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Epidemiological study on long-term health effects of low-frequency noise produced by wind power stations in Japan

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ABSTRACT

We investigated whether long-term exposure to wind turbine noise (WTN) including low-frequency noise generated by wind power facilities is a risk factor of sleep disorders. We performed an epidemiological study of living environment and health effects, surveying 9,000 residents (≥20 years) living in areas with operational wind power facilities. Sleep disorders were assessed using the Athens Insomnia Scale. To assess environmental noise in residential areas near the wind turbines, low-frequency sound exposure levels were measured at 50 community centers of the town. Multiple logistic regression analysis was used for evaluation of a risk factor for several noise exposure indices. Significant relationships between the distance from the nearest WT to dwellings and hearing, annoyance, sleep disorders were observed. By multiple logistic analysis the prevalence rate of sleep disorders was significantly higher for residents who reported subjectively hearing noise being than for those who did not. Moreover, the reported prevalence rate of sleep disorders was significantly higher in residents living at a distance of ≤1,500 m from the nearest wind turbine compared to that for residents living at a distance ≥2,000 m. The attitudes of residents towards wind power facilities and sensitivity to noise strongly affected their responses regarding sleep disorder prevalence.

Keywords: audible noise, epidemiology, infrasound, low-frequency noise, sleep disorder, wind turbine noise

1. INTRODUCTION

The effect of the noise of wind power generation facilities on health is a growing concern. This is especially true regarding infrasound, defined as sound lower in frequency than 20 Hz. Plans for new wind power generation facilities have had to be changed in some cases in Japan due to the health concerns of local residents.

Multiple cross-sectional epidemiological studies have shown a strong relationship between annoyance and living in close proximity to wind turbines. It has been reported that individual factors such as the visual impact of wind turbines, attitudes towards wind turbine installation, and economic benefits are more strongly related to the presence or absence of annoyance than the actual noise of wind turbines (1).

Other studies have reported that rather than focusing on the noise of wind turbines, more attention should be paid to cofounding factors such as attitudes toward wind power generation, impact on scenic views, economic benefits, visibility of wind turbines, sensitivity to sound, and concerns about health (2).

Previous epidemiological studies have frequently reported that audible noise generated by wind turbines is significantly associated with annoyance and sleep disorder (3, 4). On the other hand, no clear relationship has been reported thus far between infrasound and effects on health (5). Furthermore, most epidemiological studies have used a cross-sectional design, and therefore cannot confirm a causal relationship between wind turbine noise and health effects.

The present cross-sectional epidemiological study targeted local residents in Japan where wind power generation facilities were already active, and sought to determine how exposure to infrasound and noise from these facilities in Japan affects health, specifically the presence of a sleep disorder.

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2. METHODS

The target area is Nagashima-cho, Izumi-gun on Nagashima Island, located in the northern part of Kagoshima prefecture. Its population is 10,400. The island is longer in the north-south direction, with an area of approximately 110 km^2. The middle of the island is mountainous, and ports are located around the island perimeter. Wind power generation facilities (output 2.4 MW x 21 stations, wind speed rate 12.5 m/s) were introduced in August 2008, in the middle of the island. Most residences are located at least 1 km from the closest wind turbine, and there are no residences within 500 m of a wind turbine.

We conducted this survey by distributing a questionnaire to residents of Nagashima-cho aged 20 years and older (approximately 9,000 people) in December 2014. The survey was distributed to each household via a circulation board, a traditional method of disseminating information in Japanese neighborhoods, in cooperation with 57 directors of public city halls (local cultural centers, one in each school district, providing recreation and learning for local residents). Participants returned the questionnaire using a prepaid return envelope.

The questionnaire contained items addressing family structure, family residence, living arrangement, lifestyle, social and economic factors, health conditions, level of annoyance with wind turbine noise, attitude towards installation of wind power generation facilities and reaction to their visual impact, as well as basic personal attributes (gender, age, height and weight). The presence of a sleep disorder was evaluated using the Athens Insomnia Scale (AIS) (Japanese version). The AIS was developed in 2000 by the World Health organization (WHO) based on the 10^{th} version of the International Statistical Classification of Diseases and Related Health Problems (ICD-10), and its Japanese version was created in 2013. The first five items of the questionnaire pertain to difficulty in sleep induction, awaking during the night, early morning awakening, sleep duration and quality of sleep. The remaining three items consist of questions related to sleepiness, sense of well-being and the level of active functioning during the day. Each response uses a 4-point Likert-type scale (0 = no problem, 1 = minor problem, 3 = considerable problem, 4 = serious problem), and the total is calculated (range 0–32). A score of more than 6 points indicates the presence of a sleep disorder.

The distance from each household residence to the nearest wind turbine was defined using a proxy, namely the distance from the wind turbine to the public city hall of the school district in which the residence was located. The relationship between sleep disorders and noise was reviewed using the following four noise-related indicators: 1) whether or not the noise was consciously audible, 2) horizontal distance from the wind turbine to the district public city hall, 3) wind turbine noise at night (the A-weighted equivalent sound level (L_{Aeq})) and 4) difference between wind turbine noise and background noise.

A summary of the measurement method is as follows. Research was conducted to determine the infrasound/noise attenuation curve over distance from the wind power generation facility. A broadband sound pressure level meter was used to measure the level of infrasound and noise at the public city hall of each school district. Since the measurement of infrasound is easily affected by wind, we covered a microphone with a two-layer wind-proof screen. Assessment of infrasound/noise exposure levels at the public city halls was conducted for 24 consecutive hours once per season in 2014, at 72 locations; these locations were inside 47 public city halls among 57 public city halls/meeting facilities in Nagashima-cho, mainly located in the center of the island. The A-weighted equivalent continuous sound level $L_{Aeq,10min}$ was calculated based on each hour of infrasound/noise was detected from the wind power generation facilities, then the mean energy was derived from the entire time range and the wind turbine A-weighted equivalent continuous sound level $L_{\mathrm{Aeq,WTN}}$ was calculated at each measurement point. Regarding the total noise, the A-weighted equivalent continuous sound level for every hour and the sound pressure level of noise changes over time were calculated, then the sound pressure levels during daytime (6:00 to 22:00) and nighttime (22:00 to 6:00) were derived using the arithmetic mean for the percentile sound pressure levels and the mean energy for the A-weighted equivalent continuous sound levels.

Statistical analysis used the chi-squared test and multiple logistic regression analysis. Three models were evaluated using multiple logistic regression analysis: model 1, adjusted by gender and age; model 2, adjusted by the variables in model 1 as well as by three social factors, namely shift work, income and marital status; and model 3, adjusted by the variables in model 2 as well as by the attitude towards the visual impact of the wind turbines and the current attitude toward the original wind turbine installation. The distance from the residence to the wind turbine was divided into five categories: less than 1,000 m; between 1,000 and 1,500 m; between 1,500 and 2,000 m; between

2,000 and 5,000 m; and 5,000 m and above. There were 2,593 responses to the survey (collection rate 28.3%). Of these, 401 were disqualified due to missing gender or age (75 responses), missing city hall district (29 responses), and age 80 years old or older (287 responses). The final number of qualified survey responses was 2,192.

3. RESULTS

3.1 Participants characteristics and living arrangements

Table 1 shows the participants characteristics and living arrangements. The mean age was 58.1 years, and the gender ratio of males to females was 1.06. Regarding the most common living arrangements, 90.2% of participants lived with family and 82.3% had lived in the same residence for 10 years or more. The rates of smoking and drinking on an almost daily basis were 17.8% and 33.5%, respectively, with a significant difference between males and females. Approximately 40% agreed that “the wind turbine is visible from home,” and approximately 15% agreed that “the sound of the wind turbine is audible from home.” The mean distance from the closest wind turbine to each public city hall was approximately 3,000 m, and the minimum distance was 730 m. The mode of the distance category was 2,000 to 5,000 m, accounting for 56% of responses. The mode of the nighttime wind turbine noise level category was 20-50 dB.

Table 1 Basic characteristics of subject and environmental status

items	n(%)		
sex		male 1,126(51.4	female 1,066(48.6)
age	average year 58.1	58.3	57.9
marriage status			
spouse	1,671(77.0)		
bereavement	64 (7.5)		
separation	91 (4.2)		
single	245 (11.3)		
family constitution			
single life	202 (9.3)		
living with family	1,958(90.2)		
others	11 (0.5)		
residence number of years			
under 1 year	52 (2.4)		
1-3 years	105 (4.8)		
3-5 yeas	84 (3.9)		
5-10 years	145 (6.6)		
over 10 years	1,794(82.3)		
smoking status	total	male	female
no smoker	1,604(73.5)	610(54.3)	994(93.9)
smoker	389(17.8)	334(29.7)	55 (5.2)
ex-smoker	189 (8.7)	179(16.0)	10 (0.9)
alcohol drinking status	total	male	female
every day	731(33.5)	623(55.6)	108(10.2)
once a week	232(10.6)	133(11.9)	99 (9.3)
once a month	134 (6.1)	62 (5.5)	72 (6.8)
no drinking	1,083(49.7)	303(15.9)	780(73.7)
Can you see a wind turbine from one' s residence' s house			
yes	872 (41.5)		
no	1,228 (58.5)		
Can you hear a sound from wind turbine from one' s residence' s house			
yes	335 (15.6)		
no	1,813 (84.4)		
distance from the nearest wind turbine to one' s residence' s house	average 3,093m (min.730m, max.10,768m)		
<1,000m	87 (4.3)		
1,000-1,500m	187 (9.2)		
1,500-2,000m	364 (17.9)		
2,000-5,000m	1,148 (56.4)		
≥5,000m	248 (12.2)		
wind turbine noise at night (L_{Aeq})			
<20 dB	273 (14.3)		
20-25 dB	712 (37.4)		
25-30 dB	517 (27.1)		
30-35 dB	257 (13.4)		
35-40 dB	146 (7.7)		

3.2 Relationship between audible noise and distance to wind turbine and prevalence of sleep disorders

Figure 1 shows the proportion of participants who reported hearing the sound of wind power generation facilities at home, categorized by distance from their public city hall to the nearest wind turbine. For distances less than 1,000 m, 63% reported that the noise was audible, and this percentage decreased significantly with increasing distance. Even at distances of 5,000 m and over, 2% of respondents stated that the turbines were audible. Sleep disorder (AIS ≥ 6 points) was present in 26% (528 people) of participants, but this percentage was approximately 40% in those whose homes were less than 1,000 m from a wind turbine (Fig. 2). The frequency of sleep disorder decreased to 22% at a distance of 2000 m to 5000 m, but then increased to 30% at a distance of 5,000 and over. There was a statistically significant relationship between distance and sleep disorder frequency ($p < .001$).

Figure 1　The proportion of participants who reported hearing the sound of wind turbine by distance from the nearest wind turbine to residence's house

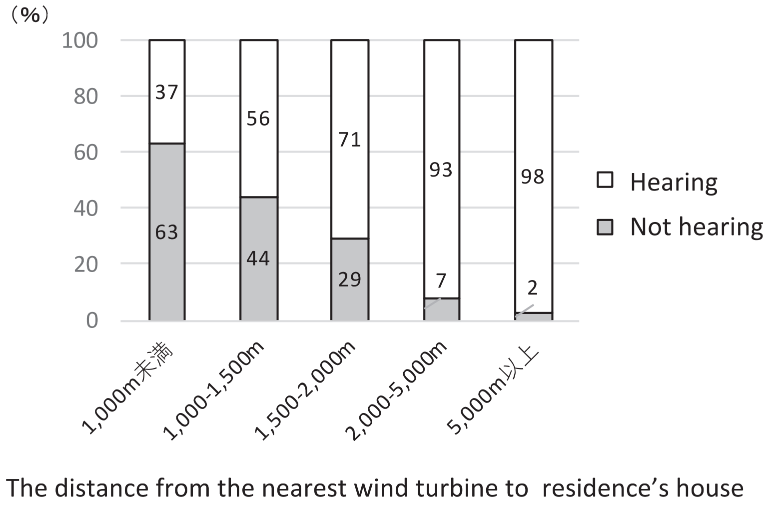
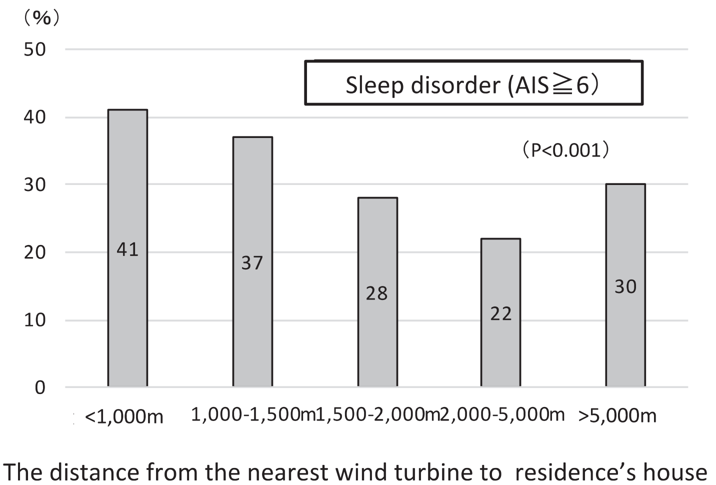


Figure 2 The prevalence of sleep disorder by distance from the nearest wind turbine to residence's house



3.3 Multiple logistic regression analysis

Multiple logistic regression analyses were performed with the presence of a sleep disorder as an independent variable, and the wind turbine noise indicator was modeled considering the following dependent variables: 1) whether or not wind turbine noise was consciously audible, 2) distance from the resident's public city hall to the wind turbine, 3) nighttime wind turbine noise (L_{Aeq}) and 4) difference between wind turbine noise and background noise. The results of this analysis are shown in Tables 2 to 5. In every model, participants who agreed that "wind turbine noise is consciously audible" had approximately twice the odds of having a sleep disorder as those who responded negatively, and this difference was statistically significant (Table 2). As for the impact of distance to the wind turbine, residents who lived within 1,500 m were approximately twice as likely to have a sleep disorder as those who lived at least 2,000 m away, indicating a statistically significant difference (Table 3). In terms of exposure to nighttime wind turbine noise (L_{Aeq}), those exposed to 35 dB or more had a 1.5-fold higher likelihood of having a sleep disorder than those exposed to the typical level of 20–25 dB, again a statistically significant difference (Table 4). Finally, regarding the difference between wind turbine noise and background noise, participants exposed to a difference of 5 dB or more had an approximately 1.6-fold higher likelihood of having a sleep disorder than those exposed to a difference of less than 5 dB, indicating a statistically significant impact (Table 5).

Table 2 The relationship between hearing a sound of wind turbine from residence's house and sleep disorder

Odds ratio (95% confidence interval)								
	N	case (%)	model 1	p	model 2	p	model 3	p
Hearing a sound	1,713	397 (23.1)	1.00		1.00		1.00	
Not hearing a sound	320	131 (40.9)	2.28 (1.77–2.93)	<0.0001	2.15 (1.63–2.83)	<0.0001	1.89 (1.89–2.52)	<0.0001

model 1: adjustment with sex and age
model 2: adjustment with sex, age, marriage status, work with income and shift work
model 3: adjustment with sex, age, marriage status, work with income, shift work, attitude to wind turbine development and visual impact.

Table 3 The distance from wind turbine to one's residence and sleep disorder

Odds ratio (95% confidence interval)								
	N	case (%)	model 1	p	model 2	p	model 3	p
Under 1,000 m	78	32 (41.3)	2.28 (1.50–3.89)	0.0004	2.36 (1.35–4.04)	0.0028	1.93 (1.08–3.38)	0.028
1,000 – 1,500 m	166	62 (37.4)	2.11 (1.49–2.98)	<0.0001	2.15 (1.63–2.83)	0.0003	1.91 (1.29–2.83)	0.0018
1,500 – 2,000 m	349	97 (27.8)	1.35 (1.02–1.79)	0.0034	1.32 (0.97–1.79)	0.0820	1.32 (0.96–1.80)	0.0859
2,000 – 5,000 m	1,079	235 (21.8)	1.00		1.00		1.00	
Over 5,,000 m	293	80 (27.3)	1.38 (1.02–1.85)	0.0377	1.25 (0.90–1.74)	0.1827	1.24 (0.88–1.73)	0.2134

model 1: adjustment with sex and age
model 2: adjustment with sex, age, marriage status, work with income and shift work
model 3: adjustment with sex, age, marriage status, work with income, shift work, attitude to wind turbine development and visual impact.

Table 4 Wind turbine noise at night (L_{Aeq}) and sleep disorder

			Odds ratio (95% confidence interval)					
	N	case (%)	model 1	p	model 2	p	model 3	p
<20 dBA	273	76 (27.8)	1.24 (0.90–1.70)	0.1880	1.20 (0.85–1.69)	0.2944	1.21 (0.85–1.71)	0.2884
20–25	712	167 (23.5)	1.00		1.00		1.00	
25–30	517	114 (22.1)	0.91 (0.69–1.19)	0.4725	0.84 (0.62–1.139)	0.2422	0.83 (0.61–1.13)	0.2297
30–35	257	91 (35.4)	1.73 (1.26–2.36)	0.0007	1.53 (1.08–2.13)	0.0153	1.43 (1.01–2.03)	0.0462
35–40	146	48 (32.9)	1.56 (1.05–2.29)	0.0272	1.56 (1.00–2.38)	0.0489	1.34 (0.85–2.08)	0.2094
>40	0	–						

model 1: adjustment with sex and age
model 2: adjustment with sex, age, marriage status, work with income and shift work
model 3: adjustment with sex, age, marriage status, work with income, shift work, attitude to wind turbine development and visual impact.

Table 5 The difference between wind turbine noise and background noise relate to the prevalence of sleep disorder

			Odds ratio (95% confidence interval)					
	N	case (%)	model 1	p	model 2	p	model 3	p
Under 5 dB	1,642	406 (24.71)	1.00		1.00		1.00	
Over 5 dB	263	90 (34.2)	1.58 (1.20–2.09	0.0015	1.59 (1.16–2.16)	0.0042	1.48 (1.06–2.04)	0.020

model 1: adjustment with sex and age
model 2: adjustment with sex, age, marriage status, work with income and shift work
model 3: adjustment with sex, age, marriage status, work with income, shift work, attitude to wind turbine development and visual impact.

4. DISCUSSION

This epidemiologic study suggested that audible noise (frequency of 20 Hz or over) that is produced by wind power generation facilities can be a risk factor for sleep disorder when the residential environment is characterized by any of the following: 1) wind turbine sound is consciously audible, 2) residence is close to a wind turbine (within 1,500 m), 3) nighttime wind turbine noise (L_{Aeq}) is 35 dB or higher and 4) difference between nighttime wind turbine noise and background noise is 5 dB or more. The results of multiple logistic regression analysis showed that the odds ratio of sleep disorder were significantly increased in these cases. This study used a nighttime wind turbine noise (L_{Aeq}) level of 35 dB and over since this level matched the cut-off value for annoyance and sleep disorder reported by Schmidt et al (6). This same value is used in wind turbine noise standard guidelines worldwide, including in Sweden and New Zealand (7). Japan previously had no standards regarding wind turbine noise, but recently the Ministry of the Environment released an administrative notice indicating that the noise limit is 5 dB above the background noise, but this standard is not used consistently across the country. The standard regarding the upper limit for nighttime wind turbine noise takes into consideration the characteristics of each area to make sure that no troubles arise in the living environment. The upper limit is set to 35 dB in some areas (especially those requiring greater degrees of silence) while other areas have 40 dB as the limit (8).

As for sleep disorder caused by infrasound, all wind turbine noise of 20 Hz or under that was measured in this study was below the human sensory threshold. The results are not shown, but in a sub analysis of participants who stated that wind turbine sound was inaudible (n = 1,813), the significant relationship between distance and sleep disorder disappeared, and thus the likelihood of a relationship between the two is low. Noise measurement results near wind power generation facilities across Japan showed that infrasound was not louder than other environmental noise. However, the amplitude modulation of sound and tonal components of noise generated from wind power generation facilities have a tendency to increase annoyance, and therefore further studies should evaluate their health effects. Jeffery et al.(3) also reported that even if infrasound from wind turbines does not exceed the human sensory threshold, it cannot be completely ignored since it may influence the vestibular system, and thus health effects other than sleep disorder also need to be reviewed.

The visibility of wind turbines and attitudes towards scenic views were identified as cofounding factors in previous studies, but no statistically significant effects were found in this study. In the surveyed area, attitudes toward accepting wind power generation were favorable compared to the areas in previous studies; this may have influenced the outcome, and therefore analyses are needed that take into account the characteristics of each area. Of the cofounding factors considered in this study, “attitude towards wind power generation facilities (past, present)” was most strongly associated with sleep disorder, increasing its likelihood by approximately fivefold. Sub-analysis of participants with a favorable current attitude towards wind turbines (n = 879) showed that annoyance with wind turbine noise was significantly related to distance from the wind turbine (data not shown); however, there was no significant relationship between distance and sleep disorder, and therefore it seems important to determine how to build consensus prior to introducing new wind power generation facilities. The Ministry of the Environment created a report called “Dealing with noise generated from wind power generation facilities” that points out the importance of promoting communication between stakeholders.

The limitations of this study are as follows. The collection rate of questionnaires was only 28.3%, which is low, and therefore although we confirmed that the overall population and a sample did not differ in the distribution of gender and age, the validity of the data remains to be verified. The distance from the nearest wind turbine was calculated from the location of the local public city hall to which each respondent belonged, rather than from each respondent’s actual residence. This may have led to inaccuracy regarding distance information. For the estimation of the wind turbine A-weighted equivalent continuous sound level (L_{Aeq}), a distance attenuation curve <$L_{Aeq,WTN}(d) = -20.9\log_{10}d + 87.9$, where d is a distance (m)> was derived based on the measurements obtained at nine locations where wind power generation facilities were visible. These consisted of five locations in area A, with horizontal distances to the wind turbine from 337 m to 1,485 m, and four locations in area B, with distances from 944 m to 1,766 m. The validity of the estimation equation is not fully confirmed. Finally, this epidemiological research design was cross-sectional in nature, and therefore it cannot be used to determine any causal relationship between exposure to noise (cause) and health effects (result). Only the possibilities of such relationships can be identified. Longitudinal studies (cohort studies) involving wind turbine noise and health effects are rare worldwide, but these are necessary to prove causal relationships.

In Japan, based on situations involving noise complaints, the Ministry of the Environment generally defines low-frequency noise as 100 Hz or lower. Internationally, the definition of low-frequency noise differs by country and no standard exists. The International Electro-technical Commission (IEC) standard 61400 series defines infrasound as 20 Hz or lower, and low-frequency noise as 20 to 100 Hz. In Japan, the Japan Industrial Standard (JIS) uses the same definition as the IEC. Japanese environmental assessment law defines noise (frequency 20 to 100 Hz) and infrasound (frequency 20 Hz and lower), and does not use the term “low-frequency noise.” Generally, in terms of wind turbine noise concerns, many residents worry about the health effects of so-called “low-frequency noise,” defined as 100 Hz and below, but they also do not realize that low-frequency noise (infrasound) is inaudible. In the future, public awareness campaigns about the proper usage of the term "low-frequency noise" are necessary not only for researchers but also for business developers and local residents. These campaigns will increase mutual understanding and the sharing of measurement results, and promote the development of new strategies regarding wind turbine noise.

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