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Longitudinal surveys on effects of changes in road traffic noise: effects on sleep assessed by general questionnaires and 3-day sleep logs

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Abstract

Adverse health effects including sleep disturbances by road traffic noise were studied among inhabitants in a residential area near Västra Bräckevägen in Göteborg city, Sweden, in 1986 and 1987, before and after the introduction of night traffic regulations. The results of those studies showed a higher prevalence of sleep disturbances and poorer sleep quality in the exposed areas as compared with the control area. This paper presents results on sleep based on new studies done with general questionnaires and daily sleep logs for a period of 3 nights in 1997 and 1999 in the same areas, before and after the opening of a new tunnel for road traffic. At this time, road traffic had been substantially reduced from about 25 000 to 2 400 vehicles per 24 h and from 1375 to 180 vehicles per night (22–06). It is concluded from these long-term investigations that exposure to high levels of road traffic noise induces adverse effects on sleep and that sleep quality is significantly improved after an extensive noise reduction. Sleep quality assessed by a single general questionnaire may give equally good precision as daily reports on sleep over several days. Furthermore, a higher response rate is achieved by a single questionnaire.

1. Introduction

Environmental noise causes a variety of adverse health effects, and the evidence is strong for annoyance and acute sleep disturbances [1,2]. For protection against sleep disturbances and to allow people to sleep with open bedroom windows, guidelines values recommended by WHO [3] are set to 40 dB $L_{Aeq,22-06}$ and 60 dB L_{Amax} outdoors. Knowledge gained in laboratory studies [4] shows that exposure to road traffic noise during nine nights over a period of 2 weeks caused

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poorer sleep quality, performance and mood, and greater tiredness both in the morning and during the day. No habituation was seen for these effects. If people who have resided in areas exposed to high levels of road traffic noise during both the day and night for many years are affected in a similar way, they may suffer from chronic sleep disturbances and perhaps develop other long-term effects. This can only be studied in longitudinal studies and/or intervention studies in connection with extensive noise abatement activities. This paper compares results of longitudinal surveys that used different methods, a general questionnaire on residential health and well being, including sleep, and daily sleep logs kept over 3 consecutive days.

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 25 000–30 000 vehicles per 24 h. A number of measures have been taken over the years to improve the environmental situation of people living along this road, and socio-acoustic studies were conducted along the road before (1986) and after (1987) these measures [5]. These focused 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. The investigations showed that the noise measures (prohibiting heavy traffic during the night and using porous asphalt, speed reductions and traffic signs that showed the message "You are driving too fast") were not sufficient to reduce the noise and its adverse effects. To improve the living environment around Västra Bräckevägen and facilitate road transport, very extensive changes were made in the road system with the opening of the Lundby Tunnel in January 1998. Results of these longitudinal surveys on annoyance and well-being and sleep assessed by wrist-actigraphs are reported in a separate paper [6].

3. Aim of the study

The aim of this part of these longitudinal surveys was to assess the effects of road traffic noise on sleep and the effects of changes in noise exposure on sleep quality by a general questionnaire and daily sleep logs and to analyze any possible differences in the results obtained by the two methods.

4. Method and materials

4.1. Investigation area

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

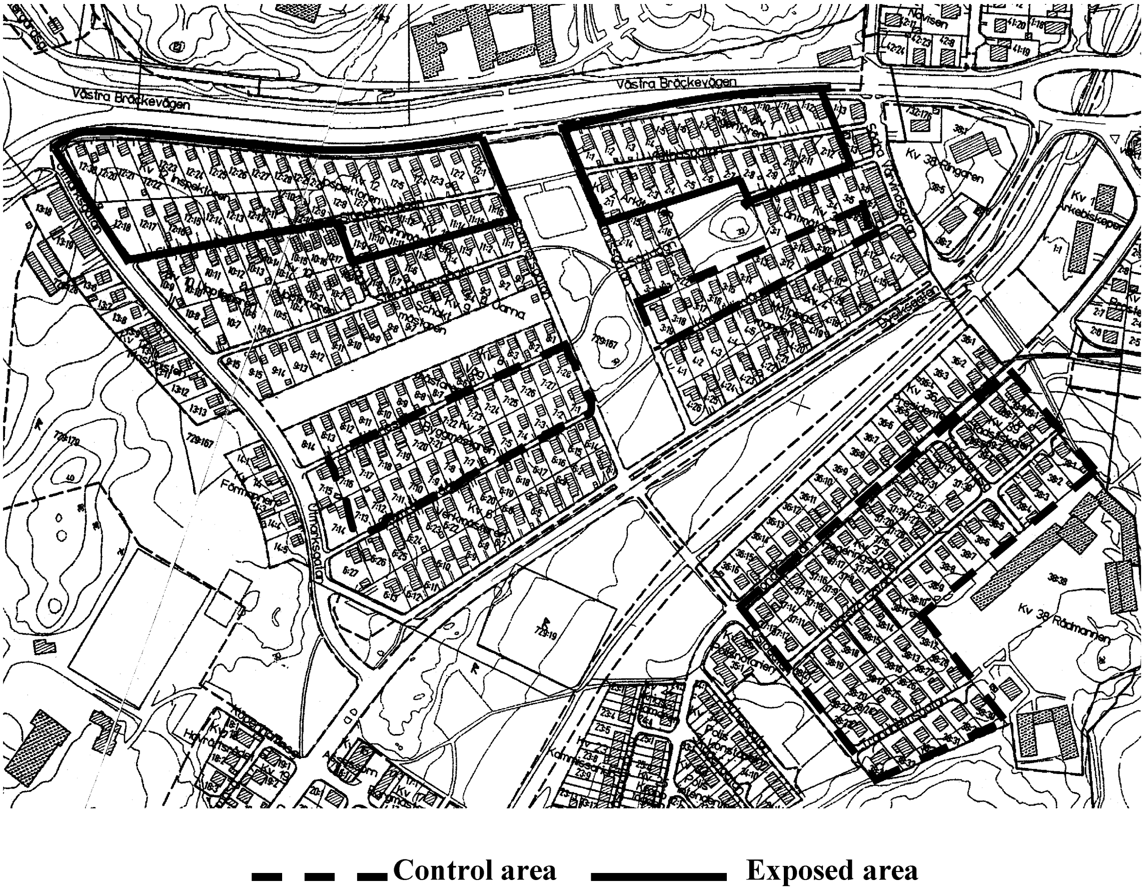

Fig. 1. Investigation area.

The houses in the area are very similar, i.e. small, detached, one-family houses built during the 1930s 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 face 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 in the exposed area ($p<0.02$) had added extra façade insulation (55% as compared to 34% in the control area).

4.2. Assessment of sleep quality

Disturbances of sleep by road traffic noise and sleep quality was evaluated by a general questionnaire and by sleep logs. The questions used in the investigations in 1986 and 1987 [5], slightly elaborated, were used. All sleep parameters studied in an evaluation of sleep using questionnaires are subjective and describe, amongst other things, experienced/remembered falling asleep, awakenings, sleep quality and after effects. In contrast to sleep measured by wrist actigraphy, or PSG (electroencephalography), questionnaires can measure how rested one feels after a night's sleep. A number of parameters of sleep quality measured by PSG (e.g., 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 reported awakening and PSG registration show that awakenings shorter than 4 min are rarely remembered, whilst the total PSG-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 reported sleep quality however, is *also* defined to a large extent by experienced difficulties, or annoyance because of difficulties in falling asleep, and how well rested one feels in the morning.

4.2.1. Questions on sleep in the general questionnaire

The effects of exposure to road traffic noise were evaluated by a general questionnaire about the living environment and general well-being. These questions on sleep concerned whether, and to what extent, road traffic noise affected time taken to fall asleep, caused awakenings or prevented people from leaving their bedroom windows open.

The same questions were asked in 1997 and 1999. In addition, the following questions were asked after the study of 1999. "If you compare with the situation before 1998, before the Lundby tunnel was built, what is your experience of disturbance by noise from road traffic now? Noise from road traffic affects: (1) *rest/relaxation*, (2) *falling asleep*, (3) *awakenings*, (4) *sleep quality*, (less, no difference, more).

Sleep quality, without reference to noise, was also evaluated in a specific section of the questionnaire. This contained questions on *location of the bedroom, time of going to bed and getting up in the morning, how often windows were kept open during the night* (almost always, most often, sometimes, seldom/never), *difficulties in falling asleep* (seldom/never, a few times a month, a few times a week, almost every day) and *the reason for that* (difficulties relaxing, worries, outdoor sound/noise), *time needed to fall asleep* (less than 10 min, 10–15, 16–30, 31–60, more than 60 min), *use of sleeping pills, use of ear-plugs* (seldom/never, sometimes, often, almost always), *habit of awakenings*, (no, yes/how many times per night), *reasons for awakenings* (another person, hungry/thirsty, toilet, sound/outdoor noise, other), *difficulties going back to sleep* (no, yes), *sleep quality* (very bad, bad, not very good, good, very good), *sleep quality* (1–10, very bad—very good), *tiredness in the morning* (very tired, tired, rather tired, rather alert and relaxed, very alert and relaxed) and *tiredness in the morning* (1–10, tired and feeble—alert and rested).

The same questions were asked in 1997 and 1999. In addition, comparison questions ("If you compare with the situation before 1998, before the Lundby tunnel was built, what is your experience of…") were asked in the after study of 1999 for *habits about keeping windows open during the night* (more seldom, no difference, more often), *difficulties in falling asleep* (much more often, somewhat more often, no difference, somewhat less often, much less often), *awakenings* (less often, no difference, more often), *sleep quality* (worse, no difference, better) and *tiredness in the morning* (more tired, no difference, more alert).

4.2.2. Questions on sleep in the daily sleep logs

In the in-depth study, sleep quality was evaluated with the help of a questionnaire, which was filled in on 3 consecutive days in the morning and evening. The same questions were asked in 1997 and 1999. In addition to questions about the night's sleep (morning questionnaire), questions were also included (evening questionnaire) about how the day was (1–10 point scales) as concerned stress, worries and tiredness (evening and day). The endpoint markings were "stressful—not stressful", "distressing—without distress" and "tired—alert". Questions answered in the morning had to do with difficulties in falling asleep (yes/no) and the reasons for the difficulties, how many minutes it took to fall asleep, the time of getting up in the morning, sleep quality—"How have you slept during the night" (scale 1–10, endpoint markings "very bad—very well") and movements/restless sleep (scale 1–10, endpoint markings "hardly moved at all—tossed around all night"), estimation of how many awakenings occurred and the reasons for the awakenings. A number of alternatives for awakenings was mentioned: the traffic, other noise, too cold, too hot, hungry/thirsty, visit toilet, dreams, other reason and, in that case, for what reason. The subjects were also asked about difficulties in falling back to sleep and what time periods during which this occurred, if there were difficulties. The final question concerned tiredness in the morning (scale 1–10 with endpoint markings "tired and feeble–alert and well rested").

4.3. Assessment of noise exposure

Noise exposure was determined by measurements and calculations. Information on the traffic load per annual mean 24-h weekday for day, night and type of vehicle was obtained from the Traffic Office in Göteborg.

4.3.1. Calculations of equivalent noise levels $L_{Aeq,24\,h}$

The calculations were made according to the Nordic Prediction Method for the most severely noise-exposed side (northwestern) and for the quieter side (southeastern) at two heights—2.5 and 5 m—which correspond to the first and second floors of the houses. The difference in the sound level between 2.5 and 5 m was marginal (± 1 dB). The calculation program has a precision of ± 2 dB.

4.3.2. Outdoor noise measurements

A sound level meter, Larson & Davis type LD 820, operated as a remote station via a wireless transmission system,. Measurements were made continuously for 3–4 days in five different positions. A mean for each position was calculated for: $L_{Aeq,24\,h}$, L_{01}, L_{90}, L_{Amax}, as well as noise events >70 dBA for three periods, 24 h, daytime (06.00–22.00) and night time (22.00–06.00). The microphone was placed on a rod 1.5 m above ground level in a free field position, that is without reflection from the façade.

4.3.3. Measurements of facade insulation

Measurements were made of the reduction at the façade (R′45°, w) in the bedrooms of seven of the houses. These measurements were made according to Swedish Standard SS 02 52 54 and ISO 140-5 with a Norsonic AS 840 measurement system. The evaluation was carried out according to SS EN ISO 717-1.

4.3.4. Determination of the equivalent noise levels inside and outside the bedroom

The indoor levels were calculated from information in the surveys as to the type of window and the direction in which the windows faced, measured façade reduction (R′45°, w) and the calculated outdoor equivalent levels on each side of each house. Double glazed windows were given a reduction of 31 dBA and triple glazed windows a reduction of 34 dB according to the results of the façade reduction measurements, which varied between 29 and 38 dBA.

Outdoor levels in $L_{Aeq,24\,h}$ outside the bedroom were determined from information in the survey and calculations of outdoor ($L_{Aeq,24\,h}$) levels on each side of each house.

4.4. Noise levels before and after reduction in road traffic

With the completion of the tunnel, road traffic on the main road (Västra Bräckevägen) fell by 90% between 1997 and 1999. This road was also reconstructed, narrowing it from 24 to 12 m, and green areas and trees were planted on both sides. The number of vehicles (mostly light vehicles) on the local street (Dysiksgatan) was reduced from 10 100 vehicles in 1997 to 4600 vehicles in 1999. Table 1 shows the number and type of vehicles on the main road in 1997 and 1999.

L_{Amax} levels were unchanged between 1997 and 1999 (87 dB). This was also the case for $L_{90night}$, whereas L_{90day} and L_{01day} decreased by 12 dBA from 52 and 72 dBA, respectively, in the exposed area.

Results of measured and calculated noise levels showed fairly good agreement (−1 to 3 dB for measured levels) at the measurement sites near the main road in the exposed area. There were large discrepancies, however, between measured and calculated noise levels at measurement sites in the control area (+2 to 9 dB for measured levels). Table 2 shows calculated noise levels from road traffic noise in $L_{Aeq,24\,h}$ outdoors and indoors. Levels are given as minimum and maximum values in each area. Noise levels in $L_{Aeq,22-06\,h}$ were 7 dB lower.

Table 1
Number of vehicles on the main road (Västra Bräckevägen) in 1997 and 1999

Number of vehicles	1997		1999	
	Total	Heavy	Total	Heavy
Day (06.00–22.00)	23 225	4475	2200	270
Night (22.00–06.00)	1375	125	180	30

Table 2
Calculated outdoor and indoor noise levels in $L_{Aeq,24\,h}$ in 1997 and 1999

$L_{Aeq,24\,h}$	Exposed area		Control area	
	1997	1999	1997	1999
Northwest façade (noisy side)	56–69	44–57	40–52	39–48
Southeast façade (quiet side)	48–64	38–50	40–51	40–48
Outside bedroom	43–67	39–55	40–51	39–48
Inside bedroom	<20–36	<20–24	<20	<20

The table shows a decrease in outdoor $L_{Aeq,24\,h}$ levels of 10–14 dB in the exposed area in 1999 after the reduction in road traffic. With the exception of one house, all dwellings in the exposed area had an "acceptable" noise environment after the traffic reduction, i.e., the noise level recommended by the Swedish Parliament ($L_{Aeq,24\,h}$ 55 dB) was no longer exceeded. Indoor noise levels in $L_{Aeq,24\,h}$ with closed windows were low also in the exposed area after the traffic reduction in 1999. However, noise from single vehicles could still be heard indoors when the windows were closed.

4.5. Study population

After establishing exposed and control areas, a geographical selection of the population was made 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 who responded to the general questionnaire were also asked to participate in the sub-study and to keep sleep logs for 3 consecutive nights. In the study in 1997 81.2% of the 142 persons who responded to the general questionnaire also kept sleep logs (40 out of 45 persons in the exposed area and 76 out of 92 persons in the control area). In 1999 81.6% of the 120 persons who responded to the general questionnaire also answered the sleep logs (35 out of 40 persons in the exposed area and 63 out of 75 persons in the control area).

Table 3 shows some population characteristics in the two study areas for those who answered the general questionnaire in 1997 and 1999. The study population in the exposed area did not deviate significantly from the population in the control area as regards age, gender, length of residence, proportion who worked outside the home, proportion with any long-term illness or noise sensitivity.

The study made before the noise reduction was carried out from October to December, 1997, and the study carried out afterwards from April to May, 1999.

Table 3
Description of the study population

	Exposed area		Control area	
	1997	1999	1997	1999
Age mean (SD)	51.0 (14.8)	50.2 (15.1)	50.4 (15.2)	48.5 (15.4)
% women	52.0	51.1	55.4	58.7
Years of residence				
Mean (SD)	11.2 (10.7)	11.1 (11.1)	13.3 (13.2)	12.5 (12.7)
Work employment (%)	52	53	64.1	69.3
Longterm illness (%)	52	49	47.8	48
Hearing deficiencies (%)	19.2	11	12	12
Noise sensitivity scale 1–4				
Mean (% very sensitive)	2.7 (14.6)	2.6 (11.6)	2.3 (10.9)	2.3 (10.7)

4.6. Statistical analyses

The χ^2 test, Mann–Witney U-test and T-test were used for tests of differences between different groups. The paired T-test and Wilcoxon sign rank test were used to test differences in results in the same group. The T-test for one group was used for analyses of results of the respondents' own comparison (e.g., "less disturbed", "no difference" and "more disturbed"). The co-variation between different variables was investigated and tested with the Spearman 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 quality assessed by the general questionnaire

The results in all sleep parameters (falling asleep, awakenings, sleep quality and tiredness in the morning) indicated significantly poorer sleep quality in the exposed area than the control area in 1997 before the reduction in road traffic ($p = 0.03$–0.002).

In 1999, after the reduction of road traffic, sleep quality in the exposed area improved and no significant differences in comparisons with the control area could be observed. Table 4 shows the results in 1997 and 1999 in the exposed area and the control area.

Table 4
Sleep quality assessed by general questionnaire in 1997 and 1999

	Exposed area			Control area		
	1997 $n = 50$	1999 $n = 45$	97/99 p-value	1997 $n = 92$	1999 $n = 75$	97/99 p-value
Seldom/never sleep with windows open (%)	44.9	22.7	0.01	19.6	30.7	—
Difficulties falling asleep every night or sometimes during a week (%)	34.6	20	0.06	16.3	13.3	—
More than 30 min to fall asleep (%)	28	13.3	0.01	12.1	10.7	—
Number of awakenings per night						
Mean	1.6	1.7	0.15	1.0	1.2	—
SD	2.0	1.9		1.3	1.2	
Sleep quality (1–5[a]), (mean)	3.9	4.0	0.15	4.3	4.1	0.08
Not very good–bad (%)	26	15.6		12.1	13.3	
Sleep quality (1–10[a]), (mean)	7.1	7.6	0.14	8.1	7.5	0.01
Tiredness morning (1–5[b]), (mean)	3.0	3.4	0.02	3.4	3.6	0.08
Tired or very tired (%)	58	35.6		39.6	26.7	
Tiredness morning (1–10[b]), (mean)	5.7	6.2	0.14	6.9	6.9	—

[a] Higher mean value means better sleep quality.
[b] More alert in the morning.

A significant improvement was seen after the reduction in road traffic in the exposed area in "time to fall asleep" ($p = 0.01$) and "tiredness in the morning" (five-point scale) ($p = 0.02$). The proportion of respondents who perceived their sleep quality as "not very good" or "poor" decreased from 26% to 16%, although this change did not reach statistical significance ($p = 0.15$). There was no decrease in the mean average number of awakenings per night, but the percentage who woke up once or more per night decreased by 6% (not significant).

No improvement was observed in the control area in any of the sleep parameters in 1999 as compared with 1997, whereas a decrease was seen for sleep quality on the ten-point scale ($p = 0.01$).

5.2. Comparisons of sleep quality before and after changes in road traffic intensity

The residents were also asked to compare their sleep quality in 1999 with their sleep quality 2 years earlier (see Fig. 2). Between 16% and 31% of the respondents in the exposed area estimated that their sleep quality had become better (windows open more often during the night, easier to fall asleep, fewer awakenings, better sleep quality, less tired in the morning). All changes were statistically significant (waking up less frequently $p = 0.02$ and other parameters $p < 0.01$).

In a direct question about whether it was felt that sleeping habits and sleep had been affected by the building of the Lundby tunnel, 24% in the exposed area versus 3% in the control area answered positively ($p < 0.001$). The reasons for the change in sleep and sleeping habits reported in the exposed area were, e.g., "quieter now", "less traffic to disturb sleep", "feels like a move to the country", "possible to sleep without the waterbed vibrating with the traffic", "better when there are no trucks to wake one up", "calmer mornings", "don't wake up because of trucks driving in the morning between five and six o'clock", "possible to sleep longer in the morning without being woken up and being sick less often".

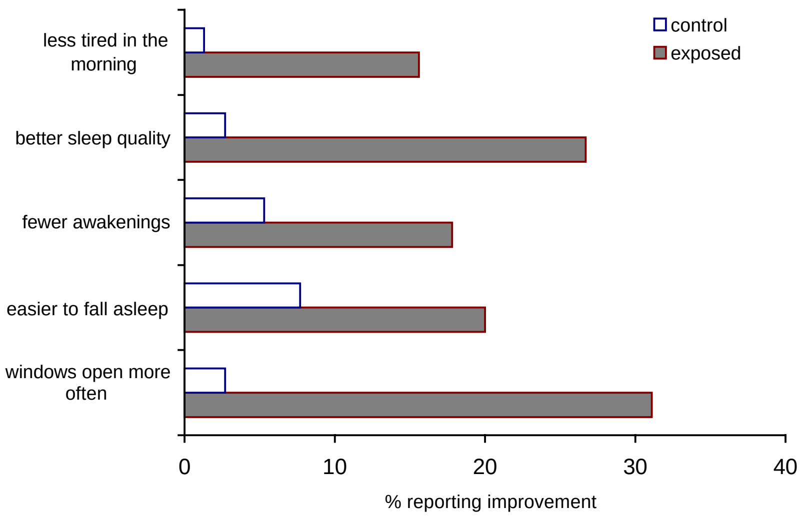

Fig. 2. Residents' own comparisons of sleep after the change in road traffic.

5.3. Sleep quality assessed by sleep logs during 3 days

Results in the 3-day sleep logs before and after traffic changes are shown in Table 5. The results are presented as averages over 3 nights based on all the participants for each study period. It should be noted that there were not only large differences between individuals but also between different nights in the same individual.

5.3.1. Comparisons before traffic changes in 1997

Comparisons between the exposed and control areas in 1997 show significantly poorer sleep as regards the variables "difficulty in falling asleep" and "time needed to fall asleep" in the exposed area. There were large individual differences in "time needed to fall asleep", and the difference between the areas was approximately 7 min on average ($p = 0.001$).

In the exposed area, 19% of respondents were woken by traffic noise at night. This was not the case in the control area. A larger proportion of those who were awakened for any reason had greater difficulty in falling back to sleep in the exposed area compared with the control area (28%

Table 5
Sleep quality assessed by daily sleep logs in 1997 and 1999

	Exposed area			Control area			*P*-value	*P*-value
	1997	1999	97/99	1997	1999	97/99	Exp/control 1997	Exp/control 1999
	$n = 40$	$n = 35$	1-tailed test	$n = 76$	$n = 63$	2-tailed test	1-tailed test	2-tailed test
Difficulties falling asleep (%)	22	16.2	—	14	9.2	—	0.04	0.11
Time to fall asleep in minutes, Mean (SD)	22.1 (22.9)	16.5 (16.7)	0.10	14.9 (15.7)	14.8 (14.2)	—	0.001	—
More than 30 min to fall asleep (%)	18.2	15.7	0.15	7.9	7.1	—	0.01	0.04
Awakenings/night Mean (SD)	1.8 (2.1)	1.9 (2.1)	—	1.6 (1.6)	1.1 (1.3)	0.02	—	0.004
Woken by traffic noise (% of those woken)	18.6	5.9	0.02	0.7	0	—	<0.0001	0.03
Difficulty falling back to sleep (%)	28.2	19	0.05	12.5	16.4	—	0.02	—
Moved (1–10[a]), Mean	4.9	5.3	—	3.8	3.7	—	0.0003	<0.0001
Sleep quality (1–10[b]) Mean	6.9	7.5	0.05	7.7	7.7	—	0.02	0.10
Tired morning (1–10[c]) Mean	6.0	6.5	0.15	6.9	7.1	—	0.005	—
Tired day (1–10[c]) Mean	6.9	6.7	—	7.3	7.1	—	0.02	0.0007
Tired evening (1–10[c]) Mean	5.4	5.0	—	5.1	4.8	—	—	—

[a] High mean value means: moved more.
[b] Better sleep quality.
[c] More alert.

compared with 13%, $p<0.02$). The number of awakenings per night (for various reasons) were on average low and did not differ between the areas in 1997.

Sleep was reported as more troubled (more movement) in the exposed area and sleep quality was significantly poorer ($p = 0.02$) than in the control area. Respondents also felt more tired in the morning ($p = 0.005$) and during the day ($p = 0.02$) in the exposed area, although there was no significant difference between the exposed and control area as regards tiredness in the evening.

5.3.2. Comparisons after traffic changes in 1999

The table shows that sleep was significantly improved in several aspects in the exposed area: woken because of traffic noise ($p = 0.02$); difficulty in falling back to sleep ($p = 0.05$); and sleep quality ($p = 0.05$). There was also a tendency towards a shorter time needed to fall asleep ($p = 0.10$).

In the control area, the number of awakenings was lower than before the traffic changes ($p = 0.02$).

Many of the differences observed in 1997 between the exposed and control population remained in 1999 (significantly fewer who reported a long time in falling asleep ($p = 0.04$) and fewer awakenings because of traffic noise ($p = 0.03$), less movements during sleep ($p = 0.0001$) and a lower level of tiredness during the day ($p = 0.0007$)). However, there were no longer any significant differences in the proportion who had difficulty in falling asleep, difficulty in falling back to sleep after awakening, tiredness in the morning or in sleep quality between the exposed and control areas.

5.4. Comparisons between sleep quality assessed by general questionnaire and 3-day sleep logs

Results for the same individuals in the general questionnaire and the 3-day sleep logs are shown in Table 6. It should be noted that mean values for the sleep logs are averaged on the basis of mean values for each individual's 3 nights.

The comparisons between the two questionnaire methods showed no differences for falling asleep, awakenings or tiredness in the morning. In the control area, sleep quality measured by sleep logs was somewhat lower ($p = 0.02$) than sleep quality assessed by the general questionnaire.

5.5. Noise levels, sleep quality and sleep habits

The relationship between *activity disturbances during night time* due to road traffic noise ("Does road traffic cause…") and individual calculated noise levels in $L_{Aeq,24\,h}$ outside bedrooms was analysed for the two samples (year 1997, $n = 142$). The correlation between noise level and difficulties in falling asleep and awakenings due to disturbances from road traffic noise, was high ($r_s = 0.56$ and $r_s = 0.48$, respectively, $p<0.001$).

The relationship (year 1997, $n = 142$) between *sleep quality parameters* and noise levels in $L_{Aeq,24\,h}$ outside bedrooms and time it took to fall asleep was lower, r_s 0.31 ($p = 0.001$), sleep quality $r_s = -0.25$ ($p = 0.01$), alertness in the morning $r_s = -0.19$ ($p = 0.01$) and number of awakenings $r_s = 0.06$.

Night is usually counted as the period between 22:00 and 06:00 h. In the 3-day sleep log the time that residents went to bed corresponded well with the start of the night period at 22:00. Only 12%

Table 6
Comparisons of sleep quality assessed by general questionnaire and 3-day sleep logs

	Exposed area ($n = 40$, 1997 and $n = 35$, 1999)			Control area ($n = 75$, 1997 and $n = 63$, 1999)		
	General quest.	3-day sleep log	p-value	General quest.	3-day sleep log	p-value
More than 30 min to fall asleep (% of the nights)						
1997	20	25	—	12.0	8.2	0.19
1999	10.5	20.5	—	12.3	9.5	0.13
Woken times/night (Mean)						
1997	1.7	1.8	—	1.0	1.6	—
1999	1.9	1.9	—	1.1	1.1	—
Sleep quality [(Mean of 1–10)[a]]						
1997	7.4	7.0	0.13	8.0	7.5	0.02
1999	7.6	7.1	0.07	7.4	7.7	0.20
Tired in the morning [(Mean of 1–10)[b]]						
1997	5.8	6.0	—	6.7	6.7	—
1999	5.8	6.4	0.09	6.8	6.7	—

[a] Higher mean value means better sleep quality.
[b] More alert in the morning.

of the residents went to bed before 22:00. The median time for going to bed was 22:35 in 1997 and 22:50 in 1999 in the exposed area. In the control area, the median time for going to bed was more or less the same, 22:55 in 1997 and 23:00 in 1999.

The median time for getting up in the morning was 06:55 in 1997 and 7:05 in 1999 in the exposed area. In the control area, the median time for getting up was more or less the same, 6:43 in 1997 and 6:59 in 1999. Thus 50% of the residents in the study areas were still in bed at 07:00. The time during the day when the participants were most annoyed by road traffic noise was mornings between 06:00 and 08:00.

6. Comments

6.1. Effects of road traffic noise on sleep before and after noise reduction

In 1997 (before the changes in road traffic), individual noise levels outside bedrooms were in some cases higher but in most cases below those recommended by WHO [3] (40 dB $L_{Aeq,22-06}$ and 60 dB L_{Amax} outdoors). The total number of vehicles was 1375 during the night period 22.00–06.00, and the noise levels varied between 36 and 61 dB $L_{Aeq,24\,h}$ and between 43 and 67 dB $L_{Aeq,24\,h}$ in front of the bedroom windows. As heavy traffic had been prohibited on Västra

Bräckevägen during night hours for a long period of time (with the exception of certain commercial traffic) and because only a small proportion of the people living in the area had bedroom windows that faced toward the road, it could have been expected that sleep disturbances would not have been especially great. In spite of the relatively low noise levels at night outside the bedroom windows, however, there were considerable sleep disturbances among the residents in the exposed area. In a direct question about the effect of road traffic noise on different activities (in the general questionnaire), it was found that disturbances of sleep and rest were relatively common before the building of the Lundby tunnel. About 25% reported disturbances from road traffic noise in 1997 in terms of difficulties in falling asleep and awakenings. The results in the general questionnaire in questions on sleep quality (without reference to noise) revealed significant differences in sleep quality between people in the exposed and control areas for the parameters of ‘‘difficulties in falling asleep’’, ‘‘awakenings’’, ‘‘sleep quality’’ and ‘‘tiredness in the morning’’, and only half as many people living in the exposed area usually slept with their windows open.

Results of cross-sectional studies on noise and sleep disturbances seldom show very strong dose–effect relationships (e.g., Refs. [7,8]). In the present study, a significant dose–effect relationship (individual level) was found between noise levels and difficulties in falling asleep and awakenings caused by road traffic ($r_s = 0.56$ and 0.48, respectively). In the field survey [8], which was designed to study exposure–effect relationships, six areas with different numbers of heavy vehicles during night hours were selected for investigation. No relation was found between sleep quality parameters and outdoor noise level in L_{Amax}, number of noise events or L_{Aeq} level. When the sample was divided into two groups (bedroom window facing/not facing the road), however, significant differences in sleep quality were found. Nevertheless, the results of the present study are in agreement with Langdon and Buller [9], who found a significant relation (group level) between $L_{10,22-06}$ and difficulties in falling asleep ($r = 0.91$) and waking during the night ($r = 0.84$) because of noise.

In the previous longitudinal survey in the same residential area [5], no improvement in sleep quality or reduction in reported noise-induced effects of road traffic on sleep were found after the prohibition of heavy vehicles during the night. Apparently the traffic regulations during night hours were not effective enough in reducing the adverse effects of noise at that time, as about 130 noise events from heavy vehicles (25 of these were above 80 dB L_{Amax}) were still present during the night. These levels correspond to an indoor noise level of about 50–55 dB L_{Amax}—levels that are known to induce sleep disturbances [10,11]. It could also be that the unchanged noise load during the daytime had a deleterious effect on sleep. In the present study the time required to fall asleep and tiredness in the morning were significantly reduced after the new tunnel was built and the previously observed differences between exposed and control areas disappeared. This time the reduction in road traffic noise was much larger, -12 dB (on average), and the number of heavy vehicles decreased from 125 to 30 during the night (22.00–06.00) in the exposed area. Furthermore, in the large majority of cases, the individual noise levels were lower than those recommended by WHO [3].

6.2. Noise levels and guideline values in relation to sleep habits

Early morning hours (06–08) were mentioned by the majority as the time of the day when road traffic caused the greatest annoyance, and it was obvious from the residents explanations of better sleep after the noise reduction measures that waking up too early because of heavy trucks had had a great effect on their sleep quality. The results in the sleep logs showed that 50% of the residents were still in bed at seven o'clock in the morning. If this is a common situation (which has been reported, e.g., by Griefahn [12]), it would be desirable from the point of view of health that restrictions/guidelines on noise during night hours cover a longer time period than 22.00–06.00 to protect against sleep disturbances.

6.3. Methodological considerations in studies on sleep disturbance

The results of investigations of sleep quality measured by questionnaires covering each of 3 weekdays (116 persons) and studies of sleep measured in a general questionnaire concerning the normal quality of sleep (142 persons) showed no differences in the results (with the exception of a somewhat lower sleep quality in the sleep logs in the control area in 1999). However, there is nothing that indicates that this deviation is caused by an overestimation of sleep quality in the general questionnaire. Deviations in the results between the two methods of studying sleep (a general questionnaire and a 3-day log) may have to do with actual differences in sleep during the 3-day period during which the sleep logs were kept. Other reasons for deviations in the results may be that it is difficult to judge sleep over a longer time period in a general questionnaire or that sleep disturbances are overestimated or sleep quality underestimated in order to motivate taking measures against road traffic noise. In the latter case, an underestimation of sleep quality/overemphasis of the effect of the traffic on sleep in the exposed area could be expected before the changes in traffic made in 1997, but this was not the case.

7. Conclusions

Sleep quality as reported by the residents is significantly reduced by exposure to road traffic at noise levels below 60 dB $L_{Aeq,22\text{–}06\,\text{h}}$ outdoors and sleep quality can be significantly improved by an extensive reduction in noise levels.

Sleep quality as assessed by single questionnaires may give equally good precision as daily reports on sleep over several days. Furthermore, a higher response rate is achieved by a single questionnaire.

The information in the sleep logs showed that 50% of the residents were still in bed at seven o'clock in the morning. If this is the usual case, it would be desirable from the viewpoint of health for restrictions on/guidelines for noise during the night period to cover a longer time than 22.00–06.00 in order to provide protection from sleep disturbances.

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