

Article

Diagnosis of Noise Inside Neonatal Incubators under Free-Field Conditions

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Abstract: The study aims to diagnose the sound pressure levels inside incubators in a controlled environment under free-field conditions. The tests were carried out in a semi-anechoic room under the standard UNE-EN ISO 3745:2012/A1:2018 in three different operating states: off, on, and on with a temperature alarm triggered. Sound pressure levels were analyzed in three different models of incubators, both inside and outside. The main noise indices analyzed were the corrected equivalent continuous level ($L_{K_{eq}}$) and the equivalent continuous level (L_{eq}) in third-octave bands. The results obtained under normal operating conditions showed variations among the different incubators, with overall values between 48.8 and 56.3 dBA. The influence of the alarm considerably worsened these data. The values obtained showed that premature newborns are exposed to noise levels above international recommendations. All incubators tested showed the presence of tonal components, both outside and inside the incubator cabin, and, in some cases, low-frequency components, but no impulsivity components were observed in any case.

Keywords: neonates; sound pressure; incubators; noise source; NICU; risk in preterm infants



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1. Introduction

Based on a literature review, it can be stated that the sound pressure levels in intensive care units (NICUs), although they are considered spaces of special acoustic protection, are usually higher than those that can occur in other types of environments [1]. The sound environment of a NICU comes from a variety of noise sources, such as alarms, air conditioning, staff conversations, telephone use, and respiratory support systems, among others [2,3]. It also contains annoying noises of short duration at irregular intervals [4] that often exceed the maximum acceptable level of 45 decibels (dB) recommended by the American Academy of Pediatrics (AAP) [3,5,6].

Exposure to sound can have both beneficial and detrimental effects on the developing fetus and premature infant [7]. On the one hand, the sound is necessary for sensory stimulation, and, on the other hand, intense and sustained sound has serious implications for the vascular and brain development of the fetus and premature infant, with negative physiological and behavioral effects [8]. Today, however, certain practices expose fetuses and premature infants to potentially harmful levels of sound [9,10].

A study by Katarzyna et al. showed that the diagnostic hearing impairment of preterm infants is between 2% to 11% vs. 0.1% in the general pediatric population [11]. Excessive auditory stimulation has also been documented to create negative physiological responses [12] which can influence not only hearing impairments, but also chromosomal abnormalities, high cortisol levels, reduced levels of lactogen, abnormal brain and sense development, speech and language problems, and abnormal social behavior after birth [13].

Several reports on noise in NICUs showed that the equivalent continuous level (L_{eq}) ranges from 50 dBA to 89.5 dBA, with peak levels (L_{max}) of 105 dBA [14–18]. These

noise levels are above the 45 dB recommended by the American Academy of Pediatrics (AAP) [5], and the recommended impulse maximum of 65 dB by the World Health Organization (WHO) was also exceeded. The Environmental Protection Agency's hospital recommendations of 35 dB for nighttime periods were also exceeded [17].

Although international recommendations are designed to promote the problem of unsafe noise environments in the early development of newborns, the actual results are far off. The Sound Study Group recommends addressing the problem of high and/or sustained noise exposure in early development in NICUs [19]. Currently, these guidelines, together with those of the AAP [5], are internationally referenced in the care of fetuses and infants [20].

The fetus has a developmental advantage over the premature infant because the tissues of the maternal abdomen and uterus filter out high-frequency sounds, reducing them by up to 50 dB [21]. Specifically, uterine structures protect the fetus from sounds above 500 Hz [22]; it is, therefore, necessary to protect premature babies from sounds above this frequency, mainly because their auditory system is not yet ready. Abnormal stimuli adversely affect neural connections throughout the central and peripheral auditory system of premature infants; it is, therefore, important to know the frequencies to which they are exposed. The fetus, up to 27 weeks of gestation, predominantly hears frequencies below 500 Hz and probably cannot detect frequencies higher than 500 Hz until 29 weeks due to maternal tissue filtering [22].

Although it is necessary to assess sound frequencies in NICUs to protect premature infants from high-frequency noise, noise measurement studies using spectral sound analysis are not often found. In this regard, results obtained in a NICU indicated that there was significant high-frequency sound within the immediate care environment of the infant [2].

On the other hand, general electrical devices and ventilation systems are known to generate low-frequency noise. Previous studies showed that exposure to low frequencies causes balance disturbances in humans and mice during adulthood [23]. The World Health Organization recognizes the special place of low-frequency noise as an environmental problem [24]. Non-auditory physiological and psychological effects can be caused by low-frequency noise levels below a person's hearing threshold [25]. Therefore, newborns may have a potential risk of exposure to low frequencies in the NICU. However, the potential risks in neonates due to exposure to low-frequency noise have not been sufficiently studied [26] in terms of possible adverse effects on the health of newborn babies, hence the great importance of acoustic studies that incorporate frequency treatment in their work.

There are many sources of noise within a NICU [2,27], however, the incubator is a singular source of noise because it not only emits noise to the outside of the cabin but also the inside of the cabin [28]. In addition, as it is the space in which the newborn spends a lot of time, it is necessary to pay special attention to it.

Although there have been several scientific studies on the noise inside incubators, such work focused on assessing the noise inside the incubator under diffuse field conditions, i.e., in a space enclosed by reflective walls, floor, and ceiling (the NICU). Some of these studies investigated, from an acoustic point of view, (i) the effect of alterations in the structure of the incubator [29,30], (ii) the most efficient acoustical configuration [31], (iii) the effects of training and handling of hatchery equipment [32], (iv) incubator characteristics that have synergies with noise such as reverberation, temperature, and humidity [33,34], and (v) the incubator when tested in different states of operation [27,35,36], but always to assess the influence of noise from all sources inside the incubator, comparing it with variations in the physiological factors [29,37] of neonates or with international recommendations such as those of the AAP or the WHO [38].

The main characteristic of the ideal free field, in acoustics, is the absence of sound reflections. Therefore, any sound generated within the free field has a drop of 6 dB each time the distance in the direction of propagation is doubled [39]. In laboratory conditions, a free-field room is a room whose walls, ceiling, and floor are lined with sound-absorbing materials to minimize all sound reflections, also known as an anechoic room [40].

In this regard, the question arises as to whether isolating the incubator cabin from outside noise is the solution or whether, on the contrary, the incubator is the source of the noise, which does not allow compliance with the recommendations of international organizations, such as the AAP or the WHO, especially at night. In this sense, this work intends to perform an acoustic spectral study of the sound inside and outside the incubator in free-field conditions, i.e., in a situation where the only polluting sound source in the room is the incubator. In this way, it will be possible to know not only the global levels but also to quantify the spectral energy to which the neonate is subjected exclusively due to this source of noise.

2. Materials and Methods

2.1. Measuring Equipment

Sound level measurements were made with Brüel & Kjaer (Naerum, Denmark) equipment, using two different sound level meters (types 2270 and 2250) and a sound calibrator (type 4231). All noise measurement equipment was checked before and after each test.

The noise measurement equipment used is currently verified and calibrated. In all cases, data were collected on environmental conditions: temperature, pressure, and humidity in both rooms.

Data processing was performed using Brüel & Kjaer's Evaluator BK 7820 software with BZ7225 version 4.7.4 and Microsoft Excel (Naerum, Denmark).

2.2. Sample

The elements under study are represented by three different types of incubators: the Ohmeda Ohio-Care Plus incubator, the Dräger Caleo incubator, and the Ohmeda Giraffe incubator (Figure 1). The incubators were provided by the neonatal service of the intensive care unit of the "Puerta del Mar" University Hospital in Cadiz. The sample was randomly selected from the three models used in the NICU of this hospital and represents 27% of all incubators in the neonatology room.

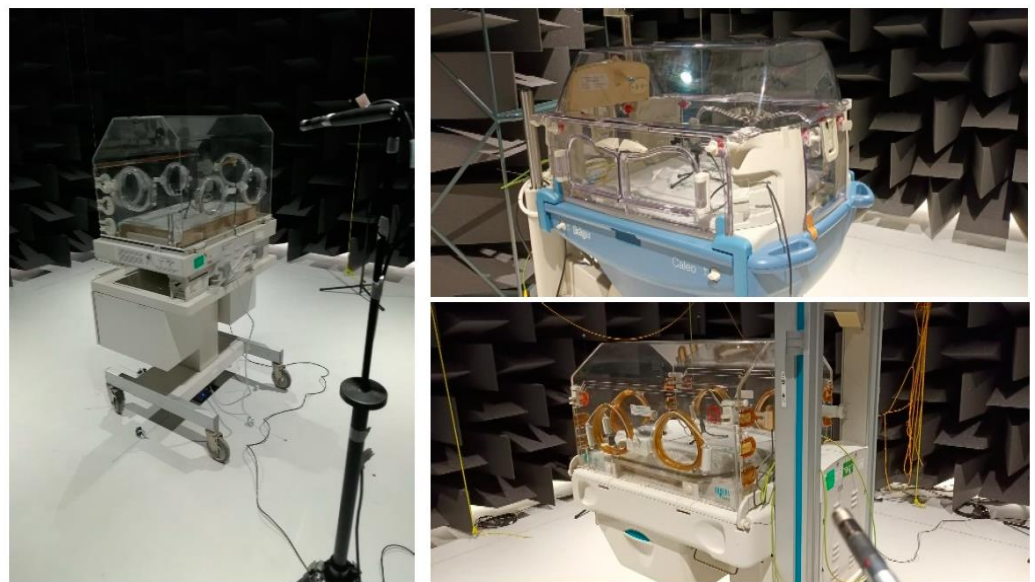


Figure 1. Ohmeda Ohio-Care Plus incubator on the **left**, Dräger Caleo incubator on the **upper right**, and Ohmeda Giraffe incubator on the **lower right**.

All three incubators use a similar noisy system, consisting of a motor and a fan, plus an alarm, which only works when an abnormality occurs in the operating conditions.

2.3. Measurement Procedure

The noise levels generated by the incubators, both inside and outside the neonatal cabin, were analyzed in a semi-anechoic room in different operating modes: (i) incubator off, to obtain the background noise outside and inside the incubator; (ii) incubator on, to obtain the sound pressure values both inside and outside the incubator; (iii) incubator running and temperature alarm triggered.

These operating modes made it possible to evaluate the sound environment generated by the incubators, how much it contributed to the interior of the neonatal cabinet, and how much it contributed to the external environment under controlled free-field conditions.

All tests were performed in unoccupied incubators located in the semi-anechoic room with a minimum cut-off frequency of 50 Hz, which provided free-field measurement conditions according to ISO 3745:2012. Microphones were placed inside the cabin (model 2270) and outside (model 2250) the incubator. Data recording was performed in third-octave bands.

The incubators were placed in the center of the semi-anechoic room, and measurements were taken in four positions at a 1 m distance from the edges between incubator faces and at a height of 1.5 m (Figure 2).

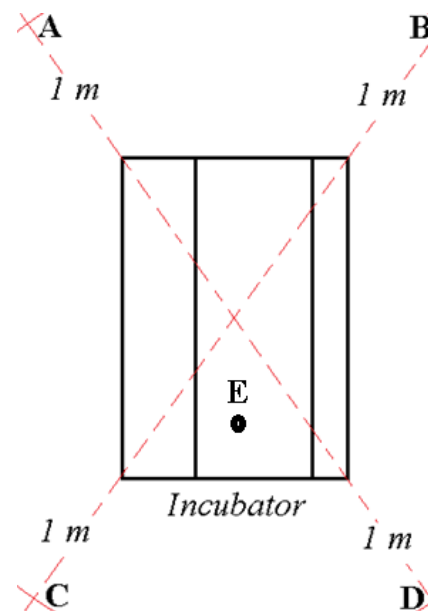


Figure 2. Microphone positions during measurements. A, B, C and D are the microphone positions, located 1 m from the edge of the incubator. E indicates the position of the microphone placed inside the incubator cabin, in the area where the neonate lays its head.

A microphone (model 2270) was placed inside the incubator in a fixed position at the place where the neonate's head rests (point E). A microphone (model 2250) was placed outside and was changed at each test between points A, B, C, and D, as shown in Figure 2. The inside/outside measurement was performed simultaneously at each of the defined points. The measurement time for each measurement was 1 min.

Linear values were recorded in third-octave frequency bands from 12.5 Hz to 20 KHz, and parameters were calculated:

- L_{Aeq} : A-weighted equivalent continuous sound level;
- L_{Ceq} : C-weighted equivalent continuous sound level;
- L_{Aeq} : A-weighted equivalent continuous sound level, measured with an impulse time constant;
- L_{AFmax} : A-weighted maximum sound level, measured with a fast time constant;
- L_{AFmin} : A-weighted minimum sound level measured with a fast time constant;

- L_{10} : the level just exceeded for 10% of the time;
- L_{50} : the level just exceeded 50% of the time;
- L_{90} : the level just exceeded 90% of the time.

The presence of low-frequency (K_f), tonality (K_t), and impulsivity (K_i) components should be taken into account, according to ISO 1996-2:2017 [41], and following the procedure below:

- Emerging tonal components: tonality is considered to exist if, in the spectral analysis in one-third octave, with Z weighting (i.e., in linear), it is verified that the difference in dB between the tonal band and the adjacent bands is at least 8 dB for frequencies between 20 and 125 Hz; at least 5 dB for frequencies between 150 and 400 Hz; and at least 3 dB for frequencies between 500 and 10,000 Hz;
- Low-frequency component: the presence of a low-frequency component is taken into account if the difference in dB between L_{Ceq} and L_{Aeq} measurements is at least 10 dB, with the values properly corrected for background noise;
- Impulsive components: the existence of impulsivity is taken into account if the difference between L_{A1eq} and L_{Aeq} is at least 10 dB, with the values properly corrected for background noise.

The criterion used in Spain to determine the corrected equivalent continuous level ($L_{K_{eq}}$) by K_t , K_f , and K_i has been used to evaluate the annoyance or harmful effects of environmental noise, which can increase the L_{Aeq} by up to 9 dB [42].

L_{10} , L_{50} , and L_{90} , together with the $L_{K_{eq}}$ value, are indicators that reflect the annoyance and harmful effects inherent to sounds with the presence of tonal, impulsive, or low-frequency components.

For the analysis of the data, the L_{Aeq} value of the highest level of those obtained in the four positions of the external microphone was taken, and, for the background noise, the L_{Aeq} value of the lowest level of those obtained in the four positions of the external microphone was taken.

3. Results

3.1. Incubator Off

As described in the methodology section, the background noise outside and inside the incubator cabin of the three incubators was obtained in the “off” incubator situation. Figures 1 and 2 and Table 1 show the values obtained in the semi-anechoic room in one-third octave and Z weighting.

Table 1. Incubator off. Background noise recorded outside and inside of the cabin incubator.

Incubator Model	Outside (Model 2250) dBA							Inside (Model 2270) dBA								
	L _{Aeq}	L _{Ceq}	L _{A1eq}	L _{AFmax}	L _{AFmin}	L ₁₀	L ₅₀	L ₉₀	L _{Aeq}	L _{Ceq}	L _{A1eq}	L _{AFmax}	L _{AFmin}	L ₁₀	L ₅₀	L ₉₀
Care Plus Rever	17.8	35	17.8	18.2	17.5	17.9	17.5	17.1	17.7	42.7	18.9	27.6	16.5	17.8	17	16.2
Dräger Medical	17.8	35.7	17.8	18.8	17.5	18.0	17.8	17.6	16.9	36.6	17.1	19.9	16.5	17.1	16.8	16.6
Giraffe	17.8	34.0	17.8	18.4	17.5	18.0	17.8	17.6	17.0	34.3	17.1	19.1	15.8	17.2	17.0	16.8

Table 1 shows that the background noise values had slight differences. The average L_{Aeq} value was 18 dBA outside and 17 dBA inside.

Under these measurement conditions, Figure 3 shows that the trends in the sound pressure levels in the one-third octave, from 200 Hz onwards, were very similar between the recordings in the semi-anechoic room and the recordings inside the incubator cabin. At low frequencies, the Care Plus incubator deviated, to some extent, from the trend between the indoor and outdoor recordings.

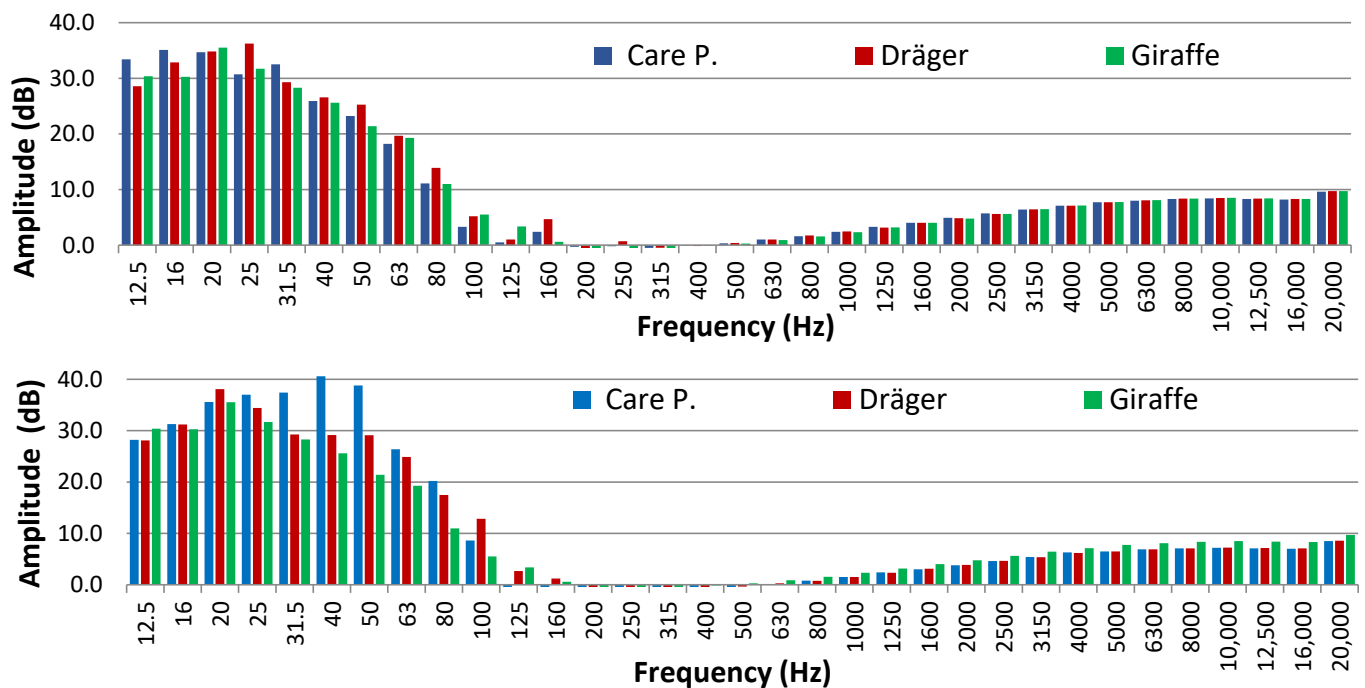


Figure 3. Background noise, incubators off: at the (top), semi-anechoic room; at the (bottom), incubator cabin interior.

3.2. Incubator On

In this situation, the incubators were kept operating during the whole test to obtain the sound pressure values both inside and outside the incubator cabin and to know the differences between one incubator and another. Under these conditions, the data obtained were as shown in Table 2.

Table 2. Incubators on: level in the semi-anechoic room and inside of the incubator cabin.

Incubator Model	Outside (Model 2250) dBA								Inside (Model 2270) dBA							
	L_{Aeq}	L_{Ceq}	L_{A1eq}	L_{AFmax}	L_{AFmin}	L_{10}	L_{50}	L_{90}	L_{Aeq}	L_{Ceq}	L_{A1eq}	L_{AFmax}	L_{AFmin}	L_{10}	L_{50}	L_{90}
Care Plus Rever	31.9	44.3	32.9	33.3	30.4	32.8	32.0	31.2	55.2	69.7	56.2	56.9	53.7	55.9	55.5	55.1
Dräger Medical	23.7	38.6	24.3	24.8	22.8	24.1	23.7	23.3	48.8	54.8	49.8	50.3	47.5	49.3	48.8	48.3
Giraffe	32.6	40.1	33.3	33.6	32.1	33.0	32.6	32.1	56.3	63.2	56.9	57.2	55.2	56.7	56.3	55.9

Table 2 clearly shows that the results inside the incubator cabin exceeded the values recorded outside. In these conditions, the Dräger model was the one that recorded the lowest levels, below 50 dBA inside the enclosure and with an outdoor emission of 23.7 dBA.

The spectrum in Figure 4 shows that this situation did not occur in all frequency bands, although it did occur in most frequency bands.

The Giraffe model recorded the highest A-weighted equivalent continuous level (L_{Aeq}) sound pressure values measured inside the incubator dome, at 56.3 dBA. This incubator model was the one that contributed the highest noise level to the external environment, with an L_{Aeq} of 32.6 dBA.

The graph also shows tones in certain frequency bands which stand out from the others, but these details are discussed in the following sections.

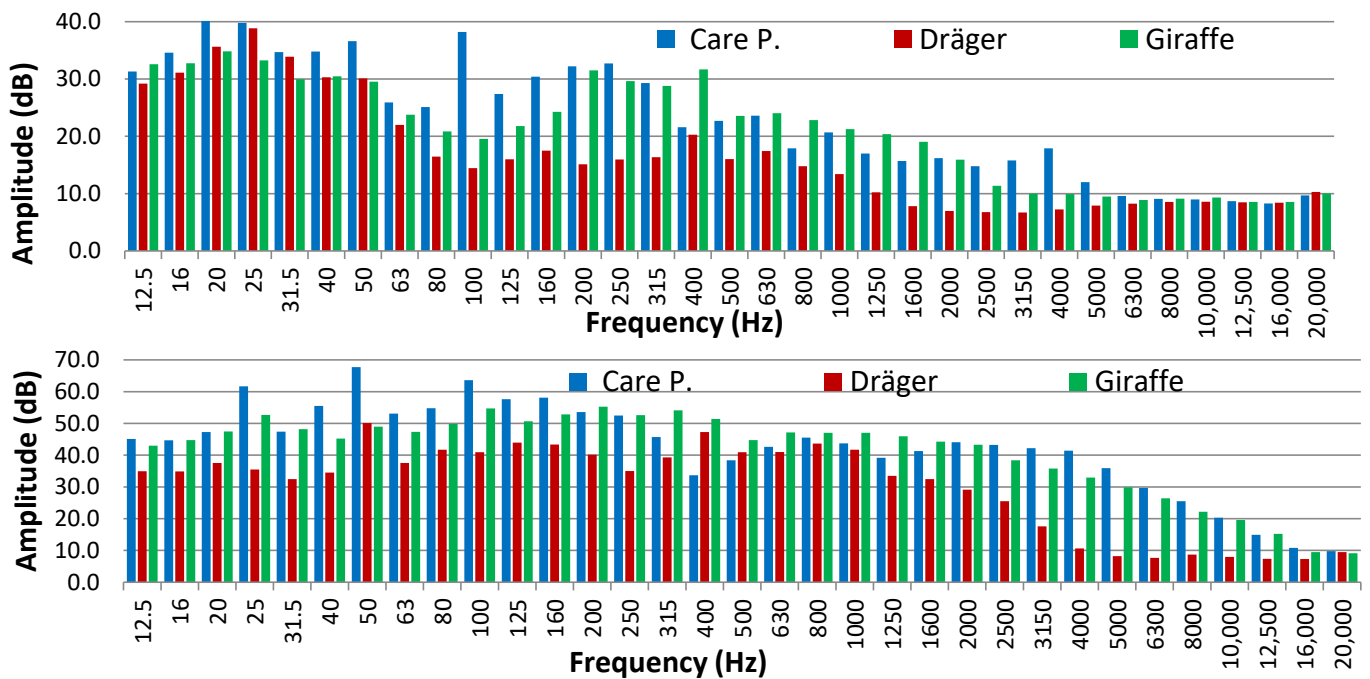


Figure 4. Incubators on: at the (top), semi-anechoic room; at the (bottom), incubator cabin interior.

3.3. Incubator on with Temperature Alarm Triggered

To analyze the influence of the presence of alarms both inside and outside of the incubator, each of the three incubator models was measured in the same positions as in the previous cases in the semi-anechoic room.

The graphs in Figure 5 show the values obtained under these conditions in one-third octave, with Z weighting, i.e., in linear.

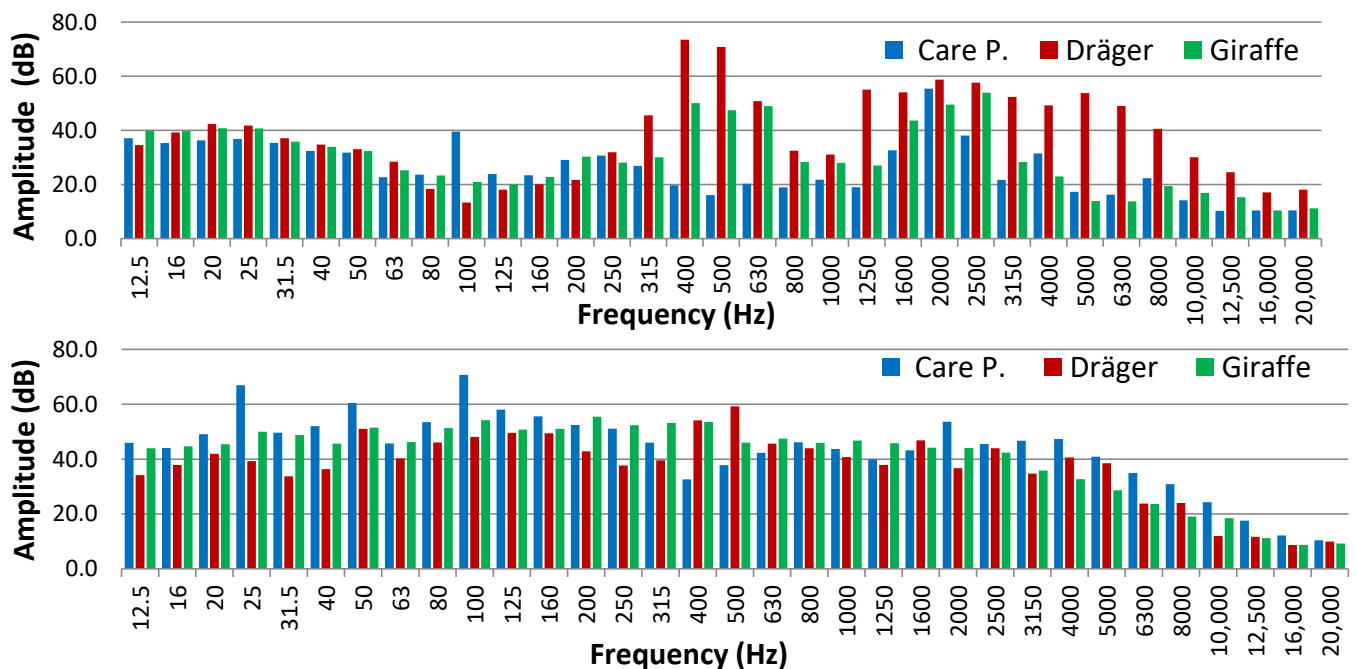


Figure 5. Incubator running with temperature alarm triggered: levels in the semi-anechoic room (top) and inside of the incubator cabin (bottom).

In these conditions, with the incubator in operation and the temperature alarm sounding, the Dräger Medical incubator model provided a higher level of sound amplitude

to the exterior than the other two incubator models analyzed in both medium and high frequencies. At the other extreme, we have the Care Plus incubator model, which produced the least noise.

The results obtained under these conditions (Table 3) show that the Giraffe is the incubator model that provides the lowest sound pressure level inside the incubation cabin.

Table 3. Incubators running with temperature alarm triggered. Noise levels in the semi-anechoic room and inside of the incubator cabin.

Incubator Model	Outside (Model 2250) dBA							Inside (Model 2270) dBA								
	L _{Aeq}	L _{Ceq}	L _{A1eq}	L _{AFmax}	L _{AFmin}	L ₁₀	L ₅₀	L ₉₀	L _{Aeq}	L _{Ceq}	L _{A1eq}	L _{AFmax}	L _{AFmin}	L ₁₀	L ₅₀	L ₉₀
Care Plus Rever	56.6	55.5	63.6	65.2	29.9	56.9	56.5	56.1	59.1	71.8	62.4	64.1	55.7	59.9	59.5	59.1
Dräger Medical	72.6	76.0	78.2	79.9	22.7	78.1	51.8	23.5	58.4	62.3	66.3	68.8	47.6	61.1	50.8	48.6
Giraffe	58.0	58.0	64.3	64.3	31.0	62.0	56.9	31.7	56.6	63.2	57.5	58.0	54.9	57.2	56.7	55.8

In general, when the alarm was triggered, the values were quite high, both outside and inside the incubator.

3.4. Equivalent Continuous Level Corrected (L_k) for the Presence of Low-Frequency, Tonal, and Impulsive Components

In this case, under the same conditions as in the previous sections (incubator running and temperature alarm triggered), the acoustic energy components that accentuate noise nuisance were analyzed. The results of this analysis are shown in Tables 4 and 5, and it is necessary to analyze the results shown in Figures 4 and 5.

Table 4. Incubators working.

Incubator Model	Outside (Model 2250) dBA							Inside (Model 2270) dBA						
	L _{Aeq}	L _{Ceq}	L _{AFeq}	K _t	K _f	K _i	L _{KEq}	L _{Aeq}	L _{Ceq}	L _{AFeq}	K _t	K _f	K _i	L _{KEq}
Care Plus Rever	31.7	43.8	32.8	6.0	3.0	0.0	41	56.1	69.0	57.9	6.0	3.0	0.0	65
Dräger Medical	23.0	45.4	23.7	6.0	6.0	0.0	32	48.8	54.7	49.7	6.0	0.0	0.0	55
Giraffe	32.4	38.9	33.1	3.0	0.0	0.0	35	56.3	63.2	56.9	6.0	0.0	0.0	62

Table 5. Incubators working and the temperature alarm is triggered.

Incubator Model	Outside (Model 2250) dBA							Inside (Model 2270) dBA						
	L _{Aeq}	L _{Ceq}	L _{AFeq}	K _t	K _f	K _i	L _{KEq}	L _{Aeq}	L _{Ceq}	L _{AFeq}	K _t	K _f	K _i	L _{KEq}
Care Plus Rever	56.6	55.5	63.6	6.0	0.0	0.0	63	59.1	71.8	62.4	6.0	3.0	0.0	68
Dräger Medical	72.5	76.0	78.2	6.0	0.0	0.0	79	58.4	62.3	66.3	6.0	0.0	0.0	64
Giraffe	58.0	58.0	64.3	6.0	0.0	0.0	64	56.6	63.2	57.5	6.0	0.0	0.0	63

To calculate the L_{KEq} , it is important to correct the previous L_{Aeq} for the background noise existing at the time of the test. Once the acoustic levels in one-third octave were obtained, we proceeded to the analysis to determine whether, for each of these values, there were emerging tonal components. Subsequently, the procedures described in Section 2.2 were used to assess impulsivity or low-frequency annoyance. If the presence of components was detected, it was necessary to add 3 or 6 dBA to the value corresponding to the A-weighted equivalent continuous level (L_{Aeq}) by the procedures indicated in the corresponding regulations [42].

Table 4 shows the L_{KEq} and K_t , K_f , and K_i values. The L_{KEq} values in the measurement period are reflected. It can be observed that, in all cases, tonal components, and, in some cases, low-frequency components, appeared.

Figure 4 shows that the noise generated outside by the Care Plus incubator had tonal components in the 100 Hz (38.2 dB), 630 Hz (23.6 dB), 1 KHz (20.7 dB), and 4 kHz (17.9 dB) bands, recorded outside the incubator, i.e., in the semi-anechoic room.

Inside the incubator cabin, the presence of tonal components was recorded in the 25 Hz (61.7 dB), 50 Hz (67.7 dB), and 100 Hz (49.9 dB) bands; the rest of the tones had values below 10 dB, which are assumed to be inaudible. The presence of low-frequency components was also detected, with a value of 12.9 dB.

Applying the procedure indicated above in the methodology section, no impulsive values were observed either outside the incubator or inside the cabin.

In the situation where the incubators were running with the presence of the temperature alarm, the values were higher (Table 5), although, in none of the cases studied, was the presence of impulsive values observed either outside or inside the incubator cabin where the premature newborn is located. It should also be noted that their duration was 1 s, which is why the algorithm used to determine the presence of the impulsive component was not adequate.

The highest $L_{K_{eq}}$ value measured outside the incubator was recorded for the Dräger Medica incubator (79 dBA), which was due to the alarm arrangement in this type of incubator. However, inside the incubator dome, the highest corrected equivalent continuous level $L_{K_{eq}}$ values were obtained for the Care Plus incubator, showing the presence of tonal components inside the incubator in the 25 Hz (66.9 dBA), 50 Hz (60.5 dBA), 100 Hz (70.7 dBA), and 2 KHz (53.6 dBA) bands and the presence of low-frequency components with a value of 12.9 dBA (Figure 5).

4. Discussion

The background noise conditions obtained during the different tests did not vary significantly above the frequency of 200 Hz; however, at lower frequencies, and due to the physical characteristics of the semi-anechoic room itself, they may have varied slightly from one test to another. It should be noted that the semi-anechoic room had a declared cut-off frequency of 50 Hz and could have influenced the low-frequency values. This cut-off frequency of 50 Hz implies that the room was not capable of absorbing frequencies below this value, and, therefore, there could have been reflections at very low frequencies.

It should also be noted that all incubators use the same system to heat the air and adjust the relative humidity, that is, a motor, a resistor, and a fan. This system, together with the incubator alarms, represents the main source of noise in the incubators analyzed. Therefore, the acoustic tone of the alarms, the number of fan blades, and the speed of the motor rotation can make a difference between one incubator and another.

On the other hand, it must be taken into account that an incubator is a relatively small enclosure, and the walls are highly reflective. This may be one of the reasons why the noise recorded inside the incubators was higher than outside the incubator in most of the cases analyzed, which coincides with other studies that took place in non-semi-anechoic rooms [28,33,35,36]. The exception was when the alarm is triggered. In this case, the work of the incubator insulation was appreciated to attenuate some of the alarm noise inside the incubator cabin [28,30,36].

Observing the graphs in Figure 3, incubator off conditions for the determination of background noise, it can be seen that the sound pressure levels in one-third octave recorded inside and outside the incubator were very similar, 200 Hz and above. Despite this, the Giraffe model stands out from the other incubators analyzed with slightly lower background noise; in any case, we are talking about noise below 10 dB for frequencies higher than 80 Hz, a noise inaudible to humans. However, below 100 Hz, it is the Care Plus incubator that stands out from the other incubators in this study, with slightly higher background noise.

When the incubators were in operation (Table 2), it should be noted that, of the three incubators, the Dräger Medical incubator was the one that contributed the fewest noise emissions to the environment. To appreciate the behavior in the one-third octave between

incubators, it is necessary to refer to Figure 4 (upper graph), where differences can be observed between one incubator and another, mainly in the range from 100 Hz to 4 kHz, a range in which the band of greatest hearing sensitivity of human beings is found. In the frequency range between 16 Hz and 250 Hz and between 3.15 kHz and 5 kHz, the Care Plus incubator showed a worse acoustic performance compared to the other models analyzed. However, in the frequency range between 400 Hz and 1.6 kHz, the Giraffe incubator had the worst acoustic performance. Therefore, in this case, the data in Table 2 ratify that the Dräger Medical incubator is the incubator with the least noise pollution in the external environment.

Regarding the noise inside the incubator cabin, the situation that affects the neonate for the most hours is that of the incubator running without the alarm triggered. This condition is shown in Table 2 and Figure 4, where the incubator with the lowest sound emission was the Dräger Medical, with an L_{Aeq} of 48.8 dBA. In addition, it should be noted that, according to the one-third octave sound pressure level data in Figure 4, the incubators showed different behaviors concerning noise. Overall, the Dräger Medical incubator had better noise performance than the other two models tested. The analysis of noise levels inside the incubator cabin showed worse acoustic behavior in the Care Plus incubator for the frequency range between 25 Hz and 160 Hz and between 2.5 kHz and 6.3 kHz. However, the Giraffe incubator provided a higher sound contribution to the cabin interior in the frequency range between 20 Hz and 1.6 kHz. In any case, the data indicate that the noise values inside the incubator cabin continued to be above the international recommendations of 45 dBA [5,24].

When the alarms were triggered, the difference between indoor and outdoor noise was reduced, although the differences were still significant. In this situation, the incubator model that provided a lower sound pressure level inside the incubator cabin was the Giraffe (Table 3). This may be due to the layout of the alarm and its acoustic characteristics, which were different in each of the incubators. However, the values obtained were still very high and were above the 45 dBA recommended by international organizations [5,24]. The third-octave sound pressure levels measured inside the incubation cabin of the models analyzed were very similar (Figure 5), although it is true that the Care Plus incubator stood out, with worse noise data than the other two incubators.

The $L_{K_{eq}}$ noise index, which represents the L_{Aeq} corrected for the presence of emergent tonal components, low-frequency components, and noise of an impulsive nature, makes it possible to assess the annoyance or harmful effects associated with sound pressure levels [19]. Although its widespread use is intended for the evaluation of activities or facilities, we believe that its application to this study is appropriate, given that the emitter that generates it is a neonatal incubator and the person who may be affected by the levels generated by the operation of this system is the neonate himself [5]. This parameter represents a starting point for assessing discomfort in neonates based on national regulations [42], and, without a doubt, it is possible to discuss whether the corrected values should be higher or lower, but there is no doubt that the presence of tonality, low frequencies, and impulsiveness increases noise annoyance in humans. We must bear in mind that noise with the same sound pressure level can become more harmful or annoying depending on its nature [20], which can be defined by the presence of those components associated with it.

Table 4 and Figure 4 show the presence of tonal components. Inside the incubator cabin, all of them show the presence of similar tonal components (K_t). It was observed that, although the Dräger incubator had lower outside L_{Aeq} than the Giraffe, the K_t values compensated for the result by equaling the $L_{K_{eq}}$ value of both incubators (K_t). Concerning low-frequency component (K_f) discomfort, the Giraffe was the only one that did not show this characteristic either outside or inside the incubator cabin. The nuisance due to the presence of impulsive components (K_i) did not manifest itself in any of the incubators in the operating state, with or without the alarms on.

Table 5 shows that the highest A-weighted corrected equivalent continuous levels ($L_{K_{eq}}$) were recorded inside the cabin of the Care Plus model incubator, reaching

values of 68 dBA. However, the incubator that provided the highest level of outside noise was the Dräger model, at 79 dBA. This was due to the alarm arrangement in that incubator. The increase concerning L_{Aeq} was due to the presence of tonality and/or low-frequency components.

Figure 5 below shows that, inside the incubator, when the temperature alarm was active, the highest noise level was in the 100 Hz band, followed closely by the 25 Hz band, for the Care Plus incubator. These values correspond to the low-frequency spectrum, between 20 and 125 Hz, which implies that the sound may be more annoying or harmful than if this low-frequency component did not exist. This situation manifested the presence of low-frequency components K_f with a value of 12 dBA. On the other hand, the sound of the alarms added the presence of tonal components starting at 400 Hz. The sound of the alarms increased the noise from the outside more than from inside the incubator cabin. In any case, it exceeded the recommendations of international organizations, 45 dBA. An improvement to reduce the influence of the alarm on noise would be to extend the duration of the alarm cycle, keeping the duration of the sound fixed (e.g., 1 s active for every 10 s inactive).

To appreciate the sound of the alarms in the spectral representation, it is necessary to compare Figures 4 and 5, although, in the Dräger incubator, it is appreciated, since it had higher alarm sound levels. In this regard, comparing Figures 4 and 5 shows that the alarms produced sounds above 400 Hz up to almost 12.5 kHz. On the other hand, the alarm sound lasted 1 s out of the 6 s of the complete cycle and was repeated until the alarm was attended. This is the reason why the procedure used did not detect the presence of impulsivity. Even if there was no presence of impulsivity, there is no doubt that the number of reiterative events would annoy, and it would, therefore, be interesting to consider a parameter that evaluates this annoyance as a function of the number and frequency of events.

A comparison of the frequency spectrum for the NICU room and the incubator inner space revealed that noise levels in the 20–250 Hz range were higher in the incubators, and, in the room, they were in the 315–2500 Hz range [36].

Until the 27th week of pregnancy, fetuses only hear the lowest frequencies; also, probably, they cannot hear frequencies above 500 Hz until two weeks later owing to efficient filtering by maternal tissues [21]. The hearing sensitivity range of a fetus in the third term of pregnancy is 500–1000 Hz, and that of a term neonate is 400–4000 Hz [43].

Based on the previous data, it is worth asking if the noise levels inside the incubators cabin affect the neonates. Based on existing references, the answer is “yes” because the sound frequencies inside the incubator cabin are within the audible noise range of a newborn.

5. Conclusions

Under semi-anechoic room conditions, it was found that:

- (i) The incubator itself represents an important source of noise for the newborn, exceeding in all cases inside the cabin the noise level of 45 dBA recommended by international organizations;
- (ii) The noise emitted by the incubator to the outside is relatively contained; however, when the alarms are activated, the noise increase is significant, reaching, in some cases, L_{Aeq} values of 72.5 dBA;
- (iii) Tonal components were detected in all cases, and, in some cases, also low-frequency components. These components accentuate noise nuisance and should be taken into account by international organizations in the future;
- (iv) In addition to those described above, it would be convenient to introduce some kind of index to assess the annoyance caused by several repetitive, noisy, transient events, thus, recommending to alarm manufacturers what is the appropriate duration of the alarm sound in the total cycle time.

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Data Availability Statement: The data obtained to carry out this work are based on original sound recordings, processed using specific software, specifically the 7820 Evaluator, developed by the company Brüel & Kjær. The 7820 type requires a license and associated HASP dongle to function. For this reason, it is necessary to apply certain restrictions to these data. The data sets generated and/or analyzed during the current study are not publicly available. Still, they are available through the authors upon reasonable request and with the permission of the director of the Acoustic Engineering Laboratory of the University of Cádiz (Ricardo Hernandez Molina).

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