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Exposure to high or low frequency noise at workplaces: differences between assessment, health complaints and implementation of adequate personal protective equipment

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Abstract. Employees are exposed to high and low frequency noise which may cause different health effects. Hearing loss first occurs in the high frequency range, low frequency usually causes sleeping disturbances and annoyance. TES 1358 sound analyzer with 1/3 octave band was used to measure the equivalent sound pressure level, the peak sound pressure level, and the noise frequency spectrum at different workplaces. All the results were compared to Estonian and International legislations. High frequency noise was studied in metal, electronics and wood processing industries. The results showed that in several cases, the normative values were exceeded and the highest values appeared in the range of speech frequencies. Frequency analysis indicated that the noise level spectra at work stations of various machines differed in patterns. The low frequency spectra on a ship showed peaks in the frequency range of 50…1,250 Hz. Most employers provided workers with personal protective equipment against noise, but when selecting ear muffs, noise frequency had not been taken into consideration and therefore workers in the same enterprise used similar ear muffs. Knowledge of the prevailing frequencies assists to decide which ear protection should be used to avoid damage. An adequate hearing protector device can reduce the noise exposure significantly.

Key words: Noise, frequency analysis, PPE, occupational hazards.

INTRODUCTION

The human perception of sound is between 20…20,000 Hz. The ear is most receptive in the range of 500…8,000 Hz, so called acoustical window, even though the most sensitive range of hearing is 1,000…4,000 Hz (Salvendy, 2012) and the spectrum of human speech ranges in the frequency region of 250…6300 Hz (Cox & Moore, 1988).

Health effects from noise exposure have been studied by many researchers. Differences in complaints between low (20…500 Hz) (Alves-Pereira & Castelo Branco, 2007) and high frequency noise have been presented in several sources. Also it has been indicated, that hearing loss tends to occur in the range of high frequencies first (Salvendy, 2012). Industrial noise can mainly be characterized with high frequency noise, but also a considerable number of workers are exposed to low frequency noise on a daily basis. There is a general agreement that progression in hearing loss at frequencies of 500, 1,000, 2,000, and 3,000 Hz eventually will result in impaired hearing, i.e. inability to hear and understand speech (Johnson et al., 2001).

This is due to fact, that the range of 600…4,000 Hz has been considered to be the most important range for intelligibility (Savendy, 2012). For years there has been a debate considering the extra-auditory, subjective and biological effects – such as sleep disturbances, hypertension, noise-induced annoyance (Alves-Pereira & Castelo Branco, 2007), fatigue and lack of concentration. Also, complications in autonomic functions have been reported (in cardiovascular, endocrine and digestive systems), as well as problems with growth and immune system (Muzet, 2007). Noise induced complaints are distinguished by the frequency. For example, high frequency noise is mainly connected with hearing loss, hypertension and fatigue. Low frequencies are associated with different (often unexplained) problems such as feeling of annoying pressure or rumble in the ears (Walford, 1983). Recent studies also indicate that low frequency noise may have serious health effects such as sleeping disturbances (Waye, 2004), vertigo, stress, hypertension and heart rhythm disorders (Leventhall, 2003).

Studies have been conducted considering the subjective perception of loudness (loudness scaling) and objective measurements of auditory steady-state responses (ASSRs). Ménard et al., (2008) suggest, that the perception of sound with different frequencies (500 vs 2,000) differ insignificantly – test subjects have considered 500 Hz sound 'comfortable' if it is 59…62 dB hearing level (HL) and 'loud' if it is 76 dB HL or above. Yet it is indistinct whether the results of 2,000 Hz are really the same as suggested or differ approx. 10 dB as Allen et al. (1990) suggest.

According to Estonian regulations (EG, 2007), two action levels have been established. With the daily noise exposure level *(L_{EX}, 8 hours)* being between 80 dB(A) and 85 dB(A) hearing protection should be made available to employees who ask for it but it is not compulsory to wear. L_{EX} (8 hours) over 85 dB(A) employees must wear the hearing protection provided and employers need to offer training on correct use. The action values for ships (MSA, 2010) differ from the general values. The values for galleys and cabins vary from general ship values. The European Union (EU) directive (EC, 2003) introduces the similar concept of exposure limit values, taking into account the attenuation of the hearing protection, which cannot be exceeded. The exposure limit values correspond to an L_{EX} (8 hours) of 87 dB(A). No specific exposure limits according to octave band spectrum is provided. However, octave band analysis is necessary in selection of adequate personal protective equipment (PPE) as it is one of the most accurate methods to predict the attenuation of a PPE (Salvendy, 2012). The effectiveness of a PPE at different frequencies varies.

In order to reduce the negative effects of noise, adequate PPE is needed. There are four general types of passive hearing protection devices (HPD): earplugs, semi-insert or ear canal caps, earmuffs, and helmets. When selecting the most suitable PPE for each workplace, there is also a variety of parameters that need to be considered in addition to noise spectrum. In general, as a group, earplugs provide better protection than earmuffs below 500 Hz and equivalent or greater protection above 2,000 Hz. In the frequencies between, earmuffs have sometimes the advantage in attenuation (Gerges & Casali, 2007). If a PPE is provided with too little attenuation, protection might not be effective. On the other hand, too much reduction of the sound can have an isolation feeling which is risky, as employees may need to remove their PPE in order to communicate with colleagues. Also there is a danger in providing too much protection for listening out for safety warnings such as fire alarms or sirens from moving vehicles. A rule of thumb is not to reduce the level of sound at the ear below 70 dB(A). The adequate sound level at the ear is 70…75 dB(A) at the ear (National Research Council, 2010). Different action levels together with references are given in Table 1.

Table 1. Action levels of noise control with references

L_{EX}, dB(A)	Exposure time	Explanation	Reference
70 dB	24 h	Adequate to protect the most sensitive person at the most sensitive frequency	EPA, 1974
75 dB	8 h	Adequate to protect the most sensitive person at the most sensitive frequency (EPA, 1974), assuming that the remaining 1 hours are quiet. Equivalent sound level.	EPA, 1974
80 dB	8 h	Lower action value in EU: if daily noise exposure (8 hours/day) is 8 dB(A) or more, the employer shall make individual hearing protectors available to workers.	EC, 2003
85 dB	8 h	Higher action value in EU: if daily noise exposure (8 hours/day) is 8 dB(A), individual hearing protectors shall be used. It is also a widely used upper limit for exposure to hazardous noise in different countries including Estonia.	EC, 2003 EG, 2007
87 dB	8 h	Exposure limit value in EU: Above 87 dB(A), the employer is entitled to take immediate action to reduce the exposure to below the exposure limit values.	EC, 2003
90 dB	8 h	Exposure limit value in USA, Japan, Argentina.	I-INCE, 1997 OSHA, 29 CFR 1910.95

Comfort of PPE is crucial since PPE is only effective if it is worn by an employee continuously. During the fieldwork of our study many workers from different enterprises complained of the inconvenience of wearing a hearing protector. Individual preferences (e.g. wearing long hair, glasses or jewelry) and ear problems (e.g. irritation or earache) may affect the wearing of a hearing protection. It has been shown by Morata et al. (2001), that two of the reasons why workers did not wear their HPDs were (1) the interference with communication (70%) and (2) the interference with job performance (46%) by muffling certain sounds from machinery beyond detection. The working environment influences the choice of protectors as well – earmuffs may not be comfortable in high temperatures or humid conditions; earplugs may not be suitable for dusty environments, as the insertion of earplugs might be disagreeable due to possible absence of adequate sanitary conditions (Gerges & Casali, 2007).

The purpose of this study was to (1) analyze the spectrum of occupational noise; (2) give a literature review of the health complaints of workers who are exposed either to low or high frequency noise and (3) suggest the selection of adequate personal protective equipment (PPE) or other safety measures according to noise frequency.

METHODS

TES 1358 sound analyzer with 1/3 octave band was used to measure: (1) the equivalent sound pressure level; (2) the peak sound pressure level; (3) the noise frequency spectrum. The analyzer was held at a 1.55 m height from the floor, in the middle of a room or next to a working machine. Measurements with an A- and C-filter lasted for 30…60 seconds and were collected from different areas. All the results were compared to Estonian and International legislations.

The study was conducted on a research ship and in three industries - wood processing, metal and electronics. Noise from the machinery and equipment was measured and analyzed. The machinery and equipment used in companies were modern: either new or little-used. The ship on the other hand was built in 1974; its engine and auxiliary device had not been modernized.

RESULTS AND DISCUSSION

High frequency noise was studied in wood processing (company A), metal (company B) and electronics (company C) industries. The results showed that in several cases, the regulative norms were exceeded.

In wood processing industry, the exposure level normalized to a nominal 8 h working day varied from 72.8…90.9 dB(A). The highest noise levels were registered near the timber vats when the bench plane was in use (89.3 dB(A) and in the planing department (the bench planes operators' working stations (90.9 dB(A)). In other workplaces, the exposure levels did not exceed the Estonian existing norm – 85 dB(A), but in several places the results exceeded the second action level – 80 dB(A), when employer has to act on implementing safety control measures. The octave band frequency analysis (Fig. 1) of specific machines indicated that the noise spectra varied from one another in different frequency ranges.

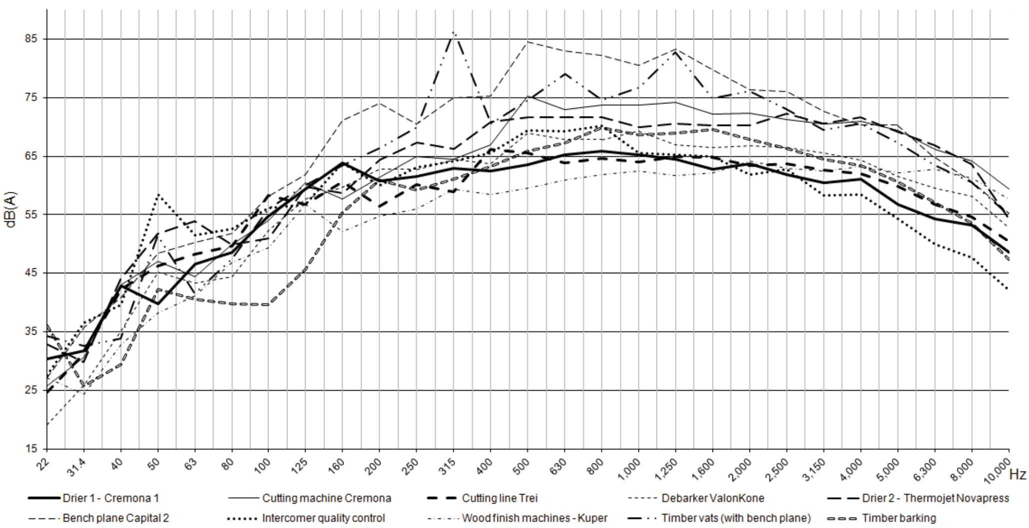

Figure 1. Noise frequency analysis, wood processing industry, Company A.

In many work stations in company A, the prevalent frequencies where the highest noise values appear are in the most sensitive range of human hearing (1,000…4,000 Hz) (Salvendy, 2012). Therefore the selection of most suitable HPD cannot be underestimated, for producing sufficient amount of attenuation. Also, the risk for overprotection has to be considered because it is crucial for the worker to hear safety signals and peers' warnings as many machines in wood processing industry involve sharp and rotating parts. Earmuffs or earplugs had been provided for company A workers. The selected PPE was with the highest attenuation number available to be sure they protect workers' hearing apparatus. The types and the attenuation data of the used HPD corresponding to frequency is presented in Table 2.

In company B (metal industry) the exposure levels normalized to a nominal 8 h working day were higher than in company A, varying from 84.1…100.4 dB(A). The highest noise level was registered in working station of Finnpower 6 punch press, but the measured noise levels depended on the material and workmode used.

Most machines in metal industry (except the punch press) produced high frequency noise, having peaks in 1,600…4,000 Hz, which is again in the sensitive range of human hearing (Fig. 2). In the enterprise B, only one sort of earplugs were available – EAR 3M E-A-Rsoft 'Yellow Neons'.

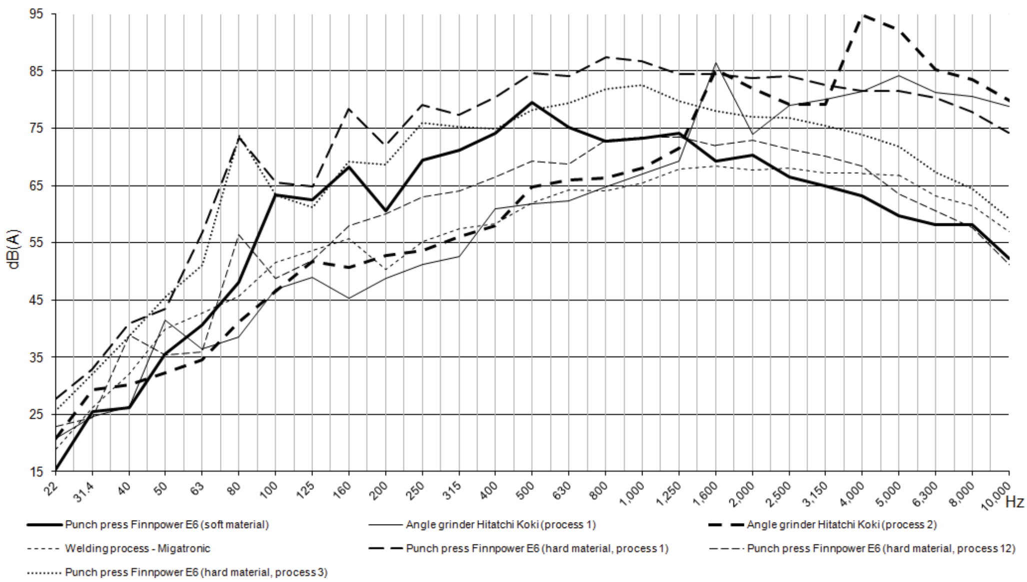

Figure 2. Noise frequency analysis, metal industry, Company B.

In company C the analysis was performed in a large production hall. Therefore, most of the workstations were influenced by noise produced by neighboring workplaces as the workstations were not separated. The exposure levels varied from 70.1 to 91.3 dB(A). All machines produced high frequency noise with clear peaks in the range of 500…6,300 Hz (Fig. 3). All employees of the company C owned similar earmuffs, the Peltor Optime 1^{TM} (3M, H510A), the same type was used in the company A.

Frequency analysis was also conducted on a fishing ship which was built in 1974. In the year 2009 the hold, galley and the main deck were renovated, but the other rooms were not modernized. The crew used earmuffs, but unfortunately it was not possible to identify neither the manufacturer nor the specifications of the earmuffs as the data was not identifiable anymore and the PPE itself was worn out.

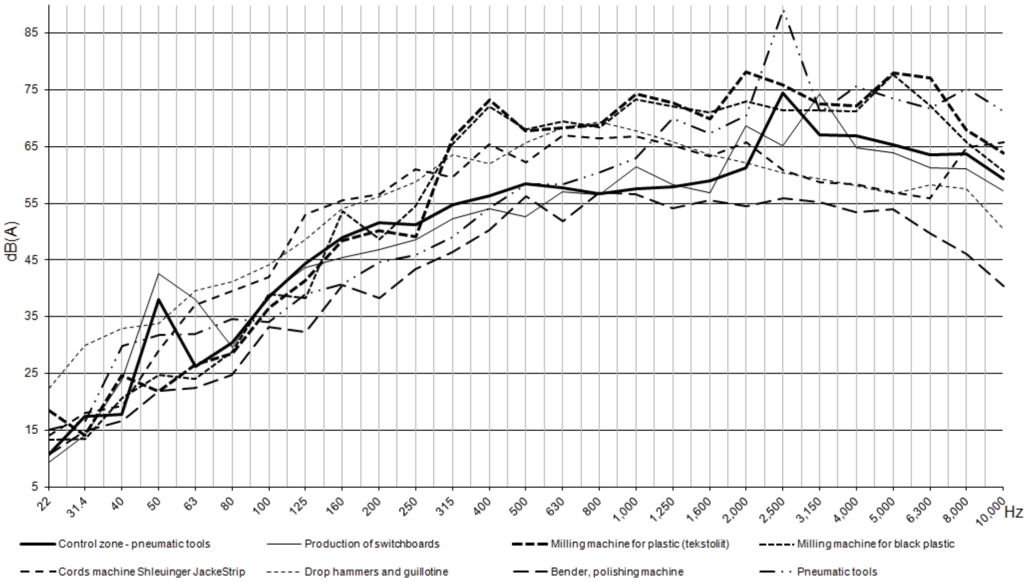

Figure 3. Noise frequency analysis, electronics industry, Company C.

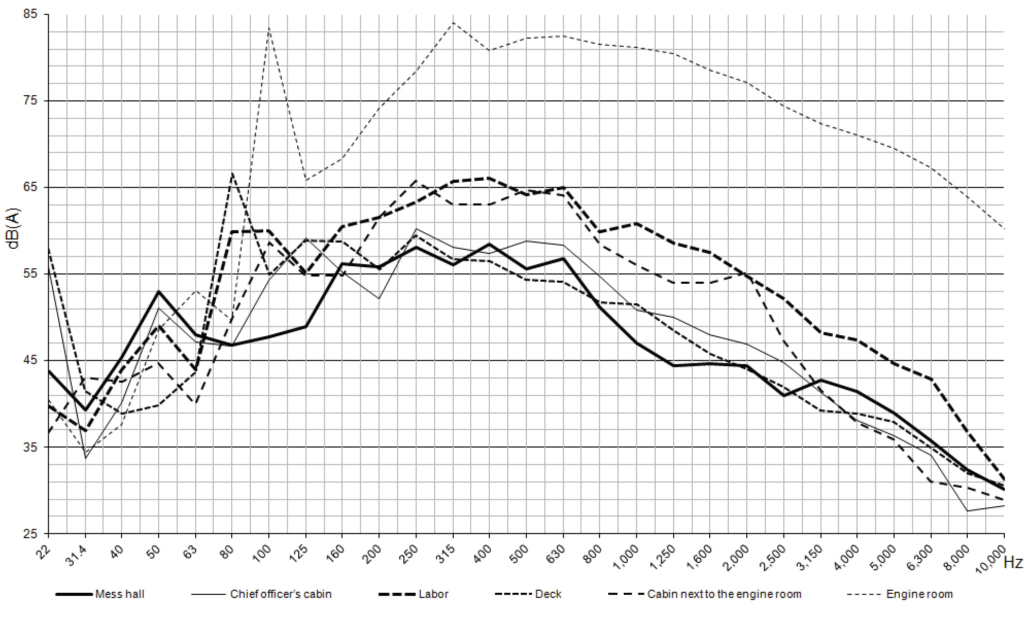

Figure 4. Ship, while anchored, noise frequency analysis.

The exposure levels normalized to a nominal 8 h working day varied from 42.0…101.4 dB(A) – the highest noise levels were measured in the engine room. On several cases (e.g. engine room, mess hall, cabins) the noise levels exceeded the national normative values. While anchored, the cabin next to the engine room had noise level of 72.1 dB(A) (peak at 250 Hz). The obtained result exceeded the 60 dB(A) normative value (MSA, 2010) by 12.1 dB(A). When sailing the noise level normative value was exceeded by 21.0 dB(A). Although the renovations done in 2009 did not include the crew's cabins, the noise measurements indicate that a widespread renovation is urgently needed. While anchored the engine room's noise level was 99.8 dB(A) (peak at 315 Hz) and during sailing 101.4 dB(A) (peak at 1,250 Hz). As there is no national normative value specifically for ship's engine rooms, the national general occupational noise normative value 85 dB(A) (EG, 2007) could be used. Our results correspond to the International Maritime Organization's recommended (IMO, 1981) values for engine rooms, which is 110 dB(A).

The 1/3 octave band frequency analysis showed that the auxiliary device (48 kW diesel generator) produced peaks in the range of 50…200 Hz, depending on the measurement point (50 Hz in mess hall, 100 Hz cabin next to the engine room). While anchored the occurring frequency range for the ship was 100…1,250 Hz (Fig. 4) and during sailing 80…400 Hz (Fig. 5). The figures indicate that most of the noise measured on the ship can be considered as low frequency noise.

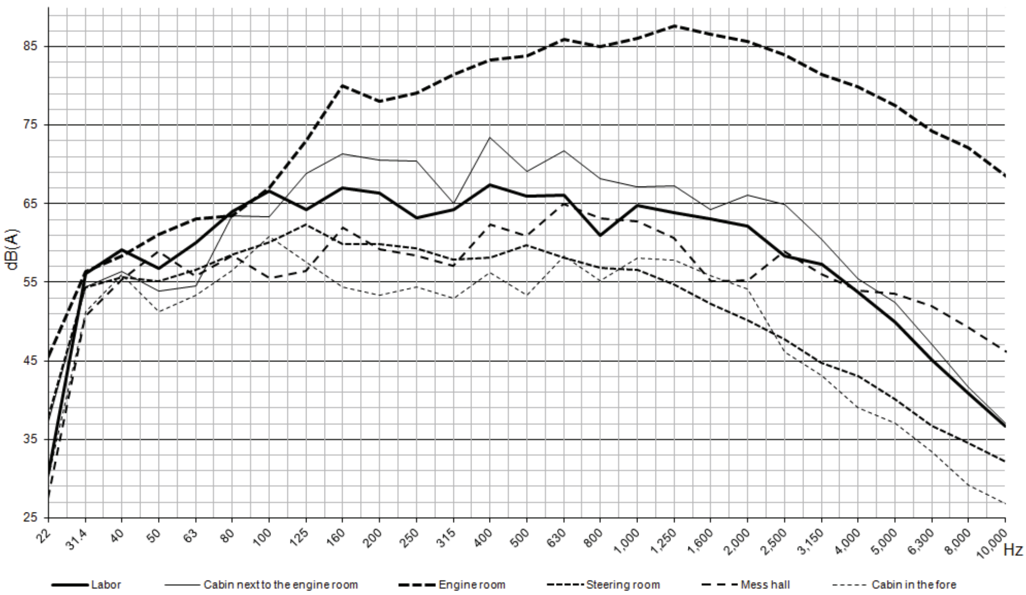

Figure 5. Ship, while sailing, noise frequency analysis.

Calculations of effectiveness of the PPE and selection of adequate PPE

Most employers provided workers with PPE against noise, but when selecting earmuffs noise frequency had not been taken into consideration and workers in the same enterprise used similar earmuffs. The current study resulted with counseling the enterprises on how to select the most suitable PPE for each workplace, based on the spectrum analysis.

For calculating the effectiveness of hearing protection the most common methods are: (1) Single number rating (SNR), (2) High, medium, low frequencies (HML) and (3) octave band method. In terms of accuracy in predicting the attenuation, the SNR method is the least accurate and the octave band is the most accurate, hence it is the preferred method (Salvendy, 2012).

Following octave band method, formula 1 was used to calculate the predicted level at the ear:

$$L'_A = \left(10\log\sum_{f=63}^{8000} 10^{\frac{L_f + A_f - APV_f}{10}}\right) + 4dB \quad , \tag{1}$$

where: L'_A – is the predicted A-weighted sound level at the ear; f – is the octave band centre frequency, Hz; L_f – is the measured octave band sound level in band f; A_f – is the frequency weighting for octave band f; APV_f – is the assumed protection value of the hearing protector for octave band f; 4 dB is added to allow for additional factors, such as badly fitted protectors.

The results are summarized in Table 2 and 3. As seen in Table 2, the L'_A values are much lower than the actual noise levels in the working places. It means that if workers wear HPDs properly and continuously during the working day, there is no high risk for hearing loss. However, while selecting earmuffs, not only the sufficient attenuation has to be considered, but also adequate hearing and understanding of the safety signals, peers' warnings and sirens from moving vehicles are crucial. Therefore, the sufficient level at the ear is 70…75 dB(A). Table 2 shows that in some workplaces, using earmuffs with a high attenuation value, could produce L'_A values as low as 42 dB (Bench plane Capital 2 in Company A) or 43 dB (welding process – Migatronic – in Company B). This however may lead to hazardous situations as workers may not hear safety warnings.

While selecting earmuffs and earplugs, in order to qualify according to other selection criteria as well, less attenuation can be recommended. While suppling the earmuffs and/or earplugs at least 2 different types should be provided in order to allow the employees to choose the most comfortable PPE. For example, instead of providing earplugs E-A-Rsoft 'Yellow Neons' (with SNR attenuation value of 36 dB), the company B can select E-A-Rsoft 21 (SNR = 21 dB) from the same manufacturer. The L'_A value would then be 70 dB for angle grinder Hitachi Koki workplace and 55 dB for welding workplace. For Punch press Finnpower 6, earplugs called E-A-R Pro-Seals would be effective with the L'_A value of 68 dB.

Company A may choose Earline 30214 model with SNR = 29 dB. Following the octave band method, the L'_A value for cutting machine Cremona would be 56 dB, the bench plane Capital 2 63 dB and for timber vats with bench plane 59 dB.

For company C, suitable earmuffs from the same company are for example Ultra 9000 (SNR = 22 dB), which gives following L'_A values: milling machine (textolite) 64 dB, milling machine (black plastic) 61 dB and pneumatic tools 61 dB.

To adjust the attenuation of an HPD to a particular noise problem (e.g. for different exposures in the same company), new earplug designs have been developed. Those may give the user some control over the amount of attenuation. These devices incorporate a leakage path that can be adjusted via a valve. One example is Variphone Earplug (NAL, 2007) which has the maximum attenuation of 34 dB, but can be reduced to 3 other levels: 30, 25 and 20 dB. Following octave band method, Variphone Earplug adjusted to 20 dB, is suitable for company A, having L'_A as follows: 64 dB for

Cutting machine Cremona, 72 dB for Bench plane Capital 2 and 65 dB for Timber vats with bench plane. Controlling the effectiveness of each octave band, the noise level by single frequency was not over 71 dB. When needed, the earplugs can be adjusted to 25 dB attenuation level.

Table 2 Attenuation of noise while using existent PPE (for all workplaces in companies A, B and C, noise level exceeding 85 dB(A))*

Co.	Work-place	PPE used	L_{EX}, dB(A)	L_L, dB(A)	L'_A, dB(A)	L_R, dB(A)
A	Cutting machine Cremona	PPE1	84.9±1.7	85	55	70…75
A	Bench plane Capital 2	PPE2	90.9±2.1	85	42	70…75
A	Timber vats with bench plane	PPE1	89.3±1.7	85	57	70…75
B	Angle grinder Hitachi Koki	PPE3	95.0±2.1	85	62	70…75
B	Welding process – Migatronic	PPE3	86.9±1.8	85	43	70…75
B	Punch press Finnpower 6	PPE3	100.4±2.2	85	61	70…75
C	Milling machine (textolite)	PPE2	87.8±1.7	85	55	70…75
C	Milling machine (black plastic)	PPE2	91.3±2.1	85	52	70…75
C	Pneumatic tools	PPE2	89.4±1.7	85	51	70…75

*Co. – company; L_{EX} – measured daily noise exposure level; L_L – noise level set by legislation; L'_A – the predicted sound level at the ear with attenuation; L_R – recommended level at the ear, derived from Table 1; PPE1 – Earline 30205 earplugs, PPE2 – Peltor Optime I earmuffs, PPE3 – E–A–Rsoft ‘Yellow Neons’

In company B, Variphone Earplugs are effective when adjusted to 20 dB for working with angle grinder and in welding workplaces (L'_A respectively 74 dB and 55 dB). When adjusted to 25 dB the earplugs are effective for Punch press Finnpower 6 (L'_A: 71 dB). Controlling the effectiveness of each octave band, the noise level by single frequency was not over 71 dB in angle grinder and welding workplaces and 69 dB in punch press workplace.

In company C, adjustment to 20 dB is enough as the L'_A-s are 61 dB for milling machine (textolite), 62 dB for milling machine (black plastic) and 59 dB for pneumatic tools.

As the earmuffs used on the ship were unidentifiable, the octave band method was not applicable to evaluate the attenuation of the HPDs. Calculations with octave band method show that using a random HPD may not give the worker enough protection. When using E-A-R E-A-RFLEX 14 Earplugs (SNR= 14 dB) the attenuation is not enough in several cases when comparing to normative values or to the recommended noise levels at the ear (shown in Table 3). When using different earmuffs (ULTRA 9000 earmuffs SNR = 22 dB), the L_R is exceeded only in the engine room with

L'_A 73.8 dB(A). PELTOR™ OPTIME™ I – P3* earmuffs (SNR = 26 dB) will give the worker enough protection against noise but over attenuation problem arises. Despite the fact that each task needs individual HPD which can be provided, the renovation of the outdated parts of the ship are necessary.

Table 3. Attenuation of noise on a ship during sailing while using specific PPE

Work-place	L_{EX}, dB(A)	L_L, dB(A)	L'_A, dB(A) PPE 1	L'_A, dB(A) PPE 2	L_R, dB(A)
Cabin next to the engine room	81.0±2.0	60	67.6	54.9	60**
Engine room	101.4±2.2	110 85	81.2	67.7	70
Steering room	71.9±1.8	85	57.9	46.1	70
Mess hall	70.9±1.8	65	58.5	44.9	65**
Cabin in the fore	68.5±1.7	60	53.1	42.0	60**

L_{EX} – measured daily noise exposure level; L_L – noise level set by legislation; L'_A – the predicted sound level at the ear with attenuation; L_R – recommended level at the ear, derived from Table 1; PPE1 – E-A-R E-A-RFLEX 14 Earplugs (SNR=14 dB); PPE2 – PELTOR™ OPTIME™ I – P3 earmuffs (SNR = 26 dB)*
**According to the legislation (MSA, 2010).

There are several aspects to consider when implementing a plan for noise reduction in the workplace. This includes noise control, audiometry, training of staff, selection of appropriate PPE. Authors would like to emphasize that a PPE is only the ‘first aid’ measure until it is possible to reduce the noise exposure by other means such as engineering control methods or administrative controls. Even when selected and applied properly the effectiveness of hearing protection will always depend on human behavior.

The fact that employees wear ear protection does not necessarily mean that workers are protected against noise. The results of Kotarbińska & Kozłowski (2009) showed that for 18.7% of the tested workers wearing earmuffs the equivalent A-weighted sound pressure levels under earmuff cups were higher than 80 dB(A) and for 7.7% of workers higher than 85 dB(A). One reason for the higher noise level at the ear can be caused by incorrect usage of earmuffs. Therefore, knowledge of the prevailing frequencies assists to decide which PPE should be used to avoid ear damage.

The comparison of health effects from different noise frequencies has been brought out in the introduction section. Several researches have demonstrated that different frequencies produce different health complaints. In the current study, the specific complaints were not investigated and no questionnaire was conducted. This remains for the future research.

CONCLUSION

The general purpose of this article is to show that with a little application of knowledge the effectiveness of hearing protection can be increased significantly.

In all studied companies (A, B, C), workplaces existed, where exposure levels to noise were over 85 dB(A), which is the current normative according to Estonian legislation. In wood processing, metal and electronics industry high frequency noise dominated. On the ship, low frequency noise dominated. Until appropriate engineering controls are applied several workers have to use hearing protection devices.

The study demonstrates, that although conventional HPDs provide sufficient protection for most noise exposures, a potential disadvantage of over attenuation may emerge. The user's speech communication with peers can be disturbed due to the static nature of the attenuation. Also the risk to miss safety signals and warnings exists. In the current study, PPE with less attenuation or adjusted attenuation were recommended as it is important to assure that the extent of the attenuation of PPE does not overprotect the user.

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