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IMPACT OF SPATIAL ORGANIZATION ON NOISE LEVELS IN OPEN-BAY NEONATAL INTENSIVE CARE UNITS

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ABSTRACT

This study focuses on the evaluation of noise levels in Open-Bay Neonatal Intensive Care Units (NICUs) across various hospitals, with the objective of analyzing how the architectural distribution of these spaces influences acoustic conditions. Despite the fact that the construction materials are consistent across all neonatal rooms and lack acoustically absorbent elements, variations in size, shape, spatial organization of equipment, and the flow of personnel significantly affect the recorded noise levels.

Noise measurements have been carried out in which data have been collected at one-second intervals over a week. The compilation of this data provides a robust foundation for future research aimed at identifying effective strategies to enhance acoustic conditions, thereby ensuring a more conducive environment for the recovery of neonates and the well-being of healthcare staff.

Adequate architectural planning is essential for mitigating noise, whereas inappropriate configurations may exacerbate acoustic challenges, negatively impacting both patients and healthcare professionals. This study underscores the importance of considering acoustics in the design of NICUs, promoting environments that support health and well-being in this critical context.

Keywords: *Architectural design, Neonatal Intensive Care Unit, Acoustic, Sources of noise.*

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1. INTRODUCTION

This communication is a continuation of the article "The Noise: A Silent Threat to the Recovery of Patients in Neonatal Intensive Care Units" [1], linked to the project "Longitudinal and cross-sectional neurocognitive study of acoustic-perceptual abilities and linguistic function in preterm infants (PretermLA)", funded by the Research Plan of the University of Cadiz (code PR2024-010), within its call for Bridge Projects (2024/2025).

Noise in NICUs presents a multifaceted challenge that not only affects newborns but also disrupts the dynamics of care, healthcare staff interactions, and family relationships. According to the American Academy of Pediatrics (AAP), prolonged exposure to noise levels exceeding 45 dBA can induce cochlear damage and negatively impact the neurosensory development of neonates [2]. While the human ear has some capacity to adapt to high noise levels, the physiological effects are persistent, leading to stress, sleep disturbances, and potential auditory and neurological deficits in newborns [3-5].

Each country has its own legislation regarding permissible indoor noise levels, depending on the intended use of the building. In the case of hospital spaces, particularly NICUs, these regulations are generally based on guidelines established by the AAP, which stipulate that noise levels in these environments should not exceed an A-weighted equivalent continuous sound level per hour ($L_{Aeq,1h}$) of 45 dBA and an hourly L_{10} of 50 dBA, meaning that noise levels above 50 dBA should not occur for more than 10% of the time. Additionally, maximum transient noise levels (L_{ASmax}) should not exceed 65 dBA [2].

In Spain, these aspects are regulated by Law 37/2003 [6] and, more specifically, by Royal Decree 1367/2007 [7], which implements the aforementioned law. These regulations set the acoustic quality objective for hospital bedrooms, establishing an $L_{Aeq,1h}$ of 40 dBA during the day and evening (8:00 – 23:00) and 30 dBA during night-time (23:00 – 8:00) (7). Furthermore, 97% of daily values must not exceed these limits by more than 3 dB, and they should never surpass them by more than 5 dB [7].

Despite these regulations, compliance remains challenging in clinical settings, primarily due to the constant activity of healthcare staff, medical equipment, alarms, and the presence of family members. In NICUs, healthcare professionals provide continuous neonatal care, which requires communication and coordination among team members, generating noise levels that exceed recommended limits even when speaking softly to adhere to the guidelines. The presence of medical equipment, alarms, and devices, as well as staff movement and family visits, significantly increase acoustic levels. Alarms, while essential for monitoring, not only contribute to stress among healthcare personnel but also lead to noise levels surpassing established limits, creating a harmful environment for neonates [8].

Numerous studies have addressed the persistent noise problem in NICUs [9-12]. Despite efforts to reduce it, recent research shows that noise levels remain a significant challenge, with average values ranging between 50 and 65 dBA, depending on the facility [12-15].

Noise sources in NICUs can be classified into structural and operational categories. Structural sources include air conditioning and ventilation systems, the opening and closing of doors, as well as the humming of electrical equipment such as computers and incubators. Operational sources encompass conversations among staff and visitors, the movement of furniture, the opening of disposable packaging, alarms, telephones, and the crying of neonates [8,14-17]. Among these, healthcare personnel are one of the key sources of noise in NICUs, significantly contributing to the maximum noise level (L_{max}), even though their conversations do not impact the continuous average noise level (L_{Aeq}) as much [8,14]. In fact, several studies have demonstrated that healthcare staff generate noise 67% of the time recorded in NICUs [14], making them the primary acoustic source in these units. Moreover, during staff shift changes, the highest peak noise levels of the entire evaluated period are often recorded [1,11,18-20].

The acoustic environment in NICUs is characterized by high noise levels, with short-duration noisy events occurring irregularly. Medical device alarms, in particular, have consistently been identified as a significant source of excessive noise, averaging 177 alarms per patient per day [11,14,21].

Regarding the spectral content of noise in these spaces, low frequencies have been observed to predominate [22,23], accompanied by some mid and high frequencies, mainly generated by equipment alarms and human voices [8]. This acoustic pattern highlights the complexity of controlling noise in a delicate environment such as the NICU. Although it is estimated that around 60% of these noises could be reduced or eliminated [14,15], the specific effects of low frequencies on neonates are still not fully understood and require further research.

It is important to emphasize that the incubator and the NICU form an interconnected system in which the ambient noise of the room directly affects neonates housed in incubators [1]. This relationship underscores the need for proper noise management in neonatal environments to protect the health and development of newborns, ensuring an optimal recovery environment. However, this does not mean that NICUs should be completely silent, as moderate exposure to sound is necessary for the neonate, contributing to constant sensory stimulation [24,25]. Additionally, early exposure to various sounds plays a crucial role in language development and linguistic skills in neonates [26].

To address this issue, various solutions have been implemented, including the use of hearing protection devices [27,28], the re-education of healthcare personnel [29,30], and the architectural renovation of NICUs [15,31-35]. The latter option involves both upgrading existing units and constructing new facilities with single-family rooms (SFR) for each patient. Regarding NICU design, several studies have compared SFR units with open-bay units [33-35]. These studies have found that SFRs have significantly lower noise levels, as they reduce interference from other equipment. This improvement not only decreases noise but also benefits the well-being of both staff and parents of neonates. In other words, open-bay units tend to have higher noise levels due to greater exposure to noise generated by staff and equipment, whereas smaller modular rooms help mitigate acoustic impact [33].

Although SFRs have proven effective in reducing noise, these improvements have not been sufficient to fully meet established noise recommendations, as levels still exceed recommended limits [11]. Additionally, some studies have highlighted that while NICUs with SFRs offer certain benefits in terms of well-being and long-term outcomes for neonates [13,32], concerns remain regarding their impact on language development due to reduced exposure to linguistic stimuli. In contrast, open-bay NICUs provide a greater amount of verbal interactions, even in the absence of parents, which could support language development in premature neonates [30].

2. METHODOLOGY

2.1 Material and Methods

To conduct this research, data on existing noise levels in the NICUs of four Spanish hospitals were collected and analyzed: Hospital Universitario Juan Ramón Jiménez (HJRJ) in Huelva, Hospital Universitario Costa del Sol (HCS) in Marbella (Málaga), Hospital Universitario Virgen Macarena (HUVM) in Sevilla, and Hospital Universitario Puerta del Mar (HUPM) in Cádiz.
To assess the noise levels to which neonates are exposed in these NICUs, one or two sound level meters were installed in each unit. The placement of these devices was determined based on the specific characteristics of each room, including volume, the number of incubators, and the layout in relation to the Neonatal Intermediate Care Unit (NIntermediateCU).
A preliminary analysis revealed that noise levels in the NICUs were consistent throughout the space, suggesting that the acoustic field in these units is predominantly diffuse. Therefore, the sound level meters were strategically positioned between two incubators, 1.5 meters away from the nearest wall and 1 meter from the ceiling. This placement was chosen to ensure a symmetrical arrangement relative to the incubators, minimizing interference from healthcare staff activities while accurately reflecting the noise exposure experienced by the neonates. The equipment used for the measurements consisted of HBK 2250 and HBK 2270 sound level meters (Hottinger Brüel & Kjaer, Virum, Denmark).
Measurements were conducted continuously over a period of eight days, with a sampling interval of one second. During this time, several acoustic parameters were recorded, including A-weighted (L_{Aeq}), C-weighted (L_{Ceq}), and unweighted broadband equivalent continuous sound pressure levels (L_{eq}). Additionally, maximum and minimum weighted levels (L_{AFmax}, L_{ASmax}, L_{AFmin}, L_{ASmin}) and impulse-weighted levels (L_{AIeq}) were captured, along with noise level percentiles (L_{10}, L_{50}, L_{90}).
Once the data was collected, it was downloaded from the sound level meters and processed using the HBK 7820 Evaluator software (Hottinger Brüel & Kjaer, Virum, Denmark), allowing for a detailed analysis of the acoustic records.
Additionally, detailed floor plans of the NICUs in each hospital were surveyed, which facilitated a more accurate interpretation of the results by considering the spatial distribution of the units and how these characteristics might influence sound propagation.

It is important to highlight that, according to consulted healthcare personnel and observations made by the measurement operators, the daily routines of nursing staff follow consistent time intervals in which the main noise sources are generated. These routines are carefully planned to avoid disrupting neonates' feeding and rest schedules. Furthermore, the number of nurses per shift (morning, afternoon, and night) remains constant, ensuring greater stability in noise conditions throughout the day.
Observations during the measurements indicated that the highest level of activity occurred during the morning shift (8:00 – 15:00), primarily due to medical procedures, the movement of equipment and incubators for tests, and cleaning and maintenance services. This early-day increase in activity resulted in higher noise levels compared to other shifts.

2.2 Features of NICUs

2.2.1 Hospital Universitario Juan Ramón Jiménez (HJRJ)

The layout of this NICU follows an L-shaped design, with a main room covering 65.7 m² and a height of 2.7 m, resulting in a total volume of 177.4 m³, accommodating up to 8 incubators. The vertical surfaces and ceiling are finished with non-porous, antibacterial paint, while the floor is covered with terrazzo.
For the noise measurements, a single sound level meter was used, as shown in Figure 1.

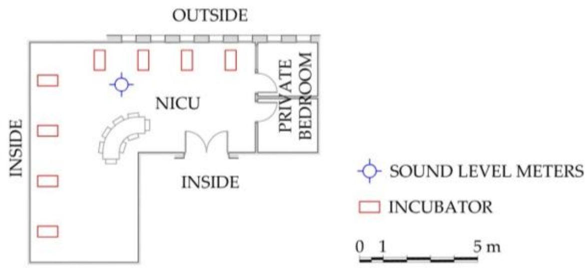

Figure 1. Floor plan of the NICU of the HJRJ

2.2.2 Hospital Universitario Costa del Sol (HCS)

The layout of this NICU is rectangular, with its main room separated from the Intermediate Neonatal Care Unit (NIntermediateCU) by a glass partition, similar to the isolation rooms for neonates with infectious diseases. The room spans 75.6 m², with a height of 2.65 m, resulting in a total volume of 200.3 m³, accommodating up to 4 incubators. The vertical surfaces and ceiling are finished

with non-porous, antibacterial paint, while the floor is covered with vinyl material.
For the measurements, a single sound level meter was used, as shown in Figure 2.

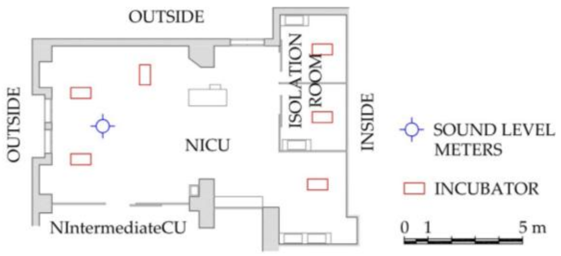

Figure 2. Floor plan of the NICU of the HCS

2.2.3 Hospital Universitario Virgen Macarena (HUVM)

In this case, the NICU follows a trapezoidal layout, separated from the NIntermediateCU and isolation rooms by glass partitions. The neonatal unit covers 84.1 m² with a height of 2.4 m, resulting in a total volume of 201.8 m³, accommodating up to 7 incubators. The surfaces are divided into three distinct zones: from the floor to 1 m high, they feature a phenolic coating; between 1 m and 2 m, glass panels are installed; and from 2 m to the ceiling, non-porous, antibacterial paint is applied, the same used for the ceiling. The floor is finished with marble.
For noise measurement, two sound level meters were used, as shown in Figure 3.

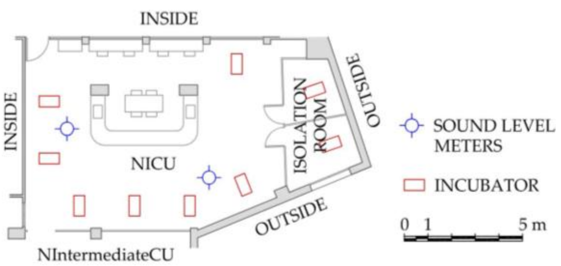

Figure 3. Floor plan of the NICU of the HUVM

2.2.4 Hospital Universitario Puerta del Mar (HUPM)

This NICU has a rectangular layout, with a main room of 156.5 m² and a height of 2.65 m, resulting in a total volume of 414.7 m³, capable of housing up to 10 incubators. Both the walls and ceiling are coated with non-porous, antibacterial paint, while the floor is finished in terrazzo.

To conduct the acoustic measurements, two sound level meters were used, as shown in Figure 4.

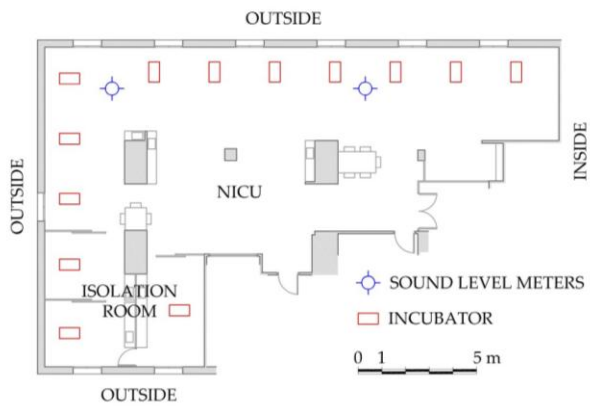

Figure 4. Floor plan of the NICU of the HUPM

3. RESULTS

The occupancy of the facilities during the measurement period remained in a moderate range, between 40 and 60%, which, a priori, could suggest that the density of patients and, therefore, the number of staff interventions, would not be the determining factor in noise generation. However, the studies carried out in the NICUs of the four hospitals showed that, despite this moderate occupancy, sound pressure levels ($L_{Aeq,1h}$) remained consistently between 57 and 58 dBA, with no statistically significant differences either between different facilities or between weekdays and weekends. During the daytime and evening periods, these values were sustained, while in the nighttime period (23:00-7:00) a significant reduction was observed, reaching a LAeq,1h of approximately 51 dBA, and even dropping to 43 dBA at the HCS hospital and 41 dBA at the HUVM during the interval between 4:00 and 6:00.
This marked nocturnal reduction suggests that the decrease in operational activity and, therefore, in the interaction between healthcare personnel, contributes to improve acoustic conditions during the night, which is crucial to facilitate the rest and recovery of neonates. The persistence of high levels, despite moderate occupancy, indicates that other factors play a determining role in the generation of noise in these units.
Among these factors, the influence of incubators and the activities associated with them stand out. The relationship between the number of incubators and the volume of the enclosure varies in each hospital (for example, in HJRJ

there is one incubator for every 22.1 m³, in HCS for every 50 m³, in HUVM for every 28.8 m³ and in HUPM for every 41.4 m³). These differences in physical space, however, were not reflected in a significant variation in noise levels, which suggests that the continuous operation of the incubators, whether occupied or not, and related activities (such as opening and closing their doors or adjusting parameters) are the predominant factor in maintaining these levels.

Another factor that could contribute to noise reduction in both the HCS and HUVM is the centralization of alarms in a monitor located in the NIntermediateCU. In this unit, alarms only sound in the incubator itself if the problem is serious, while in less critical situations, notification is received only in the centralized system. In contrast, in the HUPM and HJRJ hospitals, alarms sound both on the monitors inside the NICU and in the incubators themselves, which generates greater noise pollution in the unit.

Alarm management is a key aspect of noise reduction in neonatal intensive care settings. Several studies have shown that the excessive use of alarms generates what is known as “alarm fatigue”, a phenomenon in which healthcare personnel may become less responsive to the large number of sound alerts, which not only affects their response efficiency, but also increases the exposure of neonates to high noise levels [12]. The implementation of intelligent alarm management systems, such as the one used in these hospitals, could be an effective strategy to minimize the acoustic impact and improve the sound environment within these units.

In addition to these levels, noise peaks were identified during shift changes, with values that reached between 62 and 65 dBA, and with an average duration of 30 minutes (15 minutes before and 15 minutes after the change). These peaks show that the moments of greatest operational activity temporarily intensify noise pollution, which coincides with studies that relate the activity of healthcare personnel with an increase in the decibel level in the NICU [36].

The data, supplemented by Figure 5 which illustrates the evolution of average sound pressure levels (SPL) throughout the day, show a progressive increase in noise from the morning until approximately 15:00, followed by a decrease towards the end of the afternoon. This diurnal pattern suggests a close link between fluctuations in noise levels and changes in activities and operational routines within the units.

As for L_{A10} levels, values ranging from 57 to 64.7 dBA were obtained, the lowest being recorded at the HCS hospital and the highest at the HUPM; while the mean maximum level (L_{SAmax}) was around 87 dBA.

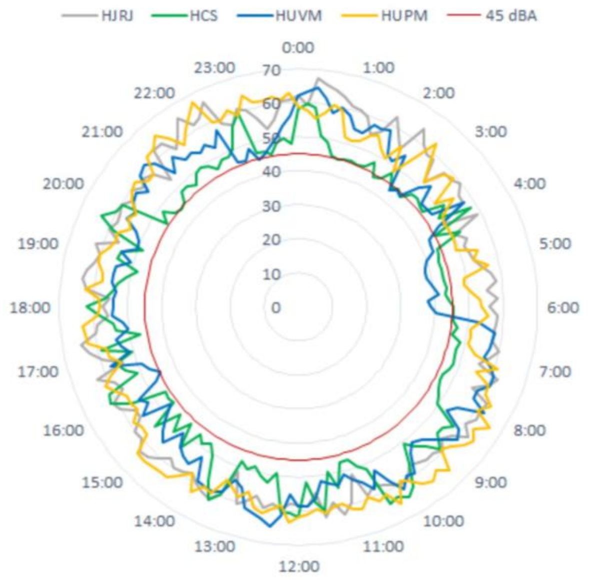

Figure 5. Comparison of A-weighted noise levels measured at different NICUs throughout 24 h.

It is relevant to consider that, although moderate occupancy might have been expected to reduce noise, the constant presence of incubators and the need for a certain number of nurses and assistants per patient (given the proportionality between the number of incubators and assigned staff) seem to offset any attenuating effect of low occupancy density.

4. DISCUSSION

NICUs present a complex environment with multiple factors that can influence their acoustic characteristics, including the number of incubators in the room, the number of patients admitted, the amount and type of medical equipment in use, the presence of healthcare staff and the materials used to cover the room itself. All these elements can contribute to the level of ambient noise, directly affecting the well-being of patients.

Proper design of the NICU acoustic environment is critical to mitigate the adverse effects of noise on the development of these infants, as prolonged exposure to high noise levels has been associated with physiological instability, impaired sleep quality and slower growth, as well as increased risk of long-term health problems [3-5]. It is therefore imperative that architectural planning takes into account the selection of acoustically efficient materials and the implementation of noise reduction strategies.

One of the most effective measures to reduce environmental noise is the integration of absorptive materials in ceilings and walls [37], together with the design of single-family rooms (SFR) that favour a quieter environment. Although the design of SFRs has shown some benefits in neonatal outcomes, it has failed to significantly reduce noise levels in the unit [10].

In addition to the use of absorbent materials, there are other effective strategies to improve the acoustic environment in NICUs. These include sound source isolation, which involves placing acoustic barriers around noisy equipment to minimise sound propagation. The use of medical devices designed to operate at lower noise levels or with settings that reduce their acoustic impact when they are not critical is also recommended.

Another key strategy is the replacement of audible alarms with visual warning systems. Constant audible alarms not only contribute to environmental noise, but also create stress for neonates and healthcare staff. Instead, the implementation of colour-coded or intensity-graded light signals according to urgency reduces noise pollution without compromising patient safety. In critical situations, the use of audible alarms would be maintained to ensure an immediate response. Additionally, monitoring these visual alarms in an adjoining room would facilitate the management of alerts without generating unnecessary noise in the NICU, optimising the response of medical staff and reducing acoustic stress.

The role of healthcare staff in noise reduction is also critical. Simple measures, such as establishing quiet periods, adjusting the volume of alarms and training staff on the harmful effects of noise can make a significant contribution to improving the NICU environment. However, despite advances in educational and technological strategies, such as the incorporation of warning lights based on noise levels detected in the room, the actual impact of these interventions has been limited. In all NICUs studied, the use of real-time noise meters, which indicate whether levels are adequate using a colour scale, has been implemented. However, these devices follow the criteria of the Occupational Risk Prevention Standard (NTP), which establishes a limit of 80 dBA to prevent hearing damage in adults exposed during an eight-hour working day [38]. This reference does not take into account the hearing sensitivity of neonates, which prevents healthcare workers from taking appropriate measures on many occasions, as the devices may indicate 'acceptable' levels when, in fact, they are not for this environment.

The challenge of maintaining a quiet environment in NICUs is compounded by the need for effective communication between healthcare professionals. In a noisy environment, the volume of conversations tends to increase to ensure that directions are clearly understood, especially in emergency situations. This further contributes to the increased noise level, making it difficult to comply with the limits recommended by bodies such as the AAP [2].

The location of these units within the hospital is another determining factor in minimising environmental noise exposure. Since the acoustic environment of a NICU directly influences the auditory and general development of neonates, its planning must be addressed with a holistic approach that considers both external noise sources and those generated within the unit. Only through a multidimensional strategy will it be possible to ensure an optimal environment for the recovery and development of preterm infants.

5. CONCLUSIONS

The results obtained indicate that, despite the differences in the architectural design of the analysed NICUs, noise levels remain high and show no significant variations. This can be explained by the use of highly reflective materials, which amplify sound rather than absorb it, and by the high density of incubators and medical equipment in confined spaces, which promotes noise accumulation.

Since the acoustic environment in these units remains a challenge, it is essential to reconsider their design to improve sound comfort. The selection of appropriate materials, an efficient spatial distribution, and better management of sound stimuli could help reduce the impact of noise, benefiting both neonates and healthcare staff.

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