ESE498, Senior Design
Spring 2008, Morley

Neonatal Intensive Care Unit Sound Level Alarm (NICU SLA)

Abstract

Premature infants placed in Neonatal Intensive Care Units require special attention, especially as their fragile bodies are still developing. One of the concerns in the NICU environment is noise "pollution", which could prove to be harmful to the infant's auditory system. Here we outline the design of a Sound Level Alarm that would serve as a visual reminder of the noise level in the NICU. Using MatLab, a graphical interface was created that displays the dBA (A-weighted decibel) level of an environment, and also alerts when pre-set levels are exceeded.

Introduction

Neonatal Intensive Care Units (NICUs) are departments in hospitals where premature babies or sick infants are placed for monitoring and medical care. The NICU environment has to be carefully constructed to promote the health of the infant, with sound being one of the important criteria. Many modern NICUs are still noisy places, with alarms blaring, phones ringing, and ventilators whooshing. Despite technological and design advances such as sound-absorbing walls and near-silent medical devices, excessive noise levels still remains a problem.

NICU sound level control is important due to the differences between a mother's womb and an incubator in a hospital room. A mother's womb is a warm, dark environment that is exposed to relatively regular sounds, as well as the mother's soothing voice. In contrast, a premature infant in an incubator faces bright lights, a myriad of nurses' and doctors' voices, and unpredictable loud noises. Excessive loud noises may contribute to hearing impairment, sleep disturbance, and altered CNS (central nervous system) development[1]. Just as repeated exposure to loud noises can result in hearing loss for adults, NICU infants can also be prone to noise-induced hearing loss. Secondly, unpredictable loud noises can disturb infant's sleeping patterns, thus inducing extraneous stress on an already fragile premature baby. Lastly, and what may be most devastating, excessive loud noises may alter how neural pathways are formed in the developing infant[1].

As aforementioned, simply improving the design of the NICU may oftentimes not be enough to control the noises that reach a premature infant. A visual reminder of the sound level in an NICU would serve to reinforce speaking habits as well as alert staff to loud outbursts. The NICU Sound Level Alarm (SLA) would display visual warning signals whenever the sound level crosses a certain thresholds.

Background

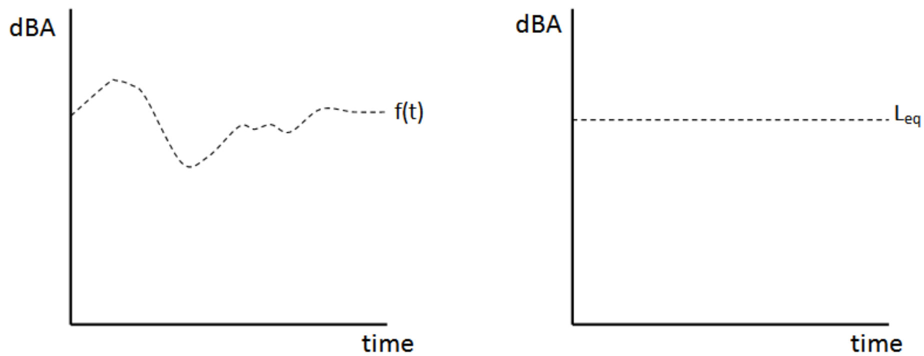
A typical NICU houses several incubators for premature, severely underweight, or very ill infants. These incubators provide a controlled environment for the infant, giving him/her a chance to survive. See Figure 1 for a typical NICU layout. Infants placed in a NICU may be treated with any of the following equipment: feeding tubes, heated beds, IV lines, and blood pressure cuff. The aforementioned equipment, along with hospital staff walking in and out, and regular conversation, all contribute to the noise level in the NICU.

Figure 1 typical NICU layouts[2][3]

In designing the SLA, we wanted to conform to the "Recommended Standards for Newborn ICU Design", which was a result of the Seventh Consensus Conference on Newborn ICU Design[4]. The recommended standards for the acoustic environment are as follows:

1. Hourly L_{eq} of less than 45 dBA
2. Hourly L_{10} of 50 dBA
3. L_{max} of less than 65 dBA

Here dBA refers to A-weighted decibel level, and all figures are for slow-response. The background of A-weighting will be discussed in a later section. Hourly L_{eq} refers to the equivalent noise level over a period of one hour. See Figure 2 on the next page for a graphical explanation of L_{eq}. Hourly L_{10} of 50 dBA means that over the course of one hour, at most 10% of that hour can the sound level reach 50 dBA. Lastly, L_{max} refers to peak noises, or sudden outbursts, and those should not exceed 65 dBA. Slow response (and fast response) refers to how quickly the instrumentation should respond to changes in noise level. Slow response corresponds to a 1 sec. response rate, while fast response corresponds to a 186 msec. response rate. The recommended standards suggest a slow response, as it approximates human hearing far closer than the latter.



f(t) is the dBA level observed over a period of 60 minutes (1 hour), Leq is the single dBA value such that → $\int_0^{60} f(t)\, dt = \int_0^{60} L_{eq}\, dt$

Figure 2 determination of hourly L_{eq}

The A-weighting filter is one of four standard acoustic weighting filters: A, B, C, and D. The A-weighting filter is based on work done back in 1933 by Fletcher and Munson when they recorded data to plot equal-loudness contours. Subjects were exposed to pure tones and then asked to adjust the level until they perceived it to equal the loudness of a 1000 Hz reference tone. The modern day A-weighting filter is based on Fletcher and Munson's 40-phon equal loudness contour, which means that the reference tone was 1000 Hz at 40 dB. The abbreviation dBA is used to indicate sound level with an A-weighting filter applied.[5]

As shown in Figure 3 below, the A-weighting filter has negative gain for frequencies below ~1000 Hz or above ~7000 Hz, while frequencies in between receive positive gain. The published recommended standards call for A-weighting, as this filter, out of the four standard filters, most closely approximates how humans perceive the relative loudness of different frequencies.

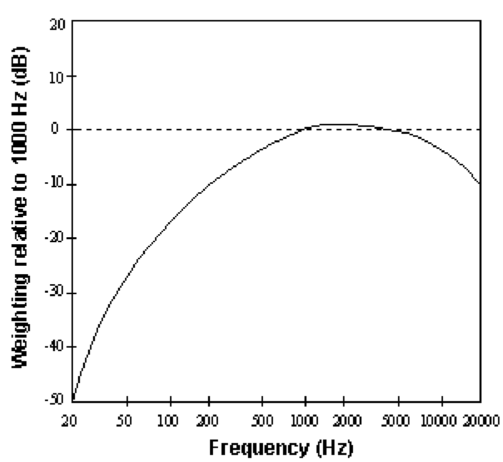


FIGURE 3 A-weighting filter relative frequency response curve[6]

With these recommended standards in mind, we set out to design a SLA that would light up whenever the noise level exceeded the following: 45 dBA, 55 dBA. At the 45 dBA level, the yellow LEDs would light up until the sound level had gone back down. Upon reaching 55 dBA, the red LEDs would light up. These visual signals would serve to reinforce talking habits as well as how particular actions are carried out, e.g., changing tubes or programming equipment.

Using a desktop computer, Matlab software, and a store-purchased microphone, we designed a Graphical User Interface (GUI) that detects and displays a room's noise level in dBA. In addition, it alerts users when the noise level exceeds the previously mentioned two numbers. Figure 4 below shows the display we created using Matlab.

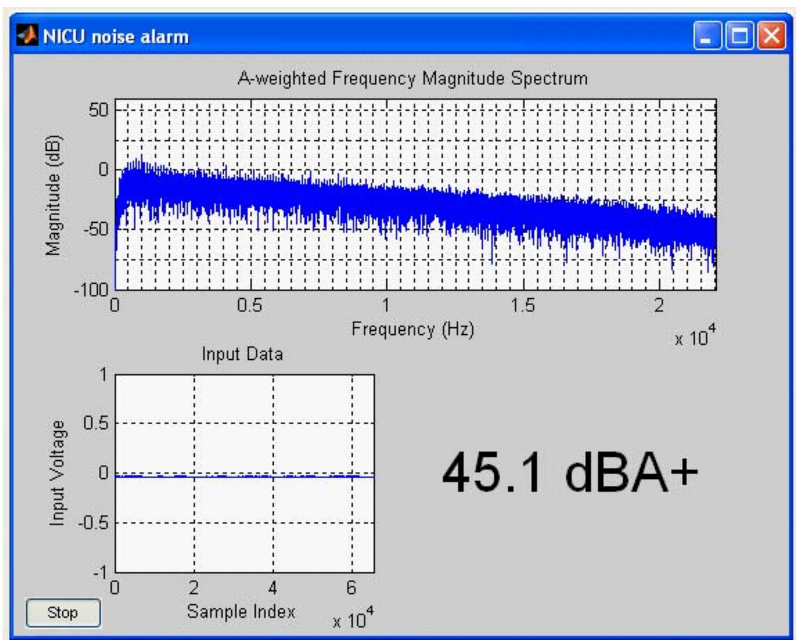


FIGURE 4 NICU SLA display
If dBA level exceeds 45, a "+" sign added after "dBA"
If dBA level exceeds 55, a "++" is added after "dBA"

Design

Materials

This list details the exact equipment parts we used for our testing and designing phases. For mass production, the list of parts recommended is described later in the "Costs" section.

* Dell Optiplex GX270 desktop computer
* MatLab
* MatLab Data Acquisition Toolbox
* Dell A225 Two-piece Stereo Speaker system
* Quest 1800 Sound Level Meter
* Quest QC20 calibrator
* Quest QE4170 microphone
* Philips PH62080 microphone

A-weighted frequency response

To mimic the human ear's response, which has a high-frequency cutoff around 20kHz, a Nyquist rate of 22.05 kHz was used. This meant that the sampling rate was 44.1 kHz. As aforementioned, our system uses slow response, so our window size is 1 second. This allows us to find the minimum number of samples in each FFT (Fast Fourier Transform) window:

$$N_{min} = f_s\Delta t = (44{,}100)(1) = 44{,}100$$

We chose the Decimation-In-Time (DIT) Radix-2 FFT for its relative computational costs. One caveat of the DIT Radix-2 FFT is that the input length must be a power of 2, thus we find the next power of 2 greater than or equal to N_{min}, which happens to be 65,536 (2^{16}).

The N sample-point DFT equation is given by:

$$(1)\quad X[k] = \sum_{n=0}^{N-1} x[n]\, e^{\frac{-2\pi k n i}{N}}$$

Where X[k] is one DFT sample, and x[n] is the time-domain sample. To find the frequency resolution Δf, we use the following equation:

$$(2)\quad \Delta f = \frac{f_s}{N} = \frac{1}{NT}$$

The standard A-weighting filter equation can be found in documentation provided by American National Standards Institute (ANSI), or online[7]:

$$(3)\ \alpha_A(f) = \frac{(3.5041384\times 10^{16})\, f^8}{(20.598997^2 + f^2)^2 \times (107.65265^2 + f^2)\times (737.86223^2 + f^2)\times (12194.217^2 + f^2)^2}$$

where *f* is any given frequency.

Equation (2) lets us determine the frequencies of each FFT sample X[k]. We then apply these frequencies, f_k, into equation (3) to determine the A-weighting filter coefficients. The A-weighted FFT samples, X_A, are thus given by:

$$(4)\ X_A[k] = \alpha_A(f_k)\, X[k] \quad \text{where } f_k = k\Delta f$$

Estimation of dBA

The preceding section described how we obtained an A-weighted frequency response spectrum. Here we show how to arrive at the average instantaneous signal energy. Now we have to integrate the total signal energy over the response interval, in this case 'short', to determine the signal level in dBA. The energy of a signal, for our purposes, sound intensity, is the sum of the squared magnitudes of the time-domain samples. However, since the A-weighting has been applied in the frequency domain, we have to apply Parseval's Theorem. Let ε_x be the energy of a signal level, then Parseval's Theorem lets us say:

$$(5)\quad \varepsilon_x = \sum_{n=0}^{N-1} (x[n])^2 = \frac{1}{K}\sum_{k=0}^{K-1} (X[k])^2$$

We can then find the average instantaneous signal energy by dividing by the window size Δt:

$$(6)\ \hat{\varepsilon}_x = \sum_{n=0}^{N-1} (x[n])^2 = \frac{1}{K\Delta t}\sum_{k=0}^{K-1} (X[k])^2 = \left(\frac{1}{f_s}\right)(N)\ \frac{1}{K}\sum_{k=0}^{K-1} (X[k])^2$$

Now we can find the dBA signal level:

$$(7)\ \text{dBA} = 10\log\left(\frac{\hat{\varepsilon}_x}{\hat{\varepsilon}_{\text{reference}}}\right) = 10\log\left(\hat{\varepsilon}_x\right) - 10\log\left(\hat{\varepsilon}_{\text{reference}}\right) = 10\log\left(\hat{\varepsilon}_x\right) - C$$

Since we do not know what input voltage corresponds to the reference sound pressure level, we have isolated the reference average energy level, $\varepsilon_{\text{reference}}$, and lumped it into a calibration constant, *C*.

Calibration of unit

Utilizing the Quest Sound Level Meter, we sought to find the appropriate calibration constant. Firstly, we knew from the Quest's manual that the Sound Level Meter has a fairly flat frequency response from 100-10,000 Hz (within ±2 relative dB). As shown in Figure 5 below, the Quest QE4170 microphone has a flat frequency response up to 4000 Hz, a peak from 4000-9000 Hz, and then a drop-off after 9000 Hz.

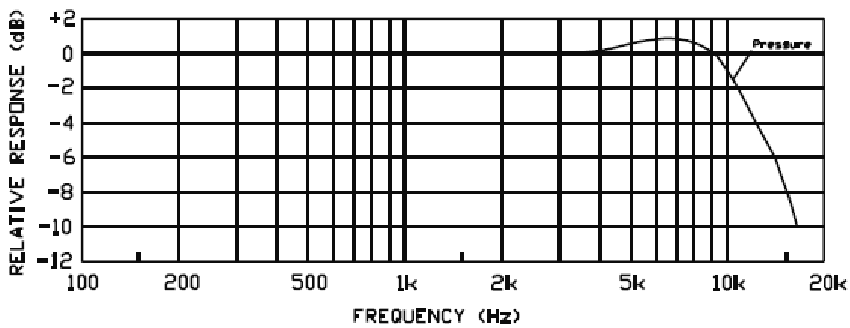


Figure 5 frequency response curve of the Quest QE4170 microphone[8]

Realizing that the desktop computer speakers may not have a flat frequency response curve, we programmed MatLab to output a series of pure tones ranging from 100 to 12,000 Hz. This range was chosen because the Dell speakers had a stated range of 100-20,000 Hz, while the Philips microphone had a stated range of 80-12,000 Hz. Each tone was outputted at the same "level", i.e., the volume dial on the speakers was not changed. At each frequency, we recorded the Quest's reading, thus giving us a frequency response curve for the speakers, shown in Figure 6 on the next page. Given the Quest's flat frequency response, we took these readings to be "reality", i.e., the dBA reading reflected the actual sound pressure level outputted by the speakers.

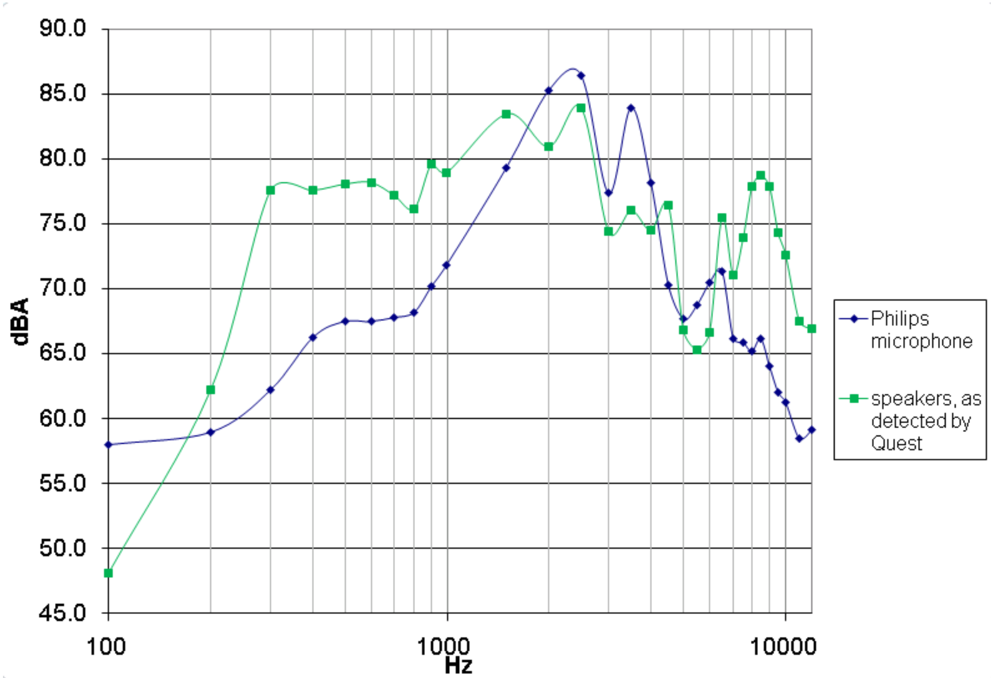


FIGURE 6 frequency response curves (A-weighted) of microphone and speakers

We also recorded the readings our Philips microphone/Matlab program gave us at each frequency. As shown in Figure 6 above, there was significant difference between the Philips microphone and the Quest. We then altered the Matlab code to give different weightings to different frequency ranges, thereby calibrating the microphone's readings to reality. See Figure 7 on the following page for our setup's frequency response post-calibration. For frequencies in between our test values, extrapolation is being used.

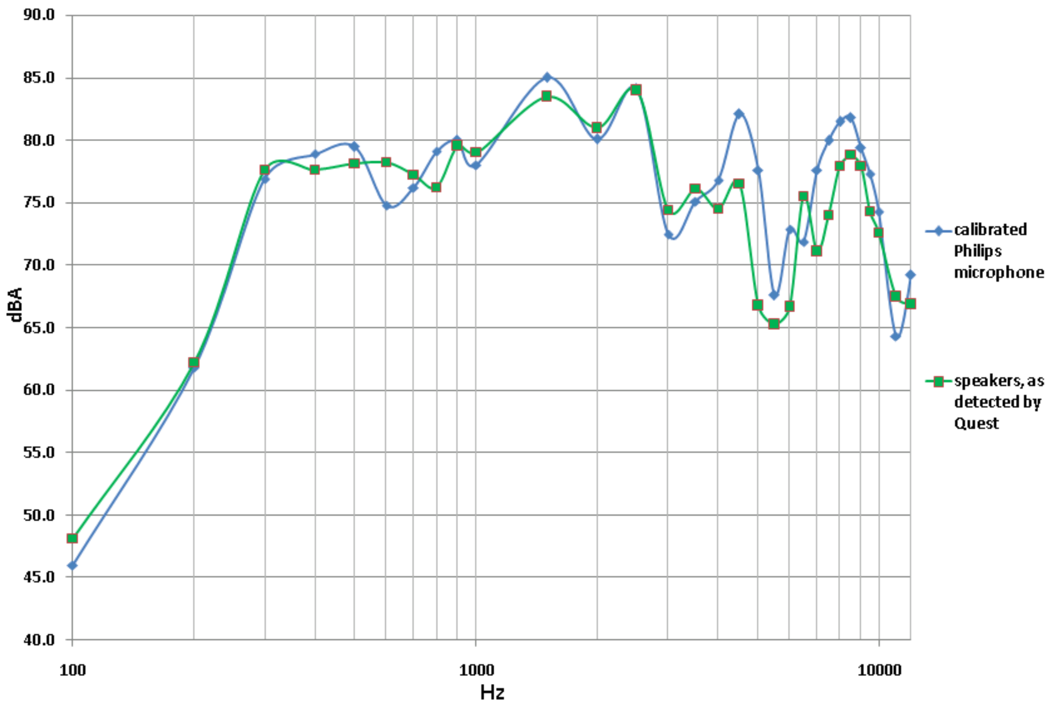


FIGURE 7 frequency response curves (A-weighted) of microphone with Matlab's calibration constants and speakers

Whole System Setup

A typical NICU could house anywhere from a few incubators to several dozen. This means that sound intensity detection in NICUs should also take into account distance, i.e., how far away the microphones are from the sound source. There is a simple relation that ties together the sound intensity detected by any two microphones:

$$(8)\ \frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

In equation (8), r_1 and r_2 are the microphones' respective distances from the sound source, and I_1 and I_2 are the sound intensities detected by the respective microphones. Sound intensity is the relevant measure here as it is directly related to decibels. Given equation (8), our NICU SLA would require three microphones placed in different corners of the hospital room.

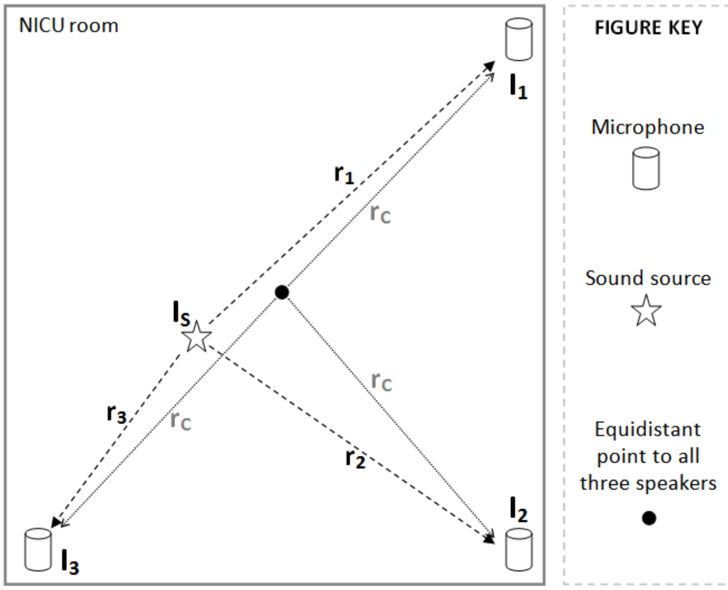


FIGURE 8 triangulation of sound source

As shown in Figure 8 above, this would allow for triangulation and determination of the sound intensity at the source. Suppose that I_S is the sound intensity at the source, and r_1, r_2, and r_3 are the distances from the source to the microphone. Knowing I_1, I_2, and I_3, we can write the following relations and iteratively solve for r_3:

$$(9)\quad \frac{I_1}{I_2} = \frac{{r_2}^2}{{r_1}^2} \qquad \frac{I_2}{I_3} = \frac{{r_3}^2}{{r_2}^2} \qquad \frac{I_1}{I_3} = \frac{{r_3}^2}{{r_1}^2}$$

The seed values for r_1, r_2, r_3 will be the distance to the "center" of the room, r_C, as we know that, ideally, a sound source equidistant to all three microphones would result in $I_1 = I_2 = I_3$. Upon installing the NICU SLA, we have the benefit of knowing r_C, as we know the NICU room dimensions. Having solved for r_3, we can then find I_S:

$$(10)\quad I_S = \frac{{r_3}^2}{{r_S}^2} I_3$$

Here r_S is the distance to a point arbitrarily close to the source, e.g., 0.5 inches. For a brief overview of solving for I_S, see the flowchart in Figure 9 on the next page.

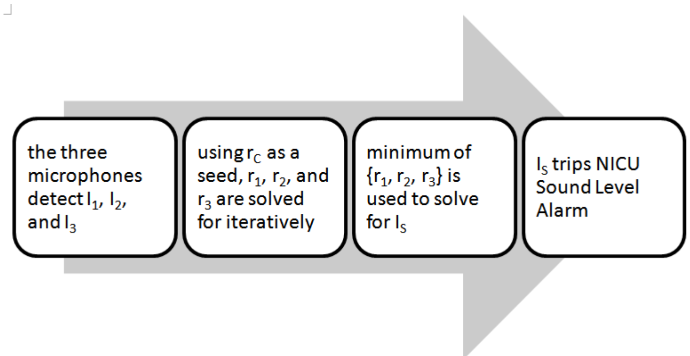


FIGURE 9 determination of Is, sound intensity at the source

Note that we have made several assumptions to find I_S, including the following:

* Rectangular NICU room layout
* Minimal obstruction of soundwaves by the equipment and staff in the NICU
* Minimal feedback detected by the microphones

For a mockup of how the system would function in an NICU, please see Figure 10 below. A yellow lit LED would indicate that the 45 dBA threshold has been crossed. This would hopefully alert staff to be aware of the current noise level and continue to monitor the situation. A red lit LED would indicate that the 55 dBA threshold has been crossed, and immediate steps should be taken to address the noise level in the NICU.

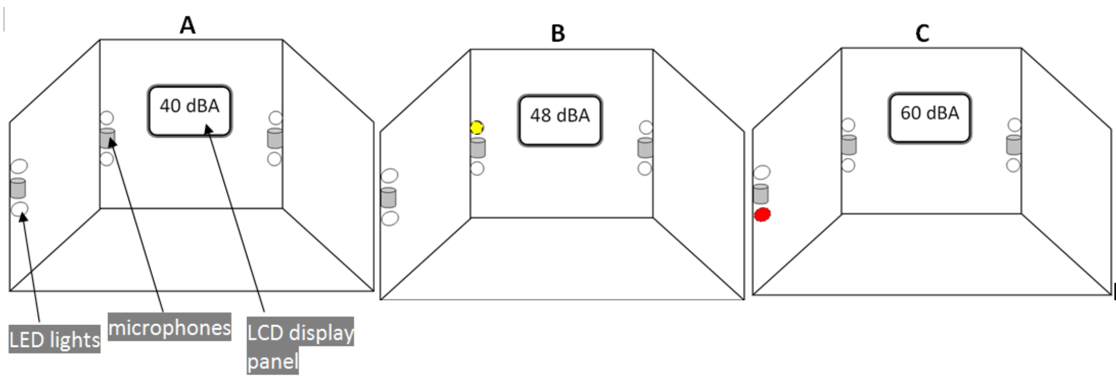


Figure 10 Sound Level Alarm mock up. Note that figure is not to scale
A: sound level in NICU is below 45 dBA, no LED lights are lit
B: sound level is between 45 and 55 dBA, yellow LED closest to sound source is lit
C: sound level exceeds 55 dBA, red LED is lit

Costs

Item	Source	Quantity	Unit Price
Panasonic Electret Condenser Microphone Cartridge WM61-A	www.digikey.com	3	$1.66
Wiring	N/A	N/A	N/A
PIC16F877 Controller Microcontroller	www.futurlec.com	1	$25
LED lights	www.theledlight.com	12	$9
Quest 1800 Sound level meter with microphone	www.quest-technologies.com	1	$2000
Installation Fee	N/A		$200-$300
Periodic Maintenance	N/A		$50

The Panasonic microphone was chosen for its cost and frequency response profile. Figure 11 below shows that the WM61-A has a very flat frequency response in the 20-20,000 Hz range. This is ideal as this hopefully translates into minimal calibration in the production process.

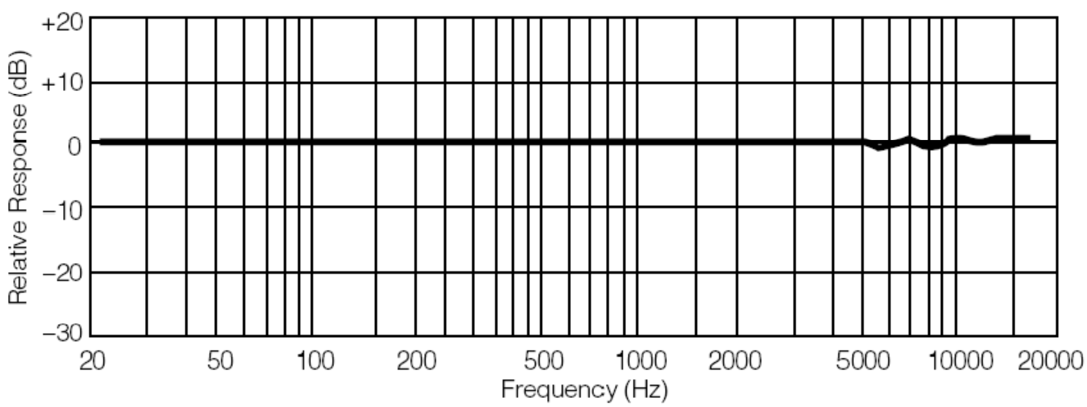


FIGURE 11 Panasonic WM61-A microphone frequency response curve[9]

Upon purchasing of the components, the microphones would be calibrated in the same fashion as outlined in a previous section. The A-weighting filter would be applied. The installation fee would largely depend on the NICU room dimensions and layout. It is crucial to perform on-site installation and testing, as different dimensions and equipment would affect the acoustics of the room. Periodic calibration would also be required to ensure the fidelity of the microphones. For a brief overview of the whole process, see Figure 12 on the next page.

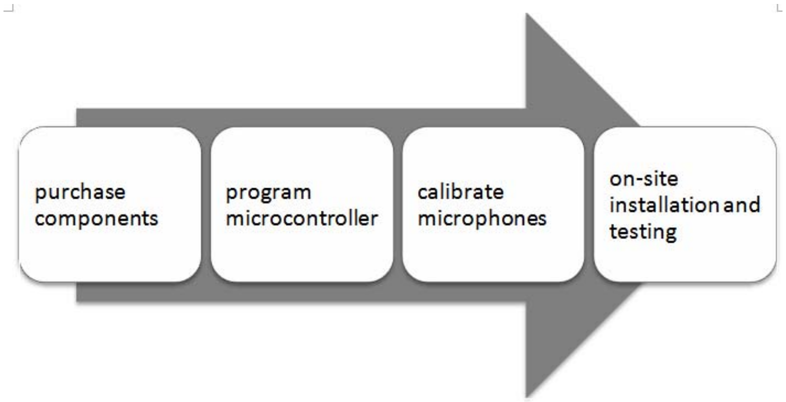


FIGURE 12 NICU SLA production process

Conclusion

Accomplishments

With sound being an important concern in NICUs, we have outlined the details of the design to a Sound Level Alarm. While other experimental models do exist[10], but there does not seem to be a retail system specifically for NICUS. If anything, the recommended step is to use an off the shelf commercial sound meter such as a Quest. However, this solution seems to have two flaws:

1. Too general – the Quest sound meter is intended for use in any environment.
2. Too powerful – a Quest sound meter costs at least $2000, buying three meters and setting them up in three corners of a NICU room appears to be overkill.

In contrast, we have designed a SLA system specifically for NICU rooms, giving thought to room dimensions and Recommended Standards.

Uncertainties

Temporal fidelity of equipment

During the design of our system, we did not have the opportunity to test the deterioration over time of the electrical equipment. It is conceivable that microphones could degrade over time, but it is not certain what the relevant timeframe is. Given the rigor of standard electrical components, it would be reasonable to schedule periodic calibrations and testing, much like fire extinguishers have to be inspected annually. Obviously the setup should be inspected post major events, e.g., earthquakes, to ensure the fidelity of the system. To minimize accusations of negligence, it is foreseeable that the equipment should be inspected once every three months, and be replaced if deemed necessary.

Differences between adult and preterm infant auditory responses

It is worth mentioning that the A-weighting filter was determined using adult human subjects. There are differences between a fully "mature" auditory system and that of an infant's, especially a pre-term infant. It is known that fetuses have a higher frequency threshold than adults, i.e., a higher sound pressure level is required for them to detect the same frequency. Figure 13 on the next page shows the frequency auditory-thresholds of a fetus, a newborn, and an adult. The 25 and 30 week newborn data are speculative projected curves, as definitive data do not exist for preterm infants. (Preterms are already under a lot of stress, thus subjecting them to a frequency response test is not always easy or ideal).

As aforementioned, our SLA "danger" levels are taken from the Recommended Standards. This is reasonable due to the fact that:

1. Even though the most definitive data on auditory response is based on adult humans, the reliability of this data outweighs the differences between adult and preterm infants. Also, since an adult has a lower threshold, this means that our system design is on the conservative side, meaning that we may be overly cautious in some cases. Given the fact that a child's hearing is at stake, this seems wise.

2. During the preterm's stay in the NICU, his/her auditory system is rapidly maturing and becoming closer to that of an adult's.

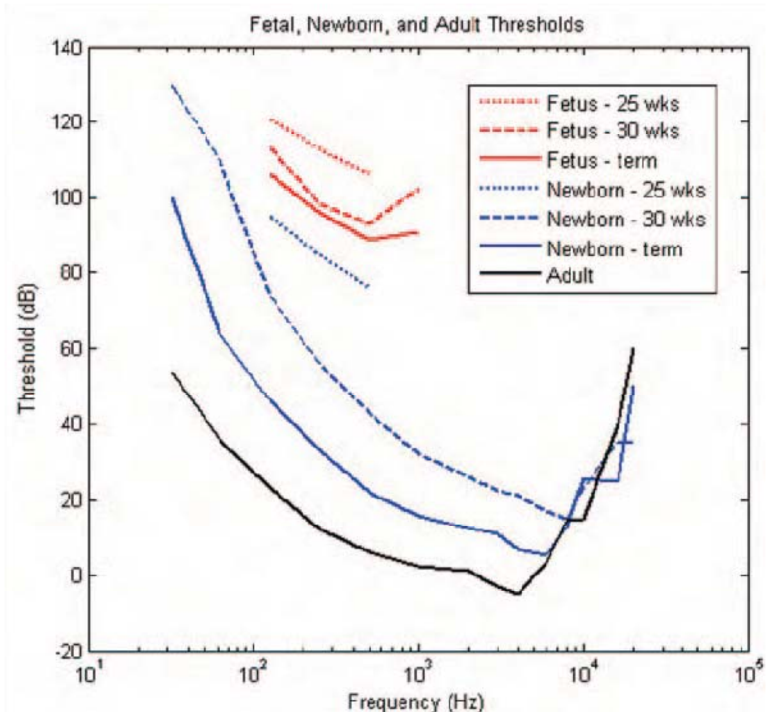


FIGURE 13 frequency auditory-thresholds. Note the scale is in dB, not dBA[11]

Ethical Considerations

It should be emphasized again that our SLA is not intended to predict, treat, or prevent any hearing disorders in infants. The SLA's primary function is to serve as a visual reminder whenever the noise level in the NICU exceeds a certain level. It is up to the staff to address the noise issues. Nevertheless, this does not mean that our device would be free from any legal ramifications. To ensure that the SLA can truly detect sound intensity to within "± x dBA", quality control on the front end must be very rigorous. Legal troubles would arise if we claimed a certain sensitivity, but the alarm fails to light up when noise levels exceed the recommended standards.

At this point, there do not seem to be any conflicts of interest. For example, it is in the interest of both the manufacturer and hospital to have SLAs that do function and can detect the correct noise levels. As aforementioned, the manufacturer would want to ensure quality not only for its own reputation, but also to minimize legal ramifications. To minimize loud noises in the NICU, the hospital should also consider other methods, in addition to the SLA, such as near-silent equipment, noise insulating walls, etc., many of which are outlined in the Recommended Standards.

Future Work/Alternatives

Even though the A-weighted filter is the most commonly accepted, probably due to historical precedent and ease of use, there are other weighting filters that could be considered. More recent work by Suzuki *et al* has established a new set of ISO226 equal-loudness contours[12]. The group combined data from several different studies and produced the new ISO226 standards. Figure 14 below compares Fletcher and Munson's equal-loudness contours to the ones established by Suzuki. The new 40-phon contour is similar in shape but does have differences, e.g., the peak is higher in the 1000-2000 Hz range. Figure 15 on the next page compares the relative dB gains of ISO226 compared to the traditional A-weighting filter. The A-weighting filter was chosen for our device due to the guidelines in the Recommended Standards. Maybe as ISO226 gains more acceptance in the audio community, the A-weighting filter will be phased out, and replaced by a filter that even more closely approximates human hearing.

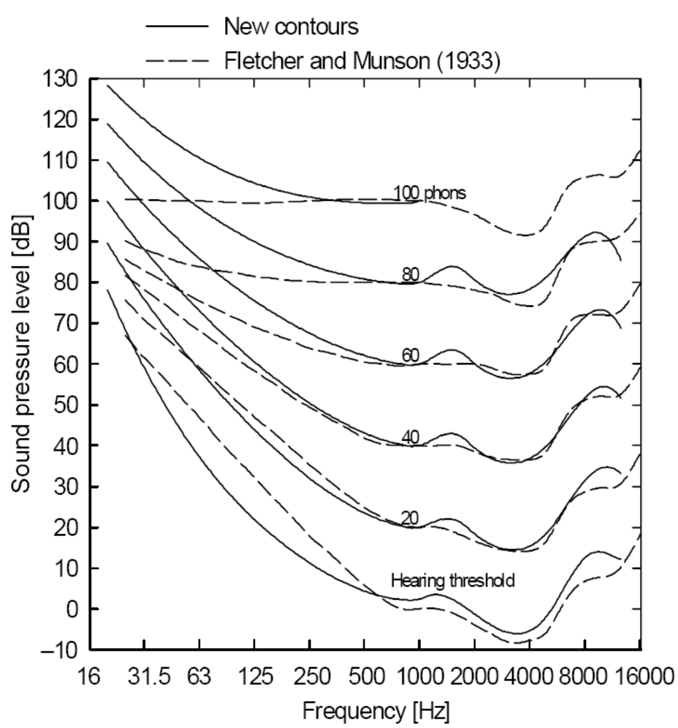


FIGURE 14 "old" and "new" equal-loudness contours[12]

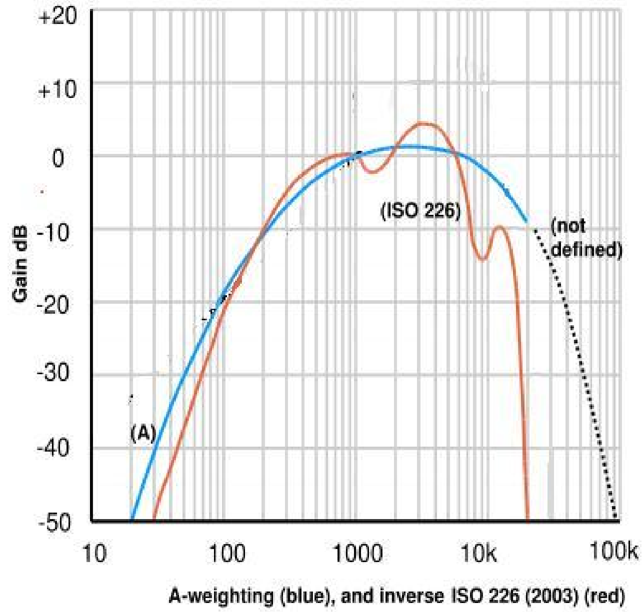


FIGURE 15 relative dB gain of A-weighting filter and ISO226[13]

It is worth noting that our device detects loud noises, but cannot be solely used to prevent the occurrence of loud noises. Having a visual reminder may train staff in terms of their speaking habits, but the SLA cannot prevent random loud outbursts of noise. Therefore, when a hospital designs a NICU, it must take into account preventative measures as well. For example, choosing quiet equipment, installing sound-dampening carpet, and situating the NICU in a more "quiet" wing of the hospital could all be considerations. When human health is concerned, especially when it comes to premature infants, every understandable precaution should be taken.

Thanks to
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