DOI: 10.61782/fa.2025.0416

FORUM ACUSTICUM EURONOISE 2025

From Research to Practice: A Collaborative Approach to Tackling Alarm Fatigue in ICUs

Idil Bostan[1,2*] **René van Egmond**[1] **Diederik Gommers**[2] **Elif Özcan**[1,2]

[1] Faculty of Industrial Design Engineering, Delft University of Technology, the Netherlands

[2] Adult Intensive Care Department, Erasmus Medical Center, Rotterdam, the Netherlands

ABSTRACT

Alarm fatigue describes the desensitization, reduced alarm response, and negative emotions experienced by ICU nurses due to the excessive number of alarms generated by patient monitoring systems. Although alarms are intended to prompt action, high numbers of non-actionable alarms undermine nurse responsiveness and pose risks to patient safety. This study builds on previous research of the authors exploring the characteristics of ICU nurses as users of the system, system features of patient monitors, and alarm load across different ICU types. In this study, we synthesized previous findings into research insights. We conducted a multi-disciplinary workshop using a sound-driven design approach with diverse stakeholders, including ICU nurses, doctors, industry experts, designers, and researchers. Previous research insights were used to stimulate discussion and develop design directions aimed at mitigating alarm fatigue and supporting ICU nurse needs. The outcomes of this workshop produced actionable solution bundles that consolidate previous insights and introduce novel approaches, offering a holistic and collaborative perspective to mitigating alarm fatigue.

Keywords:. *System design, alarm fatigue, patient monitoring systems, sound-driven design, multidisciplinary collaboration*

[*] ***Corresponding author***: *i.bostan@tudelft.nl*

1. INTRODUCTION

Alarm fatigue is the condition in which intensive care unit (ICU) nurses can be desensitized to frequent alarms generated by patient monitoring devices, often leading to frustration, stress, annoyance, and reduced responsiveness to alarms [1-4]. Despite decades of attention from both academia and the industry, efforts to mitigate alarm fatigue have only led to improvements in isolated cases, with large-scale solutions still remaining out of reach [5-6]. Past efforts to reduce alarm fatigue in ICUs have initially focused on improving alarm design and reducing non-actionable alarms [7-11]. Enhancing alarm sounds to be more informative has shown potential to lessen nurses' cognitive load, but this approach alone is limited due to the sheer volume of alarms. Reducing alarm frequency through advanced algorithms and machine learning can help prioritize actionable alerts, while networked systems integrating data from multiple devices offer fewer, more relevant alarms [12-17]. Nurse-focused interventions, such as investigating nurse-centered design directions, training on alarm settings and improved equipment use, aim to improve alarm management practices [4], [19-24]. Emphasizing collective alarm culture and awareness has led to local improvements, though sustained changes remain challenging [6], [20], [21], [22].

1.1. Bridging Perspectives for Collaborative Solutions

In the ICU, nurses listen to alarm sounds to initiate sound-induced actions [26]. However, a polluted sound environment obscures the critical alarm sounds, challenging the nurses' ability to perceive and comprehend the relevant sound events [15]. In settings which sound plays a central role, sound-driven design emerges as a required critical approach [27]. The sound-driven design model highlights the varied approaches stakeholders take towards sound, emphasizing the value of including individuals from varied backgrounds in collaborative efforts which sound plays a central role [27]. This shows that optimizing patient monitoring devices requires more than just *engineering* of systems, services or products; it calls for a multidisciplinary perspective for the designed outcome to survive its ecological relevance. Evidence-based design can help bridge this gap by providing scientific insights and evidence as input for a multidisciplinary, participatory, sound-driven design process [28].

Eradicating alarm fatigue requires a deep understanding of the complexity of the problem, and the roles and needs of each stakeholder involved in the issue. Our aim in this study is to generate consolidated design directions to mitigate alarm fatigue. To this end, we brought together experts from various disciplines to collaboratively tackle the challenge. We organized a multidisciplinary design workshop to co-create actionable design directions and recommendations to address the identified challenges and support ICU nurse needs. The input for the workshop consisted of previous work of the authors investigating alarm fatigue. Main findings from previous work were summarized into research insights and were used as input to stimulate discussion in the workshop. We promoted interdisciplinary collaboration by bringing together ICU nurses, doctors, industry specialists in ICU technologies, designers, and researchers with the goal of generating user-centered solutions.

2. METHODS

2.1 Participants

Fourteen participants (eight males) took part in the workshop. Participants consisted of three of the authors (IB and EÖ as design researchers, DG as intensivist), four ICU nurses from Erasmus MC, and seven industry experts in health technology consisting of engineers, designers, and usability experts. The participants formed three groups to work on the three distinct themes, with each group consisting of at least one ICU nurse, one design researcher, and one industry expert. Participants were informed about the study's purpose, procedures, and their right to withdraw at any time without penalty. Participants provided informed consent prior to the workshop.

2.2 Workshop Input

The issue of alarm fatigue and strategies to mitigate it were explored with a user-centered approach, scrutinizing the interaction between ICU nurses and patient monitoring systems within the ICU context. Following this triadic relationship, we developed three core themes: *user*, *system*, and *context*. Insights from the authors' prior research was used as workshop input. Through three previous studies, we explored user-related factors focusing on ICU nurses [22], system attributes of patient monitoring systems [15], and the broader alarm loads within different ICU environments (Bostan et al. *submitted*). Each of the core themes was explored by one group. We presented the participants with previous research findings related to these three themes and prompted ideation and brainstorming in groups. Although the workshop took place within the context of health technologies industry, the exploration of solutions was not confined to technology-driven ideas. Instead, we encouraged a holistic approach to address the problem of comprehensively.

The theme *user* was based on previous work categorizing ICU nurses into user profiles according to their individual characteristics such as personality traits, musicality, and sensory sensitivity [22]. This study revealed the diversity in nurses as users of patient monitoring systems. Group 1 worked on the insights from this study, scrutinizing the individual differences among nurses and their influence on system use. The theme *system* was based on previous work investigating the duration characteristics of alarms [15]. This study showed that delaying alarms by 10 seconds can eliminate more than half of the alarms. Factors related to alarm priority levels and vital parameters were identified as points to be considered in determining length of delay. Group 2 worked on these insights related to the underlying technology of patient monitoring systems, exploring potential changes to the system architecture. Finally, the theme *context* was based on a data analysis conducted on the alarm loads of three types of ICUs at Erasmus MC: Adult IC, Pediatric IC (PICU), and Neonatal IC (NICU) (Bostan et al., *submitted*). This study revealed the factors pertaining to patient physiology, unit cultures, standard routine practices, unit layout, and technological limitations as contributors to alarm load. These findings were presented to Group 3 to foster a comparative approach in identifying the context-specific needs for distinct ICU types.

2.3 Workshop Procedure

The workshop lasted one workday and was hosted in a co-creation space at Philips Design on High-Tech Campus in Eindhoven. The workshop was divided into four phases based on the 'Co-Creation Process', a Philips Experience Design implementation of design thinking: **Discover**, **Frame**, **Ideate**, and **Build** [29, 30]. The **Discover** phase was the scientific introduction to the topic for the evidence-based design practice. In this phase, one of the authors (IB) presented previous work to all participants and detailed the results in a lecture of 45 minutes.

For the phases of **Frame**, **Ideate**, and **Build**, pre-formatted posters were prepared to be populated during the workshop with ample white space. Participants used materials such as markers, post-its, and stickers, and move them around freely in response to the instructions and questions presented on the posters. After every phase, each group presented their outcomes to all participants for five minutes, and short discussions took place among all participants. Sound recordings were collected during these presentations.

The **Frame** phase consisted of each group defining the problems with the current situation and identifying what would constitute an improved situation. In the **Ideate** phase, participants explored the solution space creatively and transformed insights into ideas. This phase included prompting questions to stimulate ideation and brainstorming, impact prioritization of the generated solution ideas, and a risk/benefit analysis on the solutions deemed the most impactful. Finally, the **Build** phase consisted of further refining the ideas to make them more tangible. Each group picked several of the most impactful ideas and discussed the key enablers to build this idea and promote its use in healthcare. Enablers could be solutions, research methodologies, collaborations, capabilities, materials, and know-how.

2.4 Data Analysis

A Miro board was created replicating the posters of each phase for every group. Sound recordings collected during group presentations were transcribed into text. Further explanations, remarks, and comments made during the presentations were added on top of the posters. Data analysis was made on these enhanced digital posters. Afterwards, thematic analysis was conducted based on the workshop output [31]. The recurring patterns across the groups were identified and were categorized clustered.

3. RESULTS

Each group developed several design directions to mitigate alarm fatigue. This section presents the outcomes of the three groups focusing on insights related to the user, to the system, and to the context in respective order. Subsections first outline the identified friction points within each theme, afterwards detail the solution space generated by each group. Finally, common themes across groups emerging from thematic analysis are presented as a solution bundle.

3.1 Challenges Faced by the Users – Group 1

In considering ICU nurses as the users of patient monitoring systems, it was expressed that current systems do not accommodate for diversity among the users. Instead of offering the same system features and settings to each user, the patient monitoring systems should take user variability into account and offer customization opportunities to different types of users. A flexible system addressing the diversity in the users' capabilities, needs, and preferences is needed. In addition to user profiles, this flexibility should extend to address other varying factors such as nurse level of experience, unit cultures, and patient populations. An outcome for all users was the importance of providing a high degree of information while minimizing irrelevant noise. Overall, patient monitoring systems designed with the user needs in mind were deemed essential.

The solution strategies proposed in this theme consisted of a solution bundle. A flexible system tailored to the needs of different user profiles was seen essential. Participants stressed the need for gradual, incremental change, recognizing that the fast-paced changes do not align well with the structured, protocol-driven environment of healthcare. A slow and steady implementation allows healthcare providers time to appreciate the value of new solutions, leading to higher acceptance rates.

First step of the bundle related to creating awareness. Although nurses suffer from the number of alarms, they may not always be aware of their own role in the situation. Nurses directly influence the number of alarms by altering alarm limits and disabling parameters. Creating alarm dashboards to display descriptive statistics of the unit's alarm load and simulating how individual behavior affects alarm frequency can create awareness and accountability.

Second step related to the system settings and the alarming algorithm. Monitoring systems should be sensitive to user profiles and patient profiles, and adapt features appropriately (e.g., heart rate alarms may be crucial and prioritized for cardiac units, while not as relevant in other units). The algorithm should detect trends in patient vitals and converge information from several vital parameters to generate trend alarms and multi-parameter alarms. This prevents erroneous alarming based on single value alarms.

Third step related to the training and guidance on effective use of the system. Supportive peer models, such as buddy system in the unit or 'alarm champion' in the department, were suggested to support new nurses toward optimal use of the system. The system should also make suggestions and offer guidance on-device. The fourth step of the bundle related to the actual use of the system. Once more, the significance of trend alarms and multi-parameter alarms were highlighted, along with a profile-based system to address various nurse needs. Finally, the fifth step constituted of a feedback loop through learning. The impact of implemented changes should be constantly monitored and analyzed to inform any further steps.

3.2 Limitations of Current Systems – Group 2

Discussions on alarm durations and the potential for implementing alarm delays highlighted key concepts pertaining to multi-parameter alarms, trend alarms, and context-aware alarming systems that consider patient history. Improved blood oxygenation (SpO_2) sensors was deemed a crucial area for development. Differences in alarm duration between various units were linked primarily to patient populations and unit protocols. These differences emphasize the need for system designs that account for context-specific characteristics to ensure that alarm delays are effective.

Three main solution packages emerged. The first focused on developing alarm dashboards that display alarm loads alongside descriptive statistics. Such a logging and monitoring tool was deemed essential for identifying problem areas and brainstorming solutions. These dashboards could reveal how changes in behavior (e.g., different way of customizing alarm limits) might impact the number of alarms, helping to raise awareness. Collaboration between nurses and nurse managers would be crucial in identifying areas for improvement, directly supporting training and guidance for less experienced nurses.

The second solution direction centered on implementing alarm delays. It was considered critical that delay times be tailored based on individual patient measurements and history. Key factors included patient age (adult vs. pediatric), the magnitude of vital parameter deviations, and repetitive patterns. These "smart" rules could be established thorough data analysis and simulations. A notable outcome was the potential for collaboration with other industries, such as financial technologies.

The final solution direction focused on the need for smarter and more reliable sensors. As faulty sensors account for a significant portion of false alarms, developing sensors capable of detecting when they are producing artifacts can automatically suppress alarms. Examples included sweat detectors for electrocardiogram (ECG) sensors and motion detectors for ECG, respiration, and SpO_2 sensors. The development of affordable wireless sensors was highlighted as a strategy to reduce sensor-related artifacts and alarms.

3.3 Contextual Concerns – Group 3

Factors related to patient populations and unit cultures revealed that while some alarm-related issues and solutions are context-specific, others are applicable across all types of ICUs. For example, in the NICU at Erasmus MC, strict protocols on alarm limits and limited nurse autonomy in adjusting settings resulted in significantly more alarms compared to the PICU and Adult ICUs. Additionally, the high number of alarms in the NICU was partly due to the difficulty in securing SpO_2 sensors on neonates, whose skin is more sensitive to pressure and chemicals. Given these challenges, the importance of context-aware patient monitoring systems that can adapt alarming algorithms was identified as a crucial solution. The group identified improved SpO_2 sensors as the solution with the highest potential impact on reducing the number of alarms.

Across all units, the current practice of having all ICU medical equipment (e.g., ventilators, beds, infusion pumps) generate audible alarms—even for simple interactions like confirmation beeps—contributes to sound pollution, negatively affecting both patients and staff. To address this, participants suggested a shift to multimodal alerts that leverage haptics, lights, colors, and sound cancellation. For example, some signals could be directed solely at healthcare staff through methods like light blinking or alarms based on nurse location, thereby reducing sound pollution and improving the ICU soundscape.

The first solution strategy focused on enhancing SpO_2 sensors and improving their fixation, particularly for younger patients with sensitive skin. This approach entails further research at the intersection of medical and engineering disciplines, with a strong emphasis on material science. Collaboration between manufacturer and medical centers was deemed crucial, as this would facilitate rapid validation cycles for the developed solutions.

The second strategy involves reevaluating the necessity of audible signals for alerts and confirmations in ICU medical

Solution Category	Solution Description	Solution opportunities
Patient Monitoring System Design	Enhancing system functionalities, incorporating context-awareness, and improving on-device alarm management features.	1) **Flexible system for user needs:** Transition from one-size-fits-all system to tailored user profiles – address nurse profiles, levels of experience, unit types. 2) **Multiparameter alarms:** Make alarming decisions based on the synthesis of multiple parameters instead of conventional single parameter alarms. 3) **Trend alarms:** Observe the evolution of vital parameters and generate alarms based on trends in the data and repetition of alarming conditions. 4) **Context awareness:** Adapt system behavior to contextual factors such as patient profiles, time of day, nurse proximity, nursing procedures. 5) **Alarm advisor:** Provide on-device advice and guidance on alarm settings based on patient data, nurse preferences, and expected alarm load. 6) **Multimodal alarms:** Not all information needs to be communicated through sounds. Explore modalities like lights, colors, haptics to reduce unwanted sounds.
Supportive Technologies	Innovations in sensor technology and integration of alarm dashboards.	1) **Alarm dashboard:** Log, monitor and visualize the alarm load in the unit to identify problems. Encourage discussing solutions among nurses and nurse managers based on the observations. 2) **Improved sensors:** Large number of non-actionable alarms and artifacts can be eliminated by improving the sensors and how they are attached to the patients.
Building Awareness and Expertise	Promoting interdisciplinary collaborations, increasing awareness, and providing targeted training for nurses.	1) **Multidisciplinary and holistic approach:** Multifaceted challenge requires collaborations between engineers, healthcare professionals, researchers, UX design, data analysts, psychophysics experts 2) **Awareness and Training:** Create awareness in nurses towards the problem and empower and train to realize their behavior can contribute to the solution. Create peer support systems. 3) **Learning:** Implement incremental changes, monitor change continuously, learn, and adapt quickly through rapid validation cycles

devices. While current protocols often mandate these audible signals, the consensus was that this approach is outdated and in need of revision. Multidisciplinary teams should assess which system features truly require audible signals, balancing risks and benefits within the soundscape. Features deemed unnecessary for audible alerts should leverage other modalities, such as visual cues or haptic feedback. Simulation rooms and labs could support this research, enabling quick iteration and validation cycles.

The third solution builds on the second by addressing the potential of existing wearable devices, such as pagers. Extending the functionality of these pagers to include haptic feedback can increase the informativeness of pagers, reducing the need for certain alerts such as technical alarms. The development of such pagers should consider the body part to which the device will be attached, with attention to hygiene and contamination concerns.

The fourth solution focused on extending the functionalities of the acknowledge button, which is currently used to mute alarms for two minutes. Participants agreed that this duration is often too short. Instead, nurses should have the option to extend the mute duration in real-time. The most relevant use-case was identified as the nursing and grooming activities, such as drawing blood or cleaning the patient, where the pressure on sensors generates many false alarms. A proposed solution was to introduce a 'nursing mode' in patient monitoring systems, similar to the feature found in dialysis machines. This mode would suppress alarms generated during standard procedures, potentially by shifting them to visual-only alerts. Development of this functionality entails determining which alarms are typically generated during such standard procedures.

Last solution consisted of an overall context-aware system design. Factors such as time of day, nurse location, patient history, presence of family, and nursing procedures should be considered while designing the alarming algorithm. System features such as brightness, information display, and sound levels can be altered based on such factors, such as lower sound levels during night shifts. The system can automatically adjust such settings, with the option for nurses to customize settings as needed.

3.4 Comprehensive Solutions for Alarm Fatigue

Three workshop groups approached the issue from the three perspectives of user, system, and context. While the approaches were distinct, some solutions strategies were found to be recurring across the groups and formed patterns. Outcomes of thematic analysis summarizing synthesizing the solutions strategies are presented in the Table 1, encompassing enhancements in patient monitoring system design, supportive technologies, and approach to collaborations, development, and training.

4. DISCUSSION

Through a multidisciplinary co-creation workshop using the sound-driven design approach, we identified key solution opportunities for the issue of alarm fatigue ICUs. Results indicate that the solution space is broad, requiring enhancements across multiple aspects of patient monitoring. These include enhancements on the system design of patient monitoring systems, development of supportive technologies, and building awareness and expertise at multiple levels of healthcare infrastructure.

Identified solution strategies align with exiting literature and consolidate previous insights. Previous studies have highlighted the influence of nurses' individual characteristics on their alarm management and patient monitoring practices [1], [23], supporting the need for flexible systems tailored to varied user needs [15], [32]. Similarly, the integration of multiparameter alarms that provide system-level insights, rather than relying on conventional individual-device alarms, has been proposed as a solution [17], [33]. The concept of trend alarms, which track the evolution and recurrence of alarming medical conditions, has also been explored as a viable strategy [18], [34]. Furthermore, the detrimental effects of standard alarm sounds have been well-documented [32], [35], inspiring investigations into the effectiveness of multimodal alarms [36], [37]. Our findings consolidate these solutions into a practical package aimed at enhancing patient monitoring systems, further expanding the approach by incorporating novel elements such as context-awareness.

The second set of opportunities focused on supportive technologies to aid alarm reduction. Faulty sensors and poor fixation on the patient's skin are major contributors to false alarms, making sensor enhancement a straightforward target for reducing alarm frequency [32]. Logging, monitoring, and visually displaying alarm data to nurses and nurse managers can pinpoint issues and facilitate quick solutions. These dashboards, grounded in thorough data analysis of alarm load in the unit, would reveal the patterns that often lead to excessive number of alarms, and highlight the areas for improvement. Recent studies on ICU alarm load demonstrate various effective strategies that could guide such efforts [15], [38].

The final line of opportunities focused on enhancing awareness and expertise. Studies have shown that nurse training can significantly reduce the number of alarms and mitigate the effects of alarm fatigue [19], [20], [39]. In this study, the potential for ongoing education in best practices for alarm management was explored, emphasizing peer support models and empowering nurses to play an active role in solutions. Iterative and incremental change was deemed essential for continuous improvement. Lastly, adopting a multidisciplinary and holistic approach was recognized as the foundational strategy for all future initiatives [17], [32], [40].

In this study, we adopted a multidisciplinary approach to gather perspectives and expertise from stakeholders across various fields, an effective strategy in sound-driven design processes [27]. The value of this collaboration became clear during the workshop, as informal conversations showed how enthusiastic participants were to be involved in such an effort. The diverse perspectives of ICU stakeholders provided unique insights crucial for enhancing the overall situation and sparked inspiring discussions. This study highlights the crucial role of multidisciplinary collaboration in tackling complex challenges like alarm fatigue. Involving diverse stakeholders is critical in designing solutions which are practical, impactful, and widely supported.

4.1.1 Limitations

This study's findings are context-specific and may not generalize to ICUs with different patient populations, technologies, or cultural practices. For example, requirements in cardiac or surgical ICUs may differ from those of regular adult ICUs. The design directions proposed in this study are conceptual and require validation through empirical testing in real ICU environments. Additionally, some proposed solutions, particularly those involving changes to medical device regulations or hospital policies, may face significant implementation challenges beyond the scope of this study. These highlight the need for further interdisciplinary collaboration and policy support. Lastly, the patient perspective was not represented in this workshop. Co-creation sessions in the future can expand the solution space by including ICU patient participants.

6. REFERENCES

[1] S. Deb and D. Claudio, "Alarm fatigue and its influence on staff performance," *IIE Trans Healthc Syst Eng*, vol. 5, no. 3, pp. 183–196, 2015.

[2] L. Honan, M. Funk, M. Maynard, D. Fahs, T. Clark, and Y. David, "Nurses' Perspectives on Clinical Alarms," *American Journal of Critical Care*, vol. 24, no. 5, pp. 387–395, 2015.

[3] K. Lewandowska, M. Weisbrot, A. Cieloszyk, W. Mędrzycka-Dąbrowska, S. Krupa, and D. Ozga, "Impact of alarm fatigue on the work of nurses in an intensive care environment—a systematic review," *Int J Environ Res Public Health*, vol. 17, no. 22, 2020.

[4] B. Salameh, J. Abdallah, S. A. Alkubati, and M. ALBashtawy, "Alarm fatigue and perceived stress among critical care nurses in the intensive care units: Palestinian perspectives," *BMC Nurs*, vol. 23, no. 1, Dec. 2024.

[5] M. Dehghan, S. Mokhtarabadi, E. Rashidi, E. Rahiminejad, and N. Asadi, "Correlation between professional quality of life and alarm fatigue symptoms among intensive care unit nurses," *Health Sci Rep*, vol. 6, no. 10, Oct. 2023.

[6] K. Albanowski, K. J. Burdick, C. P. Bonafide, R. Kleinpell, and J. J. Schlesinger, "Ten Years Later, Alarm Fatigue Is Still a Safety Concern," *AACN Adv Crit Care*, vol. 34, no. 3, pp. 189–197, Sep. 2023.

[7] S. Sreetharan, J. J. Schlesinger, and M. Schutz, "Decaying amplitude envelopes reduce alarm annoyance: Exploring new approaches to improving auditory interfaces," *Appl Ergon*, vol. 96, no. August 2020, p. 103432, 2021.

[8] L. Foley, C. J. Anderson, and M. Schutz, "Re-Sounding Alarms: Designing Ergonomic Auditory Interfaces by Embracing Musical Insights," *Healthcare*, vol. 8, no. 4, p. 389, 2020.

[9] F. Pereira, R. Marques, J. Vieira, and G. Campos, "Reducing Annoyance of Healthcare Soundscapes with Harmonious Alarms," in *Perspectives on Music, Sound and Musicology*, Springer International Publishing, 2021, pp. 251–272.

[10] J. Edworthy *et al.*, "The Recognizability and Localizability of Auditory Alarms: Setting Global Medical Device Standards," *Hum Factors*, vol. 59, no. 7, pp. 1108–1127, 2017.

[11] R. R. McNeer, D. B. Horn, C. L. Bennett, J. R. Edworthy, and R. Dudaryk, "Auditory icon alarms are more accurately and quickly identified than current standard melodic alarms in a simulated clinical setting," *Anesthesiology*, vol. 129, no. 1, 2018.

[12] H. Piri, W. T. Huh, S. M. Shechter, and D. Hudson, "Individualized Dynamic Patient Monitoring Under Alarm Fatigue," *Oper Res*, vol. 70, no. 5, 2022.

[13] J. Chromik *et al.*, "Computational approaches to alleviate alarm fatigue in intensive care medicine: A systematic literature review," Aug. 16, 2022, *Frontiers Media S.A.* doi: 10.3389/fdgth.2022.843747.

[14] C. O. Fernandes, S. Miles, C. J. P. De Lucena, and D. Cowan, "Artificial intelligence technologies for coping with alarm fatigue in hospital environments because of sensory overload: Algorithm development and validation," *J Med Internet Res*, vol. 21, no. 11, 2019.

[15] I. Bostan, R. van Egmond, D. Gommers, and E. Özcan, "ICU alarm management reimagined: Sound-driven design and the role of acoustic biotope," in *Design Research Society*, Jun. 2024.

[16] J. Welch, "An Evidence-Based Approach to Reduce Nuisance Alarms and Alarm Fatigue," *Biomed Instrum Technol*, vol. 45, no. SPRING, 2011.

[17] E. Koomen *et al.*, "Reducing medical device alarms by an order of magnitude : A human factors approach," *Anaesth Intensive Care*, 2021.

[18] S. A. Paul, S. M. Treacy, and A. K. Carroll, "Designing the alarm management user experience for patient monitoring," *Conference on Human Factors in Computing Systems - Proc.*, 2016.

[19] J. Bi *et al.*, "Effects of monitor alarm management training on nurses' alarm fatigue: A randomised controlled trial," *J Clin Nurs*, vol. 29, no. 21–22. 2020.

[20] A. K. Sowan, T. M. Gomez, A. F. Tarriela, C. C. Reed, and B. M. Paper, "Changes in Default Alarm Settings and Standard In-Service are Insufficient to Improve Alarm Fatigue in an Intensive Care Unit: A Pilot Project," *JMIR Hum Factors*, vol. 3, no. 1, 2016.

[21] M. Cvach, K. J. Rothwell, A. M. Cullen, M. G. Nayden, N. Cvach, and J. C. Pham, "Effect of altering alarm settings: A randomized controlled study," *Biomed Instrum Technol*, vol. 49, no. 3, 2015.

[22] I. Bostan, R. van Egmond, D. Gommers, and E. Özcan, "Customizing ICU patient monitoring: a user-centered approach informed by nurse profiles," *Cognition, Technology and Work*, 2024.

[23] H. Ruppel, M. Funk, R. Whittemore, S. F. Wung, C. P. Bonafide, and H. Powell Kennedy, "Critical care nurses' clinical reasoning about physiologic monitor alarm customisation: An interpretive descriptive study," *J Clin Nurs*, vol. 28, no. 15–16, 2019.

[24] S. F. Wung and M. R. Schatz, "Critical Care Nurses' Cognitive Ergonomics Related to Medical Device Alarms," *Crit Care Nurs Clin North Am*, vol. 30, no. 2, 2018.

[25] L. Yue, V. Plummer, and W. Cross, "The effectiveness of nurse education and training for clinical alarm response and management: a systematic review," *J Clin Nurs*, vol. 26, no. 17–18, 2017.

[26] E. Özcan, C. L. H. Broekmeulen, Z. A. Luck, M. van Velzen, P. J. Stappers, and J. R. Edworthy, "Acoustic Biotopes, Listeners and Sound-Induced Action: A Case Study of Operating Rooms," *Int J Environ Res Public Health*, vol. 19, no. 24, Dec. 2022/

[27] S. D. Monache, N. Misdariis, and E. Özcan, "Semantic models of sound-driven design: Designing with listening in mind," *Des Stud*, vol. 83, Nov. 2022.

[28] H. C. Morales Ornelas, M. Kleinsmann, and G. Kortuem, "Exploring Health and Design Evidence Practices in EHealth Systems' Development," in *International Conference on Engineering Design*, Bordeaux, Jul. 2023, pp. 1795–1804.

[29] Philips. (2022, November 9). *Program management and co-creation*. Medium. https://medium.com/philips-experience-design-blog/program-management-and-co-cre- ation-3530751f76bc

[30] *Philips Experience Design Approach*. Philips. (2021, November 12). https://www.philips.com/a-w/about/innovation/experience-design/our-approach.html

[31] V. Braun and V. Clarke, "One size fits all? What counts as quality practice in (reflexive) thematic analysis?," *Qual Res Psychol*, vol. 18, no. 3, 2021.

[32] E. Özcan, D. Birdja, and J. R. Edworthy, "A holistic and collaborative approach to audible alarm design," *Biomed Instrum Technol*, vol. 52, no. 6, 2018.

[33] C. M. Pater *et al.*, "Time series evaluation of improvement interventions to reduce alarm notifications in a paediatric hospital," *BMJ Qual Saf*, vol. 29, no. 9, pp. 717–726, Sep. 2020.

[34] S. Charbonnier and S. Gentil, "A trend-based alarm system to improve patient monitoring in intensive care units," *Control Eng Pract*, vol. 15, no. 9, pp. 1039–1050, Sep. 2007.

[35] S. Phansalkar *et al.*, "A review of human factors principles for the design and implementation of medication safety alerts in clinical information systems," *Journal of the American Medical Informatics Association*, vol. 17, no. 5, 2010.

[36] O. Garot *et al.*, "Avatar-based versus conventional vital sign display in a central monitor for monitoring multiple patients: A multicenter computer-based laboratory study," *BMC Med Inform Decis Mak*, vol. 20, no. 1, pp. 1–10, 2020.

[37] V. Cobus and W. Heuten, "To beep or not to beep? Evaluating modalities for multimodal ICU alarms," *Multimodal Technologies and Interaction*, vol. 3, no. 1, pp. 1–29, 2019.

[38] A. S. Poncette *et al.*, "Patient monitoring alarms in an intensive care unit: Observational study with do-it-yourself instructions," *J Med Internet Res*, vol. 23, no. 5, May 2021.

[39] J. A. Phillips, A. Sowan, H. Ruppel, and R. Magness, "Educational Program for Physiologic Monitor Use and Alarm Systems Safety: A Toolkit," *Clinical Nurse Specialist*, vol. 34, no. 2, pp. 50–62, 2020.

[40] R. Sanz-Segura, E. Manchado-Pérez, and E. Özcan, "Design Framework for Audible Alarms: A Multidisciplinary and Integrated Approach," *International Journal of Design*, vol. 16, no. 2, 2022.