Characterizing the acoustic environment in a Neonatal Intensive Care Unit

ABSTRACT

In this work, noise sources were studied in a Neonatal Intensive Care Unit (NICU) by evaluating the noise from various sources, including the influence of the work of the NICU staff. The objective was to evaluate the acoustic quality in the usual conditions in NICU rooms and inside incubators by monitoring the noise in both environments, and then data were processed using artificial neural networks. Although some types of noise were accurately classified in this way, the lack of uniformity of their sound spectra, their simultaneity, and concomitance hindered the unequivocal interpretation of some results with the classification models. After analyzing the results, it can be affirmed that the alarms of equipment had a remarkable influence on the acoustic environment. Other important influences also appeared due to the conversations of the staff, the use of the telephone, and the hauling of equipment and furniture.

***Keywords*:** Neonates, sound pressure, incubator, noise source, Neonatal Intensive Care Unit (NICU), artificial neural networks.

1. Introduction

Neonatal Intensive Care Units (NICUs) should be specially designed to minimize stress on preterm neonates. Clinical practice has shown that reducing some environmental stimuli such as noise, light, smells, handling, pain, and posture can alleviate neurological damage in neonates, thereby leading to improved development of their nervous system by inhibiting stress-related behaviors [1].

Current trends in NICU design have been clearly exposed by the Spanish Pediatric Association [2], which has examined the matter from various standpoints and issued specific recommendations as regards space, placement, neonatal care, wiring and lighting systems, noise, ventilation and air conditioning, equipment, safety, nursing staff, communication systems, maintenance, and renovation. These recommendations and trends are parts of the so-called “Family-Centered Care” (FCC) [3]. In practice, the implementation of these recommendations in NICUs was difficult due to the very nature of the space [4] and its architectural characteristics [5].

Spanish legislation [6–8] has included hospital wards considered noise-sensitive among the interior spaces of special noise protection. Therefore, the Royal Decree that develops the Noise Law, among other things, in the quality objectives within some buildings [7] requires that the threshold of day and night quality for the NICU is 40 and 30 dB, respectively [7]. However, these noise levels are widely exceeded by measurements in some of the hospital rooms [9].

In any case, carefully designing NICUs in architectural terms and correctly selecting their location within the hospital is therefore very important to avoid noise in them. This is due to, like the fetal environment, the acoustic environment of an NICU plays a major role in auditory development in neonates [10]. It is known that the auditory system starts to develop around the third week of pregnancy [11], although its essential structures are already present roughly from the 25th week of pregnancy [12] and it does not develop in full until at least one year after birth. As the fetus’ auditory system matures, its sensitivity to both low and high spectral frequencies increases, and its threshold of hearing decreases [13]. In the beginning, the auditory sensitivity range is very narrow (typically 500 to 1000 Hz during the third pregnancy term) relative to a term neonate (400 Hz to 4 kHz) or, especially, and adults (30 Hz to 20 kHz) [10]. Some acoustic tests have revealed that preterm neonates born after 25 weeks of pregnancy require 65 dBA to respond to acoustic stimulation as opposed to only 25 dBA in term neonates. Interestingly, although the latter exhibited lower thresholds for sounds in the speech perception range (500 Hz to 3 kHz), they were already sensitive to low and mid-frequency sounds [14].

It should be noted that some studies show that preterm neonates are at a high risk of losing sensitivity to hearing and developing language disorders [15]. Although such disorders may also arise in newborns, they are more common among premature newborns [16]. It has been revealed that sounds within the womb are typically rhythmic and structured and come largely from the mother. Such sounds usually may reach levels between 70 and 85 dBA [17], being low-frequency since the womb cavity functions as a low pass filter (attenuating from 20 dBA to 50 Hz, to 70 dBA to 4 kHz [18]). That is the reason why fetuses are very unlikely to be exposed to appreciable noise levels above 1000 Hz [19,20]. There is also scientific evidence that some physiological disorders in neonates are correlated with the magnitude of acoustic stimuli. Thus, a noise pressure level below 60 dBA lowers heart rate whereas one above 70 dBA raises the breathing rate.

All this justifies the interest in identifying the sources of noise impacting the NICUs environment. Although some noise comes from incubators themselves, special care has to be taken with other sources like HVAC systems (heating, ventilation, and air conditioning) [21]. The life support equipment generates alarms that may contain high-frequencies that can reach 16,000 Hz [22]. Some authors claim that the acoustic profiles of NICUs rooms and incubators are mutually related [23]. This interrelation has led to the recommendation to monitor the sound pressure in the NICUs environment and incubators simultaneously [24]. That noise environment affects neonates in thermal cots —which are fully exposed to NICU noise— and in incubators rather differently. Irrespective of incubator model and age, neonates in incubators are more effectively protected from noise in the NICUs, especially from high-frequency noise, which is attenuated by as much as 12–14 dBA in some cases [25,26]).

Despite this protection, newborns inside incubators are exposed to different sources of noise [27], like handling, opening, and closing of doors, or by knocking on the cover to stimulate those under apnea or bradycardia, all of which can increase in some cases noise levels until the reported 100 dBA [28]. In addition, incubators sometimes reveal resonances stimulated by the noise of their own motor [26].

The scarcity of scientific works examining the impact of noise on premature newborns motivates this study that seeks the acoustic characterization of noise sources, including incubators and the rest of the sources present in the NICU room analyzed. Artificial neural networks (ANNs) are used for this classification, which has proven to be the most appropriate classification algorithms to build models that speed up the process of conducting noise measurement campaigns in similar environments in the future [29]. Artificial neural networks (ANNs) are well suited to deal with complex classification problems and building classification models. ANN models can check numerous competing hypotheses simultaneously [30]. So, MLPs have been used in several acoustics studies for classification and regression problems: (i) Zhang et al. [31] previously found MPL classification algorithms to be the most effective for identifying acoustic patterns in birds; (ii) also, Jena and Panigrahi [32] used an MLP to detect piston-bore faults from noise measurements, the ensuing model affording a degree of fitting of 99%; and (iii) Chesmore [33] developed an MLP model for automatic classification of animal species in terms of their sound emissions that afforded accurate identification of *Orthoptera*.

However, there are few studies that evaluate the possibility of characterizing the type of sound with ANNs. In addition, the need to characterize the sound in the NICU environment would avoid risks for newborns. For these reasons, this study assessed the possibility of characterizing the sound environment of the NICUs through MLPs.

The rest of the paper is structured as follows: Section 2 describes the experimental methodology used; Section 3 presents and discusses the results in five different subheadings [namely, (*a*) identification of noise sources, (*b*) noise impact of NICUs, (*c*) noise impact of incubators, (*d*) discussion and (*e*) automatability of result assessment with ANNs]; and Section 4 draws the most relevant conclusions based on the results.

2. Methods

The experimental approach followed here involved the selection of a case study for noise monitoring. The selected NICU and its incubators were subjected to a set of long-term (24 h) noise measurement campaigns. The data obtained were therefore used to identify and characterize diverse noise sources, as well as to train and validate various artificial neural networks (ANNs).

2.1. Case study

The study was conducted at the NICU of the "Puerta del Mar" University Hospital (Cadiz, southern Spain). The target NICU has 13 incubators equipped with the monitoring systems required to protect neonates (see Fig. 1). There are five *Dräger Caleo* incubators, another five *Ohmeda Medical Giraffe OmmiBed* incubators, one *Ohmeda Medical Ohio Care Plus 3000* incubator and two *Dräger Babytherm* thermal cots. All are furnished with *Siemens SC 7000/9000 XL* top-end monitors. Also, the NICU uses a central monitoring system for general control of the incubators.

2.2. Noise measuring equipment and collected noise parameters

Noise measurements were made with the instruments listed in Table 1, all of which were checked and calibrated prior to use. Sound level meters were installed both in the NICU room and simultaneously inside the incubators. For incubator measurements, microphones were mounted at the neonate head level. Room measurements were made with a microphone placed in the middle of the room (near two incubators), 2 m from the nearest wall and at 1.3 m high.

Data sampling is done every 1 s over a period of 24 h. The acoustic environment of the NICU and each incubator was monitored on different days in order not to interfere with staff work. The main parameters recorded every second were (*a*) A-weighted equivalent continuous sound levels L_{Aeq}, (*b*) 1/3 octave bands from 12.5 Hz to 20 kHz in the spectra; (*c*) L_{AF} percentiles, maximum and minimum, and (*d*) impulse-weighted level (L_{AIeq}). Data were processed with the software Evaluator Type 7820 and Microsoft Excel.

2.3. Artificial neural network design

As noted earlier, this work was also aimed at classifying noise sources, a purpose for which an artificial neural network (ANN) of the multilayer perceptron (MLP) type was used. Typically, an MLP consists of three or more layers, each containing a multiplicity of nodes connected by variably weighted links. The nodes in the input layer are not used for computations but rather to store values for each variable, whereas each node in the hidden layer adds up all values in the input layer and produces a response if the result exceeds a given threshold. The results are transferred to the output layer, where the process is repeated and the response value for the model, z_k, is obtained as follows:

$$z_k = \sigma\left(w_{10}^{(2)} y_0 + \sum_{j=1}^{M} w_{kj}^{(2)} \sigma\left(\sum_{i=1}^{d} w_{ji}^{(1)} x_i + w_{10}^{(1)} x_0\right)\right) \qquad (1)$$

Where $w_{10}^{(2)}$ is the weight of the bias neuron in the hidden layer, y_0 is the input value of that neuron in the hidden layer, $w_{kj}^{(2)}$ are the weights of the output layer, σ is the activation function —which was taken to be the sigmoidal function $\sigma(x) = (1 + e^{-x})^{-1}$—, $w_{ji}^{(1)}$ are the weights of the hidden layer, x_i are the values in the input layer, and $w_{10}^{(2)}$ and x_0 are the weight and input value of the bias neuron in the input layer, respectively.

In this work, two different MPLs were used for NICU and for incubator measurements. The input variables were chosen in such a way that they would be easy to monitor with any type of sound level meter and large enough in number for the ensuing model to accurately label the signals. A total of 38 input variables were thus chosen (see Fig. 2) to be used as measurement parameters (see Section 2.2). The output variables differed among noise sources (see Section 3).

The MLPs were trained by backpropagation [34][35][36], using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm [37]. Furthermore, the training was carried out through 10-fold cross-validation, which reduces the error and the variance of the model [38]. The training data set consisted of the measurements described in Section 2.2.

The set spanned 50% of all instances and its data were chosen at random, all other instances being used as the test set. MLP performance was assessed in terms of the following quality-related statistics: true positive (TP) ratio, false positive (FP) ratio, area under the receiver operating characteristic (ROC) curve (AUC), and kappa statistic (K). TP and FP ratios indicate the accuracy percentage in the estimations made by the model, AUC determines the probability that the model classifies correctly the class analysed, existing a different value for each possible label and K determines the coincidence of the estimation with the real class. Quality was assumed to be represented by near-unity TP ratio, AUC and K values, and near-zero FP values.

3. Results and discussion

3.1. Identification of noise sources

The first step in the proposed process was labeling the main noise sources in the NICU and incubators. The detected in this study are the following.

- Medical staff shifts. The $L_{Aeq,\ T=1s}$ register shows events reaching similar noise values as reported in a previous study [39]. Figure 3 illustrates the time series of sound pressure levels in the NICU during a morning shift (07:50 to 08:15 a.m.), which are and how central frequency bands in the audio spectrum were excited during peaky events.
- Telephones and mobile phones. As can be seen in Fig. 4, this noise source contributed with a peaky time series of $L_{Aeq,\ T=1s}$, reaching values greater than 64.6 dBA. Also, tonalities were detected at $L_{Zeq,\ 800Hz,\ T=1s}$, reaching values of 63.7 dB.
- Neonatal crying. In a coincidence with some studies that have shown crying to be one of the greatest sources of noise in this environment [40] [41].
- Dragging of furniture and objects was another of the major contributors to the noise but affects occasionally.
- Alarms from medical equipment were especially important owing to their persistence in time, and, redundancy. In any case, they had a stronger impact on

NICU noise levels than inside incubators levels [42] due to their high-frequency components.

The main sources of NICU noise identified are listed in Table 2.

3.2. Acoustic impact of NICU noise sources

Once noise sources were identified, their impact on the acoustic environment was assessed (see Fig. 5). For this, table 3 shows the total equivalent noise level for each source and Table 4, shows the total duration of each noise source. It is interesting to highlight that the quietest night period in the NICU was 48.1 dBA. As can be seen in table 3, the L_{Aeq} ranged from 59.8 to 69.1 dBA. The temperature alarm was the source with the greatest L_{Aeq} value. But the time persistence of noise is also of interest. As can be seen in Table 4, most alarms sounded for more than 2000 s during the measurement period; but only one, the CO-Oximeter pulse alarm rang for almost 4000 s. It should be noted that some alarms sounded simultaneous, while others sounded alternatives.

Another important aspect is that the most important contribution to the L_{AFmax} was from the NICU staff (Table 3). In fact, although the conversations contributed little to the overall L_{Aeq}, the noise of the staff was the source of noise that affected the longest time in the room, being present in 67% of the trial period (Table 4). All of this information is likely to be used for a good practice guide for hospital staff working in these sensitive spaces.

In addition, unlabeled sources anecdotally produced noise levels of 48.6–67.7 dBA that rose to 78.7 dBA in some cases.

3.3. Acoustic impact of incubator noise sources

Table 5 shows the values for each source of noise within the incubators. The drag of the furniture was detected as an episode of great relevance. Being an unusual event, it was recorded in the measurements carried out inside the incubator, in the periods in which it was not measured outside simultaneously. In fact, these events exhibited the highest L_{Aeq} and L_{AFmax} values of all measurements within the incubator. This result underscores the impact on noise in the NICUs of the drag of tool trolleys by the staff and the chairs by the visitors. The rest of the noise sources followed a similar behavior, not showing the incubators as particularly insulators to external sound phenomena registered in the room. For that reason, the temperature alarm was that exhibiting the greatest sound levels. Also, staff conversations were the source of noise that affected the longest time inside the incubator (see Table 6).

As with NICU measurements, there were other, anecdotal noise sources that could not be unequivocally identified and contributed 45.5 to 60.2 dBA to the overall noise, with peaks as high as 68 dBA.

3.4. Comparison of the acoustic impact of NICU and incubator noise sources

The values for the different noise sources exceed the acceptable thresholds set by Philbin [43]. This author recommends that the overall background noise in an NICU is below 55 dBA and it should never exceed 70 dBA. As can be seen from Table 3, the noise level in our NICU exceeded the 55 dBA threshold; by contrast, the sound pressure values for the different alarms contributing to NICU noise do not exceed the thresholds set by the following legislation and recommendations:

- The Spanish Government, which has set a maximum diurnal and nocturnal noise level of 40 and 30 dBA, respectively, for bedrooms, and mandated that these limits not be exceeded by more than 3% of daily recordings [7].
- The Brazilian Association for Technical Norms has issued NBR 10152, where it recommends that noise in hospital environments (departments, surgeries, crib wards, operating theatres) should not exceed 45 dBA and preferably be below 35 dBA (the auditory comfort threshold) [44]. These values are identical to those set by the United States Environmental Protection Agency (US-EPA) [45].
- The World Health Organization (WHO), which has issued several conditions based on Berglund's report "Community Noise" [46], namely: nocturnal

L_{AFmax} values should not exceed 40 dBA and L_{Aeq} should be lower than 35 dBA.

- The American Academy of Pediatrics (AAP) states that average sound levels in the NICU should not exceed 45 dBA [47].
- Some new studies established new recommendations regarding the presence of transients and impulsive noise components state that L_{ASmax} should be 65 dBA [48].

The measurement campaigns clearly reflect the difficulties of meeting the previous quality targets. Thus, even in the absence of activity, the lowest noise levels measured at night never fell below 48.1 dBA and hence exceeded existing recommendations and legal limits. However, improvements in working protocols and staff training are expected to reduce noise from staff, alarms and equipment, thereby increasing acoustic comfort in NICU rooms and incubators. Some strategies currently being explored include protecting neonates with silicone earplugs [49] while they are held in incubators and replacing acoustic alarms with visual signals [42]. These measures may have a favorable impact on NICU acoustic environments by suppressing the main sources of noise identified in this work. It would also be advisable to equip incubators with a small microphone to measure noise. Subsequent recordings could be correlated with the usually monitored variables of preterm newborns and see how they respond to acoustic stimuli. As noted by some health professionals [50], it could also be useful to use centrally managed monitoring and alarm systems to provide NICU staff with information about preterm newborns without the need to be close to them, and also to organize the flow of staff more efficiently and be careful about the sleep time. Other strategies to mitigate the impact of the activity of staff and visitors on the acoustic environment of a NICU go through awareness about the importance of the problem in both groups. For example through (i) the creation of new guides or improving existing protocols, and (ii) staff training.

3.5. Automatability of result assessment with ANNs

The acoustic events recorded in the two environments were widely variable. Thus, some alarms were highly persistent in the NICU but rarely detected in incubators (e.g., by monitors 1 and 2). Consequently, the acoustic environment of the NICU room was expected to differ among days. Future measurements should, therefore, be made over longer periods in order to facilitate the correlation of the acoustic environment and the time of year.

As measurements were made in a continuous manner and data were acquired at 1 s intervals, the time needed to identify accurately the main alarms and acoustic events were rather long. For this reason, artificial neural networks (ANNs) were used to label noise sources automatically. As noted in Section 2.3, two separate models were developed for NICU and incubator measurements. An output variable for each type of source was included in the models, and, such variable, stated whether a signal from the source concerned was present at the time of measurement. Table 7 shows the output variables used. The low persistence of alarms from monitors 1 and 2 in the incubator measurements led us to combine the two sources with other minor ones.

Tables 8 and 9 show the quality-related statistics TP, FP, and K for the NICU and incubator MLP, respectively, and Figs 6 and 7 show the AUC values for the two models. It should be noted that TP, AUC, and K should be near-unity and FP near-zero. As can be seen, the TP values for the NICU were quite acceptable during the MLP training stage for some noise sources, such as the low-priority alarm and conversations, but too low for others. Likewise, K and AUC exceeded 0.8 and 0.9, respectively, in the sources with an adequate TP value, but were too low in others. The poorest performers among the output variables in the training stage responded similarly to new instances in the test stage.

The incubator MLP performed worse than the NICU MLP. Thus, only three sources (viz., *Dräger Babylog* – Ventilator, *Dräger Infinity Delta* – Low priority and Temperature) had adequate quality-related statistics.

Although the statistics were not poor, the fact that they lead to an inaccurate labeling of noise sources over long periods could make them useless due to the difficulty of discriminating among several concomitant sources at a given time. As can be seen from

Fig. 8, more than 40% of NICU measurements comprised two or more compounded sources. So, MLPs could be useful for the preliminary processing of data to identify those times where measurements are highly similar to those for certain noise sources and to discriminate them from background noise. In any case, future works should be conducted on larger data sets.

4. Conclusions

The average noise level for the measurement period was 65.6 dBA, with the highest noise intensity being 87.3 dBA and the lowest being 48.1 dBA at night. Consequently, noise levels in the NICU room fail to comply with the acoustic quality objectives set in national and international legislation and guidelines —notably those of the World Health Organization— and may, therefore, have an adverse impact on biological development in preterm neonates held at the NICU.

The interest in monitoring an NICU environment over a longer period to better assess the influence of some noise sources led us to use ANNs for automatic classification of sources. Based on the results, the lack of uniformity among sources and the overlap of several at many times led to poor fitting. In any case, the preliminary processing of the MLP results could be useful to identify those times where an actual noise event occurs.

Acknowledgments

The authors are grateful to the NICU staff of the “Puerta del Mar” University Hospital (Cadiz, Spain) for their help in the conduct of this work.

References

[1] Gascón Gracia S, García Berman RM. Environmental impact on the neonate. Rev ROL Enfermería 2011;34:6–14.

[2] García Del Río M, Sánchez Luna M, Doménech Martínez E, Izquierdo Macián I, López Herrera MC, Losada Martínez A, et al. Revisión de los estándares y recomendaciones para el diseño de una unidad de neonatología. An Pediatr 2007;67:594–602. https://doi.org/10.1157/13113024.

[3] Hall JH, Jonson BH. Family centered care. Bethesda MD: Institute for Family-Centered Care: 1997.

[4] Juan C, Del R, Neonatologia SDE, Achával AA. Remodelación del Servicio de Neonatología. Propuesta de un modelo racional y funcional. Rev Del Hosp Matern

Infant Ramón Sardá 2003;22:16–8.
[5] Naresh SM. A Single-Room NICU-The Next Generation Evolution in the Design of Neonatal Intensive Care Units. Acad J 2003;6:3.
[6] Gobierno de España. Ley 37/2003, de 17 de noviembre, del Ruido. BOE276. 2003.
[7] Gobierno de España. Real Decreto 1367/2007, de 19 de octubre, por el que se desarrolla la Ley 37/2003, de 17 de noviembre, del Ruido, en lo referente a zonificación acústica, objetivos de calidad y emisiones acústicas. BOE nº254. 2007.
[8] Código Técnico de la Edificación. CTE DB-HR. Protección frente al ruido. Boletín Of Del Estado 2009. https://doi.org/10.1016/j.neuroscience.2011.09.036.
[9] Shoemark H, Harcourt E, Arnup SJ, Hunt RW. Characterising the ambient sound environment for infants in intensive care wards. J Paediatr Child Health 2016;52:436–40. https://doi.org/10.1111/jpc.13084.
[10] Avery GB, Fletcher MA, MacDonald MG. Neonatología : fisiopatología y manejo del recién nacido. Médica Panamericana; 2001.
[11] Rubel EW. Auditory system development. In: Gottlieb G, Krasnegor NA, editors. Meas. Audit. Vis. first year postnatal life A Methodol. Overv., Westport, CT, US: Ablex Publishing: Ablex Publishing; 1985, p. 53–90.
[12] Parmelee Jr AH, Sigman MD. Perinatal brain development and behavior. Handb Child Psychol Former Carmichael's Man Child Psychol H Mussen, Ed 1983.
[13] Aslin RN, Pisoni DB, Jusczyk PW. Auditory development and speech perception in infancy. Handb Child Psychol Former Carmichael's Man Child Psychol H Mussen, Ed 1983.
[14] Berg KM, Smith MC. Behavioral thresholds for tones during infancy. J Exp Child Psychol 1983;35:409–25.
[15] Schulte FJ, Stennert E, Wulbrand H, Eichhorn W, Lenard HG. The ontogeny of sensory perception in preterm infants. Eur J Pediatr 1977;126:211–24.
[16] Kurtzberg D, Stapells DR, Wallance IF. Event-related potential assesment of auditory system integrity: implications for language development. Early Identificationof Infants with Dev Disabil 1988.
[17] Gerhardt KJ. Characteristics o f the fetal sheep sound environment. Semin Perinatol 1989;13.
[18] Armitage SE, Baldwin BA, Vince MA. The fetal sound environment of sheep. Science (80-) 1980;208:1173–4.
[19] Walker D, Grimwade J, Wood C. Intrauterine noise: a component of the fetal environment. Am J Obstet Gynecol 1971;109:91–5.
[20] Abdollahi FZ, Joulaie M, Darouie A, Ahmadi T. Auditory Development in Infants. Glob J Otolaryngol 2017;10:5–7. https://doi.org/10.19080/GJO.2017.10.555800.
[21] Smith SW, Ortmann AJ, Clark WW. Noise in the Neonatal Intensive Care Unit: A New Approach to Examining Acoustic Events. Noise Heal 2018;20:121–30. https://doi.org/10.4103/nah.NAH_53_17.
[22] Kellam B, Bhatia J. Sound spectral analysis in the intensive care nursery: Measuring high-frequency sound. J Pediatr Nurs 2008;23:317–23. https://doi.org/10.1016/j.pedn.2007.09.009.
[23] Gallegos-Martínez J, Reyes-Hernández J, Fernández-Hernández VA, González-González LO. Indice de ruido en la unidad neonatal. Su impacto en recién nacidos. Acta Pediátrica México 2011;32:5–14.
[24] Moreira Pinheiro E, Guinsburg R, de Araujo Nabuco MA, Yoshiko Kakehashi T. Ruido en la Unidad de Terapia Intensiva Neonatal y en el interior de la incubadora. Latino-Am Enferm 2011;19:1214–21.
[25] Donis Paz AC. Contaminación acústica en la Unidad de Neonatología del Hospital Roosevelt. Universidad Rafael Landívar, 2013.
[26] Fernández Zacarías F, Beira Jiménez JL, Bustillo Velázquez-Gaztelu PJ, Hernández Molina R, Lubián López S. Noise level in neonatal incubators: A comparative study of three models. Int J Pediatr Otorhinolaryngol 2018;107:150–4. https://doi.org/10.1016/j.ijporl.2018.02.013.
[27] Moreno Argayo L. Valoración del manejo de la luz y el ruido en unidades neonatales. Universidad de Valladolid, 2015.

[28] Beira Jiménez LJ, Puyana Romero V, Hernández Molina R, Fernández Zacarías F, Bustillo Velázquez-Gaztelu PJ, Cueto Ancela JL, et al. Acústica de una Incubadora Neonatal. 48º Congr Español Acústica Encuentro Ibérico Acústica 2017.
[29] Pino-Mejías R, Pérez-Fargallo A, Rubio-Bellido C, Pulido-Arcas JA. Artificial neural networks and linear regression prediction models for social housing allocation: Fuel Poverty Potential Risk Index. Energy 2018;164:627–41. https://doi.org/10.1016/j.energy.2018.09.056.
[30] Soltane M, Ismail M, Abidin Z, Rashid A. Artificial Neural Networks (ANN) Approach to PPG Signal Classification. Int J Comput Inf Sci Vol2, 2004;2:58–65.
[31] Zhang L, Towsey M, Xie J, Zhang J, Roe P. Using multi-label classification for acoustic pattern detection and assisting bird species surveys. Appl Acoust 2016;110:91–8. https://doi.org/10.1016/j.apacoust.2016.03.027.
[32] Jena DP, Panigrahi SN. Motor bike piston-bore fault identification from engine noise signature analysis. Appl Acoust 2014;76:35–47. https://doi.org/10.1016/j.apacoust.2013.07.023.
[33] Chesmore ED. Application of time domain signal coding and artificial neural networks to passive acoustical identification of animals. Appl Acoust 2001;62:1359–74. https://doi.org/10.1016/S0003-682X(01)00009-3.
[34] Rumelhart DE, Hinton GE, Williams RJ. Learning representations by back-propagating errors. Nature 1986;323:533–6. https://doi.org/10.1038/323533a0.
[35] Wang YN. A neural network adaptive control based on rapid learning method and application. Adv Molding Anal 1994;46:27–34.
[36] Werbos PJ. Beyond regression: New tools for prediction and analysis in the behavioral sciences. 1974.
[37] Fletcher R. Practical Methods of Optimization. Volume 1: Unconstrained Optimization. 1980.
[38] Kohavi R. A Study of Cross-Validation and Bootstrap for Accuracy Estimation and Model Selection 1995:1137–43. https://doi.org/10.1002/prca.201200064.
[39] Muñoz V. Informe Técnico de Medición de Niveles de Presión Sonora en la Unidad de Neonatología del Hospital San José. 2001.
[40] Nogueira M de FH, Di Piero KC, Ramos EG, de Souza MN, Dutra MVP. Mensuración de ruido en unidades neonatales e incubadoras con recién nacidos: revisión sistemática de literatura. Rio Janeiro, Bras Rev Latino-Am Enferm 2011.
[41] Seto A. Evaluación de los Niveles de Ruido en una Unidad de Cuidados Intensivos Neonatales. Universidad Autónoma de Madrid, 2012.
[42] Lichtig I, Maki K. Estudos de níveis de ruídos ambientais e de ruídos gerados pelas incubadoras em uma unidade de terapia intensiva neonatal. Pediatria (Santiago) 1992;14:30–4.
[43] Philbin MK. Planning the acoustic environment of a neonatal intensive care unit. Clin Perinatol 2004;31:331–52. https://doi.org/10.1016/j.clp.2004.04.014.
[44] NBR 10152. Níveis de ruídos para conforto acústico. ABNT 1987.
[45] United States Environmental Protection Agency. Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. US Government Printing Office; 1974.
[46] Berglund B, Lindvall T. Community noise. Center for Sensory Research, Stockholm University and Karolinska Institute Stockholm; 1995.
[47] American Academy of Pediatrics. Committee on Environmental Health Noise: a hazard for the fetus and newborn. Pediatrics 1997;100:724–7.
[48] White RD, Smith JA, Shepley MM. Recommended standards for newborn ICU design. J Perinatol 2013;33:S2--S16.
[49] Almadhoob A, Ohlsson A. Sound reduction management in the neonatal intensive care unit for preterm or very low birth weight infants. Cochrane Database Syst Rev 2015;2017:551–3. https://doi.org/10.1177/0954406218780129.
[50] Gallardo Ponce I. La UCI silenciosa, mejor para niños y padres. Simp Innovaciones En Ucin n.d.

Table 1. Main technical specifications of the measuring equipment.

Equipment	Specifications	Calibration range	Measuring range
B&K 2270 Sound level meter	Class 1		20–140 dB 3 Hz–20 kHz
B&K Type 4231 calibration system	Class 1	94–114 dB 1000 Hz	

Table 2. Types of alarms identified.

Alarm (incubator model)	**Trigger**
Feed pump (*Kangaroo*)	It sounds when feeding ends, roughly 30 min after it starts.
Respirator heater (*Fisher & Paykel MR 850ALU*)	It sounds when the air temperature inside the tubes (i.e., air delivered to the neonate) rises or falls by 3 °C.
Thermal regulator (*MTRE Allon 2001*)	It sounds when signs of hypothermia are detected.
Syringe pump (*Alaris CC*)	It sounds when drug delivery ends, approximately 30 min after it starts.
Nonspecific (*Dräger Caleo*)	It sounds when one of the monitored parameters (temperature, relative humidity) is not at an appropriate level.
Blood pressure (*Dräger Infinity Delta*)	It sounds when the neonate's blood pressure falls outside the recommended range.
High-priority (*Dräger Infinity Delta*)	Blood pressure, heart rate, oxygen saturation (e.g., asystole, ventricular fibrillation).
Low-priority (*Dräger Infinity Delta*)	Blood pressure, heart rate, oxygen saturation (e.g., apnea, neonate's safety during NIBP measurements).
Pulse CO-oximeter (*Masimo Radical-7*)	Heart rate and oxygen saturation.
Respirator (*Dräger Babylog*)	Most frequent alarm when the volume is too low.
Respirator (*SERVO-i*)	Most frequent alarm for too high a breathing rate.
Temperature	Sounds when the temperature rises by more than 1.5 °C above or falls by more than 3 °C below the control value.

Table 3. Parameter values for the different NICU noise sources.

Source	**L_{Aeq} (dBA)**	**L_{AFmax} (dBA)**
Alarm: *Dräger Babylog* – Ventilator	60.0	71.4
Alarm: *Alaris CC* – Syringe pump	62.5	82.5
Alarm: *Dräger Infinity Delta* – High-priority	65.8	85.3
Alarm: *MTRE Allon 2001* – Thermal regulator	62.9	78.4
Alarm: *Kangaroo* – Feeding pump	60.8	83.4
Alarm: *Dräger Infinity Delta* – Low-priority	64.3	79.4
Alarm: *Dräger Caleo* – Non–specific	60.1	85.9
Alarm: *Dräger Infinity Delta* – Blood pressure	61.2	85.9
Alarm: *Masimo Radical-7* – Pulse CO–Oximeter	59.8	85.9
Alarm: *SERVO-i* – Ventilator	61.1	85.3
Alarm: Temperature	69.1	76.4
Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater	67.2	79.8
Conversations	61.2	87.3
Phones	62.5	84.6

Table 4. The persistence of each noise source in the acoustic environment of the NICU referred to 24 hours. These are the time periods for which the equivalent level has been calculated for table 3

Source	**Time (s)**
Alarm: *Dräger Babylog* – Ventilator	84
Alarm: *Alaris CC* – Syringe pump	1 016
Alarm: *Dräger Infinity Delta* – High-priority	773
Alarm: *MTRE Allon 2001* – Thermal regulator	1 088
Alarm: *Kangaroo* – Feeding pump	1 422
Alarm: *Dräger Infinity Delta* – Low-priority	1 766
Alarm: *Dräger Caleo* – Nonspecific	6 241
Alarm: *Dräger Infinity Delta* – Blood pressure	8 165
Alarm: *Masimo Radical-7* – Pulse CO-Oximeter	3 795
Alarm: *SERVO-i* – Ventilator	1 011
Alarm: Temperature	197
Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater	1 782
Conversations	58 401
Phones	491

Table 5. Parameter values for the different incubator noise sources.

Source	**L_{Aeq} (dBA)**	**L_{AFmax} (dBA)**
Alarm: *Dräger Babylog* – Ventilator	50.7	77.6
Alarm: *Alaris CC* – Syringe pump	49.8	66.8
Alarm: *Dräger Infinity Delta* – High-priority	52.5	66.1
Alarm: *MTRE Allon 2001* – Thermal regulator	51.4	63.8
Alarm: *Kangaroo* – Feeding pump	50.3	70.4
Alarm: *Dräger Infinity Delta* – Low-priority	52.6	67.0
Alarm: *Dräger Caleo* – Nonspecific	50.3	54.8
Alarm: *Masimo Radical-7* – Pulse CO-Oximeter	50.8	66.4
Alarm: *SERVO-i* – Ventilator	49.6	71.2
Alarm: Temperature	53.8	63.2
Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater	52.3	69.2
Conversations	51.3	80.7
Phones	51.0	61.5
Dragging	58.1	84.2
Crying	52.0	75.9

Table 6. The persistence of each noise source in the acoustic environment within the incubator referred to 24 hours. These are the time periods for which the equivalent level has been calculated for table 5

Source	**Time (s)**
Alarm: *Dräger Babylog* – Ventilator	8 230
Alarm: *Alaris CC* – Syringe pump	1 122
Alarm: *Dräger Infinity Delta* – High-priority	205
Alarm: *MTRE Allon 2001* – Thermal regulator	296
Alarm: *Kangaroo* – Feeding pump	886
Alarm: *Dräger Infinity Delta* – Low-priority	873
Alarm: *Dräger Caleo* – Nonspecific	10
Alarm: *Masimo Radical-7* – Pulse CO-oximeter	1 187
Alarm: *SERVO-i* – Ventilator	27 600
Alarm: Temperature	68
Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater	1 175
Conversations	57 356
Phones	482
Dragging	1 025
Crying	1 938

Table 7. Output variables for the MLPs.

Model	**Variables**
NICU	Alarm: *Dräger Babylog* – Ventilator
	Alarm: *Alaris CC* – Syringe pump
	Alarm: *Dräger Infinity Delta* – High-priority
	Alarm: *MTRE Allon 2001* – Thermal regulator
	Alarm: *Kangaroo* – Feeding pump
	Alarm: *Dräger Infinity Delta* – Low-priority
	Alarm: *Dräger Caleo* – Nonspecific
	Alarm: *Dräger Infinity Delta* – Blood pressure
	Alarm: *Masimo Radical-7* – Pulse CO-Oximeter
	Alarm: *SERVO-i* – Ventilator
	Alarm: Temperature
	Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater
	Conversations
	Phones
Incubator	Alarm: *Dräger Babylog* – Ventilator
	Alarm: *Alaris CC* – Syringe pump
	Alarm: *Dräger Infinity Delta* – High-priority
	Alarm: *MTRE Allon 2001* – Thermal regulator
	Alarm: *Kangaroo* – Feeding pump
	Alarm: *Dräger Infinity Delta* – Low-priority
	Alarm: *Dräger Caleo* – Nonspecific
	Alarm: *Masimo Radical-7* – Pulse CO-Oximeter
	Alarm: *SERVO-i* – Ventilator
	Alarm: Temperature
	Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater
	Conversations
	Phones
	Dragging
	Crying

Table 8. True positive rate (TP), false positive rate (FP) and parameter kappa (K) for the NICU MLP.

Output variable	**Training**					**Testing**			
	Label				**K**	**Label**			
	Yes		**No**			**Yes**		**No**	
	TP	**FP**	**TP**	**FP**		**TP**	**FP**	**TP**	**FP**
Alarm: *Dräger Babylog* – Ventilator	0.83	0.02	0.98	0.17	0.84	0.85	0.15	0.85	0.15
Alarm: *Alaris CC* – Syringe pump	0.74	0.13	0.88	0.26	0.60	0.74	0.35	0.65	0.26
Alarm: *Dräger Infinity Delta* – High-priority	0.87	0.01	0.99	0.13	0.88	0.87	0.09	0.91	0.13
Alarm: *MTRE Allon 2001* – Thermal regulator	0.83	0.02	0.98	0.17	0.83	0.81	0.31	0.69	0.19
Alarm: *Kangaroo* – Feeding pump	0.73	0.07	0.93	0.27	0.66	0.73	0.33	0.67	0.27
Alarm: *Dräger Infinity Delta* – Low-priority	0.95	0.07	0.93	0.05	0.88	0.94	0.19	0.81	0.06
Alarm: *Dräger Caleo* – Nonspecific	0.69	0.14	0.86	0.31	0.56	0.69	0.43	0.57	0.31
Alarm: *Dräger Infinity Delta* – Blood pressure	0.85	0.10	0.90	0.15	0.72	0.85	0.20	0.80	0.15
Alarm: *Masimo Radical-7* – Pulse CO–Oximeter	0.75	0.07	0.93	0.25	0.70	0.75	0.14	0.86	0.25
Alarm: *SERVO-i* – Ventilator	0.62	0.09	0.92	0.38	0.55	0.70	0.09	0.91	0.30
Alarm: Temperature	0.87	0.02	0.98	0.13	0.86	0.87	0.02	0.98	0.13
Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater	0.82	0.03	0.97	0.18	0.82	0.88	0.08	0.92	0.12
Conversations	0.95	0.15	0.85	0.05	0.81	0.92	0.18	0.82	0.08
Phones	0.48	0.01	0.99	0.52	0.59	0.47	0.05	0.95	0.53

Table 9. True positive rate (TP), false positive rate (FP) and parameter kappa (K) for the incubator MLP.

Output variable	**Training**					**Testing**			
	Label				**K**	**Label**			
	Yes		**No**			**Yes**		**No**	
	TP	**FP**	**TP**	**FP**		**TP**	**FP**	**TP**	**FP**
Alarm: *Dräger Babylog* – Ventilator	0.89	0.05	0.95	0.11	0.85	0.89	0.07	0.93	0.11
Alarm: *Alaris CC* – Syringe pump	0.54	0.02	0.98	0.47	0.59	0.54	0.33	0.67	0.46
Alarm: *Dräger Infinity Delta* – High-priority	0.88	0.01	0.99	0.12	0.89	0.86	0.46	0.54	0.14
Alarm: *MTRE Allon 2001* – Thermal regulator	0.49	0.02	0.98	0.51	0.56	0.51	0.42	0.58	0.49
Alarm: *Kangaroo* – Feeding pump	0.65	0.01	0.99	0.35	0.72	0.65	0.28	0.72	0.35
Alarm: *Dräger Infinity Delta* – Low-priority	0.81	0.01	0.99	0.19	0.87	0.81	0.07	0.93	0.19
Alarm: *Dräger Caleo* – Nonspecific	0.85	0.06	0.94	0.15	0.80	0.84	0.65	0.35	0.16
Alarm: *Masimo Radical-7* – Pulse CO–Oximeter	0.67	0.02	0.98	0.33	0.71	0.67	0.63	0.37	0.33
Alarm: *SERVO-i* – Ventilator	0.48	0.08	0.92	0.52	0.44	0.47	0.45	0.55	0.53
Alarm: Temperature	0.82	0.01	0.99	0.18	0.88	0.89	0.15	0.85	0.11
Alarm: *Fisher & Paykel MR 850ALU* – Ventilator heater	0.66	0.01	0.99	0.34	0.89	0.86	0.46	0.54	0.14
Conversations	0.93	0.23	0.77	0.07	0.72	0.93	0.23	0.77	0.07
Phones	0.58	0.07	0.93	0.42	0.68	0.56	0.49	0.51	0.44
Dragging	0.70	0.02	0.98	0.30	0.74	0.71	0.18	0.82	0.29
Crying	0.64	0.03	0.97	0.36	0.67	0.64	0.49	0.51	0.36

470

Fig. 1. NICU of the “Puerta del Mar” University Hospital.

471

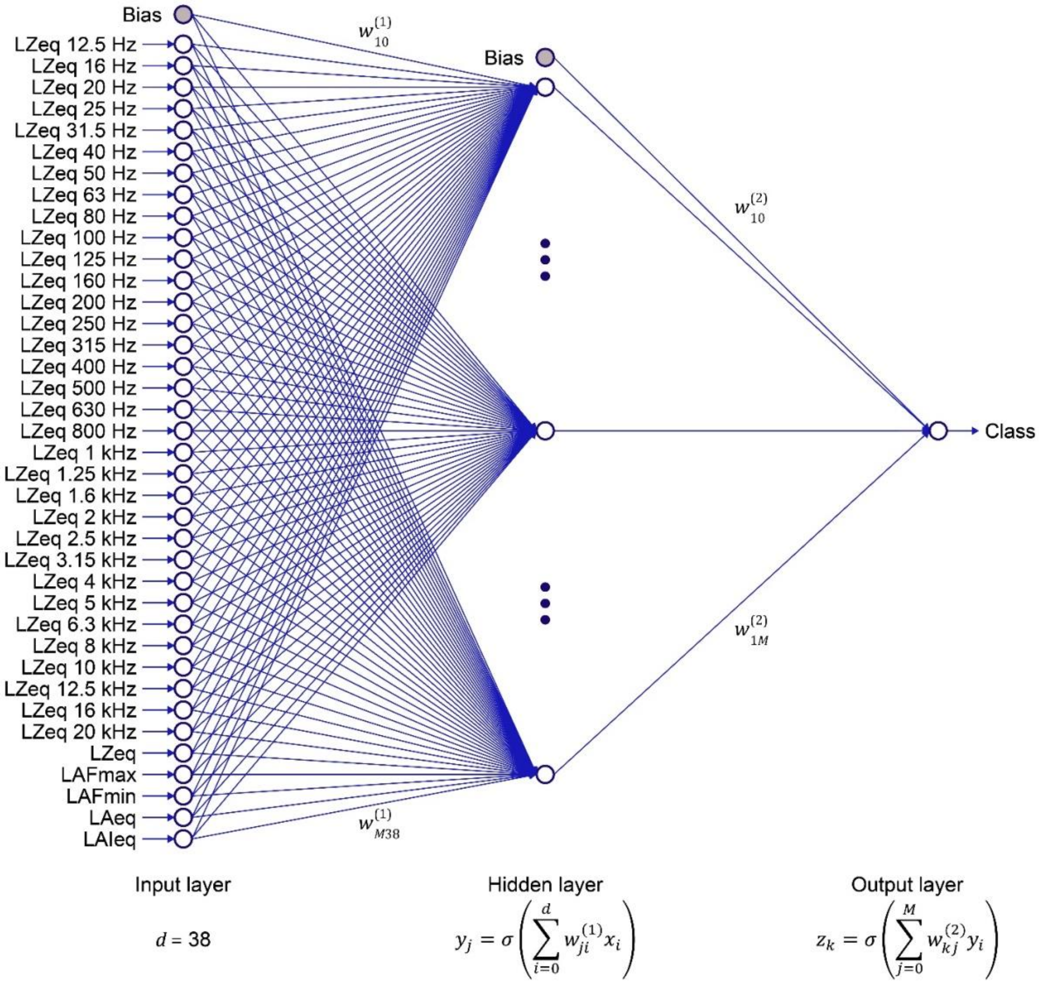

Fig. 2. Scheme of the MLP.

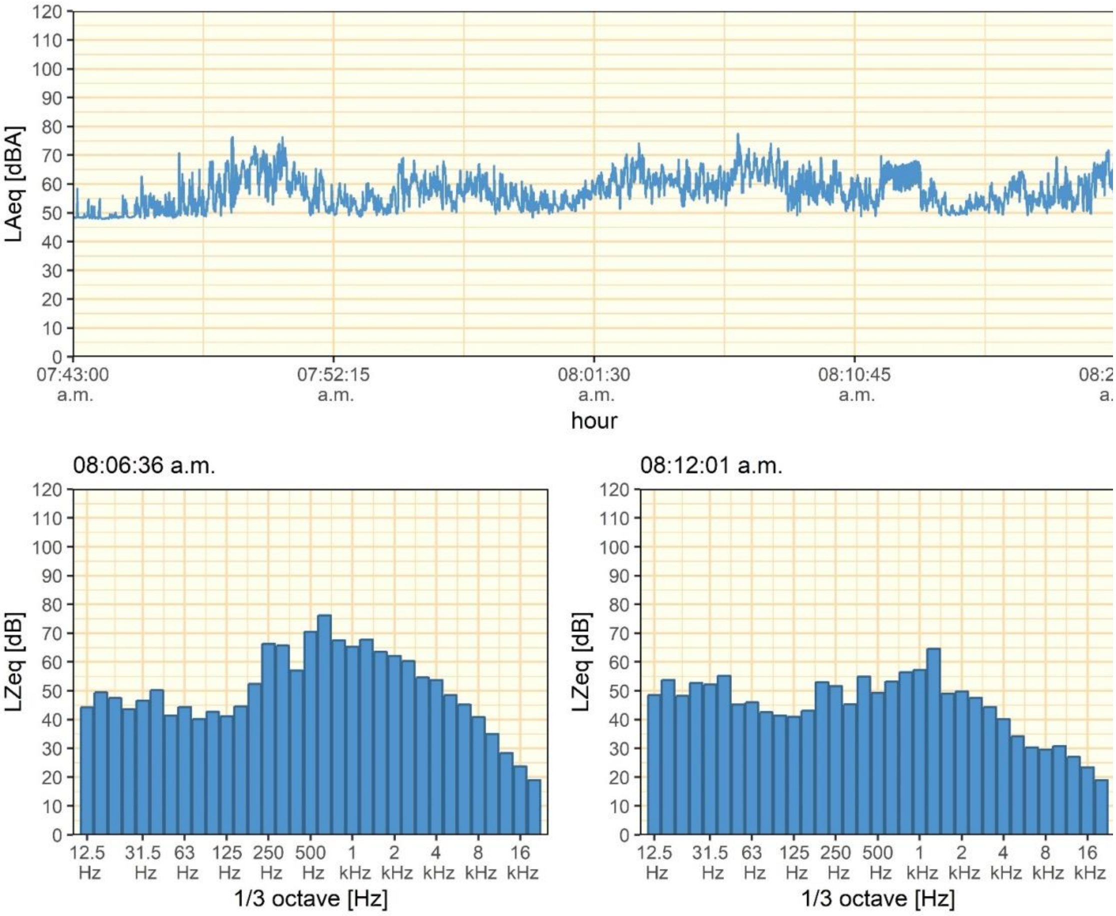

Fig. 3. An excerpt from the time series of sound pressure levels from which an example of medical staff shifts can be displayed. The third-octave spectrum of two examples of 1-second events is also shown.

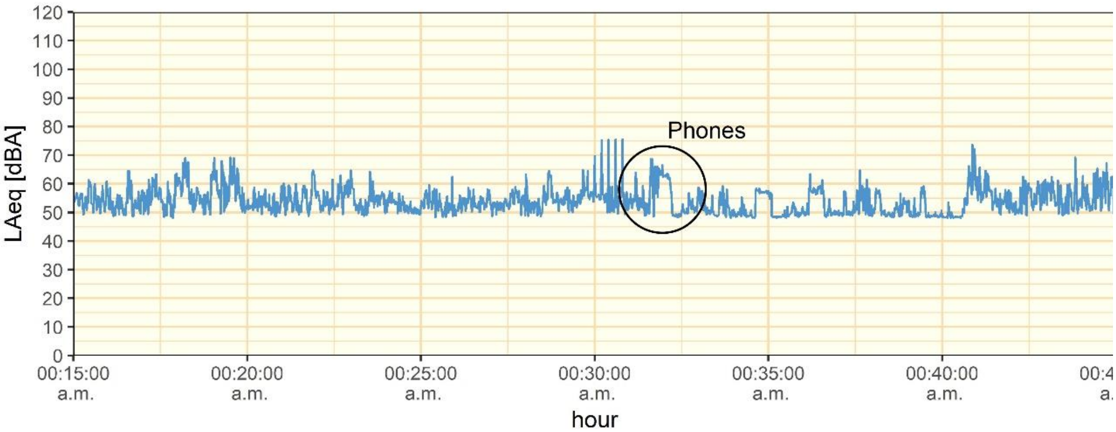

Fig. 4. An excerpt from the time series of sound pressure levels from which an example of alarms and phones can be displayed.

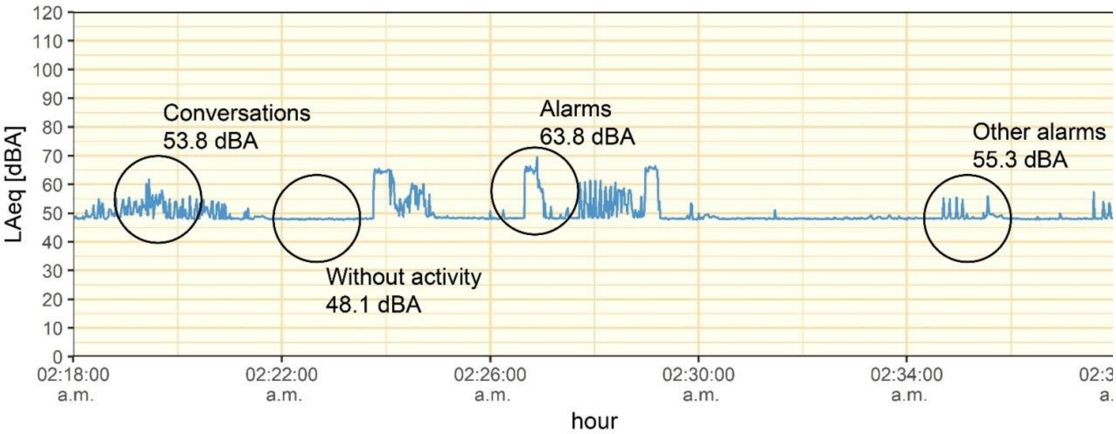

Fig. 5. An excerpt from the time series of sound pressure levels from which an example of alarms and staff conversations can be displayed.

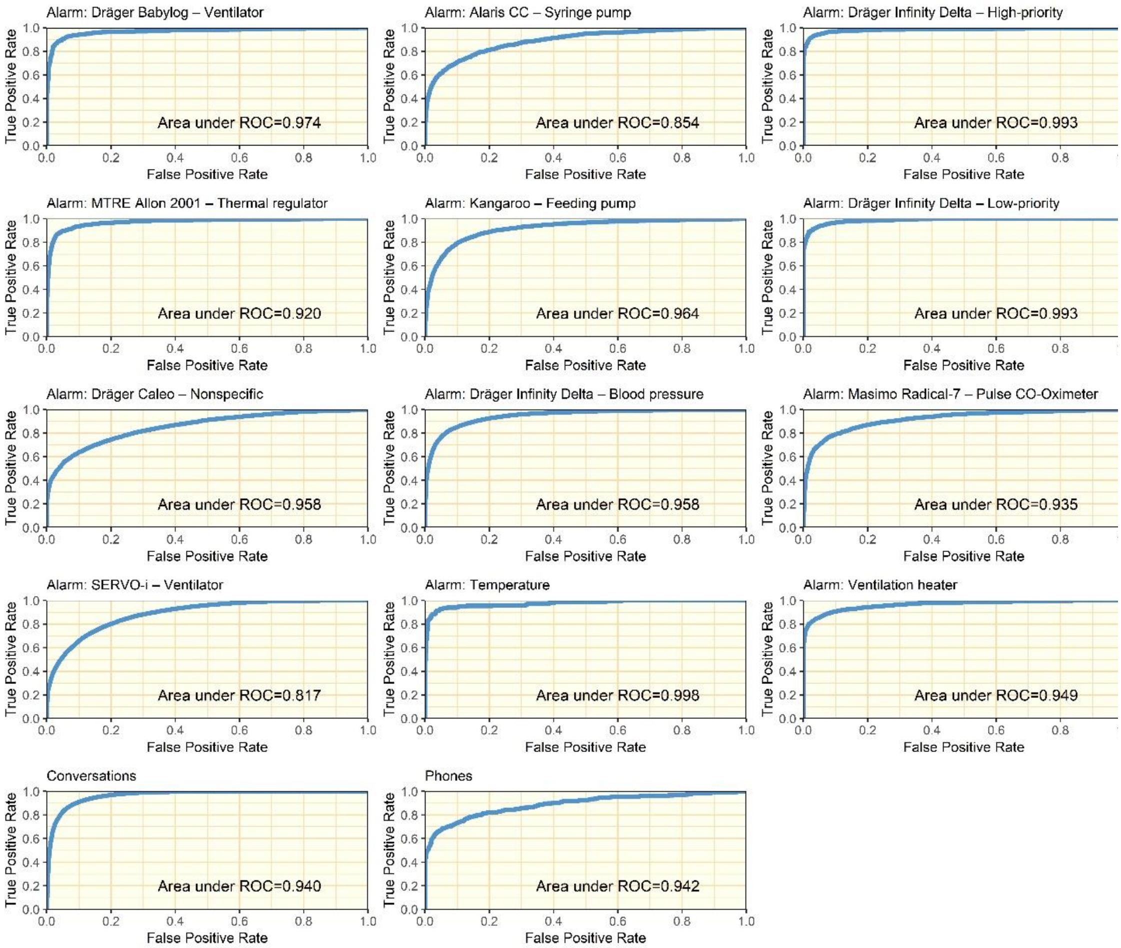

Fig. 6. AUC for each output variable in the NICU MLP.

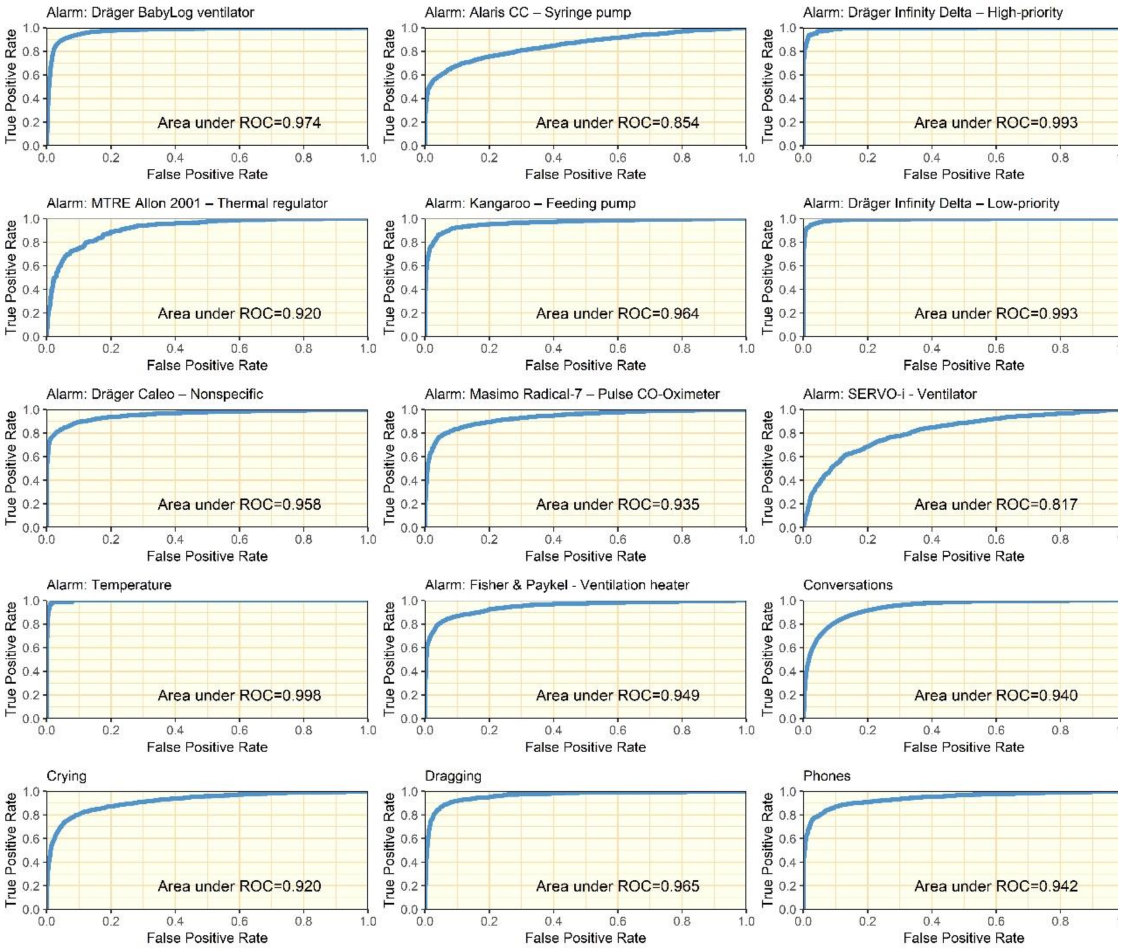

Fig. 7. AUC for each output variable in the incubator MLP.

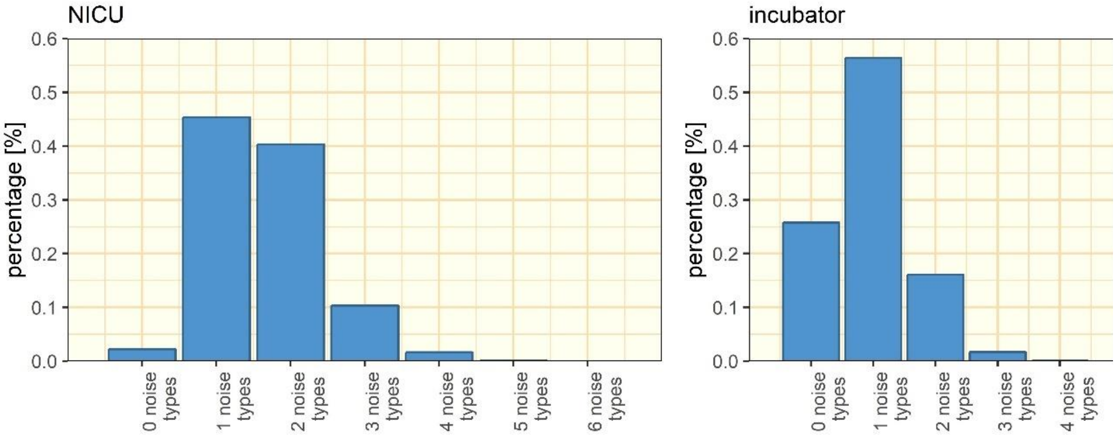

Fig. 8. The proportion of concomitant noise types in the NICU and incubators.