Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Sarah Margrethe Løvald

Sound Conditions at the Neonatal Intensive Care Unit

Master's thesis in Civil and Environmental Engineering,
Supervisor: Gabriele Lobaccaro, NTNU
Co-supervisor: Simone Conta, SINTEF & Sverre Hestetun, COWI
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Preface

This thesis is the result of a master's thesis during the spring semester of 2022 at the five-year Master of Science program Civil and Environmental Engineering, at the Norwegian University of Science and Technology (NTNU).

I would like to thank everyone who has been helpful in the work of this thesis. Simone Conta from SINTEF has been the co-supervisor of this thesis, and has contributed with excellent supervision throughout this semester. Through several meetings and mails, we have had discussions on matters such as measurement methods, post-processing and general assessment of the results. I would like to thank Simone for his contribution and interest in this project, and for excellent guidance. I could not have asked for a better co-supervisor, thank you.

Sverre Hestetun from COWI has also been my co-supervisor. His experience from work as an acoustic consultant has been most valuable for this thesis. I would like to thank Sverre for constructive discussions on measurements and results, as well as assistance during the measurement period in Oslo.

Gabriele Lobaccaro has been my main supervisor. I would like to thank him for checking up on my progress during the semester and making sure I have gotten all the help I have needed.

I would also like to express my gratitude to the excellent staff at both Rikshospitalet and St.Olavs Hospital for letting me conduct the measurements at the neonatal intensive care units, as well as providing excellent assistance during the days of measurement. Special thanks to Laila Øyen at St.Olavs Hospital for letting me come by the unit several times to conduct measurements. Also, much gratitude to Atle Moen for making it possible to conduct measurements at Rikshospitalet during a global pandemic.

Abstract

Elevated sound levels at the neonatal intensive care unit (NICU) may contribute to several physiological changes in preterm infants. Yet, recommended sound level limits are consistently exceeded at units in other countries. There is need to make similar measurements in Norway, especially on the inside of the incubator, as the possible side effects due to incubator noise have long been debated. The main objective of this thesis is to assess the sound levels at Norwegian NICUs, to evaluate the incubator sound level contribution, how this affects the sound levels inside of the incubator, and to suggest measures to achieve the recommended limit values inside of the incubator.

Sound pressure levels were measured continuously for 4-5 days at two different NICUs in Norway; one at a shared unit at Rikshospitalet in Oslo, and another at a single patient room at St.Olavs Hospital in Trondheim. Here, the equivalent sound pressure level (L_{eq}), the maximum sound pressure level (L_{max}), and the sound pressure level exceeded 10 percent of the time (L_{10}) were determined. Measurements were compared to the limit values from Journal of Perinatology: Recommended Standards for NICU design (Martin, 2003): $L_{eq} < 45$ dBA, $L_{10} < 50$ dBA and $L_{max} < 65$ dBA. Sound pressure levels inside and outside of an unoccupied incubator were also measured, and the sound power levels generated by four different incubator setting combinations were determined using ISO 3746 (ISO, 2010*a*).

The averaged sound pressure levels L_{eq}, L_{10} and L_{max} were 54.8 dBA, 56.3 dBA and 96.3 dBA at Rikshospitalet, and 48.4 dBA, 50.7 dBA and 87.3 dBA at St.Olavs Hospital. The incubator was found to attenuate environmental noise by 12 dB. Sound power level, L_{WA}=31.1 dB when only the incubator climate control was turned on, L_{WA}=31.3 dB when the oxygen supply was turned on, and L_{WA}=52.3 dBA when the vacuum pump was turned on. Inside of the incubator, L_{eq}=40.7 dBA when only the incubator climate control was active, L_{eq}=54.0 dBA when the oxygen supply was turned on, and L_{eq}=50.8 dBA when the vacuum pump was turned on.

Sound levels at both NICUs exceeded the recommended limit values, however, the sound levels at St.Olavs Hospital were lower than the levels at Rikshospitalet. The vacuum pump of the incubator contributed to exceeding the limit values on the outside of the incubator. While on the inside of the incubator, both the vacuum pump, as well as the oxygen supply and the incubator climate control were all contributing to exceeding the limit values. To achieve the recommended sound level limit values inside of the incubator, changes must be made to both the vacuum pump, the oxygen supply and the incubator climate control. Changes made to plan structure has some impact on the environmental sound levels. However, without reducing sound levels from the incubator, such a measure has little effect on the sound levels inside of the incubator. Further studies are needed to suggest measures to reduce the incubator noise. The study also poses the question whether the sound levels at the NICU are too high, or if the limit values are too strict.

Sammendrag

Høye lydnivåer på nyfødtintensiv avdeling kan bidra til flere fysiologiske endringer hos spedbarn. For å opprettholde et sunt akustisk miljø for nyfødte, bør grenseverdier for lydnivået i nyfødtavdelingen ikke overskrides. Lydmålinger fra avdelinger i andre land viser at disse grensene konsekvent overskrides. Det er behov for å gjøre lignende målinger i Norge, og spesielt på innsiden av kuvøsen da mulige bivirkninger på grunn av kuvøsestøy lenge har vært diskutert. Hovedmålet med denne oppgaven er derfor å vurdere lydnivået ved norske nyfødtintensiv avdelinger. Det er også å vurdere kuvøsens lydnivåbidrag, og hvilke tiltak som kan bidra til å oppnå anbefalte lydnivågrenseverdier inne i kuvøsen.

Lydtrykknivå ble målt kontinuerlig i 4-5 dager ved to ulike nyfødtintensiv avdelinger i Norge; en på felles avdeling på Rikshospitalet, den andre på et enkeltpasientrom ved St.Olavs Hospital. Her ble det ekvivalente lydtrykknivået (L_{eq}), det maksimale lydtrykknivået (L_{max}), og lydtrykknivået oversteget 10 prosent av tiden (L_{10}) målt. Målingene ble sammenlignet med grenseverdier fra Journal of Perinatology: Recommended Standards for NICU design (Martin, 2003): L_{eq} < 45 dBA, L_{10} < 50 dBA og L_{max} < 65 dBA. Lydtrykknivåer i og utenfor en ubrukt kuvøse ble også målt, og lydeffektnivå generert av fire forskjellige kuvøseinstillinger ble bestemt ved bruk av ISO 3746 (ISO, 2010a).

De gjennomsnittlige lydtrykknivåene L_{eq}, L_{10} og L_{max} var 54.8 dBA, 56.3 dBA og 96.3 dBA på Rikshospitalet, og 48.8 dBA, 50.7 dBA og 87.3 dBA på St.Olavs Hospital. Kuvøsen viste seg å dempe støy fra avdelingen med 12 dB. Lydeffektnivå, L_{WA}=31.1 dB når bare klimakontroll var slått på. L_{WA}=31.3 dB når oksygentilførselen var slått på, og L_{WA}=52.3 dBA når vakuumpumpen er slått på. L_{eq}=40.7 dBA på innsiden av kuvøsen når kun klimakontroll var aktiv . L_{eq}=54.0 dBA når oksygentilførselen var skrudd på, og L_{eq}=50.8 dBA når vakuumpumpen var skrudd på.

Lydnivåene ved St.Olavs Hospital var lavere enn nivåene ved Rikshospitalet, likevel overskred begge avdelingene de anbefalte grenseverdiene. Vakuumpumpen til kuvøsen genererte lydnivåer som bidro til å overskride grenseverdiene på utsiden av kuvøsen. På innsiden av kuvøsen var imidlertid både vakuumpumpen, oksygentilførselen og klimakontroll med på å overskride grenseverdiene. For å oppnå de anbefalte grenseverdiene for lydnivå inne i kuvøse må det gjøres endringer på både vakuumpumpe, oksygentilførsel og kuvøsemotor. Endringer i planstrukturen har en viss innvirkning på miljøstøynivået, men uten å redusere lydnivået fra kuvøsen, har et slikt tiltak liten effekt på lydnivået inne i kuvøsen. Ytterligere studier er nødvendig for å foreslå tiltak for å redusere kuvøsestøyen. Studien stiller også spørsmålet om lydnivåene ved nyfødtintensiv er for høye, eller om grenseverdiene er for strenge.

Contents

1 Introduction

1.1 Motivation

During the summer of 2021, one year prior to this masters' thesis, I had the opportunity to participate in a summer internship for COWI in Oslo. In the course of the internship, COWI was hired by Rikshospitalet to conduct sound measurements at a neonatal intensive care unit (NICU). Measurements were conducted due to helicopter noise from the outside building, and were to be measured at patient rooms and the neonatal intensive care unit. During my stay, I was therefore given the opportunity to participate in these measurements, and to post-process the results.

After conducting the measurements and post-processing the results, the sound pressure levels at the NICU proved to be alarmingly high. Since preterm infants residing at the NICU already are in a vulnerable state, great concern was expressed by medical staff during the presentation of the results. However, due to the completion of my internship at COWI, I was not able to see the project through. Nor were I able to learn of the measures suggested to reduce the sound levels. Thus, the motivation of this thesis is to draw attention to the elevated sound levels at NICUs, and to find measures that might help reduce these sound levels.

1.2 Background

Noise is defined as unwanted sound which is annoying and/or damaging for a person's health and well-being (Arbeidstilsynet, n.d.). According to *Forurensningsloven* (Klima- og miljødepartementet, 1983), noise is considered a source of pollution, and can cause permanent hearing loss if the noise is either sudden, or the noise load is loud and prolonged (Aasvang et al., 2014). Hearing loss can lead to ailments such as both tinnitus and mental difficulties. Other injuries due to prolonged noise exposure are; increased risk of sleep disorder, cardiovascular disease, increase in blood pressure, muscle tension, stress and digestive problems (Aasvang et al., 2014).

In a report by Hurtley (2009), children, elderly and chronically ill patients are described as particularly vulnerable to noise exposure. Especially preterm infants of low birthweight, as they have a higher risk of deafness (Douek et al., 1976). Research conducted by Gupta et al. (2018), shows that newborns exposed to high noise levels can experience several physiological changes, such as hearing damage, increase in blood pressure and heart rate, and reduced oxygen saturation. Several psychological changes are also mentioned, such as changed behavioral responses and enhanced pain perception. Similarly, Cardoso et al. (2015) concludes that low-weight neonates in incubators are prone to physiological changes such as differences in heart rate and oxygen saturation when exposed to noise.

1.3 Noise at the neonatal intensive care unit

During the autumn of 2021, I conducted a literature review to find the measured sound levels in neonatal intensive care units across the world. To take into account the noise sensitivity of newborns, both the World Health Organization (World Health Organization, 1999), the American Academy of Pediatrics (Health, 1997) and the Journal of Perinatology (Martin, 2003) state their own limit values for noise in neonatal intensive care units. However, during the literature review, I found that the environmental sound levels consistently exceeded these recommended limit values. Among 16 measurement at various hospitals across the world, all measurements showed sound levels exceeding the limit values. Based on the findings I made in the literature review, I concluded that the current sound levels at neonatal intensive care units across the world are unacceptable.

1.4 Noise inside incubators

During the the literature review, I suggested several measures to reduce sound levels at neonatal intensive care units. Measures such as implementing noise reduction protocols and sound-activated noise meters were amongst some measures. However, during the literature review, I assumed sound levels generated by the incubator were low and of insignificant contribution. Newborns admitted to neonatal intensive care units are often placed inside incubators to keep the temperature, humidity and oxygen at controlled levels. However, the possible side effects due to incubator noise have long been debated. According to Restin et al. (2021), the incubator, in particular its fan, is a major source of noise, which might have an impact on the newborns.

While conducting the literature review however, I was not aware that the incubator sound level contribution had long been debated. Because of this, the measures I chose to look for were mainly about reducing the environmental noise, and not so much about reducing the sound levels generated by the incubator itself. Had I known the incubator itself also generated elevated sound levels, the main objective would go beyond excessively focusing on environmental sound levels at the neonatal intensive care unit. Hence, the measurements conducted in this thesis will both be measured inside, as well as outside of the incubator, and will focus on to what degree the incubator itself contributes to these sound levels.

1.5 Project objective

The noise levels at neonatal intensive care units should not exceed certain limit values, yet sound measurements from units in different countries show that they are consistently exceeded (Chen et al., 2009; Valizadeh et al., 2013; Parra et al., 2017). Measurements have been made in other countries, and there is need to make similar measurements in Norway, especially on the inside of the incubator as the possible side effects due to incubator noise have long been debated.

The main objective of this thesis is to assess the sound pressure levels that preterm infants are exposed to at the neonatal intensive care unit, mainly focusing on incubator sound level contribution both inside and outside of the incubator. I will achieve the main objective by answering these research questions:

1. What are the sound levels infants are exposed to inside and outside of an incubator at the neonatal intensive care unit?
2. How does the incubator contribute to these sound levels?
3. Which measures can be used to achieve the recommended sound level limit values inside of the incubator?

1.6 Limitations

The following limitations apply to this thesis:

Firstly, the main objective and research questions were changed during the measurement period. At the beginning of the measurement period, the research questions focused on environmental sound levels and how they influenced the inside of the incubator. To be able to suggest measures, simulations were conducted in the room acoustic software ODEON (ODEON, n.d.). However, after the measurement period, changes were made to the research questions, focusing on the incubator contribution inside of the incubator instead. Due to this, simulations in ODEON were no longer necessary, and limited data was collected to answer the research questions. Ideally, more measurements should have been conducted inside of the incubator, such as measuring the reverberation time inside of the incubator and making changes to the interior of the incubator.

Secondly, the thesis is limited to Norwegian sound conditions in hospitals. However, the sound measurements were only carried out at two hospitals in Norway; Rikshospitalet in Oslo, and St.Olavs Hospital in Trondheim. The assignment will therefore not be able to represent the sound conditions at all Norwegian hospitals, as there are only a few samples and limited statistical validity. The thesis is mainly written with a building and room acoustic perspective. Although some past studies are mentioned, the thesis will not go deeper into how noise affects the health of premature babies. Neither will it elaborate how an incubator works and operates, as this is beyond my area of knowledge.

Thirdly, the assessment of the sound levels does not include other noise sources such as ventilation and water pipes. Also, only one type of incubator is represented in this thesis. The incubator used during measurement is described in Section 3.2.1 and is used at both Rikshospitalet and

St.Olavs Hospital. However, infant incubators are not the only type of containment used to maintain infants' health at the two NICUs. Another product used at NICUs is an infant radiant warmer without a lid. Because enclosing is not possible, it would have been of no interest to make measurements inside of a radiant warmer. However, it would have been of interest to measure the sound levels generated outside of a radiant warmer as this too impacts the sound levels at the NICU.

2 Theory

In this section, relevant theory used in the thesis will be presented.

2.1 Sound pressure level, L_p

When sound is generated, sound waves propagate, causing small changes in the ambient air pressure while travelling. This sound pressure can be measured with a microphone, which functions as a pressure sensor. Sound pressure level (SPL) is defined by the general equation:

$$L_p = 20\log\frac{p}{p_{ref}}[\text{dB}] \tag{1}$$

Where p is the root-mean-squared pressure in Pascals [Pa], and p_{ref} is a reference pressure ($p_{ref} = 20\ \mu$Pa) which corresponds to the hearing threshold of human beings at 1000 Hz. Due to large deviations between lower and higher pressure levels, a logarithmic scale is used, hence sound pressure levels are expressed in decibels.

2.2 Sound pressure levels L_{eq}, L_{10} and L_{max}

In this thesis, three different methods will be used to describe the sound pressure level:

1. Equivalent continuous sound pressure level, L_{eq}
2. Statistical sound pressure level, L_{10}
3. Maximum sound pressure level, L_{max}

Sound pressure levels (SPLs) are constantly changing for a given period of time, and to find an average sound level, the equivalent continuous sound pressure level, also known as the time-averaged sound pressure level, L_{eq}, is used. L_{eq} presents the average sound pressure level, which over a given period of time, has the same total amount of energy as the actual fluctuating noise.

Sound pressure levels can also be presented as a statistical parameter, L_n, which describes the L_{eq} that is exceeded n% of the time. During the measurements at the newborn intensive care unit, L_{10} will be measured, which describes the L_{eq} that is exceeded 10% of the time. In Figure 1, a visual comparison of these sound descriptors can be observed, in addition to L_{50} and L_{90}. The maximum sound pressure level, L_{max}, is also depicted, which describes the highest sound pressure level during a single noise event.

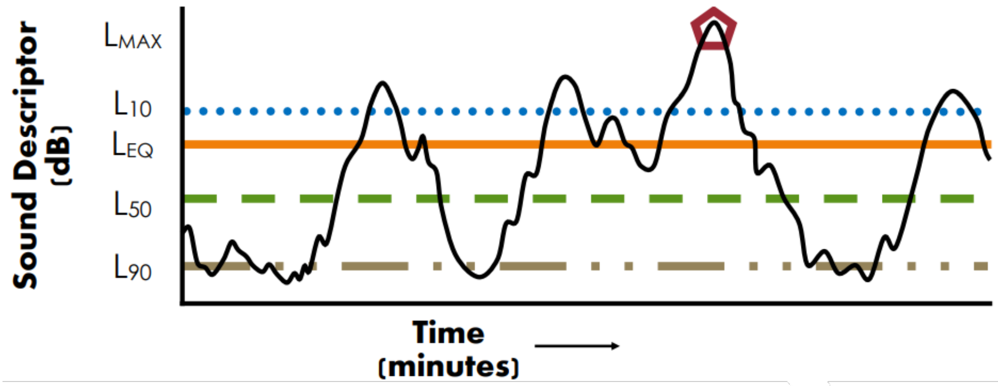


Figure 1: A visual comparison of different sound descriptors by U.S Department of Transportation (n.d.).

2.3 Logarithmic average

In this thesis, measurements will be conducted over several days and at different positions. To find an average sound pressure level (SPL), the logarithmic average value is calculated using Equation 2.

$$SPL_{average} = 10log\left(\frac{1}{N}\sum_{i=1}^{N}10^{\frac{x_i}{10}}\right) \tag{2}$$

where N is the number of measurements, and x_i is the value result of measurement number i.

2.4 Sound power level, L_W

When sound propagates, acoustic sound power is transmitted. The sound power level of a source is independent of its surrounding environment. By knowing the sound power level of a device, one can compare the sound output of different devices in a room without knowing the sound properties of the room. When frequency A-weighting (described in Section 2.5) is applied, the A-weighted sound power level is denoted L_{WA}, and is calculated using Equation 3.

$$L_{WA} = 10log\left(\sum_{i=1}^{N}10^{\frac{x_i}{10}}\right) \tag{3}$$

where x_i is the weighted sound power level at frequency i, which is calculated using Equation 4.

$$x_i = L_W(frequency_i) + Aweight(frequency_i) \tag{4}$$

where $L_W(frequency_i)$ is the measured sound power level at frequency i, and $Aweight(frequency_i)$ is the A-weight value at frequency i.

2.5 Frequency-weighting

Sound pressure levels can be divided into separate *frequency bands* (such as octave or third-octave bands), where the highest frequency is twice the lowest frequency, and the sound pressure level is the logarithmic sum of the levels in each frequency band. The hearing threshold of humans however, is not linearly increasing with increasing frequency, and must therefore be *weighted* to better represent the experienced sound level. In Figure 2, one can observe the equal-loudness curves which describe how humans perceive different frequencies relative to each other. As seen in the figure, the ear is less sensitive to low frequencies, and the maximum sensitivity region is around 3-4 kHz.

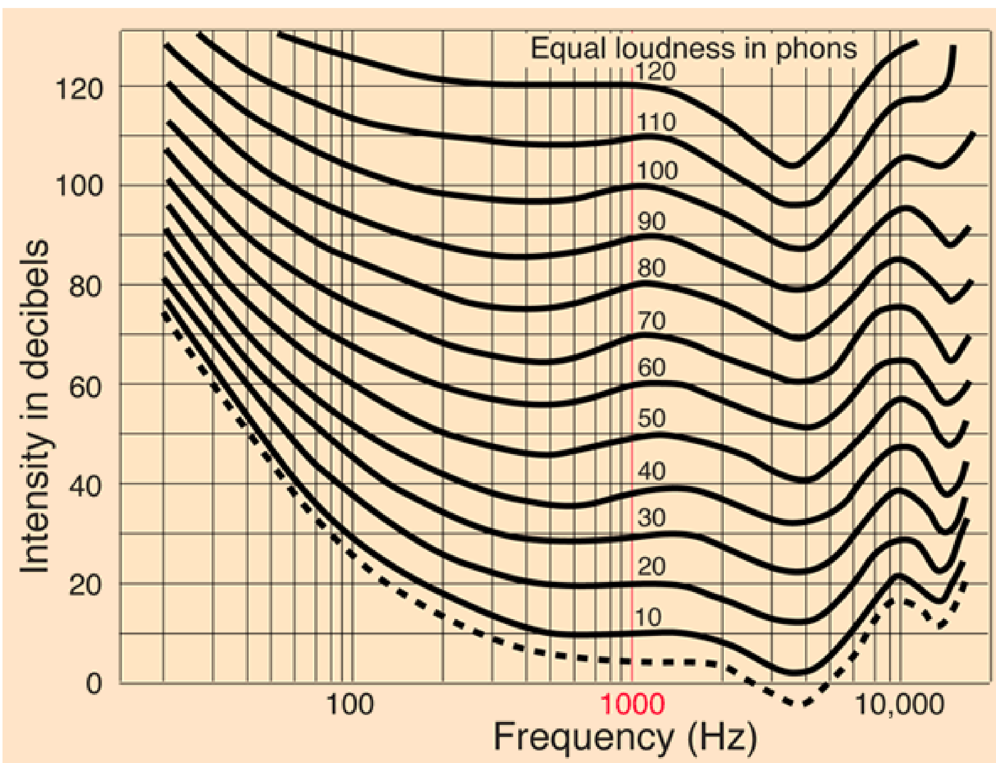


Figure 2: The equal-loudness curve (Hyperphysics, n.d.).

To account for the relative loudness perceived by the human ear, *frequency-weighting* is applied to measured sound levels. This is done by adding table values to the measured sound levels, either listed by octave or third-octave bands. Measurements are usually A-weighted, with units written as dB(A) or dBA. Other weightings exist, such as B-, C-, D- and Z-weighting.

2.6 Human perception of sound

To understand decibel ratings, it is normal to use a decibel-scale which compares different decibel ratings to common sounds which generate the same sound intensity. In Table 1, such a scale is presented. Although there are some variations for individuals, studies show a good approximation of how a change in sound level is perceived by the human ear, which can be seen in Table 2.

Intensity	Sound	Intensity	Sound
140 dBA	Jet engine at 5 meters	**70 dBA**	Vacuum cleaner
130 dBA	Machine gun at close range	**60 dBA**	Normal conversation
120 dBA	Rock concert	**50 dBA**	Quiet office
110 dBA	Loud thunder	**40 dBA**	Quiet street at night
90 dBA	Chainsaw	**30 dBA**	Soft whisper or ticking clock
80 dBA	Heavy truck traffic	**20 dBA**	Rustling leaves

Table 1: Examples of common sounds and their decibel ratings. Modified from Modular Walls (2016).

Change in sound level	Perceived change to the human ear
± 1 dB	Not perceptible
± 3 dB	Threshold of perception
± 5 dB	Clearly noticeable
± 10 dB	Twice (or half) as loud
± 20 dB	Fourfold change
± 30 dB	Eightfold change
± 40 dB	16 times
± 50 dB	32 times

Table 2: Perceived change in decibel levels. Modified from Modular Walls (2016).

2.7 Reverberation time

Due to reflections from surfaces such as walls, floors and ceilings, reverberation is created. Reverberation time is therefore the time required for sound to decay in a closed space. The reverberation time is defined as the time it takes for sound to decay by 60 dB, and can be written as T_{60}.

Measuring T_{60} accurately is often quite difficult as it is challenging to generate a sound level that is stable and consistent for the measurement. To solve this problem, it is common to measure T_{30} or T_{20} instead, and multiply these by 2 or 3 respectively to achieve T_{60}. A descriptive graph of the 30 dB decay time (T_{30}) and 20 dB decay time (T_{20}) can be seen in Figure 3.

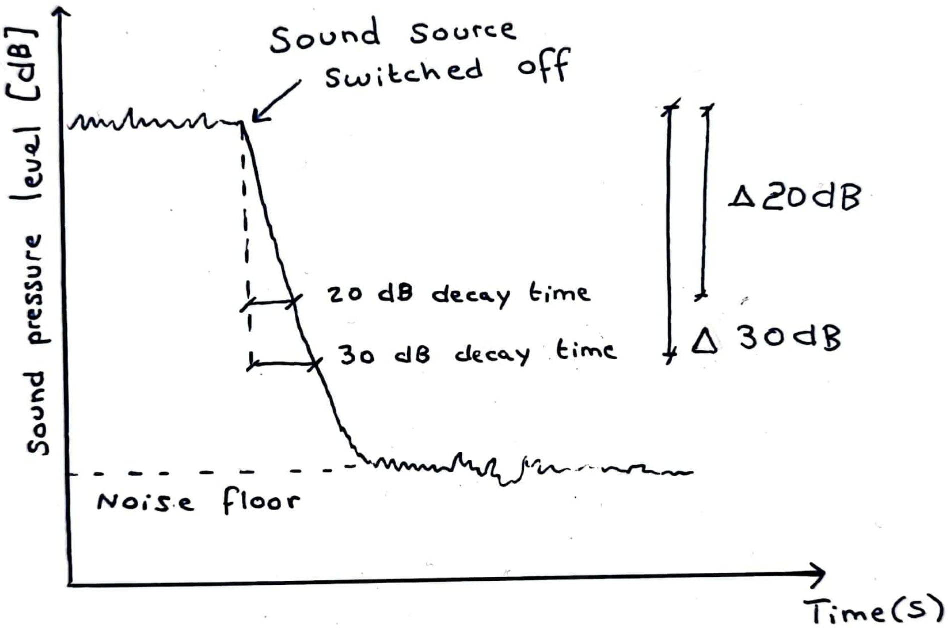


Figure 3: Graph describing T_{30} and T_{20}. Modified from Roberts (2018).

2.8 Recommendations and limit values

In Table 3, an overview of the limit values that are most often used in the literature when discussing sound levels at newborn intensive care units are listed. The table was made during the literature review described in Section 1.4. The measurements achieved in this thesis will be compared to the limit values presented in Journal of Perinatology: Recommended Standards for NICU design (Martin, 2003). I.e. the limit values: $L_{eq} < 45$ dBA, $L_{10} < 50$ dBA and $L_{max} < 65$ dBA. These limit values are applied to sound **pressure** levels, and not sound **power** levels. The A-weighted sound power level, L_{WA} will not be compared to these limit values.

	Limit values and recommendations
American Academy of Pediatrics (Health, 1997)	The neonatal intensive care unit shall develop routines and monitor noise so that L_{eq} does not exceed 45 dBA.
Journal of Perinatology: Recommended Standards for NICU design (Martin, 2003)	Noise level in neonatal intensive care unit should not exceed continuous sound level $L_{eq} < 45$ dBA, $L_{10} < 50$ dBA and $L_{max} < 65$ dBA.
Guideline Values (World Health Organization, 1999)	Guidelines recommend that hospital noise levels do not exceed $L_{eq} < 30$ dBA and $L_{max} < 40$ dBA. Indicative values for sound levels in incubators must await future research.
IEC 60601-2-19: Particular requirements for the basic safety and essential performance of infant incubators (IEC, 2020)	The noise level inside the incubator should not exceed the sound pressure level, $L_{max} < 60$ dBA. If an alarm is triggered, it shall not exceed 80 dBA.

Table 3: An overview of the limit values that are most often used in the literature when discussing sound levels at newborn intensive care units.

2.9 Measurements at neonatal intensive care units in other countries

Table 4 shows an overview of different sound measurements at neonatal intensive care units in five different countries. All measurements exceed the limit values given in Table 3, and the data was collected during the literature review described in Section 1.4.

Country	**Leq [dBA]**	**L10 [dBA]**	**Lmax [dBA]**	**Source**
Taiwan	53,4	56,1	70,1	Chen et al. (2009)
Iran	63,46	65,81	71,3	Valizadeh et al. (2013)
France	60,4	62,1	89,1	Parra et al. (2017)
India	72	No Data	92	Joshi and Tada (2016)
USA	60,44	59,26	78,39	Krueger et al. (2005)
USA	56,4	60,6	90,6	Krueger et al. (2007)

Table 4: L_{eq}, L_{10} og L_{max}, measured at neonatal intensive care units in five different countries.

3 Materials and Methods

Sound pressure levels were measured at neonatal intensive care units at two different hospitals: Rikshospitalet in Oslo in the period 28.02.22 to 03.03.22, and St.Olavs Hospital in Trondheim in the period 09.03.22 to 13.03.22. During this period, sound pressure levels outside and inside of an active incubator were measured at an unused patient room at St.Olavs Hospital. The methodology of the measurements will be presented in this section.

3.1 Measuring sound levels at the neonatal intensive care unit

In this section, measurements conducted at the neonatal intensive care unit at both Rikshospitalet in Oslo and St.Olavs Hospital in Trondheim will be presented.

Three sound pressure levels were measured at the neonatal intensive care units:

- The equivalent sound pressure level, L_{eq}
- The maximal sound pressure level, L_{max}
- The statistical sound pressure level exceeded 10 percent of the time, L_{10}

3.1.1 Measurements at Rikshospitalet

Measurements at the intensive care unit at Rikshospitalet were conducted in the period 28.02.22 to 03.03.22. Three microphones were used during the measurements. One microphone was placed inside an unoccupied, inactive incubator (M1), while the two other microphones (M2 and M3) were placed at different locations at the unit. Ideally, the microphones should have been placed further from the walls to avoid reflections. However, for practical reasons, the microphones were placed close to the wall.

As seen in Figure 4, the intensive care unit at Rikshospitalet is divided into three sections by two glass partitions. Normally, the section at the center of the unit is the most used part, and ideally, the incubator should have been placed at this section. During the installation of the microphones however, there were a lot of patients present which needed care, and the incubator had to be placed at a less used section at the unit. Therefore, one microphone (M3) was placed at the most used section, while the other microphone (M2) was placed next to the incubator, towards the hall where human activity usually occurs. Pictures of the different microphone positions can be seen in Figure 5.

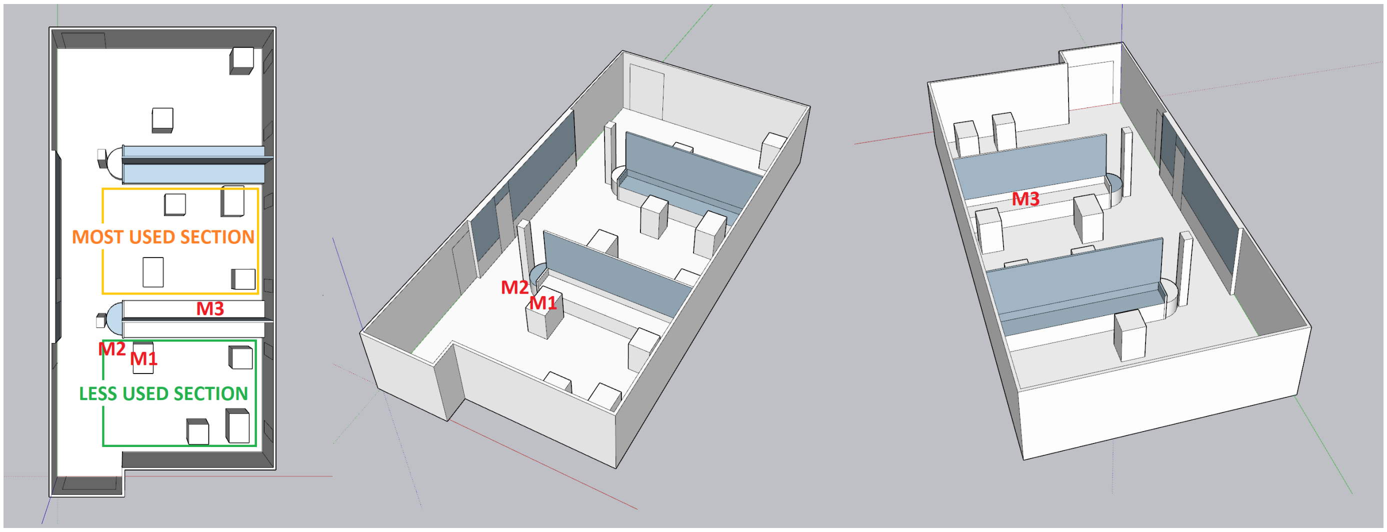


Figure 4: Microphone setup during the measurements at the intensive care unit at Rikshospitalet in Oslo. Microphone position M1 is inside of an incubator, while M2 and M3 are outside of the incubator.

Figure 5: The different microphone positions at Rikshospitalet.

3.1.2 Measurements at St.Olavs Hospital

Measurements at the intensive care unit at St.Olavs Hospital were conducted 09.03.22 to 13.03.22. Unlike Rikshospitalet, St.Olavs Hospital does not have a common room for all patients at the unit. Instead, each patient gets an individual patient room. Thus, the measurements at St.Olavs Hospital were conducted at a patient room. The room was occupied by a family during the measurements, and the incubator was occupied by the same preterm infant during the whole measurement period. Measurements were therefore only made on the outside of the incubator. Two microphones were placed at each side of the incubator at the patient room, as seen in Figure 6.

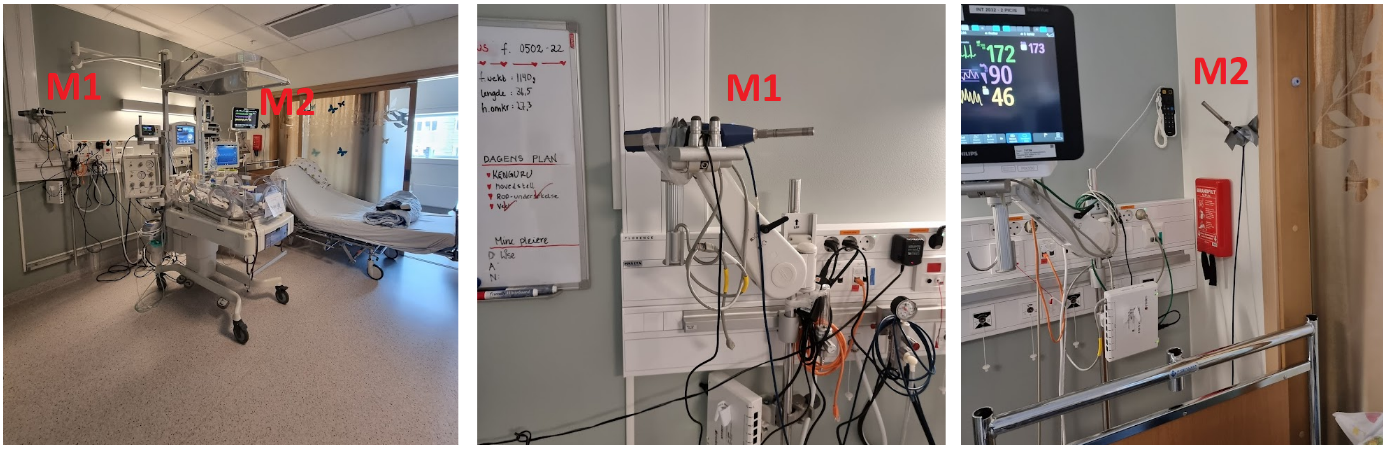


Figure 6: Microphone setup at a patient room in use at St.Olavs Hospital in Trondheim.

3.2 Measuring sound level contribution from an unoccupied incubator

In this section, measurements conducted at an unused patient room at St.Olavs Hospital in Trondheim to assess the incubator sound level contribution will be presented.

3.2.1 Measuring object

Figure 7: Pictures of the Giraffe OmniBed Care Station (Some Tech, n.d.)

Sound pressure levels were measured from a noise source under test, i.e. an incubator. The incubator used during the measurements was a Giraffe OmniBed Care Station (GE Healthcare, n.d.) which is used at both Rikshospitalet in Oslo and St.Olavs Hospital in Trondheim. The incubator controls humidity and temperature (will be referred to as *climate control* throughout the thesis). According to GE Healthcare (2019), the incubator manages sound, promoting normal growth and development. The hood cover dampens external noise, and low noise fans are used to reduce noise levels within the bed. Alarm speakers are also placed low, beneath the body of the bed, and the volume can be adjusted to minimize noise. According to Wubben et al. (2011), the Giraffe Omnibed naturally attenuates 12 dBA.

As seen in Figure 8, the incubator also has an external machine which controls the oxygen supply and vacuum pump inside of the incubator. The incubator settings can be combined in several ways depending on the needs of the patient inside the incubator. While measuring the sound pressure levels from the noise source under test, $L'_{pAi(ST)}$ (described in Section 3.2.2), four different incubator settings were tested:

- Combination 1: Incubator turned on, climate control is active, external machine is inactive.
- Combination 2: Incubator turned on, climate control is active, external machine produces 70 kPa vacuum.
- Combination 3: Incubator turned on, climate control is active, external machine produces 70 kPa vacuum, oxygen supply is turned on.
- Combination 4: Incubator turned on, climate control is active, vacuum turned off, oxygen supply is turned on.

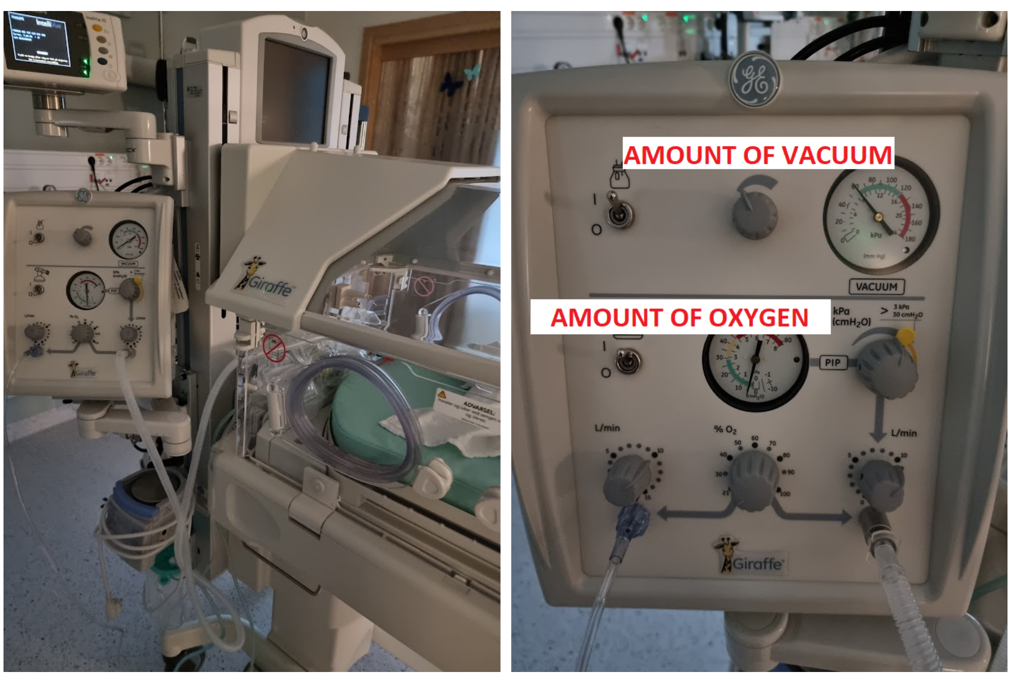


Figure 8: Pictures of the external control panel which controls vacuum and oxygen supply levels inside of the incubator.

3.2.2 Measuring sound levels outside of active incubator

The sound power level from the incubator, L_W, was determined following ISO 3746:2010 (ISO, 2010*a*), which determines sound power levels using sound pressure at an enveloping measurement surface over a reflecting plane. According to guidelines in ISO 3740:2019 (ISO, 2019), ISO 3747:2010 (ISO, 2010*b*) was also a suitable measurement method, but due to lack of a reference sound source, ISO 3746 was chosen as an appropriate alternative.

The sound power level, L_W, was determined by measuring two sound pressure levels:

- The A-weighted time-averaged sound pressure levels from the noise source under test, $L'_{pAi(ST)}$.
- The A-weighted time-averaged sound pressure level of the background noise, $L_{pAi(\mathrm{B})}$.

$L'_{pAi(ST)}$ was measured at four different microphone positions ($i = 1,\ 2\ ...\ \ N_M$) while the incubator was turned on. The measurement procedure was conducted four times, using different machine settings for each measurement. All machine setting combinations are described further in Section 3.2.1. Three sound pressure levels were measured while the incubator was turned on: L_{eq}, L_{max} and L_{10}. All measurements were done at a period of 2 minutes, at one-third-octave bands at the frequency 20 Hz to 20 kHz. However, during post-processing of the measurements, only 30 seconds of each 2 minute measurement was used. The 30 seconds chosen were the ones consisting of the least background noise interference.

In addition, before and immediately after measuring the sound pressure levels from the incubator, the time-averaged background noise, $L_{pAi(\mathrm{B})}$, was obtained at each microphone position, over the same measurement time interval as that used for the noise source under test. According to ISO 3476, $L'_{pAi(ST)}$ and $L_{pAi(\mathrm{B})}$ should both be measured at five different positions. However, due to a low room height and difficulties positioning the microphone above the incubator, only four microphone positions were used. Instead, the fifth position, which should have been 1 meter above the incubator, was found by calculating the average measured sound pressure at the four microphone positions. The microphone setup following ISO 3746 can be be seen in Figure 9. The different microphone positions in relation to the position of the external machine can be seen in Figure 10, and pictures of the actual setup can be seen in Figure 11.

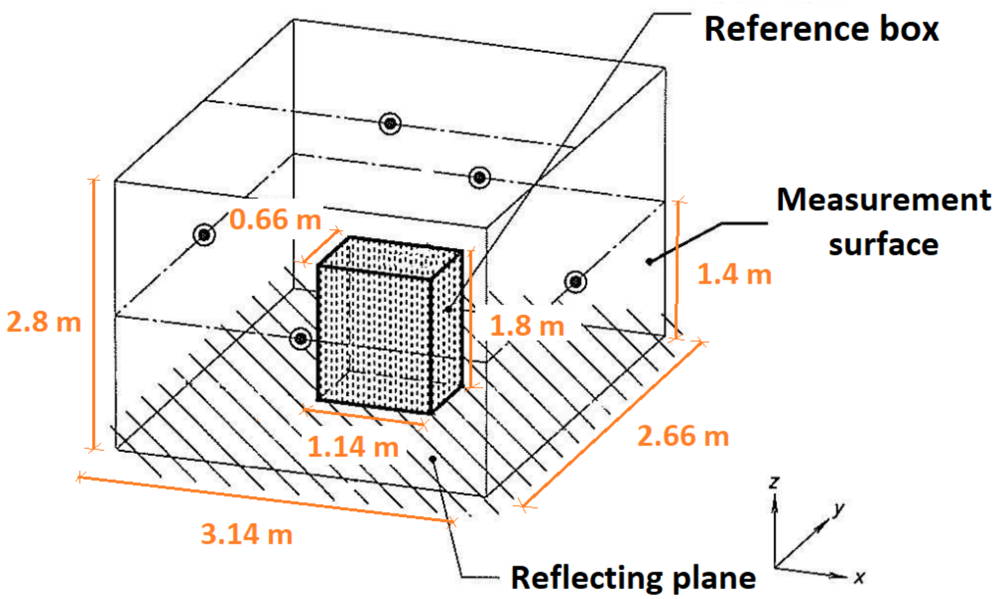


Figure 9: Measurement setup conducted at St.Olavs Hospital following ISO 3746.

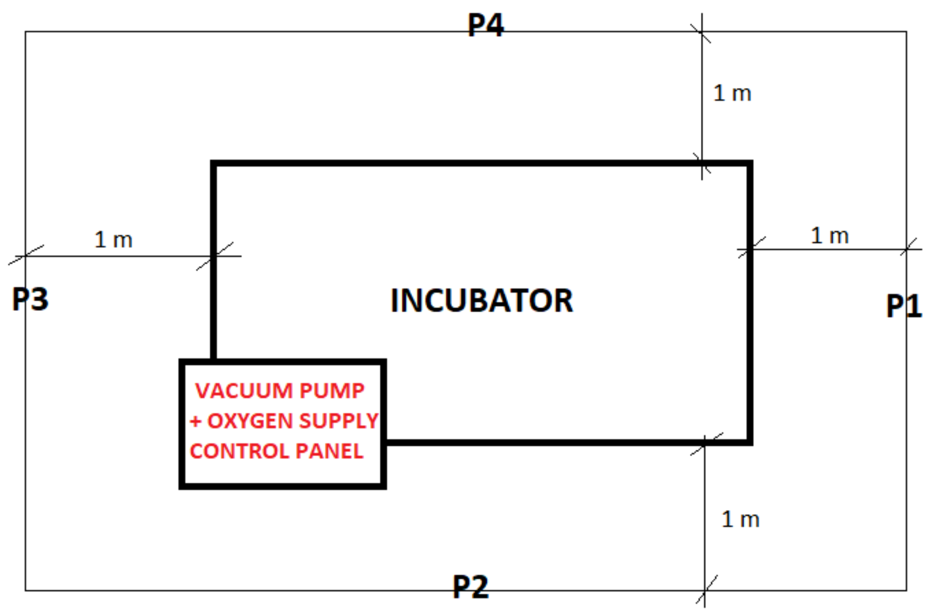


Figure 10: Measurement positions outside of the incubator as well as the position of the control panel for the vacuum pump and oxygen supply.

Figure 11: Pictures of the measurement setup outside of the incubator.

3.2.3 Measuring sound levels inside active incubator

During measurements of the sound pressure levels outside of the incubator, the equivalent sound pressure level, L_{eq}, inside of the incubator was measured simultaneously. The average newborn's head radius measures 5.2 cm (Stanford, n.d.), thus a microphone was placed 5.2 cm above the head position inside of the incubator, as seen in Figure 12.

Figure 12: Microphone setup during measurements of sound pressure levels inside of an active incubator.

3.2.4 Measuring the reverberation time

Following ISO 3746, the reverberation time, T_{20}, was measured at the unused patient room at St.Olavs Hospital. It was measured in one-third-octave band from 20 Hz to 20 kHz, following the integrated impulse response method described in ISO 3382-2:2008 (ISO, 2008). As seen in Figure 13, measurements were conducted using balloons as an excitation signal. A balloon was burst three times with the microphone placed at a new position for each burst.

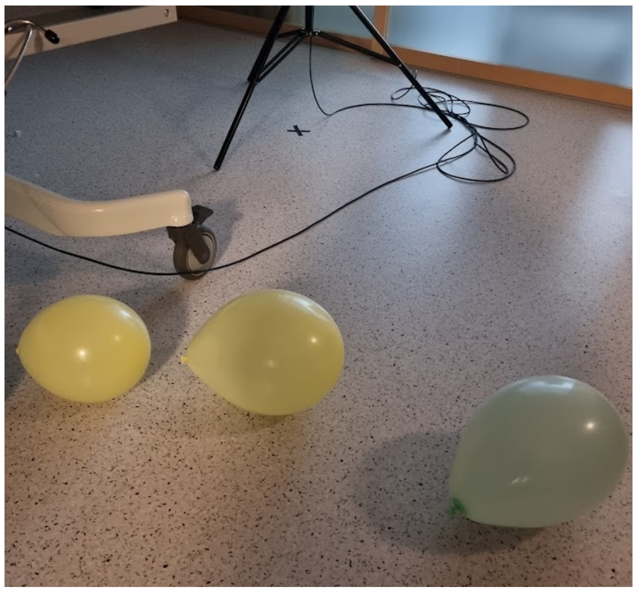


Figure 13: Balloons used during measurements of the reverberation time at St.Olavs Hospital.

3.3 Source of error during incubator measurements

During measurements of the incubator contribution, different noise signals from a loudspeaker were measured inside and outside of the incubator. These results would have been of much interest when assessing the attenuation of the incubator and its acoustical properties. However, the measurements were conducted incorrectly and therefore not used in this thesis. Also, not all settings of the incubator were tested during the incubator sound level measurements. Thus, higher sound levels could have been measured if also these settings were tested.

4 Results

4.1 Sound levels at the neonatal intensive care unit

In this section, sound levels measured at both neonatal intensive care units will be presented. The measurements were conducted in the period 28.02.22 to 03.03.22 at Rikshospitalet, and in the period 09.03.22 to 13.03.22 at St.Olavs Hospital.

4.1.1 Sound levels at Rikshospitalet

In Figure 14, the equivalent sound pressure level, L_{eq}, at all three microphone positions during the first day of measurement are plotted. The black line represents the limit value of L_{eq}. As seen in the figure, the limit value is exceeded throughout the day. The sound levels measured each day are also plotted in Appendix C.

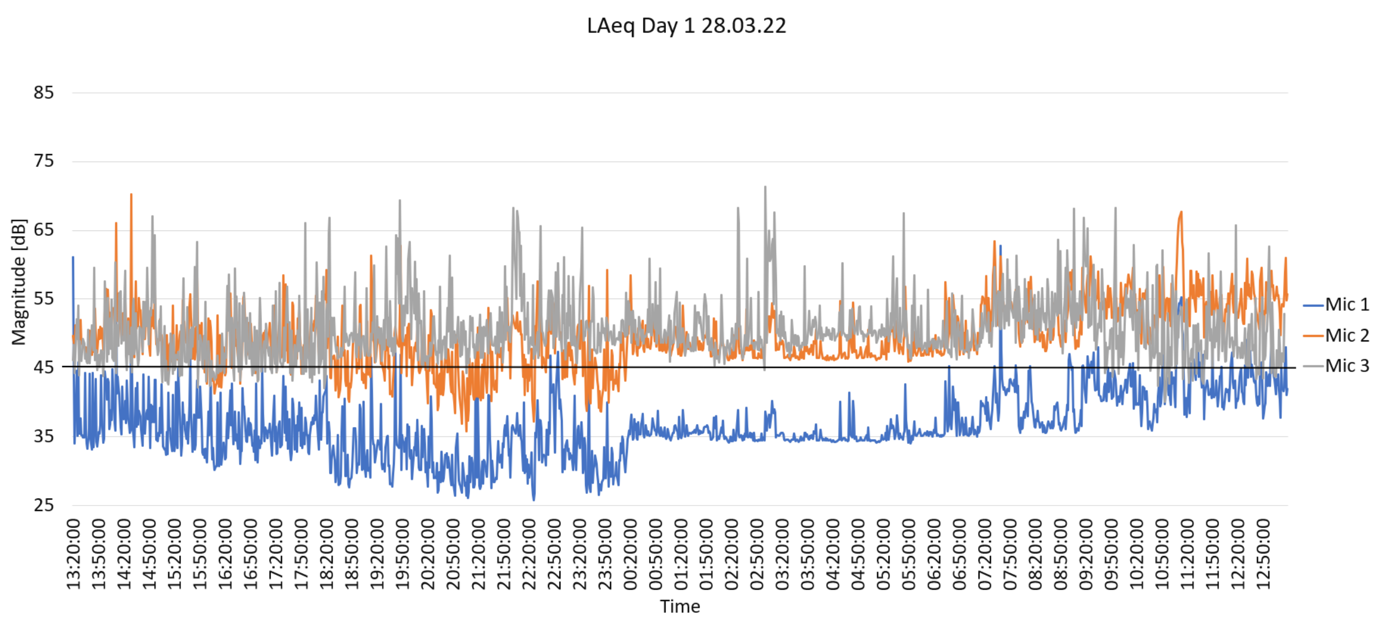


Figure 14: The A-weighted equivalent sound pressure level, L_{eq}, at all three microphone positions during the first day of measurement (28.03) at Rikshospitalet. The black line represents the limit value $L_{eq} < 45$ dBA as stated in Table 3.

Furthermore, sound levels measured at the different microphones positions are listed in Table 5. As seen in the table, there is no data at Day 2-4 at microphone position M3. The purpose of measuring at several positions at the NICU was to get more reliable measurements, however, during the installation of the microphone setup at Rikshospitalet, the settings on microphone M3 were set incorrectly. This resulted in microphone M3 only measuring the first 24 hours of the measurement period.

Also, as seen in the Table 5, the sound pressure levels L_{eq}, L_{max} and L_{10} measured outside of the incubator at microphone position M2 and M3, are consistently exceeding the limit values. The average equivalent sound pressure level, L_{eq} = 56.3 dBA, is 11.3 dB above the recommended limit value of 45 dBA. And L_{10} = 56.3 dB is 6.3 dB above the recommended limit value. L_{max}=96.3 dBA exceeds the limit value by 31.3 dB, a change in sound pressure level which is perceived as eight times louder than the limit value of 65 dBA.

As seen in the table, sound pressure levels measured inside of the incubator (M1), are significantly lower than the levels measured outside of the incubator (M2 and M3). This indicates that the incubator itself reduces some of the environmental noise. Because of this attenuation, both L_{eq} and L_{10} inside of the incubator never exceed the recommended limit values of 45 dBA and 50 dBA during the measurement period.

	Day 1:			**Day 2:**		
	Leq	**Lmax**	**L10**	**Leq**	**Lmax**	**L10**
M1	38.6 dBA	83.2 dBA	37.7 dBA	42.7 dBA	85.2 dB	44.3 dBA
M2	50.8 dBA	95.0 dBA	52.1 dBA	54.7 dBA	90.7 dBA	56.7 dBA
M3	55.0 dBA	97.6 dBA	55.8 dBA	No Data	No Data	No Data

	Day 3:			**Day 4:**		
	Leq	**Lmax**	**L10**	**Leq**	**Lmax**	**L10**
M1	42.7 dBA	78.3 dBA	44.9 dBA	44.5 dBA	92.4 dBA	45.2 dB
M2	55.3 dBA	87.8 dBA	57.2 dBA	56.5 dBA	100.3 dBA	57.7 dBA

Logarithmic average over four days (28.02.22-03.03.22) at microphone position M2 and M3 (i.e average sound pressure levels outside of the incubator):
L_{eq} = 54.8 dBA
L_{max}= 96.3 dBA
L_{10}= 56.3 dBA

Table 5: Measured sound levels at Rikshospitalet inside of inactive incubator (M1) and outside of inactive incubator (M2 and M3) as seen in Figure 4, over a period of four consecutive days. Measurements that exceed the limit values; L_{eq} < 45 dBA, L_{10} < 50 dBA and L_{max} < 65 dBA, are highlighted in red.

In Table 6, the differences in L_{eq} outside, versus inside of incubator, are plotted. In this figure, one can observe that L_{eq} outside of the incubator is reduced by 12.0-12.6 dB. This was to be expected as Wubben et al. (2011) states that the Giraffe Omnibed naturally attenuates 12 dBA.

	$L_{eq,mic2}$ - $L_{eq,mic1}$
Day 1	12.2 dB
Day 2	12.0 dB
Day 3	12.6 dB
Day 4	12.0 dB

Table 6: Difference in equivalent sound pressure level outside of incubator versus inside of incubator.

Figure 15 shows the A-weighted frequency spectrum outside and inside of the incubator. As seen in the figure, all time periods measure similar sound levels from 20 Hz to 200 Hz. From 200 Hz to 2 kHz, all time periods except 08:00 - 12:00 are still quite similar. However, there are some differences in magnitude after 2 kHz. I.e. the difference in sound pressure levels at different parts of the day seems to be due to high frequencies noise above 2 kHz. Sound levels also seem to be lower during night time.

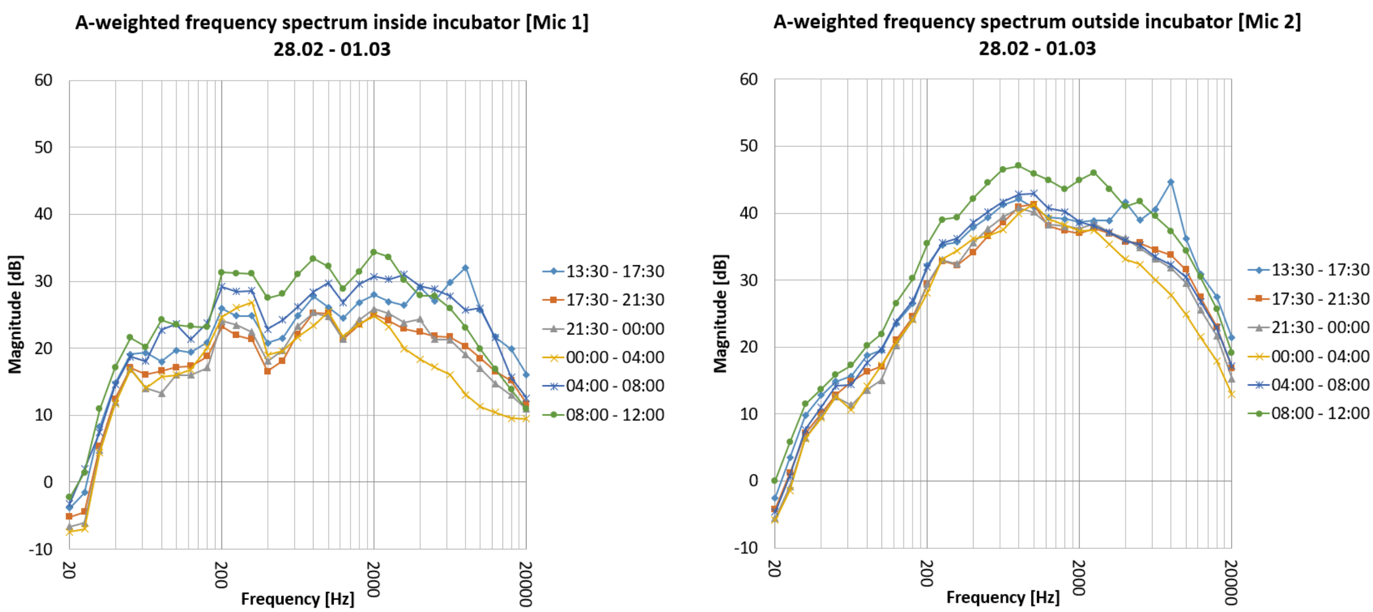


Figure 15: A-weighted frequency spectrum at microphone position M1 and M2, i.e inside the incubator and outside of the incubator. The measurements were conducted at Rikshospitalet during the first day of measurement.

Figure 16 shows the difference in sound levels, outside versus inside of the incubator. As seen in the figure, the incubator attenuates high frequencies, and from 400 Hz to 1.6 kHz, the environmental noise is attenuated by more than 12 dB. In the frequency range 2 - 20 kHz, the incubator attenuation of the environmental noise seems to be lower at the period 04:00 - 08:00. There is not enough data to say what happened during this time period. A likely scenario is that a noise source, such as a vacuum cleaner, generated sound outside of the incubator, at the opposite side of microphone M2 (Figure 4 for microphone setup). Which would result in an extra screen between M2 and the sound source, and make for a lower measured sound level at M2.

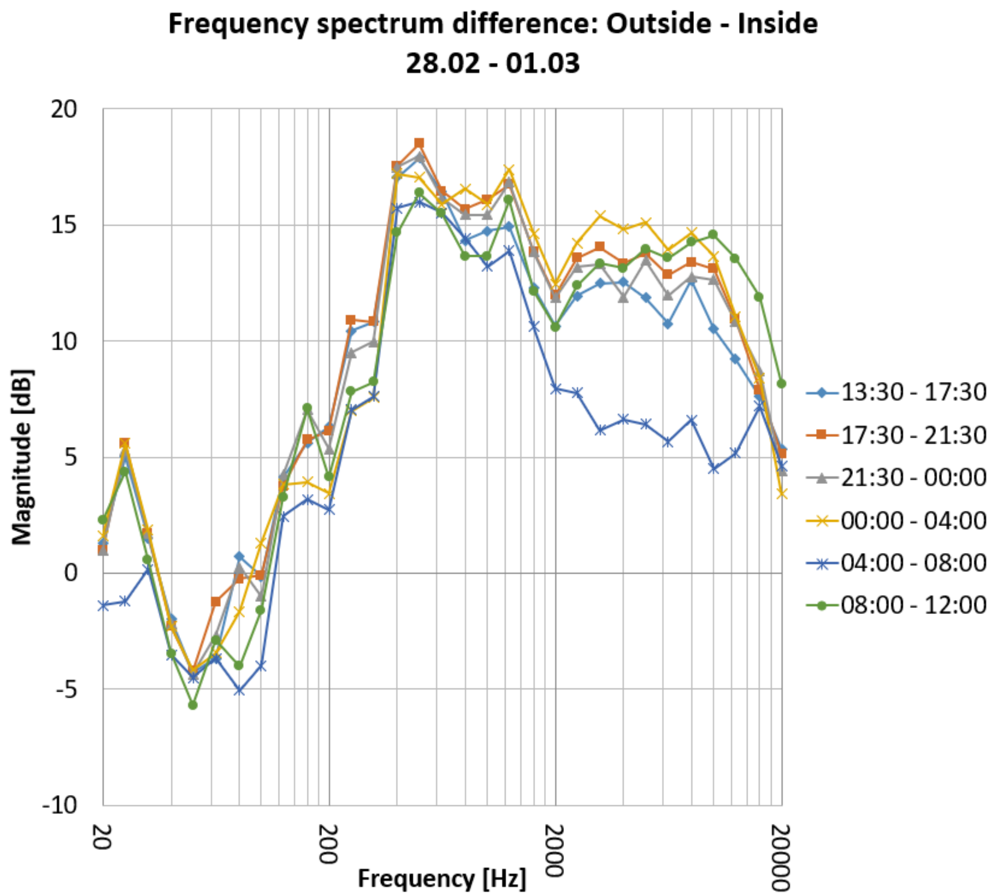


Figure 16: Difference in sound levels, outside versus inside of the incubator (M2 - M1). I.e. how much louder are the sound levels **outside** of the incubator

4.1.2 Sound levels at St.Olavs Hospital

In Figure 17, the equivalent sound pressure level, L_{eq}, at both microphone positions during the second day of measurement is plotted. The black line represents the limit value $L_{eq} < 45$ dBA. As seen in the figure, the limit value is exceeded during that day. The sound levels measured each day are also plotted in Appendix D.

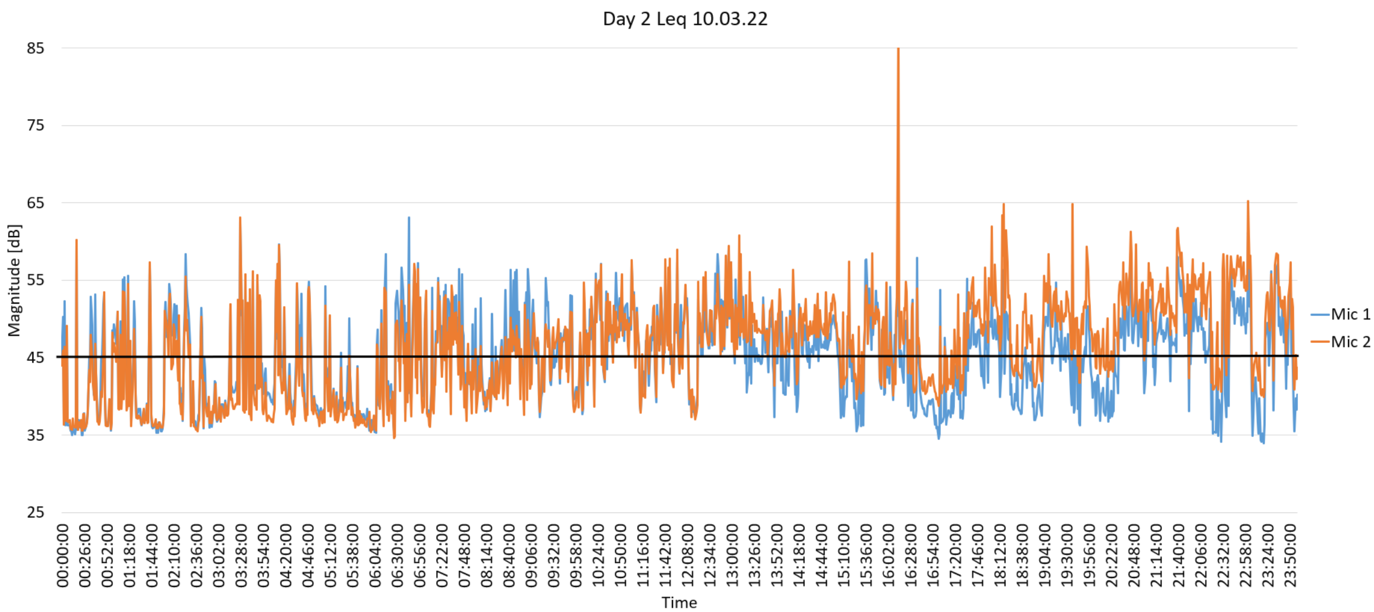


Figure 17: The A-weighted equivalent sound level, L_{eq}, at both microphone positions during the second day of measurements (10.03.22) at St.Olavs Hospital. The black line represents the limit value $L_{eq} < 45$ dBA as stated in Table 3.

Sound pressure levels measured at the two different microphones positions (M1 and M2) are listed in Table 7. As seen in the table, the averaged L_{eq} is measured to 48.8 dBA, which exceeds the limit value by 3.8 dB. The average $L_{10} = 50.7$ dBA exceeds the limit value by barely 0.5 dB, and the average $L_{max} = 87.3$ dBA also exceeds the limit value by more than 20 dB.

Day 1:

	Leq	Lmax	L10
Mic 1	49.3 dBA	84.8 dBA	51.2 dBA
Mic 2	48.2 dBA	82.5 dBA	50.4 dBA

Day 2:

	Leq	Lmax	L10
Mic 1	48.7 dBA	85.9 dBA	50.0 dB
Mic 2	50.4 dBA	89.7 dBA	52.0 dBA

Day 3:

	Leq	Lmax	L10
Mic 1	48.3 dBA	84.6 dBA	51.0 dBA
Mic 2	50.7 dBA	88.8 dBA	53.3 dBA

Day 4:

	Leq	Lmax	L10
Mic 1	48.1 dBA	82.7 dBA	50.1 dBA
Mic 2	48.8 dBA	84.4 dBA	50.9 dBA

Day 5:

	Leq	Lmax	L10
Mic 1	46.6 dBA	82.6 dBA	47.2 dB
Mic 2	47.7 dBA	92.6 dBA	48.1 dBA

Logarithmic average over five days (09.03.22-13.03.22) at microphone position M1 and M2 (i.e average sound pressure levels outside of the incubator):

L_{eq} = 48.8 dBA

L_{max}= 87.3 dBA

L_{10}= 50.7 dBA

Table 7: Measured sound levels at St.Olavs Hospital at two different microphone positions over a period of five consecutive days (09.03.22 - 13.03.22). Measurements that exceed the limit values; $L_{eq} < 45$ dBA, $L_{10} < 50$ dBA and $L_{max} < 65$ dBA, are highlighted in red.

Figure 18 shows the A-weighted frequency spectrum at microphone position M1 and M2, measured outside of a used incubator at a patient room at St.Olavs Hospital. As seen in the figure, the sound pressure levels differ during the day. They are lower during daytime and seem to be increasing at day time, especially in the frequency range 200 Hz to 2 kHz.

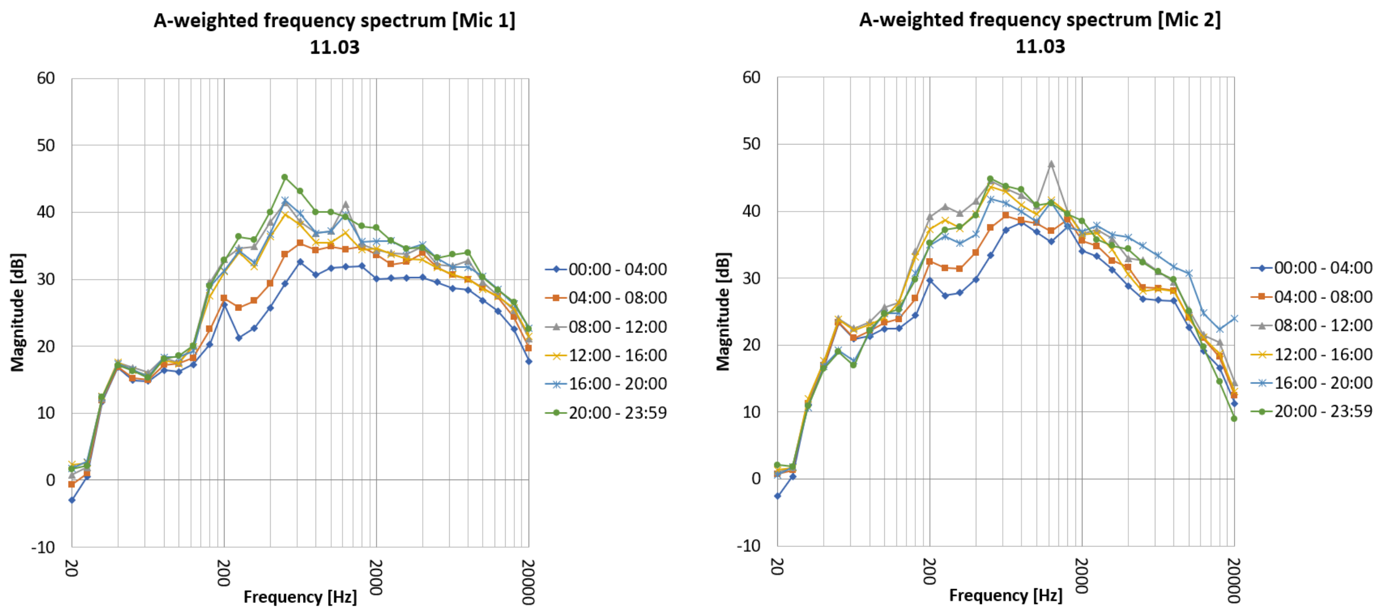


Figure 18: A-weighted frequency spectrum at microphone position M1 and M2, outside of a used incubator at a patient room at St.Olavs Hospital. The measurements were conducted during the third day of the measurement period.

4.2 Sound levels from incubator

In this section, results concerning the sound levels contribution of the incubator will be presented. The results were achieved during the measurements at an unused patient room at St.Olavs Hospital in Trondheim.

4.2.1 Sound power levels from incubator

Figure 19 shows the A-weighted sound power level, L_{WA} at each incubator combination. As seen in the figure, the sound power level, L_{WA}=31.1 dB when the incubator climate control is turned on (C1). L_{WA}=31.3 dB when the oxygen supply is turned on (C4), and L_{WA}=52.3 dBA when the vacuum pump is turned on(C3). Note that the A-weighted sound power level is not to be compared to the recommended limit values. As mentioned in Section 2.8; the limit values apply to sound **pressure** levels, and not sound **power** levels.

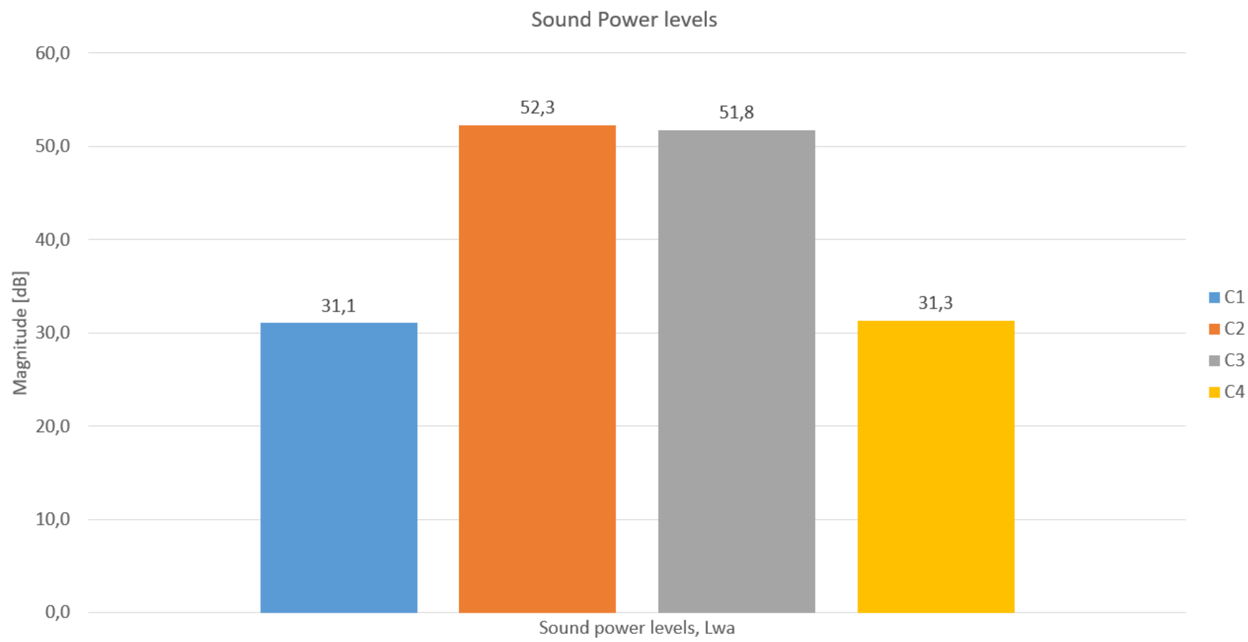


Figure 19: A-weighted sound power levels, L_{WA} from active incubator. Measured using incubator setting combination 1 to combination 4 (C1 to C4).
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
Each combination is described in Section 3.2.1.

Figure 20 shows the sound power levels generated at different frequencies. As seen in the figure, measurements in the frequency range 20 to 200 Hz are not included. This is due to background sound pressure levels exceeding the sound levels from the incubator. In the frequency range 200-400 Hz, there is little to no difference in sound power level between the different incubator settings. This indicates that the noise from the incubator climate control is the dominant noise source in this frequency range, and that it produces low frequency noise.

After passing 400 Hz, there is a particularly high increase in sound power level at combinations 2 and 3 (C2 and C3), which both describe the sound power levels when the vacuum pump is turned on. I.e. the vacuum pump is the dominating noise source in this frequency range. Also, C2 and C3 are very similar, indicating that there is little to no difference whether or not the oxygen supply is turned on. When turning off the vacuum pump (switching from C3 to C4), the sound power level is reduced significantly, which confirms the latter statement.

However, there is some increase in sound power level when turning on the oxygen supply, although not as much as the vacuum pump. When switching from C1 to C4, sound levels are significantly increased in the frequency range 4 kHz to 20 kHz, indicating that that the oxygen supply produces higher sound levels than the incubator climate control in this range.

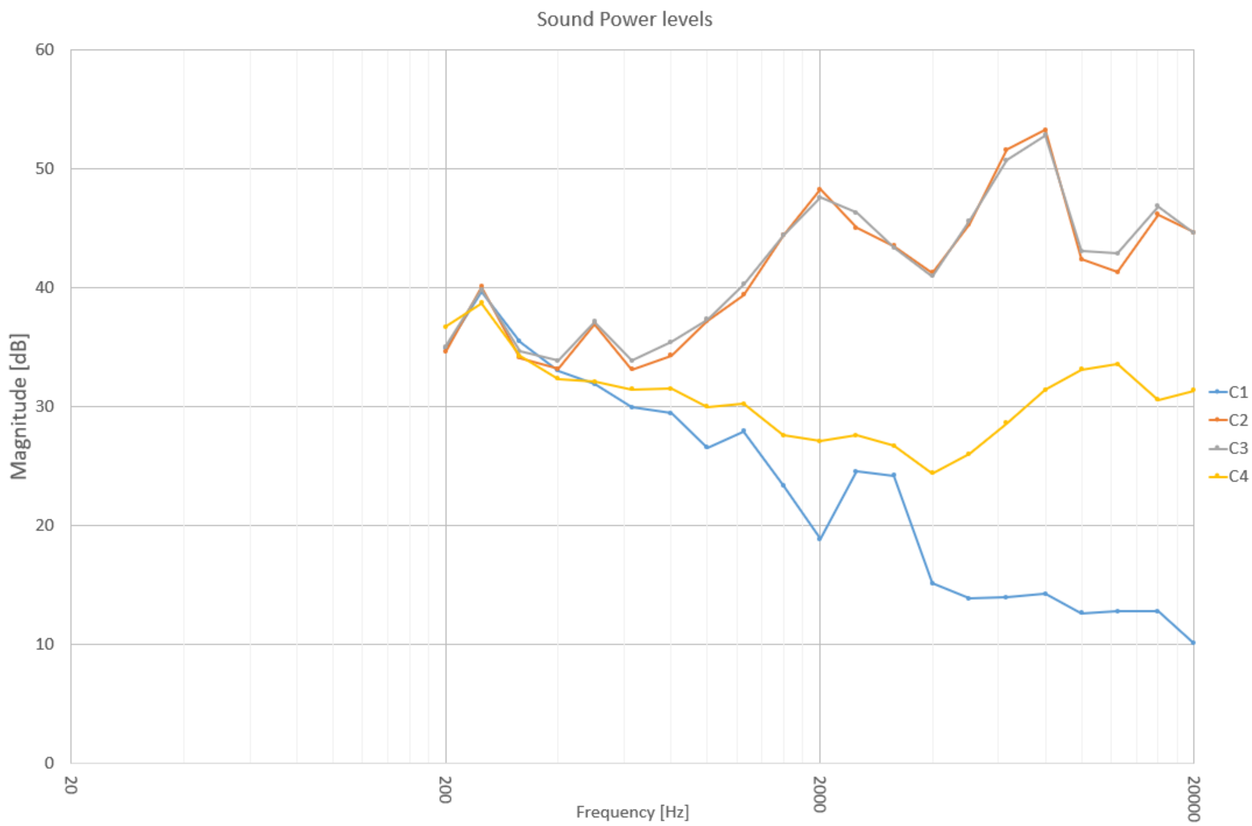


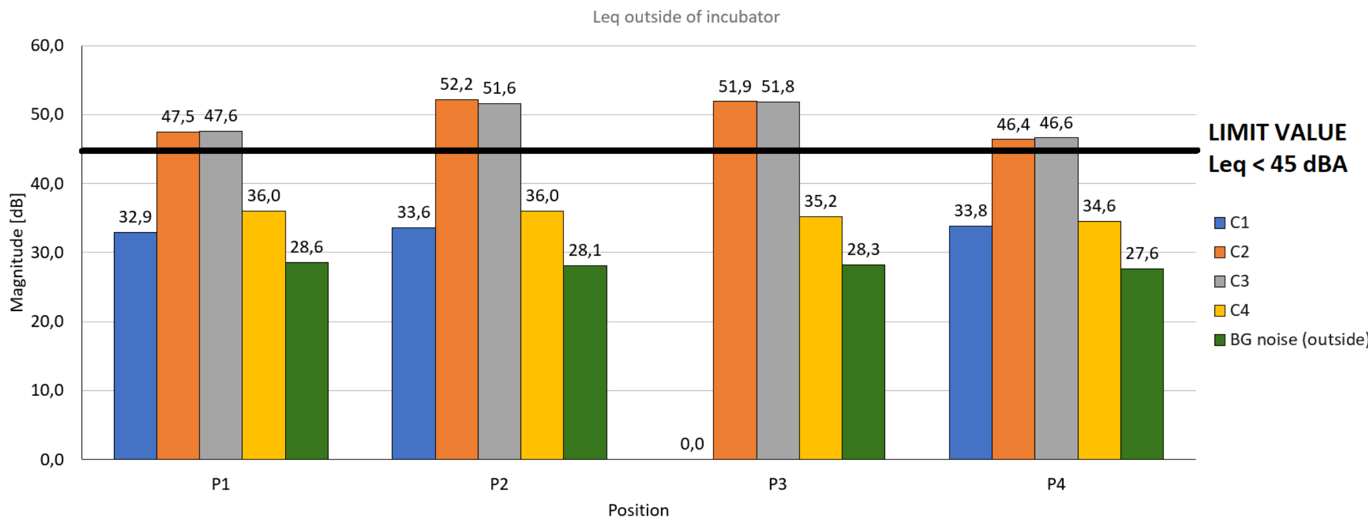
Figure 20: Sound power levels from active incubator. Measured using incubator setting combination 1 to combination 4 (C1 to C4).
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
Each combination is described in Section 3.2.1.
Measurements below 200 Hz are not included due to background sound pressure levels exceeding sound levels from the incubator.

4.2.2 Sound pressure levels inside and outside of active incubator

Figure 21 shows the equivalent sound levels, L_{eq}, measured at a period of 30 seconds, outside of an active incubator. As seen in both Figure 21 and Figure 22, there is no value at combination 1 (C1), position 3 (P3). During the measurement of C1 at P3, the measurement was not saved due to user error. This results in less reliable sound power level at C1 in Figure 20 and Figure 19. Figure 21 also shows that the background sound levels outside of the incubator are quite elevated. This could have an impact on the measured incubator sound levels and should be taken into consideration when assessing the results in this thesis. Specially at lower frequencies where the background sound levels are approximately the same as the sound levels generated by the incubator, which can be seen in Figure 24.

As seen in Figure 21, sound levels, L_{eq}, measured when only the incubator climate control is turned on (C1), exceeds the background sound level by approximately 5 dB, which is a clearly noticeable change in sound pressure. Also, the average L_{eq} at C2 and C3 are 50.2 dBA and 50.0 dBA. Indicating that the limit value of $L_{eq} < 45$ dBA is exceeded by 5 dB when the vacuum pump is turned on. The average L_{eq} is raised by approximately 17 dB when switching from C1 (incubator climate control is turned on) to C2 (incubator climate control and vacuum pump are turned). I.e turning on the vacuum pump makes for a change in sound pressure level which is perceived as almost four times as loud. The oxygen supply however, does not seem to contribute any significant amount to the sound pressure levels. Turning on the oxygen level (switching from C1 to C4) only raises the level by approximately 3 dB, a change which is just perceptible to the human ear. Indicating that the vacuum pump is the dominating sound source outside of the incubator, while the oxygen supply has little influence on the sound levels in comparison.

Also, Figure 21 shows that the limit value of $L_{eq} < 45$ dBA is exceeded outside of the incubator by more than 5 dB. Thus, when the vacuum pump is turned on, the incubator contributes to exceeding the limit values. However, this does not seem to be the case when the vacuum pump is turned off. As seen in Figure 21, turning on the oxygen supply (C4) does not contribute to exceeding the limit values, and neither does the incubator climate control (C1).



Logarithmic averaged L_{eq}:
C1=33.4 dBA C2=50.2 dBA
C3=50.0 dBA C4=45.5 dBA
BG noise(outside)=28.2 dBA

Figure 21: Sound levels measured outside of active incubator at different microphone positions. Measured at incubator setting combination 1 to combination 4 (C1 to C4).
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
BG Noise: Incubator is turned off, only background noise
Each combination is further described in Section 3.2.1.
The logarithmic averaged sound levels of all positions at each combination are also calculated.

Figure 22 shows the measured L_{eq} on the inside of an active incubator. The measurements are conducted at four different microphone positions, with five different setting combinations, including background noise measurement. As seen in the figure, the limit value $L_{eq} < 45$ dBA is exceeded at all four combinations. The background sound level does not exceed the limit value, which makes sense considering the room was unoccupied.

As seen in the figure, L_{eq} measured at combinations 1 to 4 (C1-C4) are quite similar. While L_{eq} from the incubator climate control (C1) measures 49.7 dBA, turning on the vacuum pump (C2) only raises L_{eq} by 1.1 dB, which is an insignificant change in sound pressure. Hence, turning on the vacuum pump makes little difference to the perceived sound levels inside of the incubator when the incubator climate control is already turned on. However, as seen in the figure, turning on the vacuum pump measures a L_{eq} of 50.8 dBA inside of the incubator, indicating that the vacuum pump still has some impact on the sound levels.

Turning on the oxygen supply makes for a clearly noticeable change in L_{eq}. Combination 4 (C4) exceeds combination 1 (C1) by almost 5 dB, thus the change in L_{eq} achieved when turning on the oxygen supply is perceived as clearly noticeable.

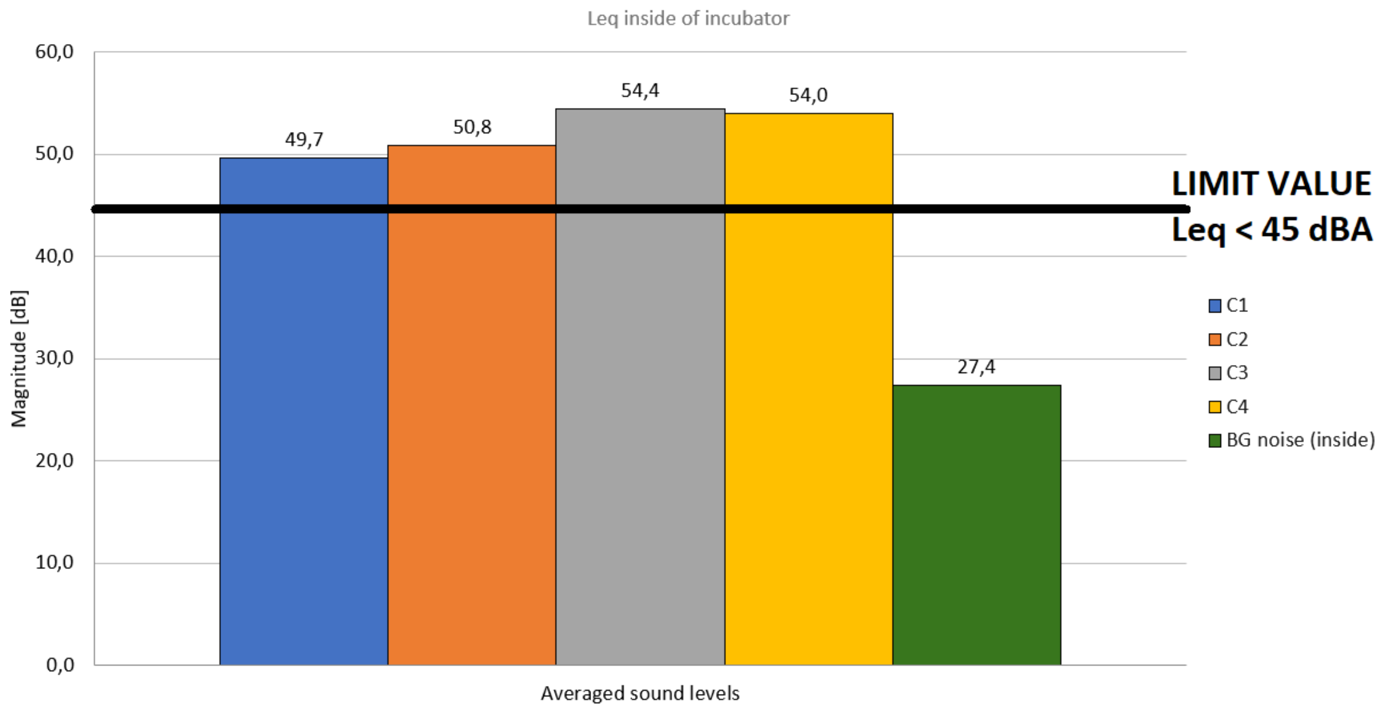
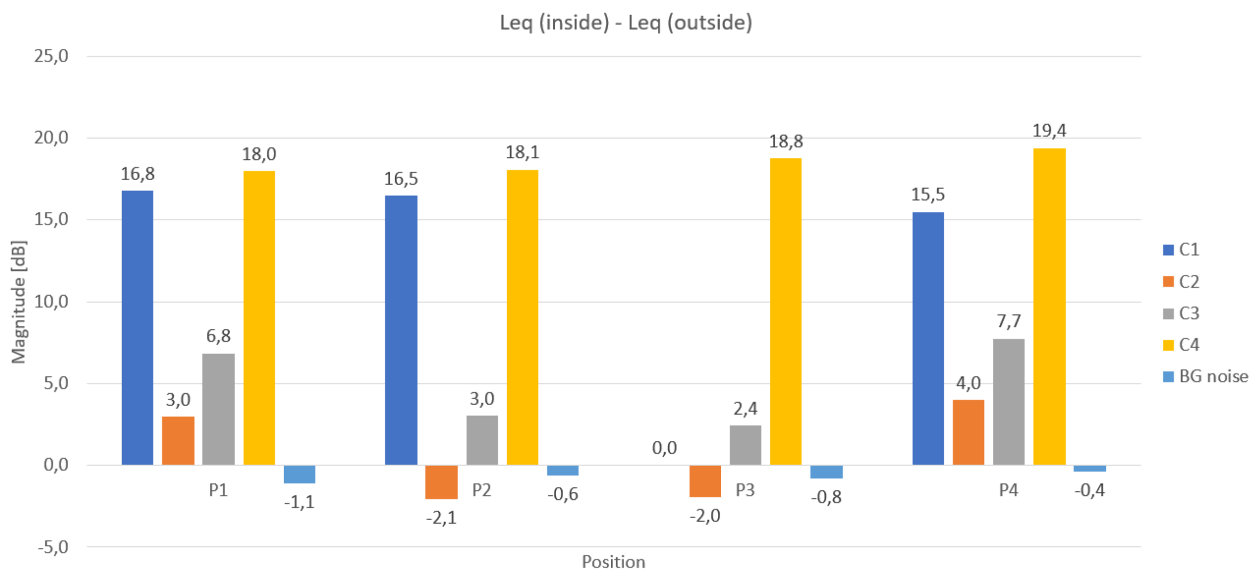


Figure 22: Sound levels measured inside of active incubator. Measured using incubator setting combination 1 to combination 4 (C1 to C4).
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
BG Noise: Incubator is turned off, only background noise
Each combination is described in Section 3.2.1.
The sound levels given in the figure were measured at each microphone position and then averaged logarithmic.

Figure 23 shows the difference in L_{eq} inside of the incubator, compared to outside of incubator. The average sound levels of all positions at each combination are also calculated. As seen in the figure, L_{eq} due to the oxygen supply (C4) is increased significantly, with an increase of 18.6 dB inside versus outside the incubator. I.e. Sound levels due to the oxygen supply is significantly higher inside of the incubator. Similar increase in sound levels can also be observed in the case of incubator climate control sound levels (C1). As seen in the figure, sound levels increase by 16.3 dB inside compared to outside of the incubator.



Logarithmic average:
C1=16.3 dBA C2=1.6 dBA
C3=5.6 dBA C4=18.6 dBA
BG noise(outside)= −0.7 dBA

Figure 23: Sound levels inside incubator subtracted by sound levels outside of incubator. The logarithmic average sound level of all positions at each combination is also calculated. Incubator setting combination 1 to combination 4 (C1 to C4):
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
BG Noise: Incubator is turned off, only background noise
Each combination is described in Section 3.2.1.

4.2.3 Frequency spectrum inside and outside of active incubator

Figure 24 shows the frequency spectrum outside of the incubator at different incubator settings. The figure shows the frequency spectrum, alongside the A-weighted frequency spectrum.

As seen in the figure, combination 2 (C2) and combination 3 (C3) have an increase in magnitude in the frequency range 400 Hz - 2 kHz. In this range, C2 and C3 are dominating the other combinations. indicating that the vacuum pump is the dominating sound source outside of an active incubator in this frequency range. Also, the vacuum pump seems to be producing high frequency noise, as the vacuum pump has a peak at 8 kHz with a magnitude of 52 dB.

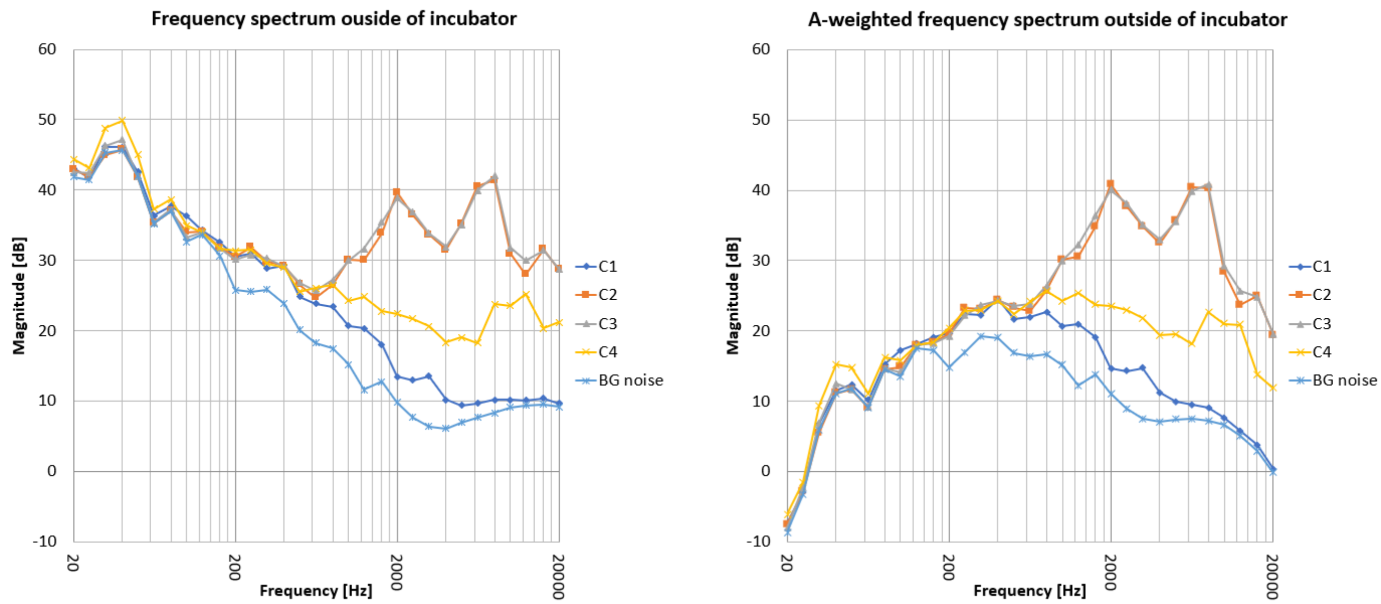


Figure 24: Frequency spectrum outside of incubator at different incubator settings. Incubator setting combination 1 to combination 4 (C1 to C4):
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
BG Noise: Incubator is turned off, only background noise
Each combination is described in Section 3.2.1.

Similarly, Figure 25 shows the frequency spectrum inside of the incubator at different incubator settings. As seen in the figure, both the oxygen supply and the vacuum pump generate high frequency noise inside of the incubator. In the frequency range 6.3 - 8 kHz, combination 4 (C4) makes a dip, whilst combination 2 and 3 peaks. This indicates that the vacuum pump is the dominating noise source in the frequency range 6.3 - 8 kHz. However, in the frequency range 800 Hz - 5 kHz, combination 4 (C4) exceeds combination 2 (C2) by approximately 8 dB. Hence, the oxygen pump is perceived as almost twice as loud as the vacuum pump in the frequency range 800 Hz - 5 kHz. In the frequency range 160 - 800 Hz however, the increase in magnitude is similar at all four combinations. Indicating that the incubator climate control is the dominating noise source at low frequencies.

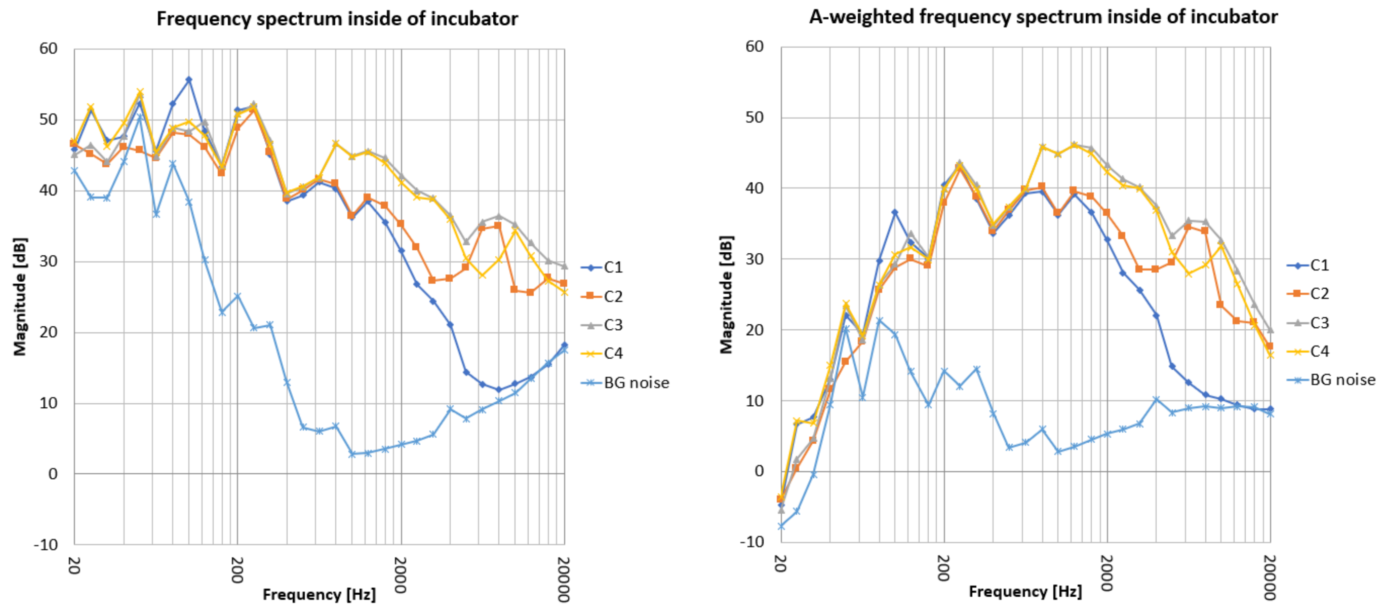


Figure 25: Frequency spectrum inside of active incubator at different incubator settings. Incubator setting combination 1 to combination 4 (C1 to C4):
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
BG Noise: Incubator is turned off, only background noise
Each combination is described in Section 3.2.1.

Figure 26 shows how much louder the sound levels at each frequency are inside of the incubator compared to outside of the incubator. As seen in the figure, in the frequency range 800 Hz - 2 kHz, oxygen supply (C4) measures 20 dB louder inside of the incubator, which to the human ear is perceived as four times as loud as outside of the incubator. I.e. the oxygen supply generates louder sound levels inside of the incubator, compared to outside of the incubator. This was to be expected as the oxygen is delivered through a tube, exiting through the tube opening inside of the incubator.

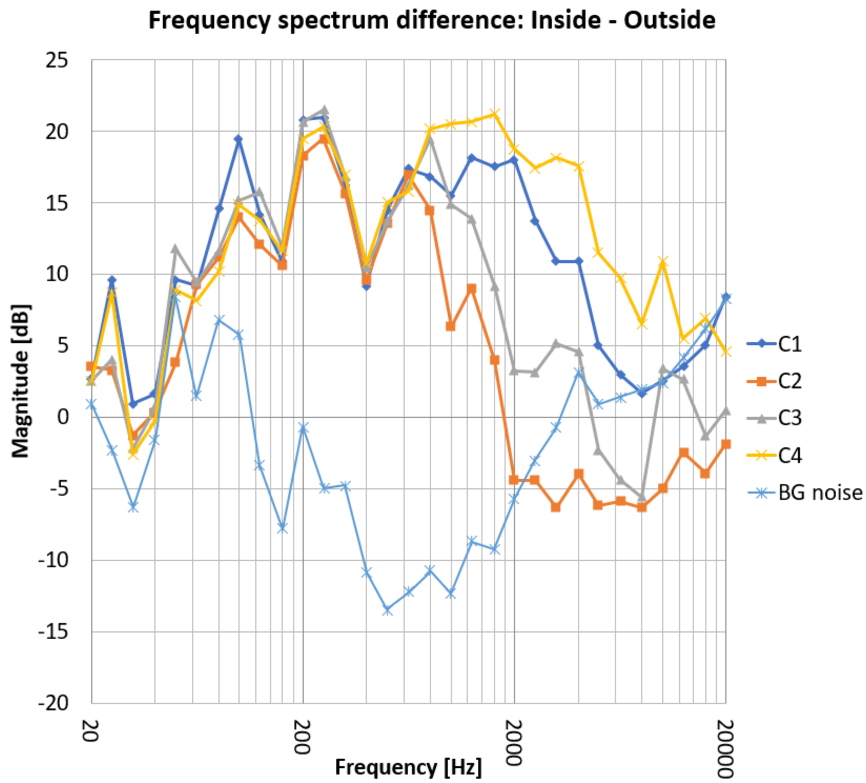


Figure 26: Frequency spectrum: difference in sound levels, inside versus outside of the incubator (M1 - M2). I.e. how much louder are the sound levels **inside** of the incubator. Incubator setting combination 1 to combination 4 (C1 to C4):
C1: Climate control is active
C2: Climate control and vacuum pump are active
C3: Climate control, vacuum pump and oxygen supply are active
C4: Climate control and oxygen supply are active
BG Noise: Incubator is turned off, only background noise
Each combination is described in Section 3.2.1.

5 Discussion

5.1 Sound levels at the neonatal intensive care unit

In this section, the sound levels measured at both neonatal intensive care units will be discussed, and will be compared to the recommended limit values presented in Table 3, as well as to each other.

5.1.1 Sound levels at Rikshospitalet

As seen in Table 5, the sound pressure levels L_{eq}, L_{max} and L_{10} measured outside of the incubator are all exceeding the limit values given in Table 3. Overall, the sound pressure levels are too high compared to the limit values. The average equivalent sound pressure level, L_{eq} is 11.3 dB above the recommended limit value, which is too high considering a change of 10 dB in sound pressure level is perceived as twice as loud by the human ear. Also, the average L_{10} reaches 6.3 dB above the limit value, and L_{max} exceeds the limit value by more than 30 dB. This too is a clearly noticeable difference in sound pressure level compared to the limit value.

In comparison to measurements in made in other countries (Table 4), the sound pressure levels at Rikshospitalet are similar to the sound pressure levels measured at other NICUs. L_{eq} measured at Rikshospitalet is quite similar to the L_{eq} measured in Taiwan (Chen et al., 2009) and USA (Krueger et al., 2007). In other words, the environmental sound levels measured at the NICU at Rikshospitalet are neither better nor worse than that sound levels measured at NICUs in other countries.

As seen in Figure 6, the incubator itself reduces some of the environmental noise at the unit. Because of this attenuation, L_{eq} and L_{10} inside of the incubator never exceed the recommended limit values. However, the measurements were conducted inside an unused, inactive incubator. In a realistic situation, the incubator would have been turned on, resulting in the incubator itself generating noise. The sound levels inside an active incubator are discussed in Section 5.2.

Inside of the incubator, L_{max} consistently exceeds the limit value, in contrast to L_{eq} and L_{10}. As seen in Table 5 however, L_{max} varies throughout the measurement period. For example; $L_{max,M1,Day3}$= 78.3 dBA, which is 14.1 dB lower than $L_{max,M1,Day4}$ = 92.4 dBA. Similarly, $L_{max,M1,Day2}$= 85.2 dBA, which is 6.9 dB higher than $L_{max,M1,Day3}$. There could be several reasons to such variations in sound pressure levels, however, the primary reason is believed to be due to the fact that L_{max} is measured over a period of 24 hours. L_{max} is the highest sound pressure level registered during a single noise event. In this case, the single noise event spans over 24 hours.

Thus, a single peak during these 24 hours could increase the measured L_{max} of an otherwise quiet environment, causing such variations in L_{max}. Due to these variations however, one could argue that L_{max} is a less suitable descriptor than L_{eq} and L_{10} when describing the sound levels at the neonatal intensive care unit.

5.1.2 Sound levels at St.Olavs Hospital

As seen in Table 7; L_{eq}, L_{10} and L_{max} all exceed the limit values. L_{eq} is measured to 48.4 dBA, which is lower than any of the measurements made at NICUs in other countries in Table 4. Hence, the neonatal intensive care unit at St.Olavs Hospital seems to handle environmental sound sources better than that of other NICUs in other countries. Which makes sense as St.Olavs Hospital has split the unit into several single patient rooms, rather than one shared unit.

However, although there are less noise sources at a patient room at St.Olavs Hospital than at a shared unit such as Rikshospitalet, limit values are still exceeded. The difference between the averaged L_{eq} and the limit value of 45 dBA is still more than 3 dB, which is a noticeable difference. L_{max}=87.3 dBA too exceeds the limit value by more than 25 dB. However, L_{10}=50.7dBA barely exceeds the limit value by 0.5 dB. But nevertheless, the limit values are still exceeded even though measures are put in place to reduce the number of noise sources. This however poses the question; is the incubator itself generating too much noise, or are the limit values too strict? This will be discussed in Section 5.1.3.

5.1.3 Rikshospitalet vs. St.Olavs Hospital

As observed, the sound levels are too high at both Rikshospitalet and St.Olavs Hospital. The results at Rikshospitalet were somewhat expected as the neonatal intensive care unit is shared by multiple infants, parents, nurses and other visitors throughout the day. As observed in Table 5 and Table 7, the average L_{eq} at St.Olavs Hospital is 6.4 dB lower than the averaged L_{eq} at Rikshospitalet. This change in sound pressure is clearly noticeable, which makes sense considering the patient room at St.Olavs Hospital only is occupied by one family at a time, resulting in less noise. However, the limit values are still exceeded at St.Olavs Hospital as well. Although there are entirely different plan structures at the two NICUs, sound levels are still too high.

So even though changes are made to the plan structure, sound levels at St.Olavs Hospital are still exceeding the limit values. This raises the question whether if the incubator itself contributes too much to the environmental noise, or if the limit values are too strict. As discussed in Section 5.2, the incubator itself generates sound levels that are exceeding the limit values. Hence, if the limit values are to be followed, incubator sound levels must be reduced. However, as seen in Table

1, a normal conversation alone has the intensity of 60 dBA. This is also the limit value of L_{max}, meaning that the maximum sound level at the NICU should not exceed that of a conversation. Similarly, according to the limit value $L_{eq} < 45$ dBA, the average sound level should stay below that of a quiet office. Thus, to not exceed the limit values, conversational noise at the NICU should be avoided, and average sound levels should be similar to a quiet office. Achieving such sound levels might be challenging though, especially at a hospital unit such as the NICU where conversational noise between staff members, parents and other visitors will occur throughout the day. There should therefore be conducted further studies as to whether the limit values are too strict.

Also, comparing results in Table 15 and Table 18, both Rikshospitalet and St.Olavs Hospital measure higher sound pressure levels at daytime compared to night time. This was to be expected at St.Olavs Hospital due to the single patient room only being occupied by one family at a time. However, it is an interesting finding that similar patterns also are seen at Rikshospitalet where multiple newborns, staff members and other visitors reside.

5.2 Incubator sound level contribution

In the following section, the incubator sound level contribution inside and outside of the incubator will be discussed.

As seen in Figure 21, the limit value $L_{eq} < 45$ dBA is exceeded outside of the incubator by more than 5 dB when the vacuum pump is turned on, which is a clearly noticeable change in sound pressure level. However, the limit value is only exceeded when the vacuum pump is turned on, generating high frequency noise with sound power level, L_{WA}=52.3 dBA. When turning off the the vacuum pump, the sound levels outside of the incubator stay under the limit value. Thus, the oxygen supply and incubator climate control do not exceed the limit values outside of the incubator, only the vacuum pump. According to Restin et al. (2021), the incubator, in particular its fan, is a major source of noise. Assuming that the vacuum pump is powered by a fan, this confirms that the vacuum pump is dominant noise source outside of the incubator. Also, as seen in Figure 20, the incubator climate control generates a noticeable amount of low frequency noise outside of the incubator.

In comparison, inside of the incubator, both the oxygen supply, the vacuum pump and the incubator climate control, contribute to exceeding the limit values. As seen in Figure 25, inside of the incubator, the vacuum pump and oxygen supply generate high frequency noise, while the incubator climate control generates low frequency noise. Hence, when comparing the sound level contribution inside and outside of the incubator, one can observe that there are different dominant noise sources which contribute to exceeding the limit values.

As mentioned, oxygen supply, vacuum pump and the incubator climate control, are all dominating noise sources. Which means that turning on more incubator functions increases the sound levels inside of the incubator. This causes an alarming side effect for the newborn residing inside of the incubator. Because a large variety of incubator functions turned on indicates that the newborn residing in the incubator is sick and in need of extra care, this means that a sick newborn is exposed to higher sound levels from the incubator, than that of a less sick newborn residing in an incubator.

Also, as previously mentioned in Section 5.1.3, there is a question whether the incubator itself contributes too much to the sound levels both inside and outside of the incubator. As seen in Table 6, the incubator itself attenuates the environmental noise by 12 dB. However, as seen in Table 22, when the incubator climate control is turned on, and both the vacuum pump and the oxygen supply are active (C3), equivalent sound pressure levels, L_{eq}, inside of the incubator reach 54.4 dBA. In other words, even if the environmental noise outside of the incubator is below the limit value and the incubator attenuates 12 dB, the limit values will still be exceeded inside of the incubator due to incubator noise.

As observed, the incubator contributes to exceeding the limit values. This poses the question whether the limit values are too strict, or if the incubator is too loud. As previously mentioned in Section 5.1.3, staying below the limit values is already challenging due to conversational noise at the unit, and adding sound from the incubator makes it even more challenging.

5.3 Measures to reduce sound levels inside of incubator

In the following section, two measures which might contribute to achieving the recommended limit values inside of the incubator will be discussed. Both measures are based on the findings during this thesis. This discussion assumes that the limit values mentioned in Section 2.8 also apply inside of the incubator.

5.3.1 Single patient room

A potential measure to reduce the sound levels inside of the incubator, is to change the design of the NICU. As discussed in Section 5.1.3, the sound pressure levels measured at St.Olavs Hospital were lower than the measured levels at Rikshospitalet due to fewer noise sources. Instead of having one large unit with several patients at once, one measure is to separate the unit into smaller patient rooms that are only occupied by one family at a time. By reducing the environmental sound levels, this can help reduce the sound levels infants are exposed to inside of the incubator. However, although the single patient room at St.Olavs Hospital measures lower sound levels than that of Rikshospitalet, the limit values are still exceeded.

Changing the plan structure to single patient rooms at NICUs might help reduce the environmental sound levels. However, as previously discussed in Section 5.2, even if the environmental noise outside of the incubator is below the limit value, it can still be exceeded inside of the incubator if the incubator is turned on.

5.3.2 Reduce incubator contribution

Another measure which might reduce the sound levels inside of the incubator, is to reduce the incubator sound level contribution. In order to reduce the sound levels inside of the incubator, changes must be made to both the oxygen supply and the incubator climate control, in addition to the vacuum pump. As previously discussed in Section 5.2, the incubator itself generates noticeable sound levels both inside, as well as outside of the incubator. Outside of the incubator, the vacuum pump is deemed to be the dominant sound source, producing high frequency noise. Thus, to reduce the noise generated outside the incubator, changes must be made to the vacuum pump.

Inside of the incubator however, both the vacuum pump, as well as the oxygen supply and the incubator climate control must be assessed to reduce the sound levels. By reducing the sound generated by these noise sources, the sound levels inside of an active incubator can be drastically reduced. To reduce high frequency noise from the vacuum pump and low frequency noise from the incubator climate control, internal changes must be made to the incubator. To reduce the high frequency noise coming from the oxygen supply, external measures might help reduce the sound levels. One measure might be to change the design of the tube that delivers the oxygen. By increasing the diameter of the tube, the airflow will become slower and generate less noise. Another suggestion is to install a silencer at the opening of the tube.. As seen in Figure 25, the oxygen supply generates high frequency noise in the range range 800 Hz to 5 kHz. Hence, the silencer should attenuate in this frequency range.

As previously mentioned in Section 1.6, limited data has been collected to suggest measures to reduce the incubator sound level contribution. Thus, further investigation is needed to test these measures. Further measurements are also needed to assess other measures which might reduce the incubator sound level contribution.

6 Conclusion

Sound levels at two different neonatal intensive care units have been measured, as well as sound levels generated by an incubator at a single patient room. The measurements have been conducted to answer the three following project objectives:

1. **What are the sound levels infants are exposed to inside and outside of an incubator at the neonatal intensive care unit?**
2. **How does the incubator contribute to these sound levels?**
3. **Which measures can be used to achieve the recommended sound level limit values inside of the incubator?**

Outside of an incubator, the average values of L_{eq}, L_{10} and L_{max} were measured 54.8 dBA, 56.3 dBA and 96.3 dBA at Rikshospitalet and 48.4 dBA, 50.7 dBA and 87.3 dBA at St.Olavs Hospital. I.e. the environmental sound levels at the NICU were consistently exceeding the limit values. However, an inactive incubator was found to attenuate environmental noise by 12 dB, resulting in both L_{eq} and L_{10} not exceeding the limit values inside of an inactive incubator. L_{max} on the other hand, consistently exceeded the limit value inside the incubator. However, big variations in L_{max} throughout the measurements suggested that L_{max} was a less suitable descriptor than L_{eq} and L_{10} when describing the sound levels at the intensive care unit.

The incubator generated sound levels which contribute to exceeding the limit values inside of the incubator, as well as outside of the incubator. On the outside of the incubator, the vacuum pump was the dominating noise source, producing high frequency noise. On the inside of the incubator however, the vacuum pump, oxygen supply and the incubator climate control were all contributing noise sources. With the vacuum pump and oxygen supply generating high frequency noise, and the incubator climate control generating low frequency noise. An interesting finding was also that due to the need of more incubator functions, a sick neonate residing inside of an active incubator would be exposed to higher sound levels.

Some measures to reduce the sound levels inside of the incubator have been suggested. One measure suggested was to change the plan structure of the NICU from one shared unit, to multiple single patient rooms. This measure has proved to help reduce the sound levels, however not enough to stay below the limit values. Nor enough to reduce sound levels inside of an active incubator, as the incubator itself contributes to exceeding the limit values. Another measure suggested was to make changes to the incubator vacuum pump, oxygen supply and climate control. By reducing the sound generated by these noise sources, the sound levels inside of an active incubator can be drastically reduced.

6.1 Further studies

This thesis concludes that the incubator contributes to increasing the sound levels inside of the incubator. However, due to limited data concerning measures to reduce the incubator sound level contribution, further investigation is needed. Further measurements and studies are needed to test the suggested measures, and to propose other measures which might help reduce the incubator sound level contribution.

This thesis also poses a question concerning sound levels outside of the incubator which requires further studies. Are the sound levels, both the environmental ones and the ones due to incubator noise, too high, or are the limit values in fact too strict? Staying below the limit values is already challenging due to conversational noise and other noise sources, and adding incubator noise makes it even more challenging. Thus, further studies need to be conducted to assess whether the limit values should be less strict, or if the incubators needs to be changed in order to achieve the limit values.

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Appendix

A Equipment list

- Precision Sound & Vibration Analyzer Nor150
  - Serial number: 15030331
  - Calibrated: 2010
- Precision Sound & Vibration Analyzer Nor145
  - Serial number: 14529619
  - Calibrated: 2021
- Norsonic Sound Calibrator Type 1251
  - 114.0 dB 1000 Hz
  - Serial number: 34858
- Norsonic Sound Calibrator Type 1255
  - 114.0 dB 1000 Hz
  - Serial number: 452520
- Microphones:
  - Nor1225
  - Nor1233
  - Nor1227

B Reverberation time

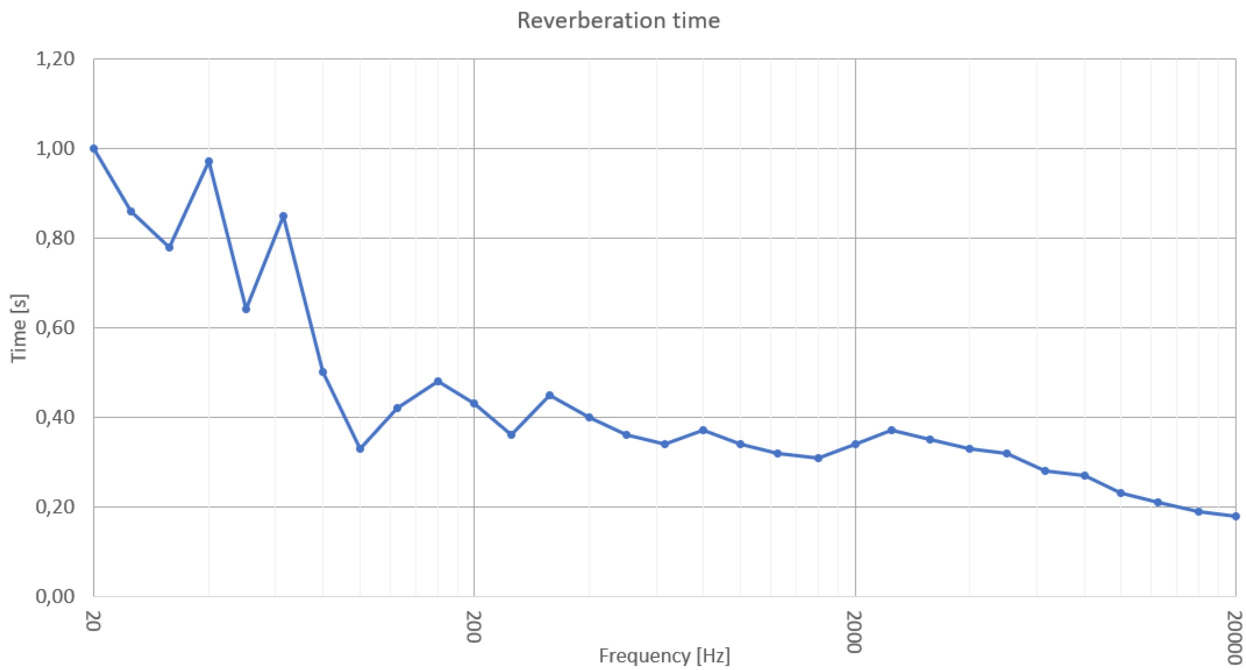

Figure 27: Reverberation time measured at an unused patient room at St.Olavs Hospital. The results are given in one-third octave bands from 20 Hz to 20 kHz.

Band	Reverberation (T20)
20 Hz	1.00
25 Hz	0.86
31.5 Hz	0.78
40 Hz	0.97
50 Hz	0.64
63 Hz	0.85
80 Hz	0.50
100 Hz	0.33
125 Hz	0.42
160 Hz	0.48
200 Hz	0.43
250 Hz	0.36
315 Hz	0.45
400 Hz	0.4
500 Hz	0.36
630 Hz	0.34
800 Hz	0.37
1 kHz	0.34
1.25 kHz	0.32
1.6 kHz	0.31
2 kHz	0.34
2.5 kHz	0.37
3.15 kHz	0.35
4 kHz	0.33
5 kHz	0.32
6.3 kHz	0.28
8 kHz	0.27
10 kHz	0.23
12.5 kHz	0.21
16 kHz	0.19
20 kHz	0.18

Table 8: Reverberation time measured at an unused patient room at St.Olavs Hospital in Trondheim.

C Sound levels at Rikshospitalet

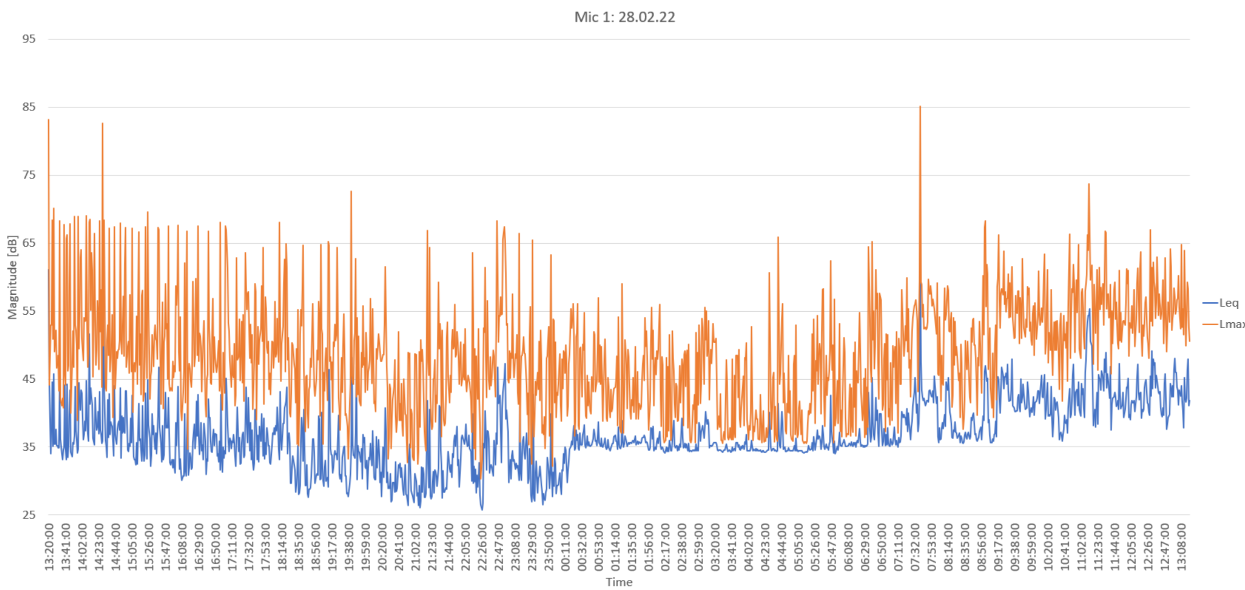

Figure 28: L_{eq} and L_{max} at microphone position 1 during the first day of measurements at Rikshospitalet.

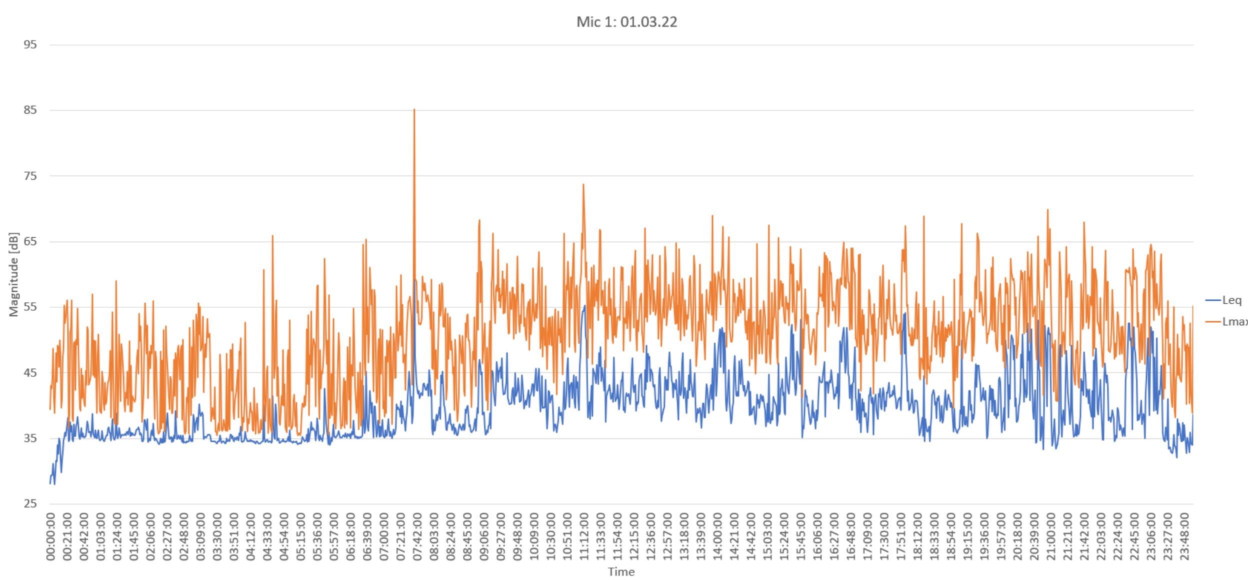

Figure 29: L_{eq} and L_{max} at microphone position 1 during the second day of measurements at Rikshospitalet.

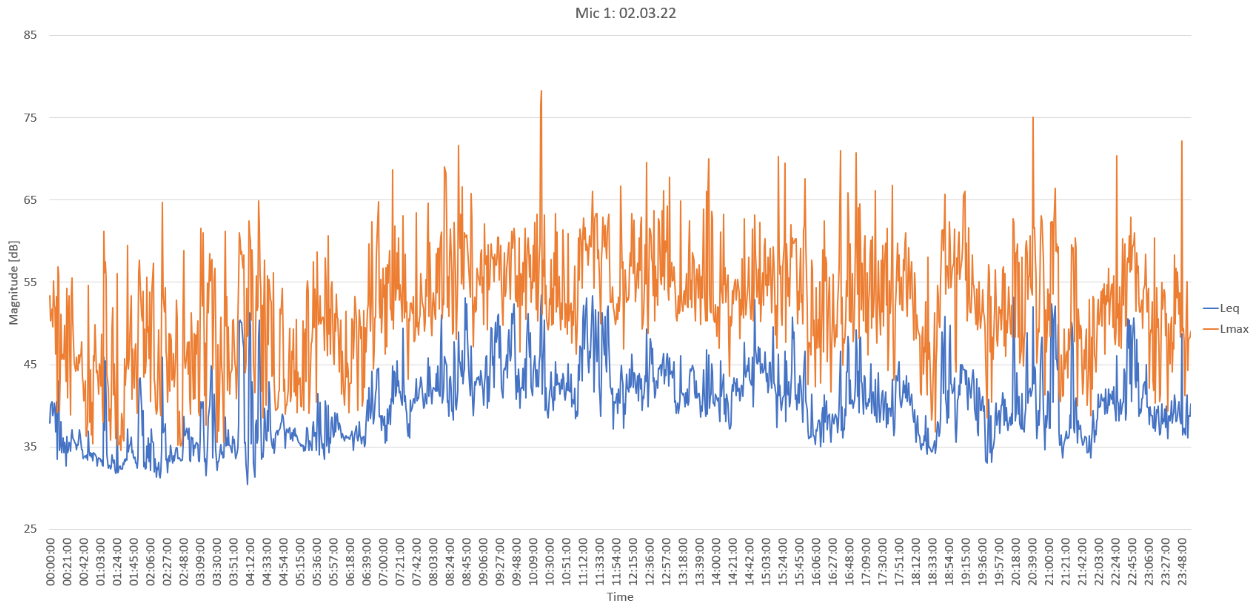

Figure 30: L_{eq} and L_{max} at microphone position 1 during the third day of measurements at Rikshospitalet.

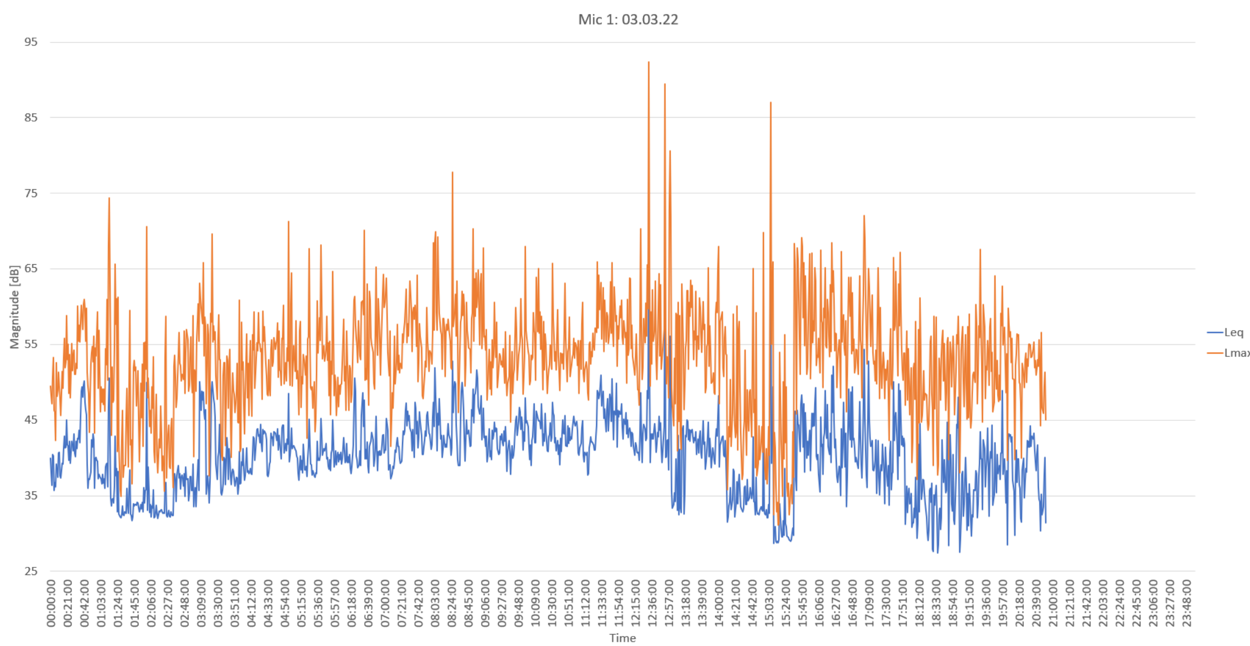

Figure 31: L_{eq} and L_{max} at microphone position 1 during the fourth day of measurements at Rikshospitalet.

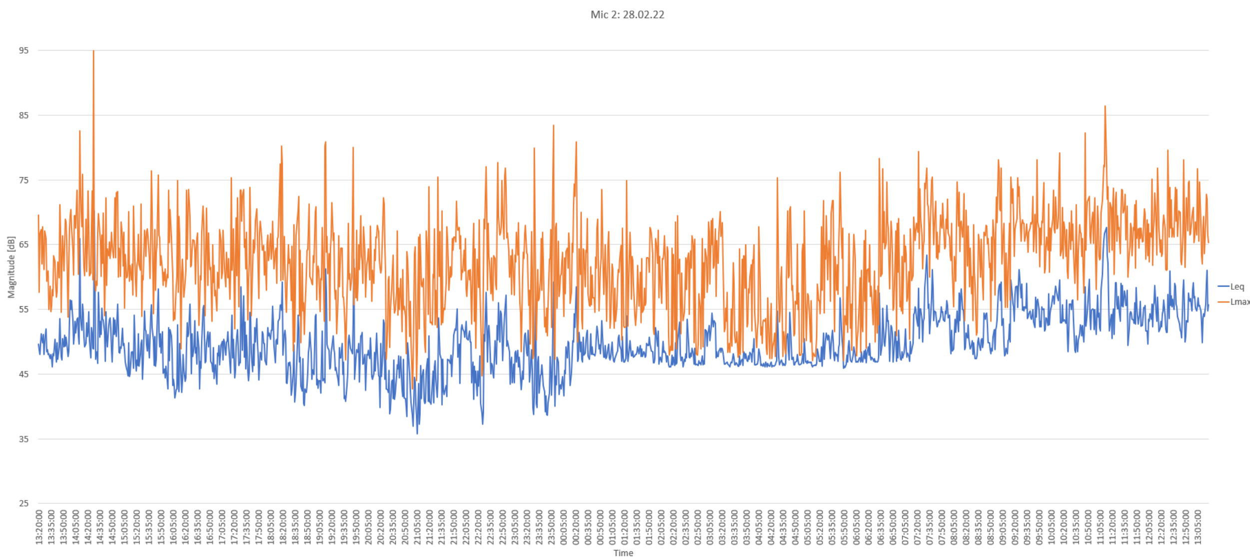

Figure 32: L_{eq} and L_{max} at microphone position 2 during the first day of measurements at Rikshospitalet.

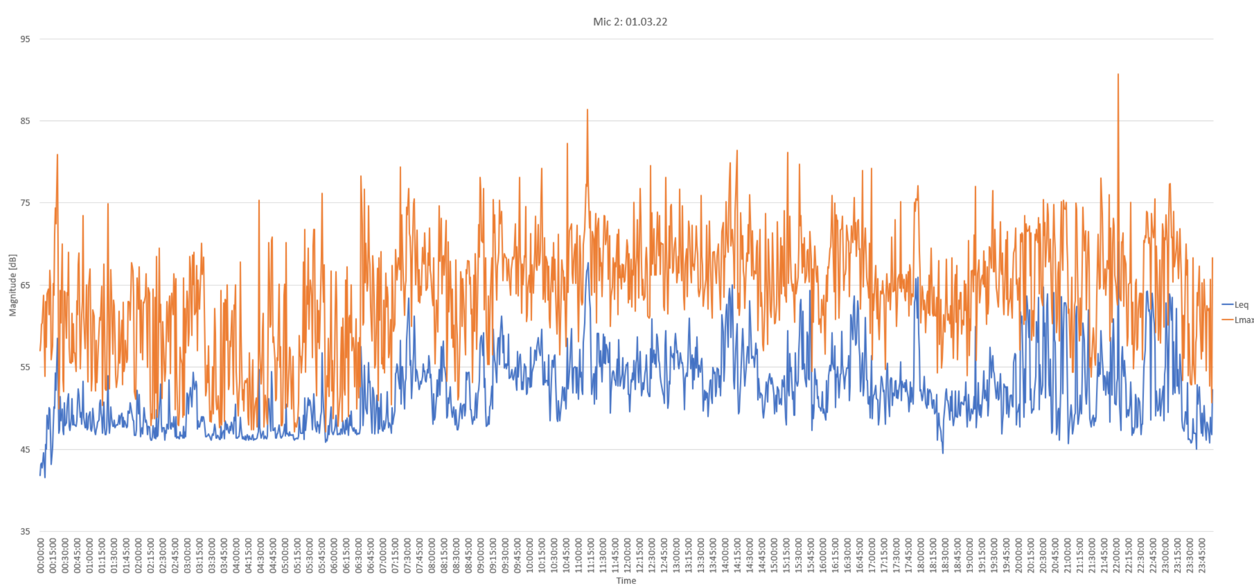

Figure 33: L_{eq} and L_{max} at microphone position 2 during the second day of measurements at Rikshospitalet.

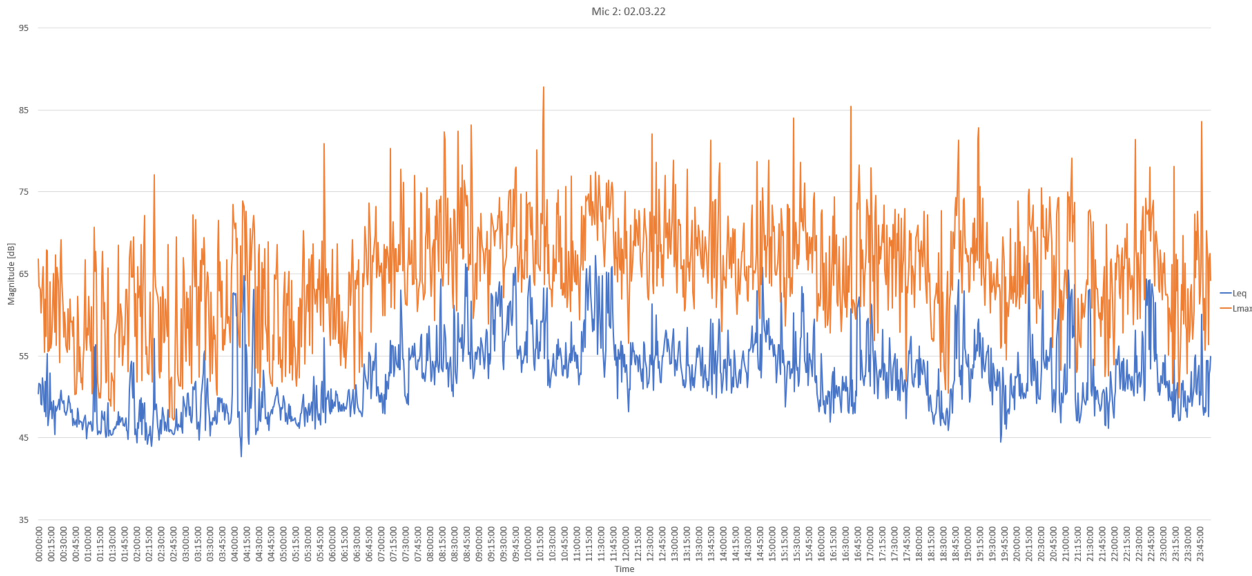

Figure 34: L_{eq} and L_{max} at microphone position 2 during the third day of measurements at Rikshospitalet.

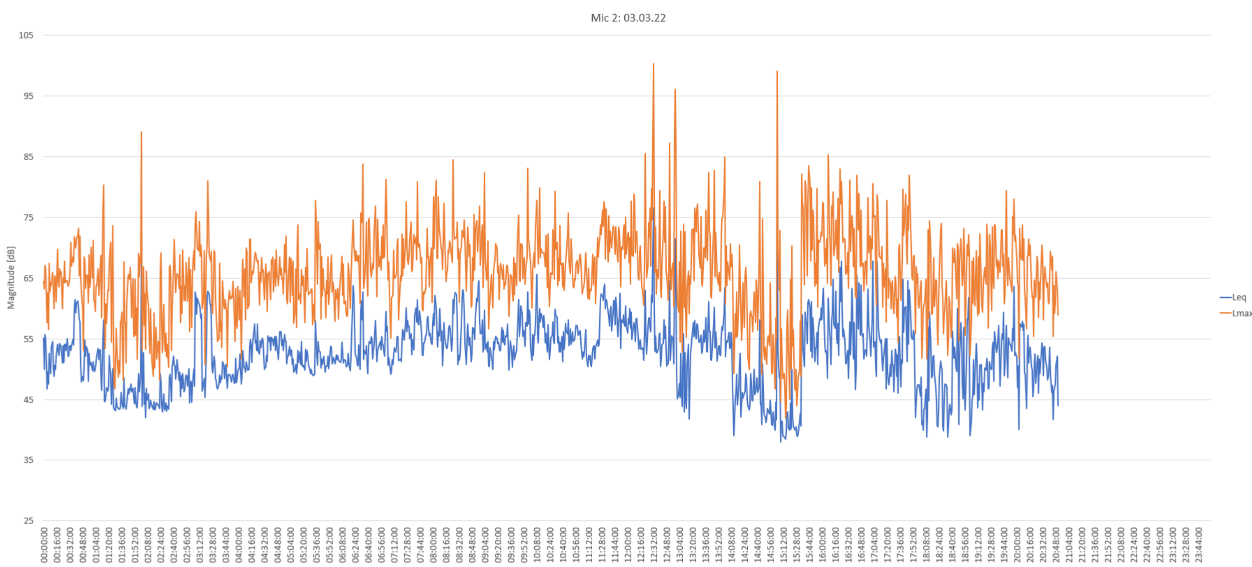

Figure 35: L_{eq} and L_{max} at microphone position 2 during the fourth day of measurements at Rikshospitalet.

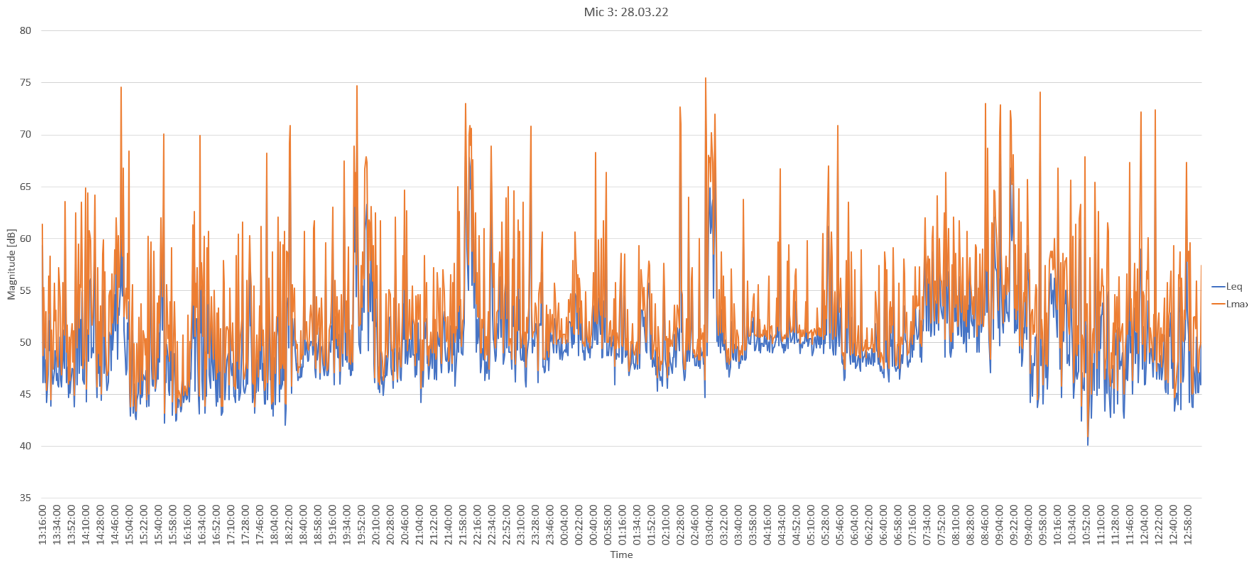

Figure 36: L_{eq} and L_{max} at microphone position 3 during the first day of measurements at Rikshospitalet.

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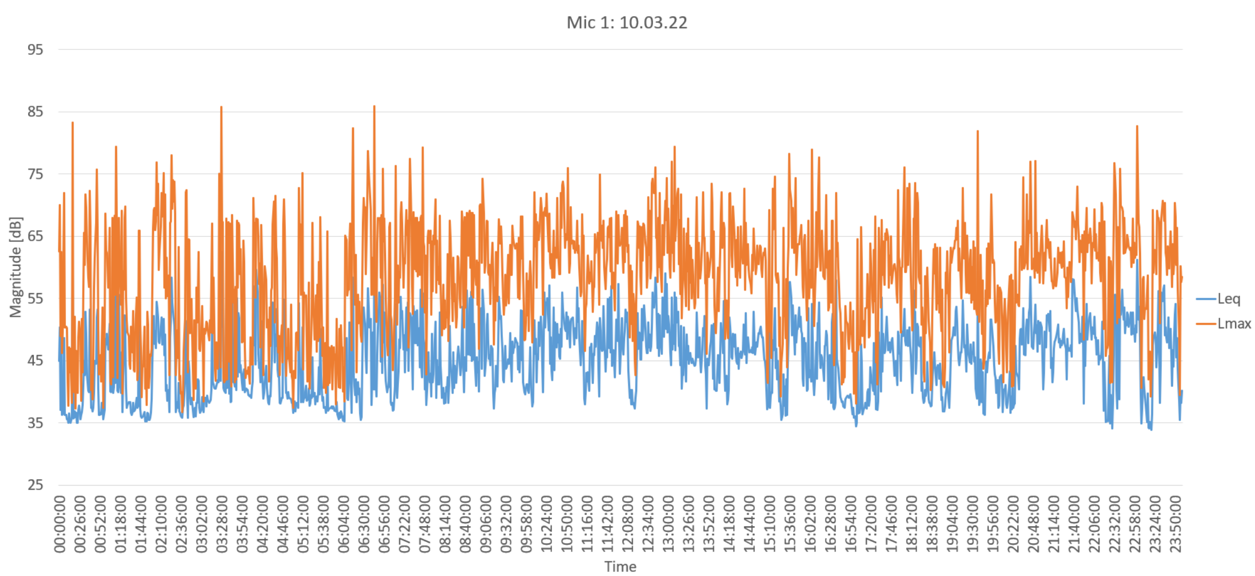

Figure 37: L_{eq} and L_{max} at microphone position 1 during the second day of measurements at St.Olavs Hospital.

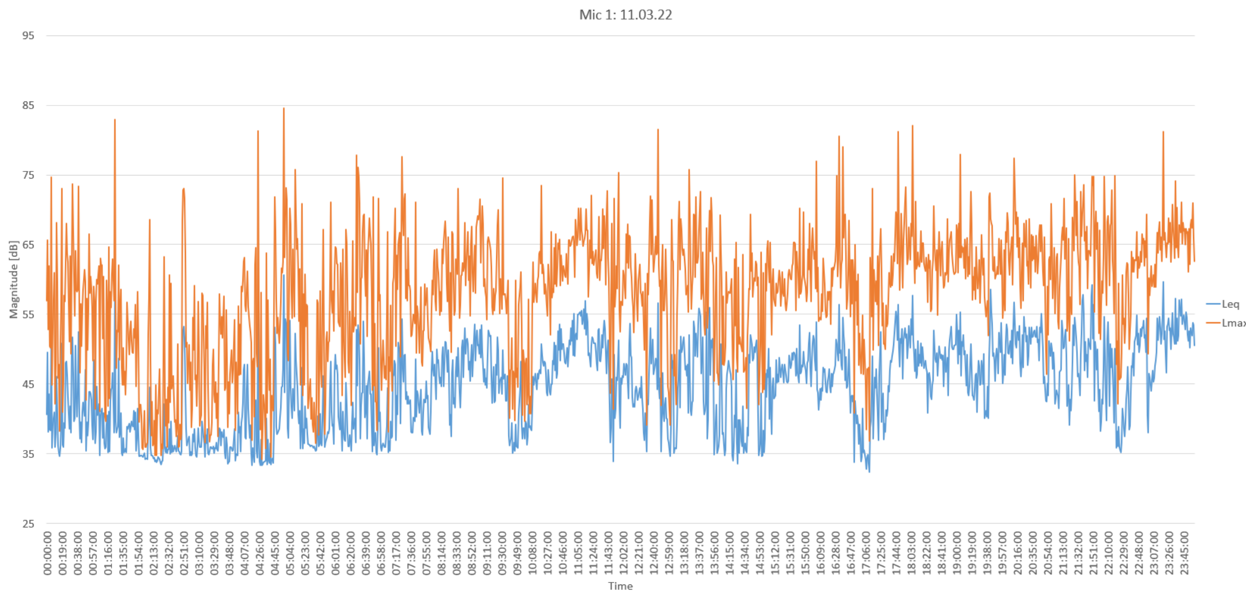

Figure 38: L_{eq} and L_{max} at microphone position 1 during the third day of measurements at St.Olavs Hospital.

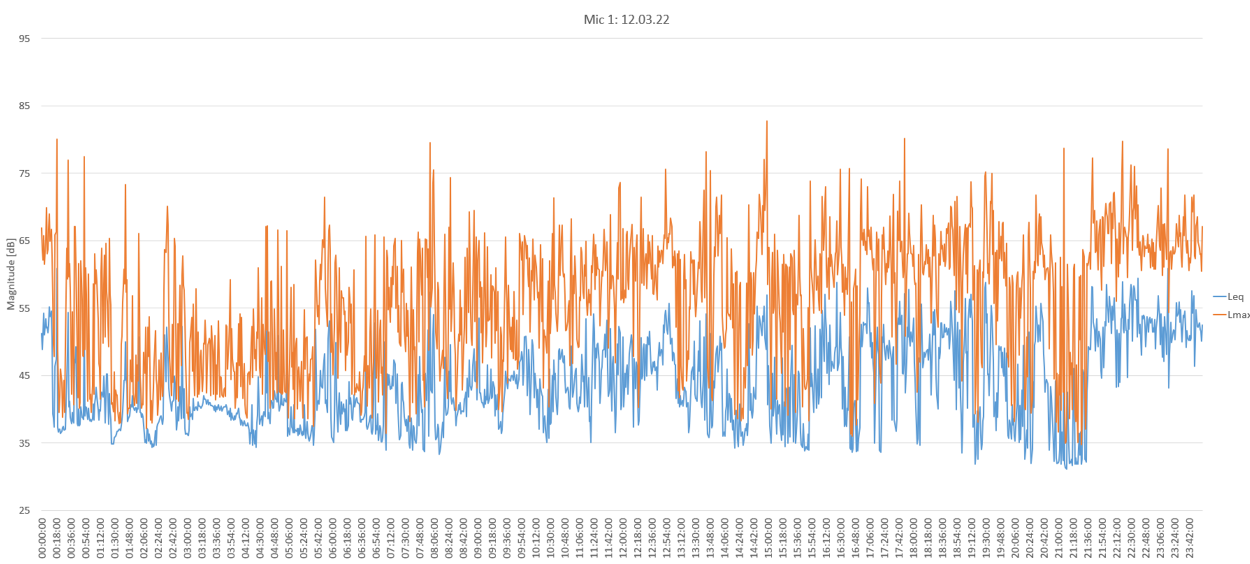

Figure 39: L_{eq} and L_{max} at microphone position 1 during the fourth day of measurements at St.Olavs Hospital.

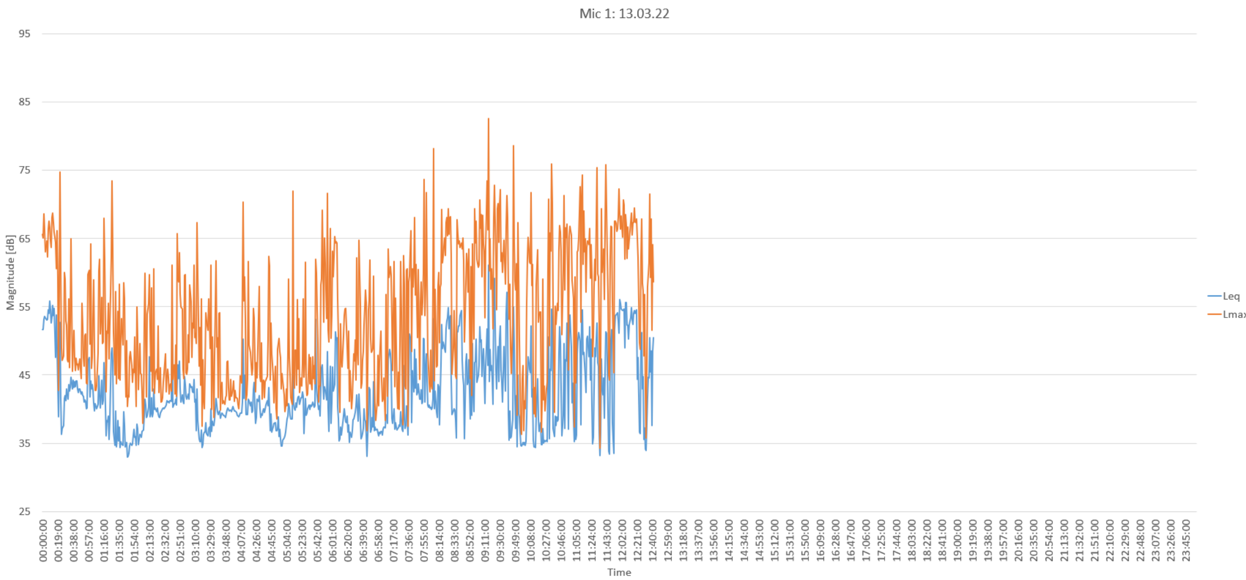

Figure 40: L_{eq} and L_{max} at microphone position 1 during the fifth day of measurements at St.Olavs Hospital.

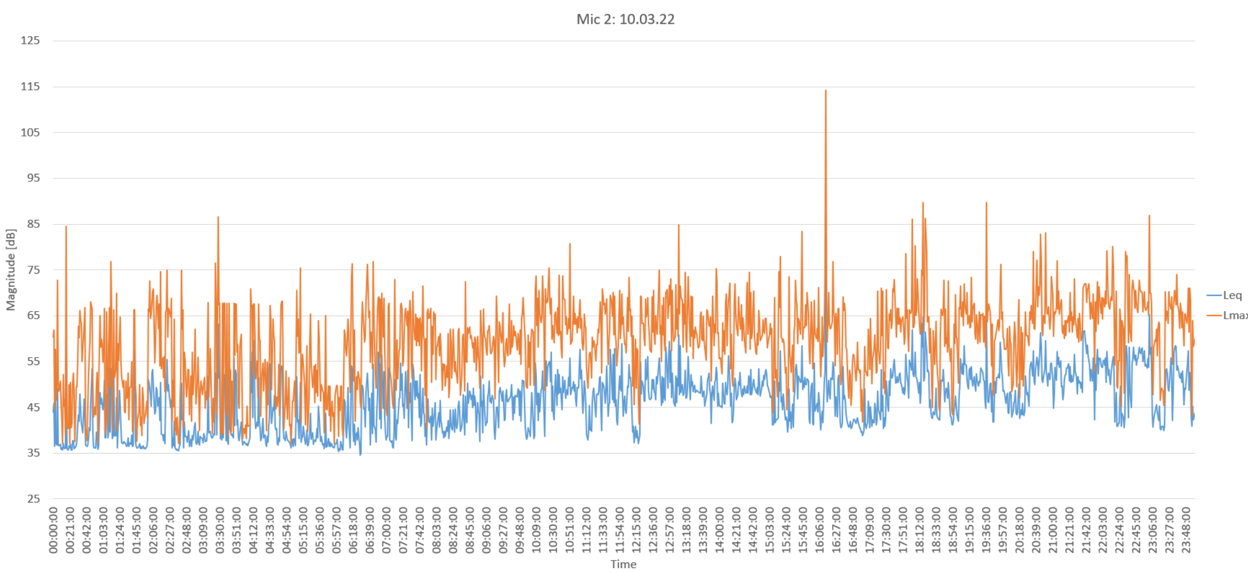

Figure 41: L_{eq} and L_{max} at microphone position 2 during the second day of measurements at St.Olavs Hospital.

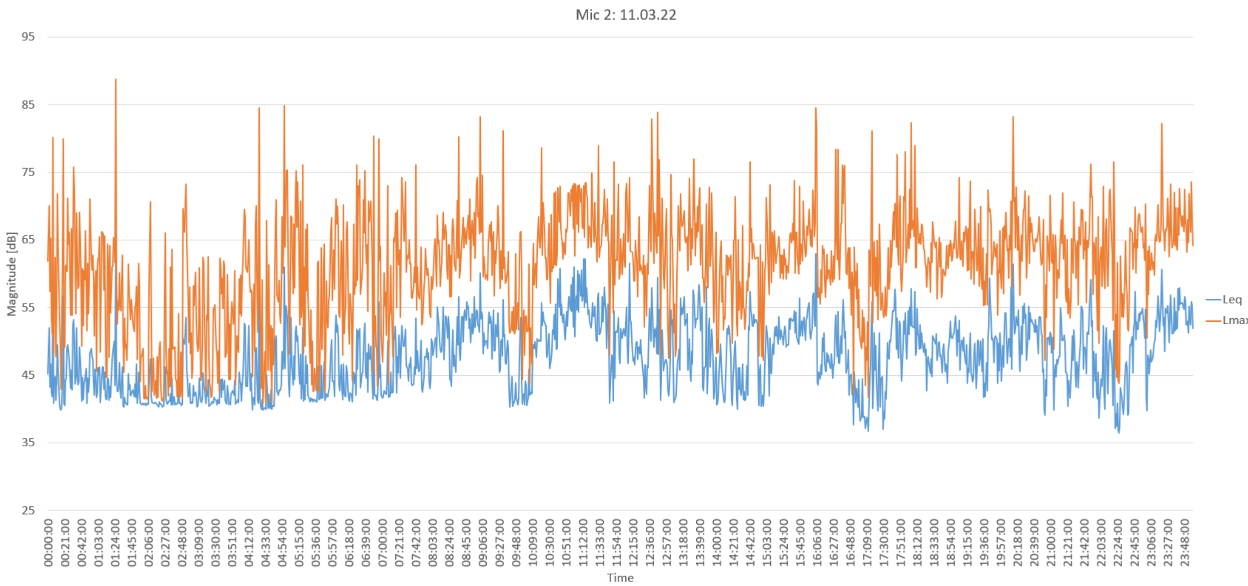

Figure 42: L_{eq} and L_{max} at microphone position 2 during the third day of measurements at St.Olavs Hospital.

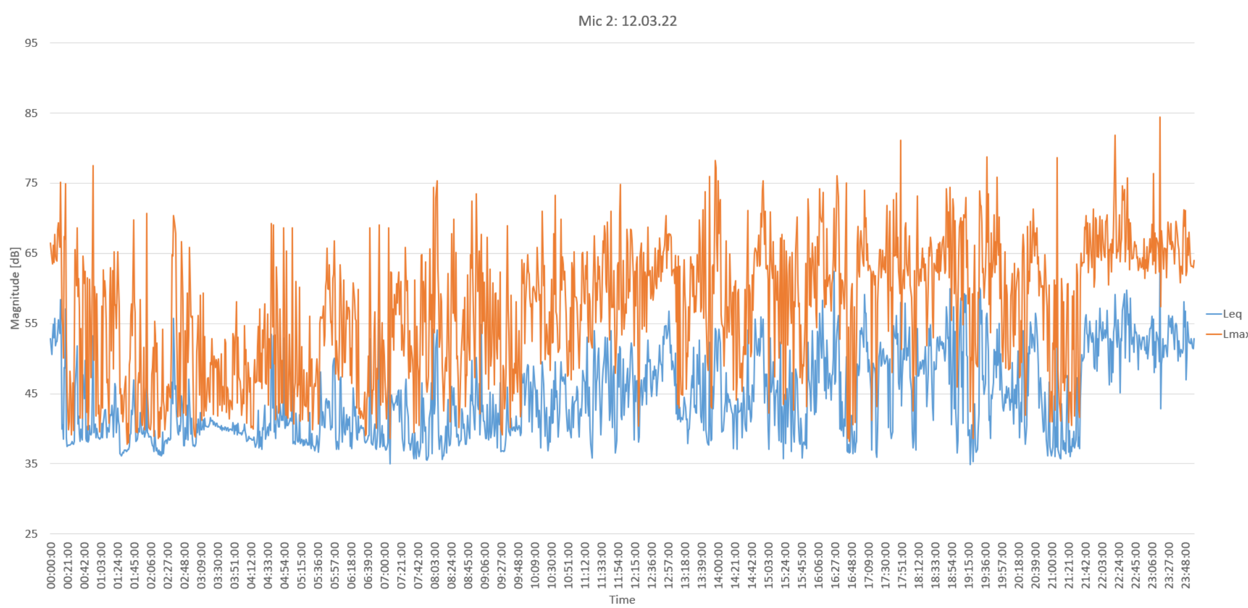

Figure 43: L_{eq} and L_{max} at microphone position 2 during the fourth day of measurements at St.Olavs Hospital.

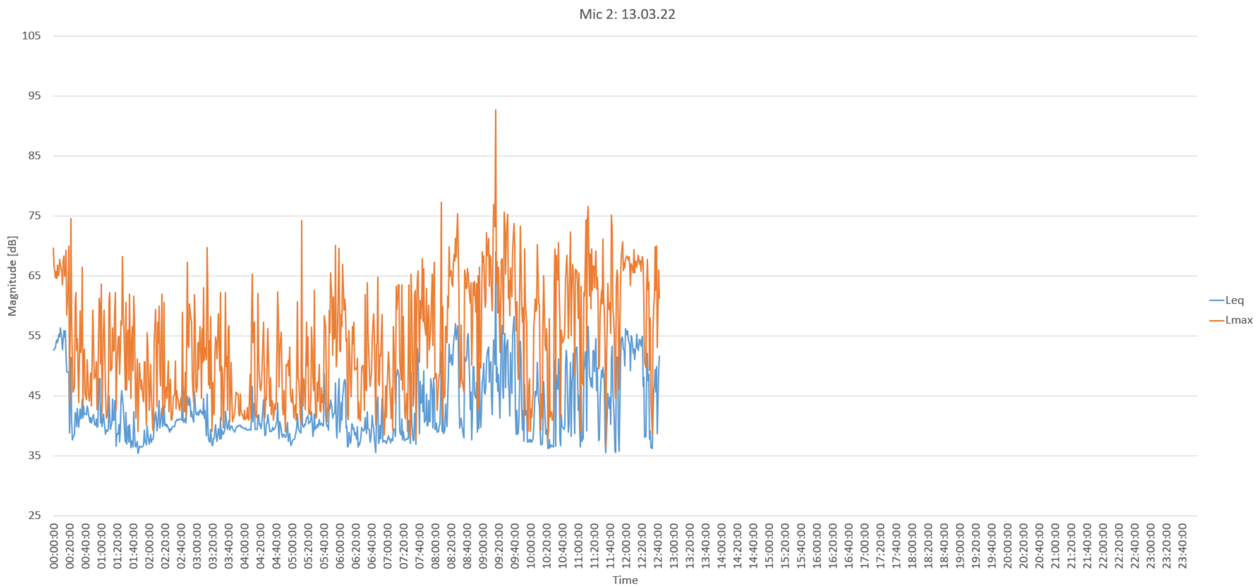

Figure 44: L_{eq} and L_{max} at microphone position 2 during the fifth day of measurements at St.Olavs Hospital.

E Sound Power Levels

	C1	C2	C3	C4
200 Hz	34.9	34.6	35.0	36.7
250 Hz	39.7	40.1	39.8	38.7
315 Hz	35.5	34.1	34.6	34.2
400 Hz	33.0	33.2	33.9	32.4
500 Hz	31.9	36.9	37.2	32.1
630 Hz	29.9	33.1	33.8	31.4
800 Hz	29.4	34.3	35.4	31.5
1 kHz	26.6	37.2	37.5	30.1
1.25 kHz	27.9	39.4	40.3	30.2
1.6 kHz	23.4	44.4	44.4	27.6
2 kHz	18.8	48.3	47.6	27.1
2.5 kHz	24.6	45.1	46.3	27.6
3.15 kHz	24.2	43.5	43.4	26.7
4 kHz	15.1	41.3	41.0	24.4
5 kHz	13.9	45.4	45.6	26.0
6.3 kHz	13.9	51.6	50.8	28.6
8 kHz	14.2	53.3	52.9	31.4
10 kHz	12.6	42.4	43.1	33.1
12.5 kHz	12.8	41.3	42.9	33.6
16 kHz	12.8	46.4	46.9	30.6
20 kHz	10.1	44.6	44.6	31.4

Table 9: Sound power levels at different incubator settings.

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