Health aspects associated with wind turbine noise—Results from three field studies

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Wind farms are a new source of environmental noise. The impact of wind turbine noise on health and well-being has not yet been well-established and remains under debate. Long-term effects, especially, are not known, because of the short time wind turbines have been operating and the relatively few people who have so far been exposed to wind turbine noise. As the rate of new installations increases, so does the number of people being exposed to wind turbine noise and the importance of identifying possible adverse health effects. Data from three cross-sectional studies comprising A-weighted sound pressure levels of wind turbine noise, and subjectively measured responses from 1,755 people, were used to systematically explore the relationships between sound levels and aspects of health and well-being. Consistent findings, that is, where all three studies showed the same result, are presented, and possible associations between wind turbine noise and human health are discussed. © *2011 Institute of Noise Control Engineering.*

1 INTRODUCTION

The rapid expansion of wind power in recent years has increased the interest in possible adverse health effects among residents in wind farm areas. However, this is not a new issue. Possible adverse health effects caused by noise from wind turbines have been a concern since the beginning of the modern wind power era in the 1970s. This concern could be due to commonplace skepticism towards new technologies, but it may also be traceable to bad experiences. The first commercial machines emitted not only aerodynamic noise but also noise from the machinery, giving them a reputation as noisy. Furthermore, some early versions were designed as downwind turbines with rather high levels of noise in the low frequency range that was negatively appraised[1]. The noise was therefore already a large issue thirty years ago. Moreover, wind turbines are often are placed in rural settings expected to be places of low exposure to environmental stressors. In such a setting technically induced noise, even at relatively low levels, could be perceived as a potential health risk. Several reports concerning the impact of wind farms on people living close by are cited in discussions regarding possible health effects that take place, for example, on the Internet. The reported symptoms are sometimes referred to as wind turbine syndrome. Results from studies of other community noise sources might hint at the kinds of effects that could be expected, although such effects are commonly found at higher sound levels than those associated with wind turbine exposure. The special characteristics of wind turbine noise and the settings in which they are placed indicate, however, that undesirable effects of wind turbine noise could be present at lower levels than expected. There is hence a need for epidemiological studies that examine the risk of adverse health effects for people living in the vicinity of wind turbines.

Response to community noise is commonly estimated in epidemiological studies as prevalence of annoyance, that is, the percentage of the studied population who are annoyed by the noise, comparing groups with increasing levels of exposure[2], and not by direct clinical health examinations. The definition of health set up by the World Health Organization (WHO) in 1948 is still the guiding principle in public health work. The definition reads as follows: Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity[3]. Such a definition suggests that, when studying the effects of an environmental exposure on health, it is necessary to not focus only on diseases or symptoms of impaired health, but to also measure well-being in a wider sense. Responding to noise by, for instance, becoming annoyed is, in light of the WHO definition, itself an

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adverse effect that should be avoided in order to retain well-being. However, annoyance could also be viewed as a measurable indicator of enhanced risk for chronic imbalance in the physiological stress system; an imbalance that could lead to more severe states, such as high blood pressure, and if prolonged, to cardiovascular diseases. The theory has been confirmed in studies where an association between high exposure to community noise, such as road traffic and aircraft noise, and high blood pressure has been found, for example, by Barregard et al.[4]. The exposure levels in these traffic studies were higher than those relevant for residents living in the vicinity of wind turbines, but it cannot be excluded that strong feelings of annoyance, despite sound levels, play a role in endocrine-influenced diseases, possibly as inhibitors of physiological restitution[5].

The indicator of community noise exposure commonly used both in scientific studies and as a basis for legislation is A-weighted equivalent sound pressure level, often transformed into values representing the diurnal rhythm of the exposure[2,6,7]. In the European Union, the Lden (annual average day-evening-night equivalent noise level), which assigns a penalty for evening and night noise exposure, has become the standard indicator for assessment of response to community noise, parallel with Lnight for predictions of noise-induced sleep disturbance[8]. However, it cannot be taken for granted that these indices are relevant also for wind turbine noise. There are several differences between wind turbine noise and noise from traffic and industry. The occurrence and the level of wind turbine noise at a dwelling are irregular. Because they depend on the wind speed at the hub of the turbine, there is no diurnal pattern[9]. Attempts to calculate Lden values for wind turbine noise have consequently resulted in values with an almost linear relationship to A-weighted equivalent sound pressure levels[10], with the transformation factor depending on the annual weather conditions at the site. C-weighted equivalent sound pressure level has also been put forward as a suitable estimator of the exposure dose for wind turbine noise, based on wind turbine sound comprising relatively high energies in the lower ranges of the sound spectra[9]. Though A-weighted levels are the dominant descriptor for community noise exposure, C-weighted levels have been used for estimations of community response to large amplitude single-event impulsive noise, such as sonic boom and artillery fire[11], of which the energies at the low frequencies at moments are of such magnitude that they could be registered by the human sensory system. However, the characteristics and the relatively low levels of wind turbine sound point towards using A-weighted levels. This approach also allows for comparisons with dose-response relationships for other community noise sources.

The objective of this paper was to explore the relationship between wind turbine noise and potential adverse health effects, using data from three epidemiological studies. The criterion used was that the relationship between exposure and a specified outcome should be statistically significant in all three studies in order to consider the outcome as a possible adverse health effect of wind turbine noise.

2 METHOD

All three studies were cross-sectional studies in which levels of wind turbine noise were compared to self-reported health status among people living in wind farm areas. Study SWE-00 was carried out in a flat, rural landscape in the south of Sweden in the year 2000[12]. Study SWE-05 also took place in Sweden, but in areas that differed in population density and topography, including suburban sites and hilly terrain[13]. Study NL-07 was carried out in the Netherlands 2007, also in a flat landscape, but with different degrees of road traffic intensity[14]. Annoyance and other health effects were measured in responses to a questionnaire conducted by postal mail. The questionnaire included questions about several potential environmental stressors, so as to not lead the respondent towards a focus on wind turbine noise. The questionnaires were delivered during the summer months, that is, when people supposedly spend time outdoors by their dwelling. The numbers of respondents in the three studies were 351, 754, and 725, respectively, for a total of 1,830. Some of the respondents did not answer all questions, and the number of respondents in this study was therefore limited to 1,755.

A-weighted sound pressure levels (corresponding to downwind conditions with wind speed 8 m/s at 10 m height) were calculated for each respondent from the sound power levels of all wind turbines nearby (logarithmically added). Two different algorithms were used for the calculations of the sound propagation, one for the Swedish studies[15] and another for the Dutch study[16]. The algorithms give similar results at the distances relevant in these studies[17] and will therefore in these analyses be treated as correct estimations of the exposure for all respondents outside their dwellings.

The data sets have, for this paper, been re-analyzed to assure similar treatment of the data. Only variables available from all three studies are included: response to noise (annoyance), diseases or symptoms of impaired health (chronic disease, diabetes, high blood pressure, cardiovascular disease, tinnitus, impaired hearing), stress symptoms (headache, undue tiredness, feeling tense or stressed, feeling irritable), and

Table 1—Association between A-weighted sound pressure levels (independent, continuous variable) and variables measuring response and/or effect (dependent, binary variable) tested with logistic regression. Statistically significant associations in bold numbers.

Symptoms	SWE-00[a] N^c =319–333	SWE-05[a] N^c =720–744	NL-07[b] N^c =639–678
Annoyance outdoors	**1.24 (1.13–1.36)**	**1.14 (1.03–1.27)**	**1.18 (1.12–1.24)**
Annoyance indoors	**1.38 (1.20–1.57)**	**1.42 (1.17–1.71)**	**1.20 (1.13–1.27)**
Sleep interruption	**1.12 (1.03–1.22)**	0.97 (0.90–1.05)	**1.03 (1.00–1.07)**
Chronic disease	0.97 (0.89–1.05)	1.01 (0.96–1.07)	0.98 (0.95–1.01)
Diabetes	0.96 (0.79–1.16)	**1.13 (1.00–1.27)**	1.00 (0.92–1.03)
High blood pressure	1.03 (0.90–1.17)	1.05 (0.97–1.13)	1.01 (0.96–1.06)
Cardiovascular disease	0.87 (0.68–1.10)	1.00 (0.88–1.13)	0.98 (0.91–1.05)
Tinnitus	**1.25 (1.03–1.50)**	0.97 (0.88–1.07)	0.94 (0.85–1.04)
Impaired hearing	1.09 (0.93–1.27)	1.05 (0.95–1.15)	1.01 (0.94–1.10)
Headache	0.95 (0.88–1.02)	1.04 (0.99–1.10)	1.01 (0.98–1.04)
Undue tiredness	0.95 (0.88–1.02)	0.98 (0.93–1.03)	1.02 (0.99–1.05)
Tense and stressed	1.02 (0.94–1.10)	1.00 (0.95–1.05)	1.01 (0.98–1.04)
Irritable	1.03 (0.96–1.11)	1.00 (0.96–1.06)	1.01 (0.98–1.04)

[a]Adjusted for age and sex.

[b]Adjusted for age, sex, and economic benefits.

[c]Range of number of respondents in the analyses. Differences in number of respondents are due to missing cases, that is, the respondents not answering single questions in the questionnaire.

disturbed sleep (interruption of the sleep by any noise source). Variables measured in the questionnaires were answered either on binary scales (no/yes) or on ordinal 5-point scales. The latter was, for example, used for noise annoyance, with the scale "do not notice", "notice, but not annoyed", "slightly annoyed", "rather annoyed", and "very annoyed". For the analyses the variables were dichotomized into "not annoyed" ("do not notice", "notice, but not annoyed" and "slightly annoyed") versus "annoyed" ("rather annoyed" and "very annoyed"). Sleep disturbance due to noise (any source) was measured differently in the three studies. In the Swedish studies, the scale used was binary (no/yes), while in the Dutch study the scale measured how often sleep disturbance occurred. Sleep disturbance once a month or more often was in this study considered as sleep disturbance.

The prevalence of health symptoms can vary with age and between males and females, which has to be taken into account. Associations between sound pressure levels and self-reported health were therefore tested with binary logistic regression. This method allows adjustments for known confounders, as several variables can be entered into the tested relationship at the same time. This method also tolerates binary and ordinal scales, and does not require normal distributed data. The binary logistic regression can be written as a linear function

$$\ln(p/(1-p)) = b_o + b_1 x_1 + b_2 x_2 + \ldots . + b_n x_n \quad (1)$$

where p is the probability of the outcome, $x_1 - x_n$ are the included independent variables, $b_1 - b_n$ their coefficients, and b_o the intercept (in this case of no interest). The outcome of a logistic regression is the odds ratio (OR) with a 95% confidence interval (95% CI). The OR is the probability of an outcome compared to no event occurring. The association between the regression and the OR is

$$p/(1-p) = e^{bj} \quad (2)$$

where j indicates the variable studied. An OR above 1.00, with a 95% CI with the lower value also above 1.00, indicates a positive correlation between the dependent (health symptoms) and the independent variable (sound pressure level or annoyance) in the regression model.

The Dutch study differed from the others in that many of the respondents in the samples with the highest exposures of wind turbine noise reported that they benefited economically from the wind turbines. Almost none of these respondents reported noise annoyance. They also differed from the rest in being younger and healthier overall. The results from the Dutch study are therefore also adjusted for economic benefits by entering the binary variable "yes/no economic benefits" into all regression tests.

Table 2—Association between annoyance outdoors due to wind turbine noise (independent, continuous variable) and variables measuring response and/or effect (dependent, binary variable) tested with logistic regression. Statistically significant associations in bold numbers.

Symptoms	SWE-00[a] $N^c = 319–333$	SWE-05[a] $N^c = 720–744$	NL-07[b] $N^c = 658–672$
Sleep interruption	**2.26 (1.76–2.90)**	**1.71 (1.35–2.17)**	**1.78 (1.49–2.14)**
Chronic disease	0.90 (0.71–1.08)	0.90 (0.74–1.26)	0.98 (0.81–1.19)
Diabetes	0.69 (0.37–1.31)	0.71 (0.40–1.28)	**1.70 (1.14–2.56)**
High blood pressure	0.82 (0.55–1.22)	1.10 (0.84–1.45)	0.86 (0.64–1.17)
Cardiovascular disease	1.07 (0.58–1.98)	1.00 (0.64–1.55)	0.95 (0.65–1.38)
Tinnitus	1.55 (0.95–2.53)	0.88 (0.60–0.98)	0.82 (0.45–1.48)
Impaired hearing	1.03 (0.96–1.19)	0.78 (0.51–1.21)	1.13 (0.76–1.67)
Headache	**1.24 (1.01–1.51)**	1.04 (0.86–1.26)	**1.25 (1.04–1.50)**
Undue tiredness	**1.22 (1.00–1.49)**	1.12 (0.93–1.35)	1.10 (0.93–1.31)
Tense and stressed	**1.25 (1.00–1.56)**	**1.22 (1.00–1.50)**	**1.27 (1.07–1.50)**
Irritable	**1.36 (1.10–1.69)**	**1.22 (1.00–1.49)**	**1.27 (1.07–1.50)**

[a]Adjusted for age, sex, and A-weighted sound pressure levels.
[b]Adjusted for age, sex, A-weighted sound pressure levels, and economic benefits.
[c]Range of number of respondents in the analyses. Differences in number of respondents are due to missing cases, that is, the respondents not answering single questions in the questionnaire.

When many statistical tests are carried out at the same time, some will show an association between two variables that are in fact due to chance. Also, situational or temporary factors that are not general could have influenced the results in one of the studies. Consistent results from all three studies, and not only for one or two, were therefore interpreted as indicating a factual association.

3 RESULTS

3.1 Relationships between Sound Levels and Subjective Variables

A-weighted sound pressure levels were in all three studies related to annoyance outdoors due to wind turbine noise, as well as to annoyance indoors, that is, an increase of sound levels led to increase in the frequency of residents annoyed (Table 1). An increase of sound levels increased the odds for annoyance outdoors somewhat less in the second Swedish study and for annoyance indoors less in the Dutch study. The increase of annoyance was, however, rather consistent over the studies.

Sleep interruption was associated with sound levels in the first Swedish study and in the Dutch study, but not in the second Swedish study. The increase in odds with increased sound levels was relatively low. Inspection of the data revealed that the proportion of respondents who reported being interrupted in their sleep by a noise source was rather stable at all levels of wind turbine sound, except at the strongest levels. In the first Swedish study the increase of respondents who reported sleep interruption appeared at approximately 40 dB. The increase came at higher sound levels in the Dutch study, at around 45 dB.

No other variable measuring health or well-being was consistently related to sound pressure levels throughout the three studies. The prevalence of tinnitus was positively related to sound pressure levels in the first Swedish study, but no such relationship was found in the other two studies. An indication of a positive relationship between the prevalence of diabetes and sound pressure levels was found in the second Swedish study. The lower limit of the confident interval was, however, just above 1.00.

3.2 Relationships between Annoyance and other Subjective Variables

Several of the variables measuring symptoms of stress were associated with annoyance outdoors due to wind turbine noise, including when adjusting for A-weighted sound pressure levels (Table 2). Feeling tense or stressed, as well as irritable, was associated with noise annoyance in all three studies. Headache was associated with annoyance in the first Swedish study and in the Dutch study. Undue tiredness was associated with annoyance in only one study. The study

Table 3—Association between annoyance indoors due to wind turbine noise (independent, continuous variable) and variables measuring response and/or effect (dependent, binary variable) tested with logistic regression. Statistically significant associations in bold numbers.

Symptoms	SWE-00[a] N[c] =318−331	SWE-05[a] N[c] =719−743	NL-07[b] N[c] =624−659
Sleep interruption	**2.62 (1.90–3.61)**	**2.58 (1.79–3.71)**	**2.03 (1.66–2.47)**
Chronic disease	0.93 (0.69–1.25)	0.94 (0.68–1.31)	1.05 (.086–1.28)
Diabetes	0.73 (0.30–1.75)	0.59 (0.22–1.59)	**1.62 (1.10–2.40)**
High blood pressure	0.065 (0.36–1.19)	0.85 (0.52–1.38)	0.83 (0.59–1.16)
Cardiovascular disease	0.99 (0.46–2.17)	0.97 (0.49–1.94)	0.76 (0.47–1.22)
Tinnitus	1.25 (0.77–2.05)	0.57 (0.24–1.33)	0.67 (0.28–1.57)
Impaired hearing	1.14 (0.72–1.79)	0.56 (0.24–1.32)	1.20 (0.80–1.80)
Headache	1.07 (0.83–1.37)	1.11 (0.81–1.52)	**1.28 (1.06–1.54)**
Undue tiredness	**1.36 (1.05–1.77)**	1.00 (0.95–1.80)	1.15 (0.96–1.37)
Tense and stressed	1.03 (0.79–1.35)	1.07 (0.77–1.48)	**1.24 (1.04–1.48)**
Irritable	1.22 (0.93–1.61)	1.23 (0.80–1.72)	**1.26 (1.06–1.50)**

[a]Adjusted for age, sex, and A-weighted sound pressure levels.
[b]Adjusted for age, sex, A-weighted sound pressure levels, and economic benefits.
[c]Range of number of respondents in the analyses. Differences in number of respondents are due to missing cases, that is, the respondents not answering single questions in the questionnaire.

design does not allow conclusions to be made regarding cause and effect; annoyance could lead to stress, or stress could enhance the risk for annoyance. Also sleep interruption was found to be associated with sound levels, which was related to annoyance, indicating a two-way relationship.

Sleep interruption was associated even more strongly with annoyance indoors (Table 3). No other variables were related to annoyance indoors in all three studies.

4 DISCUSSION

When a large number of statistical tests are carried out, some will by random chance show significant relationships where there in fact are none; if a 95% confidence interval is chosen, theoretically, 1 of 20 tests will result in a dubious outcome. Consistent results from three studies enhance the certainty. Annoyance was the only response to wind turbine noise measured in these studies that was directly associated with A-weighted sound pressure levels in all three studies. The possibility of an increase in prevalence of annoyance with increased sound levels varied, however, between the studies. The highest odds ratio (lower limit of the confidence intervals) was found in the first Swedish study, which was carried out in a rural, flat landscape with possibly lower levels of background sound than in the two other studies. It is known from aircraft studies that annoyance response in low background noise regions are higher than those in high background noise regions, even though aircraft noise levels are the same[18]. Whether this is actually due to the noise or to other qualities in the rural landscape is not clear. Rather similar values were found in the Dutch wind turbine study. Common to the first Swedish study and the Dutch study was the flat landscape where wind turbines often are visible in several directions and hence have a substantial impact on the landscape, a factor that might enhance the adverse response[19]. The second Swedish study, which was carried out in areas with differentiated topography, showed a lesser increase of annoyance prevalence with increasing sound levels for outdoor annoyance, but larger for indoor annoyance. The confidence intervals were, however, wide, due to few respondents reporting annoyance, and also indicating a large variety in responses.

A rather high number of respondents reported that their sleep was interrupted by noise, a nuisance that was found to be related to levels of wind turbine noise in two of the studies (and also to road traffic noise that was additionally measured in the Dutch study, but not discussed in this paper[17]). The impact of noise did not increase gradually with noise levels, but rather had a sharp increase around 40 dB in the first Swedish study and around 45 dB in the Dutch study, corresponding well with the recommended highest exposure levels in the two countries. Sleep interruption was not common in the

second Swedish study carried out mainly in more densely populated areas with suburban characteristics. It is not clear why sleep interruption was less common in these areas, but a combination of lowered expectations of quietness and higher levels of background noise (without incidents of heavy traffic at night) could be an explanation.

Stress was directly associated not with A-weighted sound pressure levels but with noise annoyance, in the three studies. There was a remarkable consistency among the studies in the relationship between feeling tense or stressed and annoyance. This should, however, not be taken as evidence of a causal relationship between wind turbine noise and stress, mediated by annoyance. The finding could be explained in the light of Lazarus and Folkman's cognitive stress theory[20], in which an individual appraises an environmental stressor, such as noise, as beneficial or not, and behaves accordingly. An individual already in a strenuous situation possibly appraises the noise as an additional threat to psycho-physiological restoration. As in the present case, wind turbine noise cannot be controlled by the individual, no action can be taken, and the response is manifested as annoyance. Being interrupted during sleep could possibly further increase the feeling of wind turbine noise as a threat.

This study has several limitations. All health symptoms were self-reported by the respondents. Health examinations carried out by professionals would have been a better way to assess the prevalence of possible health effects and is desired in future studies. The discrepancies between self-reported and diagnosed symptoms could, however, be hypothesized to be the same at all exposure levels (as the respondents did not know that the data would be analyzed in relation to wind turbines), and hence not influence the results. The estimations of exposure levels could also be questioned. Several other indices could have been used. The main method used here was to test whether *higher* exposure levels are related to *higher* prevalence of health symptoms, rather than to find specific thresholds. Such a method is not so sensitive to which dose indicator is chosen, as long as an increase in one indicator also means an increase in the other. It should be noted that the calculated exposure only reflected outdoor sound levels. It would have been ideal to have assessed indoor exposure in addition to the calculated outdoor levels used here, taking type of housing into account, especially as sleep disturbance was one of the reported effects.

The results of the studies are not alarming, but call for political action and further research. Annoyance due to wind turbine noise should in the future be avoided by applying proper regulations for shortest allowable distance between wind turbines and dwellings in the surroundings. Further scientific studies should explore the influence of wind turbine noise on sleep in different situations, as well as the interaction between sound exposure, noise annoyance, and stress. Longitudinal as well as experimental studies are needed, taking into account the methodological issues discussed above.

5 ACKNOWLEDGMENTS

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