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Letter to the Editor

Longitudinal surveys on effects of road traffic noise: substudy on sleep assessed by wrist actigraphs and sleep logs

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1. Introduction

Environmental noise causes a variety of adverse health effects including acute and long-term effects on sleep. Knowledge obtained from laboratory studies [1] shows that exposure to road traffic noise during nine nights for a period of 2 weeks caused decreased sleep quality, performance and mood, as well as increased tiredness both during morning and daytime. No habituation was seen for these effects. On the contrary, it is well known that habituation exists for awakenings (behavioural, reported or indicated by body motility) whereas other effects such as heart rate reactions and minor arousal reactions measured by electroencephalography (EEG) do not habituate. Field studies and laboratory experiments on noise-induced sleep disturbance show more or less conflicting results [2] depending, at least to some extent, on the type of sleep disturbance criteria [3]. Comparison of the results obtained in the research on judged sleep quality parameters [3], that used the same methods in laboratory and field studies, showed fairly good agreement for difficulties in falling asleep and reported sleep quality, whereas awakening reactions were much less frequently reported in the field studies. In this paper comparisons are made between results from longitudinal field studies obtained by sleep logs on reported sleep parameters and results on sleep parameters obtained by wrist-actigraphy.

2. Background

Västra Bräckevägen on the island of Hisingen in the city of Göteborg, Sweden, has had a very heavy traffic load for many years, with 25,000 to 30,000 vehicles per 24 h. To improve the environmental situation of people living along this road, a number of measures have been taken over the years. Socio-acoustic surveys were made along Västra Bräckevägen before (1986) and

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after (1987) these measures [4] shed light on the occurrence of different effects of noise on the population, and on whether the measures taken had an effect on the experience of disturbance caused by noise, on sleep quality and on health and well-being. These investigations showed that the measures enacted against noise (prohibition of heavy traffic during the night, porous asphalt, speed reductions and traffic signs that showed the message "You are driving too fast") were not sufficient to reduce the adverse effects of noise on sleep. To improve the living environment around Västra Bräckevägen and facilitate road transport, very extensive changes were made in the road system and a new tunnel, the Lundby Tunnel, was opened for traffic in January 1998. This paper presents the results of effects of noise on sleep in a small substudy performed by wrist-actigraphy and sleep logs before (1997) and after (1998 and 1999) the changes in road traffic.

3. Aim of the study

The aim of these longitudinal sub-studies was to assess effects of road traffic noise on sleep before and after changes in noise exposure by using a wrist-actigraphy and a short sleep questionnaire and to thereby analyse if there are differences in results obtained by the two methods.

4. Method and materials

4.1. Investigation area

The area investigated is shown on the map in Fig. 1. The northern boundary of the area is a busy thoroughfare, Västra Bräckevägen, while the boundaries to the west, east and south are smaller local streets. The investigation area was divided into an exposed and a control area in which the houses were situated 25–67 and 125–405 m, respectively, from the heavily trafficked main road.

The houses in the area are very similar, i.e., smaller, detached one-family houses built during the 1930s and surrounded by gardens of between 200 and 400 m^2. The bedroom windows in most of the houses in the exposed area do not face toward Västra Bräckevägen; only 16% of the houses' bedroom windows faced toward the road. About 40% of the houses in the exposed area had double glazed windows in the bedrooms, while the others had some form of triple glazed windows. Thirty-five per cent of the bedrooms in the control area had double glazed windows. A higher percentage of residents ($p<0.02$) had added extra facade insulation in the exposed area (55% as compared to 34% in the control area).

4.2. Assessment of noise exposure

Information about the traffic load per annual mean 24-h weekday for day, night and type of vehicle was obtained from the Traffic Office in Göteborg. Noise exposure was determined by measurements and calculations (for details see results on this study [5,6]).

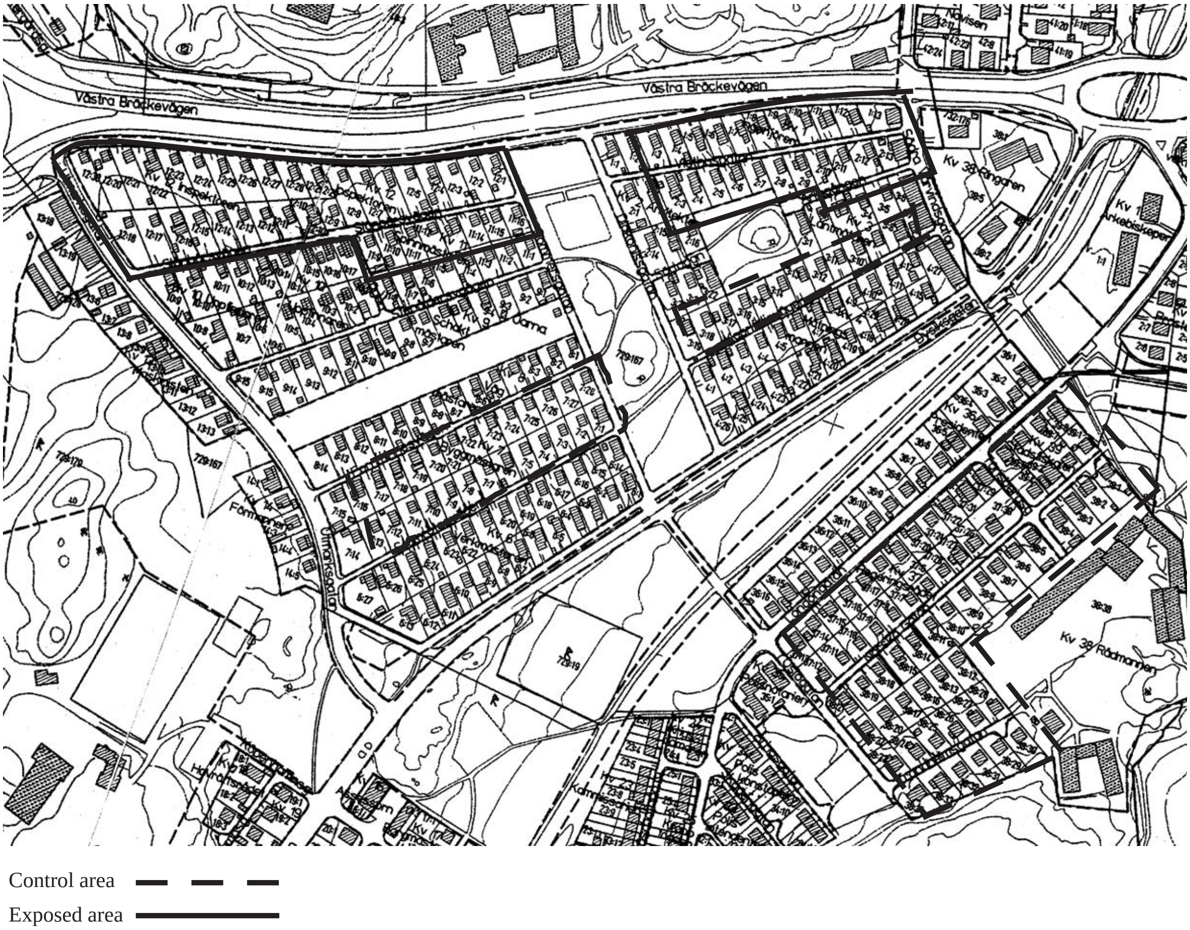

Fig. 1. Investigation area.

The total number of vehicles on the main road (Västra Bräckevägen) was 24,600 in 1997 and 2380 in 1999. Night traffic (22-06) constituted only 5.6% of daily traffic in 1997 (1375 vehicles, of which 125 were heavy vehicles) and 7.5% in 1999 (180 vehicles, of which 30 were heavy vehicles). No detailed data on traffic flow during night is available for local side streets in the control area, but the average total traffic flow (mostly light traffic) per weekday had halved after the traffic diversion.

Calculated $L_{\mathrm{Aeq,24\ h}}$ levels outside the bedroom facade, before and after the traffic diversion are shown in Table 1. As the period of sleep of many of the subjects continued even after 7 a.m., the 24-h value is given in the table. Between 10 p.m. and 6 a.m. the sound level was 7 dB lower than the 24-h level.

The calculated noise levels in $L_{\mathrm{Aeq,24\ h}}$ outside the bedroom windows were relatively low, even in the exposed area prior to the traffic diversion (50–62 dB), because all except one person had the bedroom window facing the quieter side of the house. With a facade reduction of 31–34 dBA, depending on the type of window, the indoor noise levels reached up to 31 dB ($L_{\mathrm{Aeq,24\ h}}$) in 1997.

Table 1
Noise exposure ($L_{\mathrm{Aeq,\ 24\ h}}$) outside the bedroom window before and after traffic diversion

Exposed area				Control area			
Id. no	L_{Aeq} outside 1997	L_{Aeq} outside 1999	Difference L_{Aeq}	Id. no.	L_{Aeq} outside 1997	L_{Aeq} outside 1999	Difference L_{Aeq}
1	62	49	−13	*12*	46	41	−5
2	62	49	−13	*13*	45	44	−1
3	62	49	−13	*14*	45	44	−1
4	62	49	−13	*15*	45	44	−1
5	50	40	−10	*16*	45	44	−1
6	50	40	−10	*17*	44	43	−1
7	49	39	−10	*18*	44	40	−4
8	67	55	−12	*19*	40	40	0
9	50	40	−10	*20*	40	40	0
10	51	40	−11	*21*	40	40	0
11	51	40	−11	*22*	40	40	0
				23	40	40	0
				24	40	40	0

With the window slightly open the indoor sound level is calculated to 10 dBA greater than the indoor noise level, i.e., subjectively experienced as double so high. After the traffic diversion the $L_{\mathrm{Aeq,24\ h}}$ level had been reduced by 10–13 dBA in the exposed area. In the control area the noise level was more or less unchanged (40–46 dB $\mathrm{L}_{\mathrm{Aeq,\ 24\ h}}$ in 1997 and 40–44 dB in 1999).

4.3. Assessment of sleep quality

4.3.1. Wrist-actigraphy

Body movements were registered by using a wrist-actigraph type Mini-motion-logger actigraph from Ambulatory Monitoring Inc. The actigraph is based on miniaturized acceleration sensor that translates physical motion to a numeric representation. The individuals studied had worn an actigraph on their non-dominant wrist for three nights during each study period. A button on the actigraph makes it possible to log pre-arranged events. The movement activity, registered with the wrist-actigraph, have been analysed in accordance with the Action-W manual (Windows data processing for Mini-motionlogger Actigraph. 1.05 version 1.38 [7] and as technically noted by Cole et al. in 1992 [8]. The programme classifies movement activity as a number of sleep variables, based on frequency of movement activity as well as the occurrence of time periods without movement activity. Results for the following variables are presented in this paper: duration, sleep latency, sleep minutes, activity mean, wake minutes, wake episodes and long wake episodes. *Duration*: time in bed from the moment the button was pressed on the actigraph and the light turned out in the evening, until it was pressed after waking up in the morning. *Sleep latency*: calculated as minutes to the start of the first 20-min block with more than 19 min of sleep according to the Cole–Kripke sleep-scoring algorithm [8]. *Sleep minutes*: includes total minutes scored as sleep. *Activity means*: mean activity score from counts registered by the actigraph per

30 s, which was the chosen epoch time. *Wake minutes*: total minutes scored as wake. *Wake episodes*: the number of blocks of contiguous wake epochs. *Wake episodes*: the number of blocks of contiguous wake epochs longer than 5 min.

4.3.2. Sleep questionnaire

Perceived sleep quality was evaluated by a questionnaire in the evening and in the morning for 3 days during each study period. In the evening questions on time to go to sleep [exact time for lights out and pressing the button on the wrist-actigraph) and if the bedroom window was kept open during night were answered. In the morning the person answered questions on time for getting out of bed in the morning (and pressed the button on the wrist-actigraph). Other questions concerned time for falling asleep (minutes), sleep quality ("very bad/ very good", 1–10 scale) perceived motility ("moved hardly at all/tossed and turned all night" 1–10 scale), number of awakenings and the reasons for awakenings. The person was also asked if he/she stayed awake for a long time without being able to fall asleep again, when this happened and for how long. The last question concerned tiredness/alertness in the morning (1–10 scale).

4.4. Study population

After determining the exposed areas and control areas, a geographical selection of the population was done using a population register obtained from the Town Planning Office in Göteborg. One or two individuals in each household aged between 18 and 80, who had lived in the area for at least 1 year, were chosen for the general questionnaire study. All participants who answered part one of the general study were invited to participate in the study measuring sleep with wrist-actigraphs. For this study, a small payment was offered as a thank you for taking part.

The before study was carried out from October to December 1997. The first after study was carried out in May–June 1998, after the opening of the Lundby tunnel on the 27th January 1998. The final after study was carried out in April and May 1999.

Thirteen persons participated in each area in 1997 but two persons moved out of the exposed area and could not take part in the following two studies. The study samples in the two areas were chosen to be similar as regards age and gender distribution. In the exposed area five women and six men aged between 24 and 68 years (mean 44.3) took part and in the control area. Seven participants were women and six men with an age between 24 and 67 years (mean 42.1). The proportion of employed participants in the control area was 92% compared with 63% in the exposed area. All who were employed worked during the daytime. In the exposed area, 45% had some type of long-term illness or difficulty in 1997, compared with 67% in the control area. At the time of the study in 1999, the proportion with some sort of illness or difficulty was 27% in the exposed area, compared with 38% in the control area. According to self-assessment, the number of participants, fairly or very sensitive to noise, was 36% in the exposed area compared with 54% in the control area.

4.5. Statistical analysis

The χ^2 test, Students t-test and Mann–Witney U-test were used for tests of differences between different groups. The paired t-test was used to test differences in results in the same group. The co-variation between different variables was investigated and tested with Spearman's rank correlation test, r_s. No change was expected in different effects studied in the control area and therefore the two-sided test was used. As a change was expected in the exposed area, the one-sided test was used in this case. A value of $p < 0.05$ was used as the level of statistical significance. In the tables, p-values > 0.20 are excluded to avoid information overload.

5. Results

5.1. Sleep assessed by wrist-actigraphy before and after changes in road traffic

Table 2 shows the results of sleep registration with wrist-actigraphy for three nights during 1997, 1998 and 1999. The values represent the average of the three nights for each of the three study periods for each person.

The table shows that in 1997 the participants in the exposed area spent significantly more time in bed than participants in the control area; on average 38 min from lights out to time getting out of bed ($p = 0.003$). The time, which is classified as sleep minutes, was 21 min longer in the exposed area, but this difference was not statistically significant ($p = 0.06$).

The most drastic change in sleep pattern among the participants in the exposed area was that time spent in bed (duration) decreased significantly between 1997 and 1999 (−58 min, $p = 0.02$).

Table 2
Sleep assessed by wrist-actigraphy

	Exposed area					Control area					Test exp/contr	Test exp/contr
Sleep variables assessed by wrist-actigraphs	1997	1998	1999	p-value 1997/1998	p-value 1997/1999	1997	1998	1999	p-value 1997/1998	p-value 1997/1999	p-value 1997	p-value 1999
Duration Lights out—got up (min)	474	455	416	—	*0.02*	435	396	408	*0.16*	*0.19*	*0.003*	—
Sleep latency (min)	6.4	7.6	17.1	—	*0.09*	7.1	9.8	9.4	—	—	—	—
Sleep minutes	412	407	331	—	*0.01*	391	338	346	*0.10*	*0.10*	*0.06*	—
Mean activity /30 s epoch	3.2	3.0	4.2	—	*0.14*	2.8	3.3	3.4	*0.13*	*0.10*	*0.20*	—
Total wake minutes	60.0	47.8	85.7	—	*0.15*	43.8	57.4	62.2	—	*0.11*	*0.18*	—
Wake episodes (number)	12.1	10.7	10.4	—	—	11.3	11.1	11.2	—	—	—	—
Wake episodes > 5 min (number)	12.2	10.7	3.8	—	*0.002*	11.3	11.1	4.1	—	*0.0002*	—	—

p-Values for Student's t-test one-tailed for exposed and two-tailed for controls. Test between groups: Mann–Witney one-tailed test 1997 and two-tailed test 1999.

Also the amount of time classified as sleep minutes decreased by 81 min from 412 to 331 min ($p = 0.01$). Mean activity, total wake minutes and the number of activity or wake periods did not change significantly, but the number of longer wake periods, classified as longer than 5 min, decreased significantly from 12 periods in 1997 to 4 periods in 1999 ($p = 0.002$).

The same pattern could be seen in the control area as in the exposed area, i.e., no change between 1997 and 1999 as regards mean activity, total wake minutes and the number of wake episodes but with a reduction in the number of longer wake episodes > 5 min ($p = 0.0002$).

Comparison between the exposed and control groups after the traffic diversion in 1999 showed no significant differences between the groups for any of the variables.

5.1.1. Relationship between different sleep variables measured by wrist-actigraphy

The correlations (Spearman's rank correlation, r_s) between different sleep parameters defined by wrist-actigraphs were in general significant. The sleep variable duration was significantly correlated ($r_s = 0.41$–0.51, $p = 0.001$) with the other variables, with the exception of sleep latency ($r_s = 0.31$). Sleep latency was significantly related with other measures of wakefulness (total wake minutes ($r_s = 0.46$, $p = 0.01$), the numbers of wake episodes ($r_s = 0.39$, $p = 0.05$) and the numbers of long wake episodes > 5 min ($r_s = 0.39$, $p = 0.05$)). Activity mean was not significantly correlated with any other variable, with the exception of duration. The variable sleep minutes was only significantly related with duration and total wake minutes.

5.2. Sleep quality measured by questionnaire before and after changes in road traffic

Forty-five per cent of the residents (especially those with the highest noise levels) in the exposed area, seldom or never slept with an open window in 1997, compared with 8% in the control area. The proportion that seldom or never slept with an open window had reduced from 45% to 27% in the exposed area in 1999, whilst in the control area the proportion had increased from 8% to 23%.

Table 3 shows the reported sleep quality as mean average values and SD of three nights/person in the exposed and control areas during the three study periods.

The different sleep quality parameters gave poorer results in the exposed area compared with the control area before the traffic diversion in 1997 but the only variable that significantly differed between the areas was tiredness. Participants in the exposed area felt more tired in the morning ($M = 5.7$ compared with $M = 7.3$, $p < 0.01$, one-tailed t-test).

The time that participants in the exposed area spent in bed after lights out until getting up in the morning, decreased significantly between 1997 and 1999 ($p = 0.02$), as did the total time asleep, sleep minutes, ($p = 0.05$). In 1999, after the traffic changes, participants even felt less tired in the mornings ($p < 0.02$), despite having moved more during the night ($p = 0.04$).

There was a tendency towards reduced difficulty in falling asleep and better sleep quality in 1998 and 1999 ($p = 0.08$ and 0.06–0.08, respectively) compared with 1997. Amongst participants over 43 years of age, sleep quality was significantly improved in 1999 ($M = 8.4$ compared with $M = 6.0$, $p = 0.01$).

In the control area, sleep quality did not differ between 1997, 1998 and 1999 for any of the reported sleep quality parameters.

Table 3
Sleep quality assessed by questionnaires

	Exposed area					Control area				
	1997	1998	1999	p-value 1997/1998	p-value 1997/1999	1997	1998	1999	p-value 1997/1998	p-value 1997/1999
Lights out—got up morning (min) Mean	474	455	416	—	*0.02*	435	396	408	*0.16*	*0.19*
Difficulties falling asleep (% of three nights)	33.3	18.2	24.2	*0.08*	*0.08*	25.6	8.1	20.5	—	—
Time to fall asleep Mean, (SD)	20.5 (24.2)	19 (12.1)	12.2 (6.2)	—	*0.13*	18.5 (12.5)	14.1 (10.7)	14.1 (8.6)	—	—
Sleep minutes Mean, (SD)	453 (76)	436 (29)	404 (70)	—	*0.05*	417 (83)	390 (87)	395 (44)	—	—
Moved 1–10[a] Mean	5.0	4.7	6.2	—	*0.04*	4.31	5.5	4.8	—	—
Awakenings/night Mean (SD)	1.8 (1.6)	1.1 (1.7)	2.1 (2.0)	*0.13*	—	1.8 (1.3)	1.5 (1.6)	1.8 (2.1)	—	—
Sleep quality 1–10[b] Mean	6.4	7.5	7.5	*0.06*	*0.08*	7.4	6.8	7.6	—	—
Tired morning 1–10[b] Mean	5.7	5.3	6.6	—	*0.02*	7.3	6.5	7.0	*0.20*	—

[a] Means moved more. p-Values for Students t-test, one-tailed for exposed and two-tailed for controls.
[b] Higher value means better sleep and more alert in the morning.

5.2.1. Relationship between different sleep quality variables assessed by questionnaire

The variable sleep minutes was negatively correlated (Spearman's correlation test, r_s) with sleep quality ($r_s = -0.45$, $p = 0.01$): the longer the sleep time, the poorer sleep quality. The strongest correlations to sleep quality were found with how tired/rested one felt in the morning ($r_s = 0.56$, $p = 0.01$), time to fall asleep ($r_s = -0.38$, $p = 0.05$) and the number of wake periods ($r_s = -0.36$, $p = 0.05$). There were no significant correlations between how much movement one experienced and any other sleep parameter.

5.3. Changes in sleep behaviour after the change in traffic

Results on sleep quality from the questionnaire and the wrist-actigraphs show that the participants changed their sleep behaviours between 1997 and 1999.

The median value for "lights out" remained unchanged between the years, ca. 11 p.m., in both areas. In the control area, the median for "got up" was unchanged, whilst in the exposed area the

Table 4
Correlation between sleep assessed with wrist-actigraphy and questionnaires

	Parameters assessed by wrist-actigraph					
Parameters assessed by questionnaire	Mean activity/ 30 s epoch	Total wake minutes	Sleep minutes	Sleep latency (mins)	Wake episodes (number)	Wake episodes > 5 min (number)
Sleep minutes	0.45**	0.46**	0.54**	0.35*	0.41*	0.48**
Time to fall asleep (min)	0.39*	0.48**	0.002	0.22	0.49**	0.32
Sleep quality 1–10	−0.36*	−0.35*	−0.05	−0.16	−0.39*	−0.40*
Awakenings per night (number)	0.13	−0.20	0.29	−0.19	0.09	0.12
Tired—alert morning 1–10	−0.31	−0.32	0.29	−0.18	−0.43*	−0.37*
Moved 1–10	−0.08	−0.07	0.26	−0.03	−0.05	−0.06

median showed that half of the participants got up, circa 41 min earlier in the morning compared to before the traffic changes.

5.4. Comparison between sleep measured with wrist-actigraphy and questionnaires

Table 4 shows the correlation (Spearman's correlation test, r_s) between different sleep parameters as defined both by wrist-actigraphy and questionnaires during all study nights.

The table shows that judged sleep time in minutes was significantly correlated with all variables measured with wrist-actigraphy ($r_s = 0.35$–0.54). The longer the judged time to fall asleep, the more movement activity/30 s epoch, total wake minutes and wake periods. However, judged and wrist-actigraphy defined time to fall asleep (sleep latency) was not significantly correlated ($r_s = 0.22$).

Sleep quality was significantly correlated with mean activity per 30 s epoch and wakefulness, as well as with the number and length of wake periods. However, the number of awakenings per night or movements was not significantly correlated with any of the variables assessed by wrist-actigraphy. The table also shows that tired-alertness in the morning was significantly correlated with the number of wake periods and the number of long wake periods: the more wake periods the more tired one felt in the morning.

6. Comments and discussion

As this study includes a small number of participants (in total 24 individuals over a total of 222 nights) the possibility of showing significant effects of changes in road traffic noise on sleep, or of showing significant differences in sleep between exposed and control individuals, is relatively limited. The results from both questionnaires and wrist-actigraphy registration showed that the participants in the exposed area spent a significantly shorter time in bed after a reduction in traffic intensity. This was irrespective of seasonal differences, but may be due to the fact that the individuals in the exposed area were significantly less tired after the traffic reduction. In general there was a tendency towards reduced difficulties in falling asleep and better sleep quality (measured by questionnaire) after traffic reduction. Results confirmed by wrist-actigraphy showed that the exposed individuals had significantly fewer long wake episodes as well as a shorter sleep time in minutes than before the traffic reduction.

The results from this sub-study correspond well with the results of the main questionnaire study carried out with a larger number of residents ($n = 142$) in the study area (5 and 6). The sleep of those individuals previously exposed significantly improved after the changes in traffic intensity (for three out of eight sleep variables) to such an extent that there was no longer any differences between the control and previously exposed participants. In the main study, however, as opposed to this sub-study, significant differences between the sleep of participants in the exposed and control areas could be shown before the traffic changes for all sleep variables (e.g., difficulties to fall asleep, awakenings, perceived sleep quality and tiredness in the morning).

The evaluation of sleep by wrist-actigraphy is considered to be an objective method of classifying sleep in contrast to a questionnaire, which is a subjective method. Another objective method of measuring sleep is Polysomnography (PSG), where electrical activity forms the basis for the classification of sleep into different stages. The latter method is regarded as the most exact method of sleep measurement. However, as a result of high costs and the technical difficulties that are associated with measuring PSG activity, sleep registration in studies of the effects of noise on sleep has under recent years mostly been carried out using wrist actigraphs, which is simpler, cheaper and less labour intensive.

The most common sleep parameters which are evaluated by wrist-actigraphy are awakenings and number of movements per unit of time. In the first more detailed study [9] of the relationship between single aircraft noise events and wakefulness or arousal, the relationship between noise and sleep disturbance is evaluated as the likelihood that a movement should occur in a period of time in which an aircraft event occurred. These studies, which were carried out close to different airports in England, show only a slightly increased risk of awakening as a result of aircraft noise.

In the English studies, a very large number of ‘‘spontaneous’’ movements per night [as compared with PSG-based evaluations] were recorded; movements that were classified as awakenings or at least an arousal reaction. There are different devices of actimeters with different classification programmes. Comparisons of results obtained by different devices must therefore be done with great caution. In the English study [9], wrist-actimeters manufactured by the Swiss company Gähwiler were used. The type of actimeter used in this study (AMI mini-motion-logger) identified a very large number of movements per night (an average of 2800 movements during an 8 h sleep period] and a relatively large number of sleep parameters. New versions of classification programmes [10,11] have been developed as a result of experiences from recent studies.

Sadeh et al. [12] in their review conclude that actigraphy provides useful measures of sleep–wake schedule and sleep quality and that despite its limitations, may be a useful, cost-effective method for assessing specific sleep disorders. In general there are some disadvantages and uncertainties associated with evaluation of sleep using actimeters. Wakefulness is classified as a time period in minutes or parts of minutes during which movement occurs, and sleep as a time period in minutes during which no movement occurs. There is thus a risk of wrongly classifying the sleep pattern. For example, if an individual is lying totally still but is in fact awake this is classified as a period of sleep. In the same way there is a risk of wrongly classifying a relative large amount of movement while sleeping as a period of wakefulness. This is the case in sleep stage 2 or during transition to a deeper or lighter sleep. Artefacts may result when patients place their wrists on or under their head or stomach during sleep [breathing artefact). Some devices have shown sensitivity to humidity or temperature and some fail for unknown reasons [12].

Actigraphy and daily logs are complementary and should thus always be used concomitantly. Actigraphy can provide objective rest-activity information [13] that the subject is often unaware of or unable to report in detail and daily logs provide essential information for editing the actigraphic data (placement, removal, possible artefacts, etc.) in addition to reporting subjective sleep-related experiences. All sleep parameters studied in an evaluation of sleep using questionnaires are subjective and describe, amongst other things, experienced falling asleep, sleep quality and after effects. In contrast to sleep measured by wrist-actigraphs, questionnaires can measure how rested one feels after a nights sleep. A number of parameters of sleep quality measured by PSG [length of time in different stages of sleep, wakefulness, etc.) often do not have a strong association to sleep parameters defined by the questionnaire method. Experiences from comparisons between subjective experienced awakening and PSG registration show that awakenings shorter than 4 min are rarely remembered, whilst the total EEG registered wakefulness period among young, healthy individuals is at least 15 min per night. How well a questionnaire can measure what happens during the actual sleep period, from the time when the light is switched off until the time of getting up, depends partly on how well the person remembers the awakening. The experienced sleep quality however, is also defined to a large extent by experienced difficulties in falling asleep and how rested one feels in the morning (e.g. Ref. [3]). A long period of sleep from falling asleep to getting up does not necessarily indicate better sleep quality, as is shown in this study which shows a *negative* relationship between total sleep time and experienced sleep quality. It has also been shown [14] that extension of time in bed could result in decreased sleep efficiency assessed by wrist-actigraphs.

6.1. Comparison of results obtained by questionnaires on sleep and wrist-actigraphy

The main aim with this in-depth study of sleep in a smaller study group was to investigate if the two methods of studying sleep and sleep disturbances as a result of noise—wrist-actigraphy and sleep logs—give different results, or if one method is more sensitive than the other, and what the relationship is between subjective measures of sleep quality and sleep measured by wrist actigraphs. The study samples in the two areas were chosen to be similar as regards age and gender distribution to reduce individual differences. Large individual differences in sleep for judged and wrist-actigraphy defined parameters were however, observed (e.g. mean movement activity ranged from 0.9 to 16.8 per epoch). It is also known from the literature (e.g. Ref. [12]) that individual differences in activity levels occur not only as a function of age and gender but possibly also as a function of other individual characteristics such as body weight. The inter-individual variation in combination with the small amount of study material reduce the possibility to assess and verify changes in sleep, and also to a certain extent affects the possibility of comparing the two methods.

The comparison of results in this study based on sleep parameters measured with questionnaires and wrist-actigraphs is made from the assumption that those variables that show best conformity might be more relevant in studies of sleep. Length of analysis or "duration" is the same in an assessment of an individual's sleep for questionnaires and for wrist actigraphs. The person who is being registered presses an indicator button when he/she switches out the light in order to go to sleep, and again when he/she gets up in the morning. If the subject failed to press the button, the time reported in the questionnaire was used to assess time-in-bed period with wrist-actigraphs.

Similar sleep measures which show *good* conformity ($p<0.05$) in this study is sleep in minutes. The relatively good conformity between sleep minutes assessed by wrist-actigraphs and reported sleep minutes ($r_s = 0.54, p<0.01$) is expected as the total length of time in bed (duration) is almost identical in both methods. Similar measures which show *poor* conformity ($p > 0.05$) in this study are judged time to fall asleep versus sleep latency, reported movements (moved 1–10) versus all wrist-actigraphy measures and reported awakenings versus all wrist-actigraphy measures. It is reasonable that these measures show poor conformity as time to fall asleep can only be roughly assessed and sleep latency with wrist-actigraphs might be incorrectly assessed. It is difficult to remember brief periods of awakening shorter than 4 min. Neither is it likely that one is aware of how much one actually moves during sleep.

Different types of subjective sleep measures which are well correlated ($p<0.05$) with wrist-actigraph measures in this study were *reported sleep quality*, *reported time to fall asleep and tiredness in the morning*. Reported sleep quality is significantly correlated with number of wake episodes > 5 min, wake episodes, mean activity/epoch and total wake minutes, ($r_s = 0.35$–0.40). Reported time to fall asleep was significantly correlated with wake episodes, total wake minutes and mean activity/epoch, ($r_s = 0.39$–0.49). Tiredness in the morning was significantly correlated with wake episodes ($r_s = 0.43$) and wake episodes > 5 min ($r_s = 0.37$). These findings are supported by findings in laboratory studies (e.g. Ref. [1]) that judged sleep quality and judged time to fall asleep are significantly correlated with reported number of awakenings as well as with large body movements assessed by an accelerometer fastened to the bed.

7. Conclusions

Conclusions which can be made from the in-depth sleep study carried out by wrist actigraphs type AMI mini-motion-logger and questionnaires are that there is several significant relationships between sleep parameters measured with the two methods. As the variation between individuals was large, especially as regards several of the wrist actigraph-defined parameters, larger or more homogenous study material is required in order to verify statistically significant differences in sleep between exposed and control groups.

Studies of sleep using only single general questionnaires, or daily sleep logs can be carried out using considerably less resources than when sleep is measured by wrist-actigraphy or by the PSG-method. If the choice is between studying fewer and solely subjective sleep parameters in a larger group, or studying both wrist-actigraphy with this type of devise and subjective sleep parameters in a smaller group, the results from this study indicate that the former should be chosen, i.e., to study noise-induced sleep disturbances with the aid of questionnaires.

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References

[1] E. Öhrström, M. Björkman, Effects of noise-disturbed sleep—a laboratory study on habituation and subjective noise sensitivity, *Journal of Sound and Vibration* 122 (1988) 277–290.
[2] K. Pearsons, D. Barber, B. Tabachnick, S. Fidell, Predicting noise-induced sleep disturbance, *Journal of Acoustic Society of America* 97 (1995) 331–338.
[3] E. Öhrström, Sleep disturbances caused by road traffic noise—studies in laboratories and field, *Noise & Health* 18 (2000) 71–78.
[4] E. Öhrström, Sleep disturbance, psycho-social and medical symptoms—a pilot survey among persons exposed to high levels of road traffic noise, *Journal of Sound Vibration* 133 (1989) 117–128.
[5] E. Öhrström, Longitudinal surveys on effects of road traffic noise—annoyance, sleep disturbance and psycho-social symptoms, *Journal of Acoustic Society of America* 115 (2004) 719–729.
[6] E. Öhrström, A. Skånberg, Consequences of the Lundby tunnel, Part I: studies on annoyance, sleep and wellbeing among people living nera Västra Bräckevägen in Gothenburg. Part II: substudies on sleep (in Swedish), Report 4/99, Department of Environmental Medicine, Göteborg University, 1999.
[7] Action-W, Windows data processing for Motionlogger Actigraph, Version 1.05, 1.38 User's Guide, 1996 Ambulatory Monitoring, Inc., 731 Saw Mill River Road, Ardsley, NY.
[8] R.J. Cole, D.F. Kripke, W. Gruen, D.J. Mullaney, J.C. Gillin, Automatic sleep/wake identification from wrist activity—technical note, *Sleep* 15 (1992) 461–469.
[9] J.A. Horne, F.L. Pankhurst, L.A. Reyner, K. Hume, I.A. Diamond, A field study of sleep disturbance: effects of aircraft noise and other factors on 5,742 nights of actimetrically monitored sleep in a large subject sample, *Sleep* 17 (1995) 146–159.
[10] Action-W, User's Guide, Version 2.0, Copyright 1999, 2000, Ambulatory Monitoring, Inc., 731 Saw Mill River Road, Ardsley, NY, www.ambulatory-monitoring.com.
[11] Motionlogger®, User's Guide, Version 2K1.1, Ambulatory Monitoring, Inc., 731 Saw Mill River Road, Ardsley, NY, www.ambulatory-monitoring.com.
[12] A. Sadeh, P.J. Hauri, D.F. Kripke, P. Lavie, The role of actigraphy in the evaluation of sleep disorders, *Sleep* 18 (1995) 288–302.
[13] M.J. Chambers, Actigraphy and insomnia: a closer look; Part 1, *Sleep* 17 (1994) 405–408.
[14] B. Levine, M. Lumley, T. Roehrs, F. Zorick, T. Roth, The effects of acute sleep restriction and extension on sleep efficiency, *International Journal of Neuroscience* 43 (1988) 133–139.