54 (SD 27.85)	142.47 (SD 41.49)	157.40 (SD 42.58)
Red Alarms	10.94 (SD 2.43)	10.99 (SD 2.82)	14.99 (SD 5.89)	15.81 (SD 4.01)
Yellow Alarms	108.48 (SD 37.86)	107.71 (SD 26.68)	126.23 (SD 37.93)	140.56 (SD 41.08)
Technical Alarms	5.10 (SD 2.17)	5.03 (SD 2.97)	10.30 (SD 2.30)	10.84 (SD 2.51)
	non-COVID	COVID	p-value	Cohen's D
Alarm Load	122.21 (SD 22.37)	151.26 (SD 31.02)	<.001	1.04
Red Alarms	10.98 (SD 1.90)	15.51 (SD 3.33)	<.001	1.67
Yellow Alarms	108.33 (SD 21.73)	134.59 (SD 29.24)	<.001	1.02
Technical Alarms	5.06 (SD 1.87)	10.62 (SD 1.86)	<.001	2.98

Alarm load is reported as alarms per bed per day in mean (SD) and subdivided in total alarm load, red and yellow alarms, and technical alarms. The P-values have been corrected using $P' = P \cdot 4$ All group sizes were n= 113.

Hypothesis 2: More alarms from ECG, NIBP, and IBP devices are issued in COVID ICUs than in non-COVID ICUs

Table 2 shows the results of hypothesis testing for alarms issued by the IBP and ECG devices, subdivided by alarm color and ICU type. In both ICUs types, the IBP device was responsible for the majority of alarms, followed by the ECG and NIBP device. Yellow alarms caused by IBP and NIBP devices and red alarms caused by the ECG device occurred significantly more often in COVID ICUs (P<.001). However, we did not find significant differences in the occurrence of yellow ECG alarms and red IBP alarms. The results of the alarm load, subdivided by medical device and alarm color from all ICUs can be seen in Supplementary Table 4. While certain alarm types exhibited significant differences, the overall impact was not profound enough to affirm the second hypothesis, with the exception of the notable difference in red ECG alarms frequency (as indicated by Cohen's D of 1.13).

Table 2. Results of the hypothesis testing of H_2.

Alarm	non-COVID	COVID	p-value	Cohen's D
ECG (yellow)	39.01 (SD 17.65)	38.79 (SD 18.70)	1	0.00
ECG (red)	2.51 (SD 1.18)	4.60 (SD 2.34)	<0.001	1.13
IBP (yellow)	53.87 (SD 11.38)	66.16 (SD 18.22)	<0.001	0.81
IBP (red)	5.16 (SD 1.14)	5.22 (SD 1.34)	1	0.05
NIBP	0.34 (SD 0.40)	0.56 (SD 0.51)	<0.001	0.49

The alarm load of all devices and colors was calculated in alarms per bed per day and reported in mean (SD). The P-values have been corrected using $P' = P \cdot 5$. Cohen's D has been reported in absolute values. All group sizes were n =113.

Hypothesis 3: The alarm duration in COVID ICUs is higher than in non-COVID ICUs

All ICUs had a median clinical alarm duration of 10 seconds. Yellow alarms issued by the NIBP device had the longest alarm durations (Table 3). The durations of yellow alarms triggered by IBP and ECG devices were shorter compared to alarms from all other medical devices, a pattern consistent across all types of ICUs. The median duration of technical alarms in COVID ICUs was significantly longer. Yellow alarms issued by NIBP, temperature, and SpO2 devices had significantly longer durations in COVID ICUs (P<.001; see Table 3). The results of the median alarm duration, subdivided by medical device and alarm color, can be seen in Supplementary Figure 4. The results show a mixed picture: less than 50% of total alarms had a significant difference in alarm duration between the ICU types, implying that most alarm durations don't differ significantly between the two ICU types. As such, our data do not provide sufficient empirical evidence to support hypothesis 3.

Table 3: Results of the hypothesis testing of H_3.

	Surgical	Medical	COVID-A	COVID-B
Clinical alarms	10 (4-27)	10 (4-25)	10 (3-28)	10 (3-29)
Technical alarms	7 (4-66)	4 (62)	13 (4-65)	14 (4-68)
	non-COVD	COVID	p-value	Cohen's D type
Technical alarms	5 (3-27)	14 (4-67)	<0.001	0.016
NIBP	62 (25-179.75)	99 (29-337)	<0.001	0.094
Temperature	24 (8-86)	32 (9-192)	<0.001	0.009
SpO2 (yellow)	14 (7-32)	23 (11 - 57)	<0.001	0.069
SpO2 (red)	28 (11 - 89)	33 (14-75)	0.108	0.004
IBP (yellow)	13 (6-32)	11 (4-30)	1.000	0.014
IBP (red)	24 (9-84)	20 (9 - 48)	1.000	0.005
ECG (yellow)	4 (3-9)	3 (2-7)	1.000	0.014
ECG (red)	23 (9-119)	16 (8-35)	1.000	0.005

Median alarm durations of clinical and technical alarms in seconds, interquartile ranges in brackets and results of the hypothesis testing of H3. The P-values have been corrected using $P' = P \cdot 10$. Cohen's D has been reported in absolute values. All group sizes are reported in Supplementary Table 4.

Hypothesis 4: Staff's alarm fatigue in COVID ICUs is higher than in non-COVID ICUs

The questionnaire was completed by 707 participants, 78 questionnaires were returned blank and 44 were returned incomplete. We included 144 participants that were at the examined units, 88 from non-COVID ICUs (32 from Medical and 56 from Surgical), and 56 from COVID ICUs (48 from COVID-1 and 8 from COVID-2). The majority of the respondents were intensive care nurses, comprising 25 of 56 in COVID ICUs and 67 of 88 in non-COVID ICUs. COVID ICUs had a notable proportion of respondents of additional support staff, which included nursing students and nurses from regular wards (24 of 56 participants) in comparison to non-COVID ICUs (9 of 88 participants). The least represented group among the respondents were physicians, with 7 of 56 in COVID ICUs and 9 of 88 in non-COVID ICUs. The overall mean alarm fatigue score was higher in COVID ICUs with a value of 56.00 (SD: 15.80) compared to non-COVID ICUs, which had a mean of 55.27 (SD: 13.76).. Statistical testing of the alarm fatigue score reveals no significant differences between COVID and non-COVID ICUs $t(105.41) = 0.2841$, $p = 0.3884$, Cohen's D = 0.05. Importantly, when considering only experienced ICU staff — comprising nurses and physicians — the alarm fatigue scores were significantly higher in COVID ICUs compared to non-COVID ICUs: $t(109) = 1.7332$, $P = .04295$, and Cohen's D = 0.363. Supplementary Figure 7 depicts the results of the questionnaire, subdivided by profession. Nurses and physicians reported a higher alarm fatigue score compared to support staff, which generally reported an overall low alarm fatigue score in both ICU types. Given the results of the hypothesis testing, we cannot conclusively validate Hypothesis 4, especially when considering all staff types; however, among ICU staff there is evidence suggesting higher alarm fatigue in COVID ICUs compared to non-COVID ICUs.

Table 4: Results of the hypothesis testing of H_4.

	non-COVID	COVID	p-value	Cohen's D
All Participants	55.27 (13.76)	56.00 (15.80)	0.3884	0.05
Clinicians (Nurses + Physicians)	59.00 (13.05)	64.28 (14.20)	0.04295	0.363

Insights from the exploratory data analysis

While the surgical and medical ICU were approximately fully occupied over the entire period, the COVID subunits were often only partly occupied depending on the patient load. Average bed occupancy was 97.26% and 92.27% in the surgical and medical ICU, and 88.79% and 82.75% in COVID-A and B. Supplementary Figure 1 displays the unit occupation over the entire period.

The use of the alarm pause function was significantly less frequent in COVID ICUs with a mean value of 5.08 (SD: 1.69), compared to 12.21 (SD: 2.21) alarm pauses per bed per day in non-COVID ICUs. The medical ICU recorded the highest proper pause to pause ratio of 0.08, followed by the surgical ICU and COVID-A both at 0.04. COVID-B had the lowest value at 0.03.

In COVID units, alarm floods per bed per day occurred on average 35% more frequently with mean values 2.60 (SD: 1.29) for COVID-A, and 2.73 (SD: 1.47) for COVID-B, compared to their non-COVID counterparts: Surgical units had a mean of 1.71 (SD: 1.33), and Medical units had a mean of 1.95 (SD: 0.92). Additionally, COVID units experienced on average 27% more concurrent alarm duration per bed per day, with a mean value of 5201.76 (SD: 1156), versus 4101.42 (SD: 965) in non-COVID ICUs.

Discussion

We compared the alarm situation of two provisional COVID ICUs with that of two non-COVID ICUs. Interviews with nurses and physicians who worked in COVID ICUs led us to hypothesize that COVID ICUs have a higher alarm load, a higher number of specific alarm signals and longer sounding alarms than non-COVID ICUs. We also hypothesized that staff of COVID ICUs is more alarm fatigued than staff of non-COVID ICUs.

There was a higher alarm load in provisional COVID ICUs

COVID ICUs had a significantly higher alarm load from red, yellow, and technical alarms. This higher alarm load led to an increased number of alarm floods and concurrent alarm duration, escalating the nurses' workload and potentially causing sensory overload [38]. While some differences are probably caused by COVID — such as the higher number of critical red alarms, possibly due to the high mortality and bad condition of the patients — we suspect that most differences in alarm load are due to the interaction of staff with the alarm system (e.g., not using the pause function when turning a patient from prone to supine position, not adjusting thresholds specifically to patients' conditions, not installing or not using COVID-patient-specific monitoring profiles or improperly applying sensors).

COVID patients had similar alarm signals as non-COVID patients.

We anticipated some devices to generate more alarms on COVID ICUs due to the unique physiological manifestations of COVID, such as ECG, NIBP and IBP devices, but this was not the case. Only red ECG alarms were notably more frequent than on non-COVID ICUs, other numbers of different clinical alarm signals were similar across all ICUs and seem to be a recurring theme, similar results were reported in previous studies (such as Poncette et al., [22] and Varisco et al., [12]).

In both ICU types, *ECG Lead off* was the most frequent technical alarm signal; Interestingly, it occurred more than twice as often in COVID ICUs. This also might be attributed to practices such as moving patients between prone and supine positioning, which necessitates the removal and subsequent reattachment of all sensors and electrodes each time.

The alarm duration was equally long in both ICU types

While our initial theory posited that alarm durations would be longer in COVID ICUs — owing to the time staff would need to put on protective clothing before entering a patient's room — our findings did not confirm this hypothesis. We found no significant differences in the overall median alarm durations between COVID and non-COVID ICUs, but only in a few medical devices.

Devices displaying visual information like ECG waveforms allow staff to rapidly assess alarm urgency. In contrast, devices that only show numerical values, such as those measuring temperature, or NIBP require more time for staff to interpret, potentially causing longer alarm durations.

We must also acknowledge the impact of other factors, for example, the floor layout of the unit, different unit policies [23], nurse-patient-ratio [39], or individual traits of the staff members [40].

Interestingly, red alarm signal alarm durations are consistently longer than yellow alarm signal alarm durations across all medical devices and in both ICU types. This may be due to healthcare providers promptly silencing yellow alarms without checking the patient [39], placing more emphasis on critical alarms, and only then checking the patient's condition.

In our exploratory analyses we found that the alarm pause function was used more frequently in non-COVID ICUs than in COVID ICUs. This might be explained by the fact that many nurses in COVID ICUs had only little critical care experience and therefore did not know that this function exists, or how it should be used; COVID ICU staff also might have entered the patients' rooms less often because they were required to put on protective gear, which is a time-consuming process.

ICU staff was more alarm fatigued in COVID ICUs

While overall alarm fatigue questionnaire scores were similar between both types of ICUs, the situation varied among different healthcare professionals. Nurses and physicians in COVID ICUs had significantly higher alarm fatigue scores, whereas support staff in both types of ICUs reported low alarm fatigue scores. Notably, a substantial portion of questionnaire participants in COVID ICUs consisted of support staff i.e. students, or nurses from normal wards (42.86%; 25 of 56, compared to 10.22%; 9 of 88 in non-COVID ICUs), reflecting the recruitment of nurses from other services and students with varying levels of critical care experience due to the exceptional circumstances. Unlike the experienced and well-rehearsed teams typically found in non-COVID ICUs, COVID ICU teams often incorporated diverse teams that lacked experience in critical care medicine, training, and familiarity with the monitoring system and alarm management. This inexperience extended to their training and understanding of monitoring systems and alarm management, mirroring findings from existing literature [41]. In some hospitals, the patient-to-nurse ratio was increased, which occasionally resulted in poorer quality of care [42]. However, it's important to note that greater fatigue was identified among those working in COVID beds, rather than directly associating alarm fatigue with COVID itself.

There seemed to have been challenges with the alarm system in the COVID units that might have impeded appropriate monitoring. Due to the absence of central monitors in the corridors, dispensary room, and physician's room, it was difficult for healthcare providers to localize alarms. Interviewees mentioned the protective gear worn in the COVID ICUs as an additional burden when responding to alarms. The gear can impede swift movement, thus slowing response times to alarms, which might intensify the stress and sensory overload associated with alarm fatigue. This finding aligns with the conclusions drawn by Akturan et al., (2022) that suggested that personal protective equipment could increase alarm fatigue.

Recommendations for ICU alarm systems in future pandemics

Due to intensive international traffic, the future risk for pandemics stays high in a globalized world [43] and COVID will be followed by a new pandemic at some point. Such pandemics will again likely require provisional ICUs to cope with rapid patient admissions. When preparing for such events, we recommend also preparing the alarm systems and their human operators. Even outside of pandemics, the shortage of specialist staff is increasing the willingness to deploy untrained personnel in certain functions in the medical field.

Alarm management aims to reduce the number of unnecessary alarms on the premise that a lower alarm rate decreases alarm fatigue among staff [22]. Provisional ICUs can benefit from effective alarm management, as do regular ICUs to date, where it helps significantly decrease the number of false alarms and the overall alarm burden [44–48].

Causes for unnecessary alarms from insufficient alarm management knowledge comprise: using default instead of customized alarm limits, rarely using the pause function during patient manipulation, or the unawareness that it exists, using insufficient consumables, or improper attachment of electrodes [49]. Previous studies [50] highlight a lack of knowledge about these functions among nurses, pointing to a pressing need for education on physiologic monitors [51].

Given the urgency with which new staff has to be onboarded, the training should be decentralized and easily accessible. To cater to these requirements, we recommend developing educational microcredentials like video tutorials that provide guidance on adjusting alarm limits on specific monitoring devices, implementing remote alarm termination, and transitioning from individual to smart alarm systems. To visualize and operationalize our approach to pandemic-preparedness in ICU alarm systems, we propose a bi-cyclical strategy, as illustrated in Figure 1. This strategy underscores the significance of continuous learning and adaptability in alarm management. Operating modern bedside monitors requires a blend of cognitive knowledge, psychomotor skills, critical thinking, and understanding of alarm systems [52]. Hence, this educational program should use the skillmap from Sowan et al., [50] as a foundation, expanding it to address the broader technical and practical aspects of monitor use. Modular content that teaches specific skills can be easily adapted to meet unique situational needs. For example, tutorials can be designed to explain how to respond to alarms while wearing protective gear or how to mobilize patients in prone position without causing alarm artifacts. These resources could be beneficial for ICU staff training, not only during pandemics but also in routine situations.

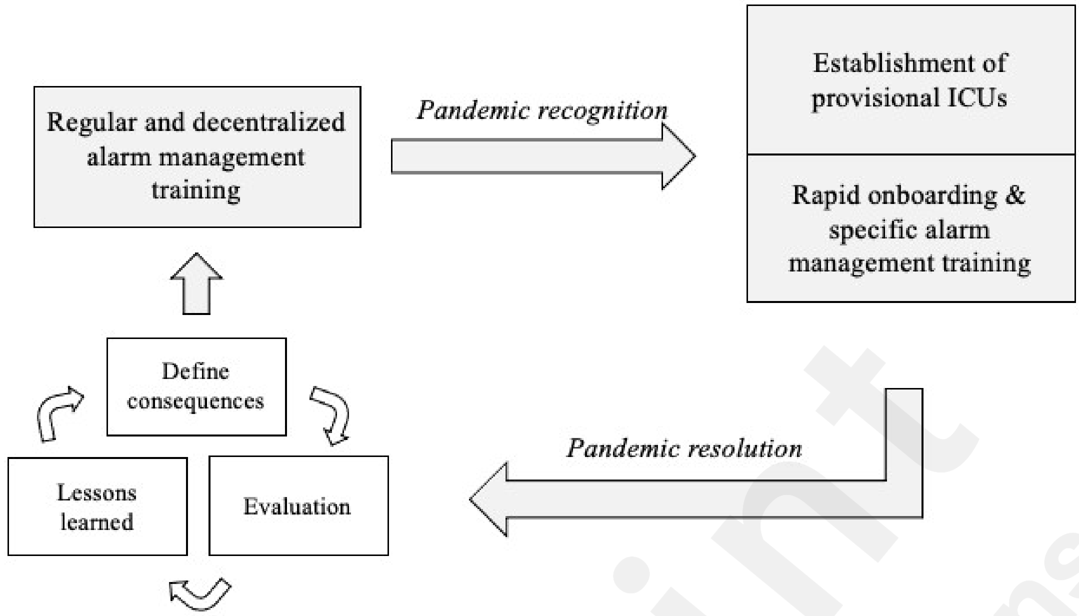

Fig. 1 Our proposed bi-cyclical strategy for preparing and refining ICU alarm systems during pandemics. During non-pandemic times, staff continuously undergo both regular and decentralized alarm management training to maintain proficiency and readiness. At the onset of a pandemic, the initial response involves rapidly onboarding ICU staff and a decentralized training of specific alarm management skills required for the clinical picture of the disease. In parallel, provisional ICUs are set up to address the surge of patients. After the pandemic resolution, the alarm system undergoes an evaluation cycle, encompassing the steps of evaluation, lessons learned, and defining consequences for refinements in alarm management strategies. This bi-cyclical strategy not only ensures adaptability to pressing health crises but also fortifies preparedness for future pandemics.

Limitations

ICUs function as complex sociotechnical systems, making it inherently challenging to compare them. All ICUs were equipped with similar technical equipment (e.g., mechanical ventilators and dialysis devices), but our comparison between ICUs was complicated by the variations in the specific devices used across units, leading to differences in alarm signals. Therefore, we only included alarms that occurred in all units. In addition, numerous devices in all ICUs are not connected to the central monitoring system, meaning that the alarms could not be recorded and evaluated. Alarms from mechanical ventilation had to be excluded from the ICU data due to a technical error, preventing us from testing our hypothesis about an increase in such alarms in COVID ICUs.

The monitoring systems in the two ICU types varied in their version numbers and settings, further affecting the comparability. In COVID ICUs, the *ECG lead off* alarm was set as a yellow alarm, while in non-COVID ICUs, it was set as a blue alarm. This discrepancy likely stemmed from a lack of awareness or understanding about the settings. We had to exclude this alarm from the yellow alarm load comparison due to this discrepancy.

Our metrics, calculated relative to the number of occupied beds per day, could potentially skew the results. When metrics are calculated this way, it might not accurately reflect the real-life impact of alarm floods on healthcare workers. In a larger ICU (like one with 26 beds), the same rate of alarms per bed would create a larger absolute number of alarms because there are more beds. As a result, the staff in that ICU would be exposed to a higher number of total alarms than the staff in a smaller ICU (with 10 beds), even though the rate of alarms per bed is the same. While the surgical and medical ICUs were approximately fully occupied over the entire period, the occupancy of the COVID subunits often varied, depending on the patient load. The average bed occupancy was 97.26% and 92.27% in the surgical and medical ICU, and 88.79% and 82.75% in COVID-A and B. The occupancy of all examined ICUs is reported in Supplementary Figure 2. The staff interviewed from the COVID ICUs was not the same team as from the non-COVID ICUs, which introduces a limitation related to team differences and experience levels.

Regarding the alarm durations, we could not investigate the impact of the isolation process by analyzing alarm response times between COVID ICUs and isolation rooms in non-COVID ICUs. Due to the provisional and time-limited character of the COVID-ICUs, the alarm fatigue in health care providers might not only reflect conditions in the COVID-ICUs but the individual exposure to alarm load during their former career. We cannot definitively determine whether the causality of the increased alarm load is due to the COVID condition itself or the different ICU settings.

Unfortunately, more detailed clinical data for every patient associated with the alarm data was not available at the time of the study. From a clinical perspective, the patient cohorts in the COVID ICUs and general ICUs were comparable in terms of the severity of their conditions. Additionally, fatigue among healthcare professionals working with COVID patients is inherently greater due to the overall stress and workload of managing COVID cases, which cannot be attributed solely to alarm load. We suggest propensity score-matching or similar statistical techniques as areas for future research. Similarly, determining isolation rooms from non-COVID ICUs is recommended for further studies to gain a deeper understanding of the isolation process's impact on alarm response times.

Conclusion

In our study, COVID ICUs registered significantly more alarms than non-COVID ICUs. The higher number of alarms led to a higher level of alarm fatigue among the ICU-experienced personnel. We believe this was caused by the high proportion of untrained staff who were deployed to the temporary intensive care units during the pandemic, and the provisional setting. The absence of central monitors in individual rooms and corridors further compounded these challenges, making it difficult for healthcare providers to swiftly identify and respond to alarms. However, it is important to note that our findings are limited by the study design and specific circumstances during the pandemic, which might affect the strength of our conclusions. Further studies are warranted to better understand the broader implications of alarm management in different ICU settings

To mitigate alarm overload in provisional ICUs during future pandemics, we recommend creating skill-oriented video tutorials on alarm management and monitor use. These should provide easily accessible training for new staff, who may be rapidly recruited and could have limited or no prior ICU experience. This educational material could equip them with the necessary knowledge to effectively navigate the ICU alarm system.

Ethics approval

The IRB approval for this study was granted by the Ethics Commission of the Charité – Universitätsmedizin Berlin (EA4/218/20).

DATA AVAILABILITY

All data generated or analyzed in the course of this research study are publicly available and can be accessed via the Zenodo open data repository, under the designated DOI: 10.5281/zenodo.10418594.

CODE AVAILABILITY

The code of this study is not openly available but is available from the authors upon reasonable request.

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Author contributions

ASP and MW had the idea for the study. The study was conceived by NF, MW, ASP, and FB. NF, and MW analyzed the data and conducted the interviews, supported by ASP. NF wrote the manuscript, supported by ASP, CH, SAW and MW. FB supervised all parts of the study. All authors critically reviewed and approved the manuscript. The article was extracted from the M.Sc. thesis of NF.

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Conflict of interest

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Appendix

Supplementary Material - Tables

Supplementary Material - Figures

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Abbreviations

ABP Arterial blood pressure

ApBpD Alarm per bed per day

ARDS Acute respiratory distress syndrome

COVID Coronavirus disease 2019

ECG Electrocardiogram

ECMO Extracorporeal membrane oxygenation

GLM Generalized linear model

HF Heart frequency

IBP Invasive blood pressure

ICU Intensive care unit

LOS Length of stay

NIBP Non invasive blood pressure

PACU Post anesthesia care unit

SARS-CoV-2 Severe acute respiratory syndrome coronavirus 2

SD Standard deviation

SpO2 Oxygen saturation

Supplementary Files

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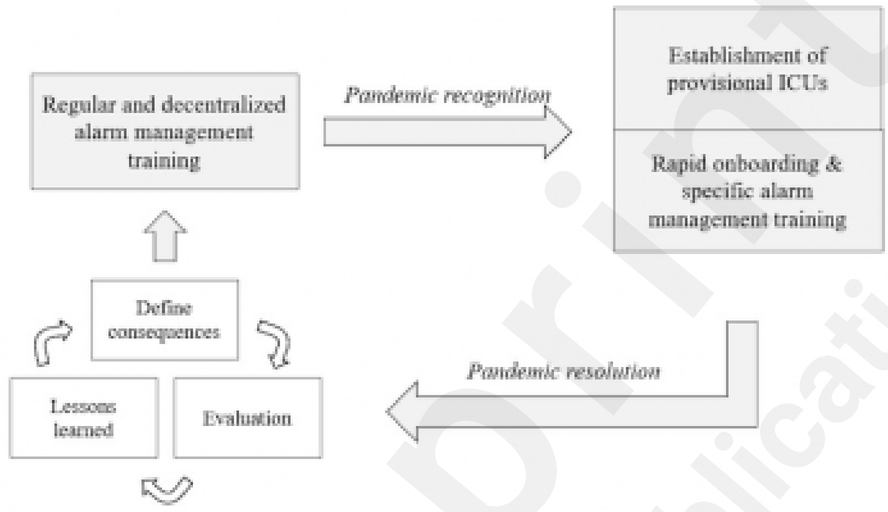
Figures

Fig. 1 Our proposed bi-cyclical strategy for preparing and refining ICU alarm systems during pandemics. During non-pandemic times, staff continuously undergo both regular and decentralized alarm management training to maintain proficiency and readiness. At the onset of a pandemic, the initial response involves rapidly onboarding ICU staff and a decentralized training of specific alarm management skills required for the clinical picture of the disease. In parallel, provisional ICUs are set up to address the surge of patients. After the pandemic resolution, the alarm system undergoes an evaluation cycle, encompassing the steps of evaluation, lessons learned, and defining consequences for refinements in alarm management strategies. This bi-cyclical strategy not only ensures adaptability to pressing health crises but also fortifies preparedness for future pandemics.



Multimedia Appendixes

Violin plots of threshold changes and profile changes per bed per day from all ICUs and ICUs. a Profile changes per bed per day b Threshold changes per bed per day. In the medical ICU, profiles and thresholds were adjusted the most often. Results from COVID ICUs are colored in olive, non-COVID ICUs in cyan. All distributions are heavily skewed to the right; therefore, values are reported in median.
URL: http://asset.jmir.pub/assets/eff23806d5faa5524a860ade3f0ffcce.png

Results of the alarm fatigue questionnaire subdivided by ICU type and staff profession. a Completed questionnaires. b Self-reported alarm fatigue. The values displayed are the average reported alarm fatigue c Results of the alarm fatigue score. The displayed values are the average alarm fatigue score. Nurses are displayed in orange, physicians in yellow, and support staff in blue. Nurses and physicians in COVID ICUs had a higher alarm fatigue score but a lower self-reported alarm fatigue.
URL: http://asset.jmir.pub/assets/075cc800844a4a2c4442472003a9bdbb.png

Supplementary material (Figures and Tables).
URL: http://asset.jmir.pub/assets/88e06230971f96559b4ebd78add662a4.docx

Unit occupancy of all examined ICUs and subunits. Non-COVID ICUs had a higher unit occupation than COVID ICUs.
URL: http://asset.jmir.pub/assets/9aa6d7a68e105a65b1b1099deae64f67.png

Boxplots of median alarm durations of clinical alarm durations splitted by medical device and alarm color. a Alarm durations caused by red alarms. b Alarm durations caused by yellow alarms. Alarm durations from red alarms are similar across Medical and COVID-A and B, while they differ in Surgical. All alarm durations from red alarms are longer than alarm durations from yellow alarms from the corresponding medical devices.
URL: http://asset.jmir.pub/assets/c8495acc2c61631a6902c8c866dcff71.png

Fig. 1 Average clinical alarm load subdivided by alarm color (red and yellow alarms) and medical device of all ICUs and ICUs. Bars represent mean (SD). a Alarms caused by temperature device b Alarms caused by Non-Invasive Blood Pressure device (NIBP) c Alarms from ECG device d alarms from SpO2 device e Alarms from IBP device. The average number of alarms from yellow alarms differs between COVID and non-COVID ICUs. While the average number of red alarms is similar within the ICU types, it differs between them.
URL: http://asset.jmir.pub/assets/b0c7d02cf9736a235d7d336003050112.png

Related publication(s) - for reviewers eyes onlies

Extended abstract with preliminary / related results.
URL: http://asset.jmir.pub/assets/6c763bd658aa1f8faa8e9200aab487d2.pdf