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High-frequency-noise-induced hearing loss: a field study on the role of intensity level and accumulated noise dose

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Summary. Based on audiometric tests in the range of 10 to 20 kHz, of 106 ultrasound operators, as well as on measurements of high-frequency noise, the problem of safety limits for high-frequency noise exposure was investigated. Analyzing the relation between noise levels of ⅓ octave bands at center frequencies of 10, 12.5 and 16 kHz and the accumulated noise dose on the one hand, and changes of hearing at 10 to 12, 11 to 13 and 14 to 16 kHz respectively, on the other hand, a harmless level up to 80 dB and a harmless noise dose up to 1 unit for people not older than 40 years have been found. For older people this level and this noise dose can be dangerous.

Key words: High-frequency hearing – High-frequency hearing loss – High-frequency noise – Hygienic limits – Ultrasound – Hearing loss

Introduction

Still unsolved, in the field of hygienic limitation of high-frequency noise-exposure, is the problem of reliable exposure criteria, especially for frequencies in the range of 10 to 20 kHz. The known proposals [1, 2, 4, 7] are based mainly on experimental data and therefore need to be verified by results achieved on defined groups of workers exposed to noise generated by ultrasonic (Uls) devices or other high-frequency noise sources encountered in industry. This paper presents an attempt in this direction. On the basis of measurements of high-frequency noise at Uls work-places and audiometric tests in the hearing range of 10 to 20 kHz, we tried to determine the sound-pressure-level above which hearing impairment might be expected, and to clarify if this hearing impairment is dose-related.

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Noise intensity level in dB	Daily exposure time in hours	Exposure period in years	ND in units
70	8	15	0.1
80	8	15	1.0
90	8	15	10.0
95	8	15	31.5
70	8	10	0.067
80	8	10	0.67
90	8	10	6.7
95	8	10	21.1
70	4	10	0.034
80	4	10	0.34
90	4	10	3.4
95	4	10	10.8

Table 1. Dependence of the noise dose (ND) on the noise level, the daily exposure time and the period of exposure

Material and methods

Hearing-threshold sound-pressure levels (HT-SPL's) at 10 to 20 kHz of 106 operators of Uls-devices were determined twice, before work, with a method described in an earlier paper [6]. High-frequency noise measurements at their work places in 12 factories were performed with a set of Bruel and Kjaer instruments [5]. The HT-SPL at 10, 11, and 12 kHz, at 11, 12 and 13 kHz and at 14, 15 and 16 kHz were analyzed taking into consideration the noise-SPL in dB of ⅓ octave bands, at center frequencies of 10, 12.5 and 16 kHz, respectively.

Additionally analyzed was the HT-SPL with respect to the noise dose (ND), which was calculated as follows: The measured intensity-level in dB was converted into intensity expressed in Wcm^{-2} and then multiplied by the added exposure time in seconds (daily exposure time multiplied by 235 d per year, multiplied by the number of exposure years). The resulting ND is a magnitude which grows over the professional life of the examined Uls-operators. The ND depends especially on the intensity level, but also on the period of exposure and daily exposure time (Table 1).

Results

The results obtained are given in Tables 2 to 4. Table 2 shows the relationship between mean noise-pressure levels of ⅓ octave bands and the mean HT-SPL, in comparison with the age-matched control group.

According to the ⅓ octave-noise-pressure level, which the Uls-operators were exposed to, each individual was classed into group "a" (up to 80 dB) or group "b" (above 80 dB). This noise-SPL was chosen, because at lower levels no significant differences of HT-SPL's between the two exposed groups were visible.

Table 3 includes Kendall's rank-correlation coefficient [3] and illustrates the statistical significance. Because this procedure verified the positive correlation between the ND and the HT-SPL, at least for younger age groups (20–29 and

Table 2. Hearing threshold sound pressure levels (HT-SPL's) in the range 10–16 kHz of Uls-operators in relation to noise-pressure-levels of ⅓ octave bands with center frequencies of 10 kHz (A), 12.5 kHz (B) and 16 kHz (C)

N = number of ears c = control group
SD = standard deviation a = Uls-operators (noise levels up to 80 dB)
t = statistical significance b = Uls-operators (noise levels above 80 dB)

Age in years	Exposure period in years		Mean and extreme noise levels			Hearing—frequence kHz								
						10			11			12		
	a	b	a	b		c	a	b	c	a	b	c	a	b
A														
			71	90	N mean	126	46	18	126	46	18	126	46	18
20–29	4.2	2.4	56–80	81–94	HT-SPL in dB	22	22	23	25	24	29	27	27	35
					SD	–	–	–	–	10.7	20.0	–	11.4	19.8
					t	–	–	–	–	1.30		–	2.00	
			74	90	N mean	78	62	16	78	49	29	78	47	29
30–39	5.0	4.6	64–80	81–94	HT-SPL in dB	26	32	36	31	36	43	34	40	50
					SD	7.8	16.2	14.3	7.5	18.0	19.1	9.0	16.6	19.5
					t		0.90			1.37			1.89	
			71	91	N mean	48	54	18	48	54	18	48	49	18
40–49	5.0	4.0	56–76	84–98	HT-SPL in dB	34	38	44	42	47	51	49	54	57
					SD	11.9	14.2	17.6	14.4	16.0	17.0	17.4	13.7	20.3
					t		1.46			–			–	

Table 2. Continued

Age in years	Exposure period in years		Mean and extreme noise levels			Hearing—frequence kHz								
						11			12			13		
	a	b	a	b		c	a	b	c	a	b	c	a	b
B														
			74	88	*N* mean	126	42	22	126	42	22	126	42	22
20–29	3.4	2.5	67–80	83–92	HT-SPL in dB	25	24	27	27	28	33	31	29	35
					SD	–	–	–	–	12.1	18.0	–	14.1	19.4
					t	–	–	–	–	1.30		–	1.40	
			73	90	*N* mean	78	55	22	78	53	22	78	52	21
30–39	4.7	4.4	60–79	84–97	HT-SPL in dB	31	34	44	34	36	51	39	43	58
					SD	7.5	17.9	17.3	9.0	16.9	16.7	12.4	19.9	18.1
					t		2.22			3.48			2.96	
			73	89	*N* mean	48	54	18	48	49	18	41	47	17
40–49	5.0	3.0	66–80	81–107	HT-SPL in dB	42	46	52	49	54	58	56	66	63
					SD	14.4	15.9	16.5	17.4	15.1	16.3	19.1	16.5	15.2
					t		1.36			–			–	

Table 2. Continued

Age in years	Exposure period in years		Mean and extreme noise levels			Hearing—frequence kHz								
						14			15			15		
	a	b	a	b		c	a	b	c	a	b	c	a	b
C														
			76	89	*N*mean	126	36	25	126	35	24	126	34	21
20–29	4.7	2.3	56–80	82–107	HT-SPL in dB	38	37	39	49	46	54	60	57	68
					SD	–	–	–	–	18.5	12.5	–	18.9	13.0
					t	–	–	–	–	1.82		–	2.30	
			75	89	*N* mean	76	33	33	74	29	20	65	23	11
30–39	4.7	4.4	66–80	81–107	HT-SPL in dB	48	51	60	63	63	66	73	74	80
					SD	14.7	19.6	19.5	14.7	15.3	14.9	12.3	–	–
					t		1.85		–	–		–	–	–
			75	88	*N* mean	31	17	27	27	8	12	14	2	–
40–49	5.0	5.0	66–80	82–107	HTSPL in dB	64	73	69	73	78	76	82	–	–
					SD	16.7	11.5	14.2	11.9	7.0	9.9	5.8	–	–
					t	–	–	–	–	–	–	–	–	–

Table 3. Kendall's rank-correlation coefficient calculated for the noise dose (ND) in ⅓ octave bands with center frequencies of 10, 12.5 and 16 kHz and hearing threshold sound pressure levels (HT-SPL's) of 10 to 16 kHz for different age groups

Correlation between	Age in years	Kendall's rank-correlation coefficient	Statistical significance
ND at 10 kHz and	20–29	0.18	0.1%
HT-SPL at 10–12 kHz	30–39	0.15	0.1%
	40–49	0.04	insignificant
ND at 12.5 kHz and	20–29	0.24	0.1%
HT-SPL at 11–12 kHz	30–39	0.11	5%
	40–49	0.07	insignificant
ND at 16 kHz and	20–29	0.14	1%
HT-SPL at 14–16 kHz	30–39	0.04	insignificant

Table 4. Mean hearing threshold-sound pressure level (HT-SPL) of ultrasonic (Uls)-operators exposed to noise dose (ND) calculated for ⅓ octave bands with center frequencies of 10 kHz (A), 12.5 kHz (B) and 16 kHz (C) in comparison with the control group

A

Age in years	*N*		Mean HT-SPL at 10, 11, 12 kHz			Standard deviation in dB		*t*	*P*
	a	b	c	a	b	a	b		
20–29	168	23	25	25	29	13.8	13.5	1.31	insignificant
30–39	191	31	30	34	47	16.9	18.0	3.90	0.001
40–49	165	30	42	45	52	15.7	21.3	2.18	0.05

B

Age in years	*N*		Mean HT-SPL at 11, 12 kHz			Standard deviation in dB		*t*	*P*
	a	b	c	a	b	a	b		
20–29	108	20	26	24	43	10.8	20.2	2.88	0.01
30–39	113	36	33	36	48	17.3	18.0	3.58	0.001
40–49	107	28	46	50	54	16.0	19.1	1.67	insignificant

C

Age in years	*N*		Mean HT-SPL at 14, 15, 16 kHz			Standard deviation in dB		*t*	*P*
	a	b	c	a	b	a	b		
20–29	146	27	49	48	53	17.9	19.3	1.32	insignificant
30–39	117	34	61	62	66	18.9	14.9	1.14	insignificant

N = number of ears
a = Uls-operators (noise dose up to 1 unit)
c = Uls-operators (noise dose above 1 unit)
c = control group

30–39 years) we tried to ascertain the minimal ND responsible for changes of hearing.

Results presented in Table 4 are arranged analogically to Table 2, but instead of noise levels in dB, the appropriate ND was taken into account. Every Uls-operator was classed into group "a" (up to 1 unit of the ND) or group "b" (above 1 unit). This value of 1 unit is equivalent to the noise level of 80 dB 8 h daily for 15 years.

Discussion

1. Noise pressure levels at 10 kHz (A), 12.5 kHz (B) and 16 kHz (C) and the HT-SPL

A. Age group 20–29 years. Table 2 A shows that, in this age group, the mean HT-SPL at 10 kHz of group "a" (22 dB) and group "b" (23 dB) did not differ from the mean HT-SPL of the control (22 dB). At 11 kHz the mean HT-SPL of group "b" was insignificantly increased (29 dB) in comparison with group "a" (24 dB) and the control (25 dB). At 12 kHz the mean HT-SPL of group "b" (35 dB) was significantly elevated in relation to the mean HT-SPL of group "a" and the control group (both 27 dB). It can therefore be concluded that in this age group the noise level 80 dB did not alter the HT-SPL at 10 to 12 kHz, but a noise level above 80 dB caused an HT-shift, at least at the hearing frequency of 12 kHz.

Age group 30–39 years. The mean HT-SPL increased in group "a" (32 dB) and group "b" (36 dB) in relation to the control (26 dB), but only the difference between group "b" and the control was significant (t = 4.22). The same results were observable at 11 and 12 kHz: a significant difference of the mean HT-SPL between group "b" and the control one. Thus, in this age group a negative effect on hearing at the noise level above 80 dB at 10 to 12 kHz is unquestionable.

Age group 40–49 years. No important elevations of the mean HT-SPL at 10, 11 and 12 kHz of group "a" (38, 47, 54 dB, respectively) in comparison with the control group (34, 42, 49 dB) were observed. A considerable increase of te mean HT-SPL of group "b" (t = 2.60 at 10 kHz and t = 2.14 at 11 kHz) in relation to the control group was seen, but the increase of the mean HT-SPL of this group at 12 kHz was insignificant.

B. Age group 20–29 years. There were no differences at hearing-frequencies 11, 12 and 13 kHz between the mean HT-SPL of group "a" (24, 28, 29 dB, respectively) and the control group (25, 27, 31 dB, respectively). The slight increase of the mean HT-SPL of group "b" (27, 33, 35 dB) in relation to group "a" or the control was insignificant, probably as the consequence of the short period of exposure (2.5 years).

Age group 30–39 years. The mean HT-SPL of group "b" was significantly increased at 11, 12 and 13 kHz in relation to both group "a" and the control. The slight increase of the mean HT-SPL of group "a" at this hearing frequencies was insignificant in comparison with the control. The negative effect of noise levels above 80 dB on hearing was confirmed in this age group.

Age group 30–39 years. The mean HT-SPL of group "b" was significantly increased at 11, 12 and 13 kHz in relation to both group "a" and the control. The slight increase of the mean HT-SPL of group "a" at this hearing frequencies was insignificant in comparison with the control. The negative effect of noise levels above 80 dB on hearing was confirmed in this age group.

Age group 40–49 years. A significant increase of the mean HT-SPL of group "b" at 11 kHz and nearly significant at 12 kHz in relation to the control group was seen. The mean HT-SPL at 11 and 12 kHz of group "a" insignificantly increased, whereas at 13 kHz it was considerably elevated in relation to the control group, which indicates that, for older workers, the noise level 80 dB at 12.5 kHz might not be harmless.

C. Age group 20–29 years. At 14 kHz the mean HT-SPL of group "a", group "b" and the control group did not differ, which means that the noise level at 16 kHz has no effect on hearing at 14 kHz in this age group. At 15 kHz the mean HT-SPL of group "b" (54 dB) was elevated in relation to group "a" (46 dB) reaching the limit of significance ($t = 1.82$). The mean HT-SPL of group "a" did not differ from the control group. At 16 kHz the mean threshold of group "b" was significantly ($t = 2.30$) increased (68 dB) in relation to group "a" and to the control group. This verifies the negative effect of a noise level above 80 dB on hearing.

Age group 30–39 years. The mean HT-SPL at 14 kHz of group "b" was significantly increased in relation to the control group ($t = 3.50$) and nearly significant in relation to group "a" ($t = 1.85$). At 15 and 16 kHz the mean HT-SPL of group "a" did not differ from that of the control. In group "b" the mean HT-SPL was insignificantly increased in relation to both group "a" and the control. These results indicate that the percentage of ears responding at these hearing frequencies was considerably decreased, especially in group "b". Taking the number of ears responding at 14 kHz as 100%, the fraction of ears responding at 15 and 16 kHz in the three groups is:

	15 kHz	16 kHz
Control	95%	88%
Group "a"	88%	70%
Group "b"	60%	33%

It can be seen that noise levels higher than 80 dB at center frequency 16 kHz doubtless affect the hearing ability at 15 and 16 kHz.

Age group 40–49 years. The effect of noise levels higher than 80 dB at 16 kHz was a loss of hearing at 15 and 16 kHz, which is illustrated by the percentage of ears responding at these frequencies in the groups compared:

	15 kHz	16 kHz
Control	87%	45%
Group "a"	47%	12%
Group "b"	44%	none.

These data indicate that noise levels lower than 80 dB, but probably close to this value, are harmful for older people. Summarizing, it may be said that noise levels up to 80 dB in the frequency range of 9000 to 18,000 Hz are harmless for people up to 39 years. Such levels can affect the hearing of persons older than 40. Noise levels higher than 80 dB in the frequency range discussed impair hearing independent of age.

The effect of the noise level at 20 kHz on hearing was not analyzed, because of the small number of ears responding at 20, 19 and 18 kHz. In general, in the exposed group (E), the fraction of ears responding at these frequencies decreased in relation to the control group (C), which is illustrated below:

Age group		18 kHz	19 kHz	20 kHz
20–29	C	58%	30%	13%
	E	36%	14%	6%
30–39	C	22%	12%	–
	E	15%	3%	–
40–49	C	–	–	–
	E	–	–	–

The mean noise level at 20 kHz was 92 dB, which enables us to conclude that a noise level of this magnitude is harmful for hearing.

2. Noise dose at 10 kHz (A), 12.5 kHz (B) and 16 kHz (C) and hearing

A. Age group 20–29 years. As can be seen from Table 4, the HT-SPL at 10 to 12 kHz of group "a" (ND up to 1 unit) did not differ from that of the control. The HT-SPL of group "b" (ND above 1 unit) was elevated, but insignificantly in relation to group "a".

Age group 30–39 years. The mean HT-SPL of group "b" was significantly increased (t = 3.90) in relation to group "a" (34 dB) and the control group (30 dB). This indicates that an ND higher than 1 unit affects hearing.

B. Age group 20–29 years. The mean HT-SPL of group "a" (24 dB) did not differ from that of the control (26 dB), but was significantly increased (t = 2.88) in group "b" in relation to both group "a" and the control.

Age group 30–39 years. The same was seen in this age group: a significant increase (t = 3.58) of the mean HT-SPL of group "b" (48 dB) in relation to group "a" (36 dB) and the control group (33 dB).

The results in these two age groups confirm the negative effect on hearing of an ND higher than 1 unit.

Age group 40–49 years. An insignificant increase of the mean HT-SPL of group "a" (50 dB) and group "b" (54 dB) in relation to the control group (46 dB) was seen.

C. Age group 20–29 years. The mean HT-SPL of group "a" was similar to that of the control group and the elevation of the HT-SPL of group "b" was insignificant.

Age group 30–39 years. Analogical results were seen in this age group, where a 4 dB increase of the mean HT-SPL of group "b" was insignificant in comparison with both group "a" and the control.

Despite the lack of significance, the tendency of elevation of the mean HT-SPL of group "b" indicated that an ND higher than 1 unit might be assumed to be harmful.

Age group 40–49 years was not analyzed, because of a too small a number of ears in the exposed group, responding at 14, 15 and 16 kHz.

The described changes of the hearing of Uls-operators in confrontation with noise levels in the frequency range of 10 to 20 kHz at their work places indicate that levels up to 80 dB and an ND up to 1 unit should be regarded as harmless only for people younger than 40 years.

Conclusion

1. Noise levels higher than 80 dB of ⅓ octave bands at center frequencies of 10, 12.5 and 16 kHz or an accumulated ND higher than 1 unit might cause a hearing loss in the range of 10 to 16 kHz.
2. Noise levels up to 80 dB or an accumulated ND up to 1 unit may be viewed as safe for people up to 40 years. For older ones this limit does not assure keeping the hearing threshold at a physiological level.
3. A noise level of 92 dB at 20 kHz (center frequency of ⅓ octave band) is responsible for the loss of ability to respond to tone signals at 18, 19 and 20 kHz with a SPL of 85 dB. Thus, the safe noise level at 20 kHz is probably lower.

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