Review Article

Wind turbines and adverse health effects: Applying Bradford Hill's criteria for causation

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Abstract

The weight of evidence indicates occurrences of adverse health effects (AHEs) from living and working near industrial wind turbines (IWTs). Descriptions of the AHEs being reported by those living or working near the turbines are similar. While these occurrences have been associated with exposure to audible and inaudible noise annoyance, the causation of reported wind turbine-associated health effects remains controversial. Establishing an argument of causation of adverse health outcomes has important clinical, scientific, and societal implications. Bradford Hill (BH) criteria have been widely used to establish causality between an environmental agent and risk of disease or disability, but have not previously been used to evaluate the relationship between IWTs and AHEs. The objective was to apply the BH criteria to evaluate the relationship between IWTs and AHEs. The nine criteria include the strength of the association, consistency, specificity, temporal sequence, biological gradient, plausibility, coherence, experimental evidence, and analogous evidence. These nine criteria have been applied to IWT exposure and reported AHEs using peer-reviewed and other published literature that describes clinical, animal, and laboratory studies, testimony and reported experiences, and internet sources. Applying the BH criteria to the IWT-related clinical, biological, and experimental data demonstrates that the exposure to IWTs is associated with an increased risk of AHEs. This analysis concludes that living or working near IWTs can result in AHEs in both people and animals. Our findings provide compelling evidence that the risk of AHEs should be considered before the approval of wind energy projects and during the assessment of setback distances of proposed and operational projects.

Keywords: Adverse health effects, Bradford Hill criteria, evidence of causation, industrial wind turbines

INTRODUCTION

Proof of causation typically requires the rigor of a scientific standard. Consequently, the evidence required to make a scientific determination about causality has a higher standard than the Precautionary Principle that is recommended by the World Health Organization (WHO).[1] The Bradford Hill (BH) criteria, sometimes referred to as Hill's criteria for causation, are a set of nine criteria that have become a frequently cited framework for establishing epidemiologic evidence of a causal relationship between a presumed cause and an observed effect. They were established by Sir Austin Bradford Hill[2] and have been

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reviewed in numerous articles and presentations.[3,4] Researchers have applied Hill's criteria in examining the evidence of causality of environmental and other exposures on health, for example, connections between smoking and asbestos and cancer, ultraviolet B radiation, Vitamin D and cancer, Vitamin D and pregnancy and neonatal outcomes, alcohol and cardiovascular disease outcomes, infections and risk of stroke, nutrition and biomarkers related to disease outcomes, and sugar-sweetened beverage consumption, and the prevalence of obesity and obesity-related diseases.[4-12]

The nine criteria described by Hill are strength of association, consistency, specificity, temporal relationship, biological gradient, plausibility, coherence, experimental evidence, and analogous evidence. Three recent additional approaches that have been used to evaluate potential outcomes are (i) directed acyclic graphs, (ii) sufficient-component cause models, and (iii) the grading of recommendations, assessment, development, and evaluation methodology. The criteria that have been examined using these approaches are consistent with the BH criteria: strength of association (including analysis of plausible confounding); temporality; and plausibility and experiments (including implications of study design on exchangeability).[3,4] The overlap between the BH viewpoints and the other approaches substantiates the ongoing influence and the application of BH criteria in causal assessments.

There have been a number of public hearings/inquiries and publications addressing and interpreting the adverse health effects (AHEs) of industrial wind turbines (IWTs). Some qualified experts have testified under oath during judicial proceedings that the causality of indirect effects on health by turbines cannot be assessed using BH criteria because of insufficient information and/or available measurements. Such statements can impact the outcome of legal cases and affect consideration of the potential risks of exposure. It is important to apply the BH criteria to this environmental exposure in a scientifically rigorous manner.

Evidence gathered at multiple public hearings/inquiries and reported in peer-reviewed articles and conference papers,[13-29] by a 6-month investigation by le Coz and Sherman 2017,[30] and through social media sites,[31-35] supports the position that emissions associated with operating IWTs can cause serious harm to the health of a proportion of individuals in the vicinity of the turbines. Effects such as emotional/psychological and sleep disturbances/disruptions, headaches, fatigue, difficulty concentrating, and effects on quality of life have been reported to occur from living near wind energy facilities.[16,17,26,35-40]

It has been proposed that the contributing emissions are electromagnetic/radio frequency (EMF/RF) energy,[22] audible and inaudible noise (infrasound and/or low-frequency sound), and vibration.[41-49] While a decision of a judicial proceeding determined that IWT-related adverse effects could occur through the direct/causal and indirect pathways,[50] some witnesses testified that the literature/evidence was insufficient to determine causality that the noise produced is not enough to cause AHEs.[51-54]

Both direct and indirect effects of IWTs on health have been assessed. Indirect measures include noise annoyance, recurring sleep disturbance, anxiety and stress, and related physiological measures. In comparison, direct effects are recorded through anatomical and physiological measures and generally refer only to hearing loss.[1]

Purpose

The purpose of this paper is to utilize the nine BH criteria to determine the degree of confidence of causality between exposure to IWTs and AHE, and to explore whether there is a high probability some people who live and/or work near IWTs will experience significant harm to health on exposure to IWTs, through critical examination of the scientific literature and other evidence on this topic

METHODS

The nine BH criteria were applied and are presented in the descending order of importance according to that described in the literature.[55-57] Examples related to the application of each criterion to IWTs are described. Table 1 provides a brief explanation of each criterion[2,58] with a list of the references described in this paper that are associated with each criterion. In some cases, more than one criterion will apply to a study.

Evidence relating to adverse events experienced by individuals living and/or working in the proximity of IWTs was gathered from multiple sources including peer-reviewed references, other published literature, case reports, government-sponsored hearings/inquiries, records related to judicial processes such as transcripts from testimony by expert witnesses and decisions from judicial processes, government records including those obtained through Freedom of Information requests, and health surveys. The evidence relating to IWTs and health effects was then evaluated by applying the BH criteria.[2] Causality and proposed contributing factors toward the reported AHEs were then assessed.

RESULTS

Applying the BH criteria to the IWT-related clinical, biological, and experimental data gives evidence that

Table 1: Summary of current literature relevant to the application of the Bradford Hill's criteria to adverse health effects in individuals associated with exposure to industrial wind turbines

Criterion	Description	Primary related references
Strength of the association	A small association does not mean that there is not a causal effect, though the larger the association, the more likely that it is causal	Krogh *et al*., 2019, Wind Concerns Ontario, 2021 (Canada)[23,35] Nissenbaum *et al*., 2012 (USA)[24] Thorne 2011, 2012 (Australia)[88,89] Health Canada 2014 (Canada)[90]
Consistency	Consistent findings observed by different persons, or measured, in different locations with different samples/exposures strengthens the likelihood of an effect	Abbasi *et al*., 2015, 2016 (Iran)[80,81] Ambrose *et al*., 2012 (USA)[42] Swinbanks, 2015 (UK)[86]
Specificity	Causation is likely if a very specific population at a specific site and disease/morbidity with no other likely explanation	Krogh *et al*., 2011, 2019 (Canada)[23,68] Wind Concerns Ontario, 2021 (Canada)[35] Thorne, 2013 (Australia)[118]
Temporality	The effect has to occur after the cause (and if there is an expected delay between the cause and expected effect, then the effect must occur after that delay)	Pierpont, 2009 (USA)[26] Hansen *et al*., 2014 (Australia)[119] The Acoustic Group, 2014 (Australia)[47] Krogh *et al*., 2020a, b, 2021 (Canada)[69-71]
Biological gradient (dose-response effect)	Greater exposure should generally lead to greater incidence or severity of the effect	Pedersen and Waye, 2004 (Sweden)[102] Bakker *et al*., 2012 (Sweden)[135] Yano *et al*., 2013 (Japan)[136] Palmer, 2020 (Canada)[137] Nissenbaum *et al*., 2012 (USA)[24]
Plausibility	A plausible mechanism between cause and effect is helpful but knowledge of the mechanism can be limited by current knowledge	Qibai and Shi, 2004 (China)[141] Alves-Pereira and Castelo Branco, 2007, Alves-Pereira *et al*., 2019 (Portugal)[41,142] Salt and Hullar, 2010 (USA)[143] Kelley *et al*., NASA, 1982 (USA)[178] Cooperative Measurement Survey, 2012 (USA); Schomer *et al*., 2015 (USA)[43,146]
Coherence	Coherence between epidemiological and laboratory findings increases the likelihood of an effect	Echteler *et al*., 1994, Escaler. *et al*., 2013 (USA)[151,154] Salt and Hullar, 2010 (USA)[143] West, 1985 (USA)[152] Haneke *et al*., 2001 (USA)[150] Schofield, 2001 (USA)[153]
Experimental evidence	Occasionally, it is possible to appeal to experimental evidence	Ambrose and Rand, 2011, Ambrose *et al*., 2012 (USA)[42,82] The Acoustic Group, 2014 (Australia)[47] Inagaki and Nishi, 2015 (Japan)[83] Verzini *et al*., 1999 (Argentina)[155]
Analogous evidence	The effect of similar factors may be considered	Weichenberger *et al*., 2020 (Germany)[160]

exposure to IWTs is associated with an increased risk of AHEs.

Criteria 1: Strength of the association

The bulk of scientific evidence associated with AHEs due to IWT installations comes from individual exposure information from both those living near IWTs and from industrial workers.

Evidence includes thousands of case reports and incident reports that have been submitted to the Government of Ontario, Canada,[23,35] and international reports that are available through government inquiries, judicial proceedings, and from the Internet.[15-17,19,20,31-34,37] Some individuals have testified under oath during judicial proceedings and described the occurrence of AHEs when living near IWTs.[60,61] Some have gone so far as vacating/abandoning their homes while others have contemplated doing so.[30,61-71] Case studies such as testimony during government hearings in the USA, Australia, Northern Ireland, and Canada have described serious adverse effects with exposure to wind turbines.[15-17,19,37,72,73] Several reviews and research results propose that there is an association between exposure to wind turbine noise and annoyance,[46,74-76] distress,[77] sleep problems, and effects on quality of life.[27,78,79] A meta-analysis by Onokpoya *et al*. of six cross-sectional studies with a total of 2364 participants found a statistically significant risk of annoyance (odds ratio [OR] = 4.08) and sleep disturbance (OR = 2.94) as well as increased probability of AHEs ($P < 0.05$) in individuals with greater exposure to wind turbine noise.[78]

Those working in the vicinity of IWTs, including those employed by a turbine company, have reported AHEs that are similar to those described by those living near wind energy facilities,[42,80-86] indicating that IWTs represent a potential occupational health hazard (See Criteria 2: Consistency).

As early as 1985, complaints had been received from about a dozen families living within a 3-km radius of a US DOD/NASA (2 MW) turbine. Under the auspices of the United States Department of Energy and National Aeronautics and Space Administration (NASA), Kelley *et al*. investigated the physical mechanisms and human response/noise complaints and vibrations related to operation of the turbine. Physical measurements of the characteristics of the acoustic emissions, the internal acoustic pressure variations, and other measurements of two of the affected homes were obtained through a series of field surveys. The authors noted that the annoyance reported by nearby residents was attributable to the wind turbine-generated impulsive low-frequency acoustic impulses propagated into the structures in which they lived. Another conclusion of this study was that the threshold levels of emissions measured in a home that caused sensitivities were consistent with documented cases of human annoyance known to be associated with industrial sources of low-frequency noise (LFN)[87] (See also Criteria 6: Plausibility).

In addition to case reports and the formal filing to government of incident reports/complaints by residents, controlled studies have been performed that documented findings of sleep disturbance, noise annoyance, negative effects on quality of life, and other adverse effects with proximity to IWTs. Several of these studies are described below.

- A study by Nissenbaum *et al*. in Maine USA described and compared sleep and general health outcomes between participants living closer to (375 m to 1.4 km, $N = 38$) or farther from (3.3–6.6 km, $N = 41$) IWTs in a stratified cross-sectional study involving two rural sites. Validated questionnaires were used to collect data on sleep quality (Pittsburgh Sleep Quality Index [PSQI]), daytime sleepiness (Epworth Sleepiness Score [ESS]), and general health (SF36V2), together with information on psychiatric disorders, both prescription and nonprescription medications, attitude, and demographics. Analysis of the results indicated that the IWTs negatively impacted sleep and the SF36 mental component scores. Significant dose-response relationships between the SF36, PSQI, ESS and log-distance to the nearest IWTs were identified. There was an increased use of psychotropic medications by those living near IWTs as compared to those who were further away[24] (See below Criteria 5: Biological Gradient, for description of the effect of distance to the IWTs on various health outcome measures).
- Similarly, an Australian study by Thorne (2011, 2012) examined the potential for adverse health due to wind turbines by comparing the WHO quality of life measures, full audible and infrasound measurements, and health/annoyance measures in 23 individuals living between 700 m and 3.5 km from two Australian wind facilities and two from a locale that did not have wind turbine activity. Twenty-one (84%) of the exposed participants reported severe-to-moderate AHE. Thus, the data demonstrated significantly disturbed sleep using the PSQI sleep quality questionnaire in residents exposed to wind turbines. Other AHEs included headaches, noise sensitivity, irritability, anxiety, pressure on eardrums, sinus problems, panic attacks, vertigo/balance problems, erratic/high blood pressure, tightened scalp/forehead, eye strain, and nausea. Nausea attacks were cited as being common, with some residents having to leave their home to sleep away from turbine emissions.[88,89] Those affected by the wind energy facility appeared to fall into two distinct groups: those affected almost as soon as the wind farm started operating and those affected 6–8 months later.

Self-reporting health surveys in Australia, Canada, the Netherlands, New Zealand, the United Kingdom, and the USA have also been conducted. Individuals residing up to 7.5 km from IWTs reported similar AHEs in the different countries, as shown in Table 2.

Table 2 briefly summarizes some of the self-reporting health surveys that have been conducted in various countries.

In collaboration with Statistics Canada, Health Canada conducted a cross-sectional study – one that measures the outcomes and the exposures of the study participants at the same time – and published the results between 2014 and 2018.[76,90-98] Survey data were collected from adults aged 18–79 years (606 males and 632 females) randomly selected from households between 250 m and 11.22 km from operational wind turbines. The study consisted of three primary components: in-person questionnaire administered to randomly selected participants living at varying distances from wind turbine installations; collection of objectively measured outcomes that assess hair cortisol, blood pressure, and sleep quality; and recording wind turbine noise levels at residences. While their analyses indicated that some of the self-reported symptoms commonly described by those living near wind turbines were not related to levels of wind turbine noise, it was also reported that high levels of annoyance toward several wind turbine features, including noise, blinking lights, shadow flicker, visual impacts, and vibrations increased proportionally and significantly with increasing wind turbine noise levels. Overall, however, it was concluded that, beyond annoyance, the data to didnot support an association between exposure to wind turbine noise up to 46 A-weighted decibels (dBA) and the evaluated adverse health-related end points.[94]

Krogh *et al*. reviewed and discussed limitations regarding the methods, findings, and conclusions of the Health

Table 2: Self-reporting health surveys

Author, year (country) [reference]	Subjects participating	Distance from IWTs	Measure	Results
Harry *et al.*, 2007 (UK)[100]	*n*=42 Aged 18 or over	300 m to 2 km	Contacted either by telephone or in writing	The survey results indicated: All were suffering from health-related problems that they felt were caused by their proximity to the turbines 76% had seen a physician about their problems The most common general complaints were fatigue, lack of sleep, headache, stress, and anxiety (incidence approximately 78%, 72%, 70%, 58%, and 51%, respectively); specific events were migraine, depression, tinnitus, hearing loss, and palpitations (incidence approximately 26%, 23%, 21%, 18%, and 16%, respectively)
Van den Berg *et al.*, 2008 (Netherlands)[40]	*n*=725	17 m to 2.1 km wind turbine noise 24-54 dBA	Postal survey, based on that used by Pedersen *et al.* (2005, 2007) Included "perceived health" consisted of the validated GHQ. Annoyance was analyzed in 5 dBA-intervals of sound levels	Participants heard more sound the closer to the turbines they resided: 80% noticed noise at sound levels 40 dBA or higher Of respondents in the 40-45 dBA group, 19% were rather or very annoyed, and 12% were very annoyed Those receiving economic benefits from the turbine installations reported almost no annoyance. When excluding participants benefitting financially, 66% reported being rather or very annoyed, and 28% were very annoyed in the 40-45 dBA group Annoyance from wind turbine sound was related to difficulties with falling asleep and to higher stress scores Respondents (4%-13%) were also annoyed by vibrations, the movement of rotor blades, or their shadows in- or outdoors
Pierpont 2009 (USA)[26]	*n*=38 from 10 affected families Age: Infant to 75 years	305 m-1.5 km	Documented case histories of symptoms pre, during, and post exposure (when away from home) to operating IWTs Adults and older teens completed a detailed clinical interview about their own (and their children's, if applicable) symptoms, sensations, and medical conditions	A pattern of symptoms associated with those living near a wind energy facility was identified. Symptoms included an internal pulsation, quivering, or jitteriness, accompanied by nervousness, anxiety, fear, a compulsion to flee or check the environment for safety, nausea, chest tightness, and tachycardia; headache/migraine; tinnitus, ear popping, pressure, and pain; effects on balance; nausea; motion sickness; sleep disorders; cognitive effects; and mood disorders were also described by participants Families vacated their homes because of the severity of the AHEs. (See below Criteria 4: Temporality for additional details)
Shepherd *et al.*, 2011 (New Zealand)[27]	(i) *n*=39 or (ii) *n*=158	(i) <2 km (ii) Over 8 km	Cross-sectional study A nonequivalent comparison group posttest-only design Questionnaires delivered included the brief version of the WHO QOL scale Participants were also asked to identify annoying noises and to indicate their degree of noise sensitivity	Statistically significant differences were noted in some HRQOL domain scores Those closer to IWTs reported significantly lower overall QOL, physical QOL, and environmental QOL as well as significantly lower sleep quality and self-reported energy levels Study participants who cited wind turbine noise as more annoying also scored lower on sleep satisfaction ratings No differences were found in terms of psychological and social HRQOL, or in self-rated health
Krogh *et al.*, 2011 (Canada)[68]	*n*=109	350 m to 2.4 km	The survey contact flyer was distributed in five areas Survey design, based on that of Harry, was to collect demographics and information on any new AHE and changes to QOL since the start of the IWT projects	"Altered Health" or "Altered QOL" was reported by 102 (93.6%) of respondents; sleep disturbance was reported by 69% >50% reported headaches, tinnitus, and anxiety, and impaired QOL with an apparent inverse correlation between a number of adverse health outcomes and distance to the turbines When the study was expanded to include 170 participants, a similar relationship between AHE and distance from turbines was observed (present study)
Australia (Waterloo Wind Farm) Morris 2012[101]	93 households	Within 10 km	Survey to establish the percentage of people disturbed by noise, shadow flicker or TV/radio interference and the distance from the turbines the occurred	What were perceived to be turbine impacts disturbed 49% of households, including noise, visual flicker or television reception Overall, 39% reported daytime noise disturbance, 40% reported night time noise disturbance, and 29% reported sleep disturbance For those living within 5 km of the turbines, 56% were disturbed by daytime noise, 56% by nighttime noise, and 39% experienced sleep disturbance
Australia (Cullerin Range Wind Farm) Schneider, 2012[181]	100 households	19 were up to 5 km of IWTs, 40 were up to 7.5 km, 41 were 10 km or more away	The study was in response to residents complaining about IWT noise and impacts Hand delivered the same self-reporting survey as that of Morris[101]	Of those households out to 5 km, 85.7% heard noise generated by the IWTs at their residence and property during the day and/or night, and 78.5% reported sleep disturbance from the noise Of the residences out to 7.5 km, 82.4% of households indicated turbine-related noise was present at their residence and property during the day and/or night, and 76% reported sleep disturbance

dBA, A-weighted decibels are an expression of the relative loudness of sounds in air as perceived by the human ear. IWTs: Industrial wind turbines, GHQ: General health questionnaire, AHEs: Adverse health effects, WHO: World Health Organization, QOL: Quality of life, HRQOL: Health-related QOL

Canada cross-sectional study described above. The appraisal supported Health Canada's advisories that its study design did not permit any conclusions about causality and proposed that the identified gaps and limitations should be carefully considered when the results of the Health Canada study are used to predict or protect from health risks of wind turbine noise.[99]

Despite the thousands of records supporting an association of causality, it has been argued by proponents and some regulators that the evidence establishing a causal relationship between exposure to wind turbine noise and sleep disturbance is limited.[75] At the same time, the cited studies and exposure information (such as the high volume of formal incident reports/complaints, the finding of wind turbine noise annoyance, outcomes of field work, and testimony under oath during judicial proceedings) demonstrate an association between exposure to IWTs and AHE.

Criteria 2: Consistency

Compelling information is derived from the consistency of effects as described in published case reports and thousands of adverse event reports of those affected living near IWTs. These effects occur despite the range of international locations and the language spoken in the country in which these events originate. The descriptions of effects reported in different countries are consistent; the common factor is the siting of IWTs near family homes or in occupational settings.[24-27,46,49,70,72,80-89,100-102] Epidemiological studies, reviews, and reports describe proximity to IWTs as being most commonly associated with annoyance/human distress, sleep disorders, headaches, mood disorders, inability to concentrate, tinnitus, and vestibular problems. Some describe effects from nonauditory pathways such as vibratory sensations, heart palpitations, or pressure changes.[15,16,19,26,47,87,89,103] While Poulsen *et al*. found no conclusive evidence of an association between wind turbine noise and myocardial infarction or stroke,[104] it was suggested that indoor low-frequency wind turbine noise at night may trigger cardiovascular events.[103] Some witnesses testifying during hearings have described occurrences of increased blood pressure and palpitations.[16,60]

Research related to occupational workers exposed to IWTs also reveals the occurrence of AHEs consistent with those described by people who are living near IWTs. The following four studies support consistency of findings in different locations.

- At the Manjil wind facility in Iran that has more than 170 IWTs ranging from 0.3 to 0.66 MW, all 53 workers participated in a study by Abbasi *et al.* The impact of wind turbine noise on sleep quality of employees who worked close to wind turbines and exposed to high levels of noise was examined. The authors reported that sleep disturbance increased by 26% per each 1 dB increase in equivalent sound level. They concluded that "this technology has health risks for all those exposed to its sound."[80]
  In the same population of workers, Abbasi *et al.* assessed the noise effect of wind turbine on the general health of staff using the 28-item general health questionnaire. Workers were divided into three groups: maintenance, security, and office staff (*N* = 22, 17, and 14, respectively). Analysis of the results showed that noise exposure up to 83 dBA is statistically significantly correlated to all subscales of general health, except for depression. They concluded that wind turbine noise has negative impacts on the health of directly exposed people. They also indicated that long-term noise exposure was a psychological stressor that can cause mentally abnormal responses and AHE, likely through interactions between the autonomic nervous system, neuroendocrine system, and the immune system period. [81]
- In Massachusetts USA, neighbors living near wind turbines (NOTUS energy) complained for months that they "could not adjust to the fluctuating sound, the endless swish and thumps," and that the noise was "intrusive and disruptive to normal at home activities." Two acoustical consultants who were investigating these complaints reported experiencing similar adverse events that included sleep problems, nausea, dizziness, irritability, headaches, reduced appetite, concentration issues, desire to leave the environment, anxiety, feeling miserable, performing tasks at a reduced pace and a preference for being outdoors rather than indoors. The onset of adverse health symptoms was gradual while near the IWT. Detailed sound measurements taken during the investigation correlated with the negative effects experienced by the consultants. It was determined that dynamically modulated low-frequency and infrasonic energy was produced by NOTUS turbines.[42]
- A case study in the UK documented that while installing acoustical equipment in a home, acoustical consultant Swinbanks experienced a significant sense of lethargy within 3–5 h which progressed to difficulty in concentrating, nausea, and feeling unwell. These symptoms worsened to feeling extremely ill, with the same symptoms as seasickness in a rough sea, including balance and co-ordination completely compromised. Detailed measurements were taken during the time of exposure. The adverse effects were attributed to "be due entirely to wind-turbine infrasound yet manifest under superficially benign conditions where no such adverse effects were anticipated."[86]

Globally, some physicians[15,17,21,26,36,46,72,73,100,105-110] and physician groups and specialists[111-115] have conducted research and/or commented on the potential health risks of siting IWTs near family homes. The descriptions of these symptoms are consistent with the diagnostic criteria described by McMurtry and Krogh.[116]

There is strong evidence supporting consistency of an association between documented AHEs and proximity to IWTs based on incident reports/complaints, case reports, results of clinical studies, testimony during judicial and other proceedings by experts, people living near the turbines, and occupational workers from a variety of countries.

Criteria 3: Specificity

Exposure to a risk factor does not necessarily result in a uniform incidence rate of AHE. For example, not all smokers develop lung cancer. The same is true of AHE resulting from IWTs where a nontrivial percentage, but not all, of the exposed population reports adverse events.[25] Incident reports/complaints can serve as a valuable resource and a form of public health surveillance during the introduction of IWTs – a new noise source – into quiet rural communities.[23] In Ontario, government records obtained by Freedom of Information requests revealed that the environment ministry received more than 5,800 incident reports/complaints associated with IWT-related noise, vibration, and sound pressure for the period between 2006 and 2018. Requests for reports received during 2019 and 2020 remain outstanding.[35] In New Zealand, 906 IWT noise complaints were made to a local council between April 2009 and end of March 2010 by residents who were reporting AHEs period.[118]

The large number of AHE formally reported to governments, the self-published reports on social media and Internet websites, and those collected systematically, such as the WindVOiCe collection from Ontario by Krogh *et al.*, 2011,[68] and the investigations by physicians such as Harry and Pierpont[26,100] indicate that the AHEs associated with IWT exposure go well beyond a few rare individuals who are extremely susceptible.

In 2014, McMurtry and Krogh proposed a case definition and a model for a study to establish a confirmed diagnosis associated with living near IWTs. A detailed inventory of the symptoms commonly reported was provided. It was recommended that a "uniform" approach be used to assist in the patient diagnoses. The report concluded that "If the criteria for probable diagnosis are satisfied and investigation reveals no logical alternative to explain the health effects, a presumed diagnosis of AHE/IWT may be made."[116]

Criteria 4: Temporality

A case-crossover study provides one of the most compelling sources of epidemiologic data. In a study of this type, subjects are exposed to a substance or environmental factor of perceived threat and exhibit symptoms, followed by a reduction of their exposure to that substance or factor and then followed once more by re-exposure. To date, only limited case-crossover safety studies have been performed on exposure to IWTs. Three such studies are described below.

- A case series crossover study by Pierpont in the USA included families from Canada, the United States of America, Ireland/United Kingdom, and Italy. Data documenting health status and medical problems for residents were collected: (1) before exposure to operating wind turbines, (2) during exposure, and (3) when people reduced their exposure to operating wind turbines by leaving their homes or spending a prolonged period away. The study involved 38 people from ten affected families (aged infant to 75 years), living 305 m to 1.5 km from IWTs. Adults and older teens completed a detailed clinical interview about their own and their children's symptoms, sensations, and medical conditions. A clear pattern of symptoms relating to exposure to operating wind turbines was documented. Symptoms developed are described in *Criteria 1: Strength of Association*. Symptoms developed after the turbines started operating near their homes and went away when the subjects temporarily and/or permanently vacated/abandoned their homes. The symptoms returned when the affected people went back to their homes. Eventually, 8 of the 10 families moved away with some abandoning their homes.[26]
- An Australian case series crossover study was conducted and reported by Hansen *et al*. Hansen *et al*. documented symptoms correlating with the intermittent shut down of turbines. Full spectrum acoustic monitoring was conducted at six locations at distances from 1.3 km to 7.6 km from the Waterloo Wind Energy facility. The study compared the effects on the residents when the wind turbines were operating, then not operating for a week, and then when again operating. The authors documented symptoms in the residents that correlated with the intermittent shut down of the turbines. The acoustic survey report confirmed that sleep disturbance correlated with exposure to wind turbines at a distance of up to 8 km. The range in the overall A-weighted levels was noticeably larger indoors and ranged from 5 dB(A) to 38 dB(A). There was a direct correlation between LFN events and complaints registered in noise diaries. The Danish LFN guidelines were exceeded on a number of occasions, generally in downwind conditions and when hub height wind speeds were greater than 8 m/s. Based on these observations, the authors concluded that "there is a LFN problem associated with the Waterloo wind farm."[119]

A comprehensive acoustic survey was conducted at the Cape Bridgewater Wind Development in Australia by Cooper, an independent acoustical consultant, with The Acoustic Group (2014), where turbines were temporarily shut off and on. The study was commissioned by the wind energy developer to address several years of noise complaints received since the project was put in service in 2008. Tests, including measuring noise emissions, were performed inside three homes (6 occupants) located between 650 m and 1.6 km of the wind facility over 8 weeks. At the end of the 2nd week of the test program, the wind turbines were shut down daily for 10–12 h per day for 2 weeks. Residents were asked to record in a diary perceived impacts of noise, vibration, and other disturbances, on a 1–2 hourly basis. The study did not include any testing in relation to sleep disturbance. The results obtained showed a trend toward an association between the high-level "Sensations" disturbance and the operating power of the turbines. Sensation measured included headache, pressure in head, ears, or chest, ringing in ears, heart racing, or a sensation of heaviness. Participants recorded a significant sensation disturbance occurring when the turbines were about to start up, with a change in power output of 20%, and when the turbine had reached maximum power. No correlation of sensation disturbance with the dB(A) noise levels or impacts that residents identified as coming from the turbines was detected, indicating that emissions outside the hearing range were likely causing the sensations.[47]

In addition, before and after impact studies have reported that residents were symptom free before the start-up of an adjacent wind turbine project, and developed symptoms subsequent to the onset of wind turbine operation.[26,69,70]

Another means of assessing a temporal impact is to document a significant change in owner's use of a property pre- and post-IWT installation, for example, their choice to vacate a property.

- A Canadian study by Krogh et al. explored the events that influenced families who were living or had lived within 10 km from wind energy facilities to contemplate or actually vacate/abandon their homes. The study used a qualitative, grounded theory methodology and audio recorded interviews. All 67 individuals associated occurrences of AHE, or the potential occurrence for such effects, with IWTs. Of the 67 interviewees, 28 had permanently vacated/abandoned their home, 31 were contemplating to do so, 4 pre-emptively left before the initiation of the IWT operations, and 4 intended to remain in their homes. With respect to that last category, two intended to remain in their home unless adverse effects occurred; and the other two expressed a preference to live in a rural environment. Before permanently vacating their homes, 24 of the 28 study participants had temporarily and intermittently left their homes during the day and/or night to alleviate AHE. At the time of the interviews, 12 of the 31 participants considering permanently vacating their homes were also temporarily and intermittently leaving during the day and/or night for similar reasons. Overall, of the 67 interviewees, a total of 36 reported taking these steps to obtain temporary and/or partial relief from AHE.[69-71]

Reports of adverse effects on animals located near IWTs indicate that there may be a temporal relationship between proximity to wind turbines and stress-related reactions and adverse effects on fertility, development, and reproduction. AHEs in animals that have been attributed to proximity of IWTs include reproduction and teratogenic effects in the USA,[120,121] Canada,[122,123] Denmark,[124] and Japan;[125] deformities in Portugal;[65] mortalities in Canada, France,[126-129] and Taiwan;[130,131] stress in the UK;[132] and other effects[133] [Appendix 1 for further details].

In summary, both examination of effects of IWTs when intermittently shutdown and pre- and post-exposure in humans and animals indicate a temporal relationship between exposure to IWTs and AHEs.

Criteria 5: Biological gradient (dose–response effect)

The process of quantitatively assessing the dose received and response by a biological entity produces a dose–response relationship. This is recognized as an important part of the process in assessing health risk associated with exposure to various contaminants in the environment.[134] A correlation has been documented between distance to IWTs and/or the associated noise energy and reported AHE. Below, five studies are described: Four examined the association between AHE and noise levels, followed by one examining the effect of distance.

- To evaluate the prevalence of annoyance due to wind turbine noise and to investigate a dose–response relationship, a cross-sectional study was conducted in Sweden by Pedersen and Persson Waye. Respondents (N = 351; response rate 68.4%) from five areas totaling 22 km^2 were exposed to a total of 16 turbines. Doses were calculated as A-weighted sound pressure levels (SPLs) for each respondent's dwelling. Subjective responses were obtained through questionnaires delivered at each household and collected a week later. Interrelationships were assessed between noise annoyance and sound characteristics, as well as the influence of subjective variables such as attitude and noise sensitivity. A statistically significant dose–response relationship was found between A-weighted SPLs and levels of annoyance. A higher proportion of people reported annoyance than expected from the dose–response relationships for transportation noise. Sound exposure was also related to sleep disturbance and psychological distress among those who reported that they could hear the sound. Individuals living in an area with a sound level of 45 dBA reported three times more sleep disturbance than those living in an area with noise levels of less than 30 dBA, establishing a correlation between noise level and annoyance. In addition, 23% were slightly, rather or very annoyed while outdoors. It was suggested that some of the additional annoyance might have been due to the sound characteristics and visual interference related to the IWTs.[102]

- Bakker *et al*. conducted another cross-sectional study in seven areas of Sweden located in the vicinity of IWTs with dissimilar terrain and different degrees of urbanization. Data regarding living conditions including response to wind turbine noise were gathered from questionnaires that were sent by mail and completed by 754 subjects. These data were complemented by the determination of outdoor A-weighted SPLs which were calculated for each respondent. Perception and annoyance attributed to wind turbine noise in relation to sound pressure levels were analyzed with respect to physical dissimilarities in the areas. The study revealed a dose–response relationship between emission levels of wind turbine sound and self-reported noise annoyance. That is, as sound emissions increased, so did the noise annoyance reported.[135]
- A socio-acoustic survey was carried out by Yano *et al*., 2013 throughout Japan over a 3-year period. Noise and annoyance were examined to obtain a baseline for a wind turbine noise policy. The study involved 36 sites with turbines and 16 control sites away from turbines, with a sample size between 3 and 42 subjects per site. In total, 747 and 332 subjects at turbine sites and nonturbine sites, respectively, were surveyed; the response rates were 49% and 45% for the two sites, respectively. Face-to-face interviews were performed, with annoyance evaluated by ICBEN 5-point verbal scale. The wind turbine noise was measured at several points in each site for successive 5 days with the average SPL at regular turbine operation during the nighttime taken as noise exposure. In total, 651 noise exposures at residences were recorded, ranging from 26 to 50 dB. Analysis based on all data demonstrated a correlation between noise and annoyance a period.[136]
- A dose/response relationship of AHE with noise was also confirmed in Ontario by Palmer, 2020. Two families who lived near an array of 140 IWTs and had experienced AHEs for 5 years, collected data by two independent methods: the first a continuously recording system, and the second by triggering audio recordings while experiencing annoyance. The recorded data were analyzed to ascertain any correlation of AHE with wind turbine operational performance, and for tonality, Analysis of the sound files confirmed high correlation between times the residents described as tonal and the presence of tonality by a graphical method of comparing the tonal peak to the magnitude of the sound outside the critical bandwidth centered on the tonal peak. There was a correlation of over 84% between complaints and tonality from 5 dB to over 20 dB. This tonal condition was described by the residents as irritating and annoying, resulting in loss of sleep and in loss of enjoyment of normal use of their property.[137]
- A stratified cross-sectional study by Nissenbaum *et al*. was performed in the USA to compare sleep and general health outcomes of participants living close to IWTs with those living further away from them. As described in *Criteria 1: Strength of Association*, enrolled participants lived between 375 m and 1.4 km ($N = 38$) and 3.3 km and 6.6 km ($N = 41$) from IWTs. Validated questionnaires were used to collect information on sleep quality (PSQI), daytime sleepiness (ESS), and general health (SF36v2), together with psychiatric disorders, attitude, and demographics. Descriptive and multivariate analyses were performed to determine if the distance to the nearest IWT had any effects on various health outcome measures. Analyses showed that participants living within 1.4 km of an IWT had worse sleep, were sleepier during the day, and had worse SF36 mental component scores compared to those living further than 1.4 km away. Significant dose–response relationships between PSQI, ESS, SF36 mental component score, and the log distance to the nearest IWT were identified after controlling for gender, age, and household clustering.[24]

Taken together, the above studies demonstrate that dose–response relationships exist between exposure to IWTs and AHEs, as determined either with "dose" calculated as the distance to the turbines or SPLs. The responses (i.e., the AHEs) observed include annoyance, effects on sleep, and effects on mental health score. It is of importance to note that noise annoyance, including that associated with operational IWTs, has been acknowledged as a health/AHE by Health Canada (2005), quoting the WHO and by others.[37,39,44,138,139]

Criteria 6: Plausibility

Research, incident reports/complaints, and reports by people living near IWTs indicate that wind turbines impact people's senses, resulting in adverse health symptoms. There may be more than one factor contributing to the effects. Evidence suggests that a plausible mechanism involves responses to audible and inaudible noise, including infrasound and LFN. In addition, evidence is emerging indicating that EMF and RF energy[16,22,36,38,140] and shadow flicker[76,88,101] contribute to turbine-associated AHE.

The precise noise and vibration frequencies which are causing the reported symptoms in people near IWTs are not fully elucidated. Indeed, the safe exposure cumulative dose (short and long term) of noise and vibration frequencies has not yet been defined for any age group.

The general physiological effects of LFN/infrasound are illustrated in the following study summaries.

- In an investigation of the physiological and psychological effects of infrasound by Qibai and Shi, ten students were exposed to infrasound below the audible perception threshold (2.14 Hz 110 dB and 4.1 Hz 1200 dB). After 1 h, students experienced physiological changes (blood pressure elevation and increase in heart rate) and symptoms such as nausea, tiredness, headache, and fretfulness. Although these levels were well above those emitted by IWTs, the study demonstrated that even short-term exposure to inaudible infrasound can cause AHEs, and that perception thresholds of infrasound are not necessarily the most relevant measure.[141]
- Alvez-Pereira *et al*.[41,142] summarized studies that investigated the impact of infrasonic emissions, selecting those that focused on the cellular and tissue changes observed in laboratory, occupational, and residential settings, using light and electron microscopy. Most of the studies were concerned with occupational exposures to infrasound and did not consider continuous exposures at less than 90 dB. Collectively, the data indicated that exposure to infrasound could result in widespread vascular changes and changes to organs of the reproductive and auditory systems. The authors concluded that exposure to infrasonic and lower frequency airborne pressure waves can cause damage to a variety of cell and tissue types depending on frequency, dB level, and length of time of exposure.

There is evidence that exposure to the infrasound component of wind turbine noise can influence the physiology of the ear.

- An analysis by Salt and Hullar showed that, although hearing perception mediated by the inner hair cells of the cochlea is insensitive to infrasound, other sensory cells or structures in the inner ear such as the outer hair cells are more sensitive and can be stimulated by low frequency sounds at levels below those that are audible.[143]

Such changes in the vestibular system could potentially contribute to some turbine-related AHE. Dysfunctions in the vestibular system can cause disequilibrium, nausea, vertigo, anxiety, and panic attacks. These symptoms have been reported in individuals located near IWT facilities, and those with highest risk factors for the symptoms include having a pre-existing problem with inner ear pathology.[26]

As noted previously, evidence that IWTs produce perceptible levels of infrasound as well as audible LFN above 20 Hz has been available since the 1980s.[45,87,144] Moreover, contemporary wind turbines have markedly increased in size, power output, and emissions from earlier models. An analysis of 48 wind turbines by Møller and Pedersen determined that the relative amount of LFN emission is significantly higher for large turbines (2.3–3.6 MW) than for small turbines (≤2 MW).[145] Van den Berg *et al*., 2008 commented, "There is increasing evidence that the local impact of wind turbines may be more negative than expected. The experience gained in the 1980s and 1990s may not apply to the tall, modern onshore wind turbines with peak electric power outputs up to 3 MW and tower heights of 80–100 m."[40]

Two studies that examined the effects of exposure to the infrasound component of wind turbine noise on complaints and AHE are described.

- In 1985, complaints had been received from about a dozen families living within a 3-km radius of a 2 MW wind turbine. Under the auspices of NASA, Kelley *et al*. investigated the possible physical mechanisms responsible for the generation, propagation, and human response/noise complaints and vibrations related to the DOE/NASA MOD-l (2 MW) turbine. Through a series of field surveys, physical measurements documented the characteristics of the following: acoustic emissions, the vertical structure of the atmospheric velocity and thermal fields controlling the sound propagation, and the internal acoustic pressure variations and structural vibrations of two of the affected homes. The results indicated that the reported annoyance was caused from impulsive infrasound and LFN generated by the single wind turbine. Noise propagated both upwind and downwind caused complaints. The authors concluded that the sensitivity of threshold levels measured in a home was consistent with documented cases of human annoyance known to be associated with industrial sources of LFN[87] (See Criteria 1: Strength of Association for discussion of the AHE).

- Evidence of the role of infrasound at frequencies between 0 and 10 Hz in causing symptoms such as nausea and headaches was shown in an acoustic survey of LFN and infrasound at the Shirley wind project in Wisconsin, USA.[43,146] Four independent firms of acousticians including those working for wind developers and those working for sick residents authored a common report. The acousticians met with residents reporting problems with the wind turbine acoustic emissions, including members of three families who had abandoned their homes. They reported that (i) at most locations where symptoms occurred, the wind turbines were generally not audible; (ii) some residents reported that they could sense when the turbines were turned on and off without hearing or seeing the turbines; and (iii) the residents who reported motion sickness-like symptoms as major adverse effects associated with the wind turbines were also sensitive to motion sickness. The authors concluded that to induce major effects, the noise source must be at a very low frequency, approximately 0.8 Hz or below, with maximum effects at approximately 0.2 Hz. Moreover, they suggested that as the same organs in the inner ear, the otoliths, may be central to the two similar symptoms (motion sickness and turbine-induced nausea), the wind turbine acoustic emissions may induce motion sickness in those prone to this condition. The authors concluded with their opinion that LFN and infrasound from turbines could be a sufficiently serious issue to pose a threat to the industry.[43]

International reviews of studies involving LFN reveal that some of the symptoms described by complainants associated with IWT noise are similar to those caused by LFN. The literature indicates that it has been known for decades that LFN and/or infrasound in general[147,148], including that produced by wind turbines, can result in noise annoyance and other AHEs.[45,144,149,150]

The vast majority of studies of sound from wind turbines do not accurately measure the presence of LFN or infrasound.[99] This failure of public health authorities and governments to monitor the impact of LFN and infrasound on exposed individuals impedes the proper interpretation of results and is not consistent with the WHO report "Guidelines for Community Noise" that states: "When prominent low-frequency components are present, noise measures based on A-weighting are inappropriate" and "It should be noted that a large proportion of low-frequency components in noise may increase considerably the adverse effects on health."[1]

See also Criteria 8: Experimental Evidence for further evidence that those exposed to infrasound display adverse events similar to those experienced by those near IWTs.

Criteria 7: Coherence

In describing his criteria for causality, Bradford Hill noted that "... lack of such [laboratory] evidence cannot nullify the epidemiological effect on associations."[2] However, as described above, in experiments during which people were exposed to infrasound, similar symptoms are reported by those living and working near turbines.

Although low-frequency hearing sensitivity depends on many factors including the mechanical properties of the middle ear, it is known to be correlated with cochlear length for many species with nonspecialized cochleae, including humans and guinea pigs.[143,151,152] The thresholds of guinea pig hearing have been measured with stimulus frequencies as low as 50 Hz; the average sensitivity recorded in four studies at 125 Hz was SPL of 37.9 dB, which is 17.6 dB less sensitive than the sensitivity of humans at the same frequency and is consistent with the shorter cochlea of guinea pigs. It is therefore reasonable to assume that if responses are present in the guinea pig at a specified level of low-frequency sound, then they will be present in the human at a similar or lower stimulus level. Thus, the guinea pig may represent a valid experimental model which is likely to under-estimate the effect in humans.

Haneke *et al*., of the U.S. National Institute of Environmental Health Sciences, summarized studies identified in the literature where humans or various species of animals (rats, mice, guinea pigs, and chinchillas) had been exposed to infrasound in the laboratory. Most studies reported some health effects attributed to infrasound exposure, including stress response. Generally, the doses of infrasound were higher but of much shorter duration than the limited data sets of full spectrum acoustic measurements inside and outside homes at existing wind developments. The report identified that there are significant knowledge gaps with respect to chronic exposure to infrasound and low-frequency sound at lower "doses." Although the authors did not comment on IWTs, they did note that many of the human subjects exposed to infrasound reported the same AHEs = fatigue, sleeplessness, nausea, and heart disorders = that afflict those living near wind turbines.[150]

Consistent with AHEs being reported several kilometers from IWTs, Schofield measured vibration signals at the Stateline wind farm in Oregon (US) that consisted of 399 wind turbines, each with a rated power of 0.66 MW. The study found that the propagation of a 4.3 Hz vibration signal was measurable at distances up to approximately 18 km from the turbines.[153] Escaler and Mebarki demonstrated that vibrations measured in full-scale wind turbines were highest at less than 1 Hz.[154]

Criteria 8: Experimental Evidence

While large-scale controlled clinical studies have not been performed, there is increasing evidence that the adverse events reported by those living at least 10 km from IWTs could in part be the result of infrasound emitted by the turbines. In experiments where people have been exposed to infrasound, similar symptoms are reported as by those living and those working near turbines.

Three clinical studies investigating adverse effects of IWTs are described below.

- A study by Ambrose *et al.*,[42] known as the Bruce McPherson infrasound and LFN study,[82] was commissioned to investigate and confirm or deny the presence of infrasonic and LFN emissions at a home, to determine why there were so many strong complaints about the loss of well-being and hardships experienced by people living near large IWTs operating in Falmouth, Massachusetts. The investigators experienced the same symptoms described by those living at this location and living at other large IWT sites, such as dysfunctions in the vestibular system/balance, nausea, vertigo, anxiety, and panic attacks. Sleep was disturbed during the study when the wind turbine operated with hub height wind speeds above 10 m/s. The onset of AHEs was within 20 min and persisted for some time after leaving the study area. It took about a week to recover from the AHEs experienced during the study, with lingering recurring nausea and vertigo for almost 7 weeks for one of the investigators. Measurements of dBA, dBC, and dBG were made. dBA is most commonly used for environmental noise measurement and has emphasis on noise with frequencies over 60 Hz; dBC measures have less attenuation of LFN; and dBG measures frequency range up to 315 Hz with emphasis on noise below 20 Hz (low-frequency and infrasound). The dBA and dBC levels and modulations did not correlate to the health effects experienced; the strength and modulation of the un-weighted and dBG-weighted levels increased indoors consistent with worsened health effects experienced indoors. The dBG-weighted level appeared to be controlled by in-flow turbulence and exceeded physiological thresholds for response to low-frequency and infrasonic acoustic energy. Health effects moderated when dBG levels fell well below the 60 dBG guideline when the wind turbine was off. This study revealed that people can experience, within a few minutes, the same debilitating health effects described and testified to by neighbors living near the wind turbines, even when they do not have a pre-existing sleep deprivation condition and are neither tied to the location nor invested in the property. This was not seen in other studies as A-weighting and sound-level averaging do not reveal this low-frequency information period.
- A small acoustic survey was initiated by Pacific Hydro, conducted at its Cape Bridgewater Wind Development in Australia.[47] Six occupants of three households located between 650 m and 1,600 m of the wind facility were surveyed over 8 weeks. This included a 2-week shutdown of the turbines. No audible infrasound was found in any of the houses when 85 dB(G) was taken as the hearing threshold of infrasound. The residents suffered from sleep disturbance, headache, ear pressure, tinnitus, and elevated pulse rate. The onset of most symptoms correlated with changes in the turbine output power. There was a positive correlation between the power level of wind turbines and the dB(A) LF level determined inside residential dwellings. There was no correlation with the dB(A) noise levels or impacts that residents identified as coming from the turbines (See Criteria 4: Temporality for study details).
- In a Japanese study by Inagaki and Nishi (2015), aerodynamic noise generated from a modern large-scale wind turbine (including the infrasound with extremely low-frequency band) was measured and analyzed. To verify the physiological impact of such amplitude modulation, 15 healthy adults aged 21–24 years received various sound stimuli, including the recorded aerodynamic noise and a synthetic periodical sound, and brain waves were examined with an electroencephalography. The authors found that the study subjects generally could not be relaxed or concentrate when listening to the infrasound noise and that "infrasound (e.g., low frequency and inaudible for human hearing) would be considered to be an annoyance to any technicians who work in proximity to a modern large-scale wind turbine."[83]
- Verzini *et al.* conducted a study of health effects of low-frequency sound using a pressure chamber in Argentina. Twenty-two college students (18–25 years) performed the same tasks in three randomized

experimental conditions, with a 1-week interval between experiments. Test conditions were 30 min exposure to either 110 dB tone, a boiler noise filtered in 1/3 octave band centered on 10 Hz at 105 dB, or no sound stimulus. There were significant increases in anxiety measures in the 110 dB tone group and an increase in body vibration (especially head, ears, and neck) and annoyance. The boiler group experienced similar sensations. There were no significant differences in physiological variables between the control or test groups.[155]

Additional examples of clinical studies are included in Appendix 2. They include examination of effects of noise with the acoustical characteristics of wind turbine noise on sleep disturbance,[156,157] annoyance,[158] and other AHE.[159,160] Some studies found no association with complaints and proximity to wind turbines. For example, a Polish study by Mroczek *et al.* found that proximity of wind farms did not result in the worsening of the quality of life using the Norwegian version of the SF-36 general health questionnaire and the visual analog scale. The authors commented that the results may indicate the influence of other contributors such as economic factors that were not taken into consideration during the analysis.[161]

There is experimental evidence that exposure to LFN/infrasound can lead to adverse events in animals as well as in people. Animal studies have demonstrated serious health effects from proximity to IWTs: geese,[162] pigs;[163] LFN: chick embryo;[164] and high-frequency vibration: rats[165] [Appendix 2 for additional AHE in animals and details].

There is clear experimental evidence that exposure to IWTs cause adverse events in animals and people. LFN/infrasound such as that emitted by IWTs can lead to adverse events similar to those reported by people living near IWTs. This suggests that the infrasound emitted by turbines contributes toward the adverse events reports by those living within 10 km or more of IWTs.

Criteria 9: Analogous evidence

Stimuli that are not perceived by the senses, such as ionizing radiation and carbon monoxide, can be pathogenic. The claim that noise must be audible to be considered significant is not a defensible conclusion by analogy or by virtue of the literature on LFN, infrasound, vibration, and other potential contributors. AHEs reported in people living and working near IWTs, the effects on animals, and the correlation between LFN and effects when turbines are turned off and on (described above) reveal an association between AHEs and IWTs.

DISCUSSION

The BH criteria represent an important tool for determining cause between an environmental exposure and a health outcome (i.e., disease or disability) in a scientifically rigorous manner. The criteria are far more stringent than the Precautionary Principle, which the WHO (1999) provides as the environmental management principles on which government policies, including noise management policies, can be based.[1] The WHO document states that: "When there is a reasonable possibility that the public health will be endangered, even though scientific proof may be lacking, action should be taken to protect the public health, without awaiting the full scientific proof."[1]

The application of the stringent BH criteria gives compelling evidence that IWTs cause significant health problems in a nontrivial fraction of residents living and working near them. Despite the resources available to Health Canada for the Wind Turbine Noise and Health study, the public was advised that the study would not determine causality. At the same time, the Erickson v. MOE ERT decision states: "*This case has successfully shown that the debate should not be simplified to one about whether wind turbines can cause harm to humans. The evidence presented to the Tribunal demonstrates that they can, if facilities are placed too close to residents. The debate has now evolved to one of degree.*"[44] And the results of a review commissioned by the Ministry of Environment in Ontario, Canada stated that the audible sound from wind turbines is expected to result in a nontrivial percentage of persons being highly annoyed, and that the annoyance can be expected to contribute to stress-related health impacts.[117] Global research published in peer reviewed journals and conference papers, reports from exposed neighbors, case reports, government hearings, testimony during various judicial and other proceedings, and the almost 6,000 incident reports/complaints documented by the Ontario Ministry of the Environment support the determination of causality. These findings have been repeatedly observed by different persons, in different places, and under different circumstances and times. The thousands of adverse event reports by residents, alone, provide strong evidence for a causal relationship and acknowledgment of the seriousness of the problems. It has been argued that the adverse event reports are under-appreciated as a source of evidence and are more compelling than the formal studies because of the following: sheer volume, the similarity of health problems across reports and countries, the fact that individuals are capable of recognizing both the exposure and outcomes, and the fact that relief occurs upon relocating or when staying somewhere other than the subject's own home.[25,26,69-71,166] The reports are consistent with controlled studies and other systematically-gathered data. Many of the published adverse event reports include those with rigorously documented case crossover observations and experiments. These factors move the collective evidence beyond plausible doubt.

Most reports describe a core list of symptoms, such as those observed by Harry, 2007 and Pierpont, 2009.[26,100] The range of symptoms commonly reported by individuals is consistent globally, and includes sleep disorders, headaches, mood disorders, inability to concentrate, tinnitus, effects on vestibular (balance) and heart, and vibratory sensations. In some cases, there is variable expression and latency of symptoms in different people. A number of plausible causes have been proposed such as amplitude modulation; lack of night time abatement; audible LFN; inaudible LFN/infrasound; tonal noise; electrical pollution/stray voltage; and visual impacts such as shadow flicker and flashing lights.

People with vestibular sensitivities may have a predisposition to AHE, but the effects go beyond a few rare individuals who are extremely susceptible.

Neither the frequency of events nor the safe distance from turbines can be defined with certainty. Case reports are not all publically available and typically do not provide information regarding how many people experienced events but did not report them. Studies indicate that serious health effects occur in between 5% and 10%[118,167] and up to 20% of exposed individuals.[168] Most studies report an even greater number of individuals suffer from the health effects of noise annoyance and sleep disturbance. Typically, there is an increase in the number of incident reports from those living nearer to the IWTs.

Although some may consider annoyance insignificant, an increased health risk from chronic noise annoyance has been acknowledged as a health/AHE.[39,138,169] The Superior Health Council of Belgium 2013 commented that annoyance and disturbed sleep can lead to "undue stress, which may adversely affect the health and well-being of those concerned."[115] WHO-related research acknowledged an increased health risk from chronic noise annoyance: The LARES study states that a central effect of noise is annoyance and concluded that the result "confirms the thesis that for chronically strong annoyance a causal chain exists between the three steps: health-strong annoyance-increased morbidity."[170] LARES also concluded that the "results of the LARES study – with regard to criteria for causal relations – confirmed, on an epidemiological level, an increased health risk from chronic noise annoyance."[171]

The WHO states "Noise is an underestimated threat that can cause a number of short-and long-term health problems."[172] Among these problems are "sleep disturbance, cardiovascular effects, poorer work or school performance, hearing impairment including tinnitus, aberrations in social behavior such as aggressiveness and passivity, pain and hearing fatigue, speech problems, and hormonal responses (stress hormones) and their consequences on human metabolism, and immune system problems".[172,173] These effects are similar to those reported by those living near wind turbines. The WHO also cites sleep disturbance from environmental noise at 40 dBA as having health impacts.[117]

The placement of IWTs near family homes and noise compliance monitoring is typically based on predictive noise modeling measured in dBA.[99,175,176] The WHO indicates that the "yearly average of night noise level outside at the façade" can be used as a noise indicator,[174] resulting in peak levels not being measured. In some cases, even the average sound levels are exceeded at some residences located near IWTs. The use of dBA does not include low-frequency audible noise (20–200 Hz) and inaudible infrasound (0–20 Hz) emitted by IWTs, yet wind turbines were known to emit lower frequency sound and vibration energy decades ago.[176-178] LFN has been shown to cause physiological effects (e.g., to the cochleo-vestibular system in animals). In 2004, LFN was reported as a recognized "special environmental noise problem," especially for sensitive people residing in their homes, and that the A-weighted level is very inadequate in that it underestimates annoyance for frequencies below about 200 Hz.[147] There is evidence that wind turbines generate low-frequency sound and vibration energy, resulting in reports of the occurrence of adverse effects.[42,43,45,82,89,106,175] More recently, Basner *et al.* emphasized that "non-auditory health effects of environmental noise are manifold, serious and, because of the widespread exposure, very prevalent," and commented that noise levels from different noise sources cannot be merged into one indicator of decibels.[179] Cooper explained the variation in identified audible noise when wind turbines are operating, which was found to be a modulation of the amplitude occurring at a blade pass frequency. An amplitude modulated signal is associated with the output speed of the gearbox being modulated at the blade pass frequency. The level of the true amplitude modulation does not affect the overall A-weighted level so is not generally measured; the modulation is related to LFN.[182]

As reliance on dBA lacks measurements of the variable IWT-audible/inaudible tonal and amplitude modulation noise emissions, there is a lack of consideration of risks of sleep disturbance and AHE in sensitive individuals. As concluded by Pedersen and Waye, there is a need to consider the unique environment when planning a new IWT project in order to avoid AHE.[39] This includes effects of emissions from off-shore turbines, as LFN is readily propagated above water and through it.

To date, no large-scale epidemiological studies have focused on the health effects of long-term exposure to infrasound and LFN produced specifically by wind turbines. To strengthen the understanding of the health effects and validate our conclusions of causation, long-term studies are required that are performed in the field using actual-non-averaged-audible and inaudible noise levels, as well as EMF/RF energy. Ideally, these should be large-scale, controlled, and blinded "on–off" studies involving all age groups. Measurement of LFN, EMF, and other potential emissions out to a distance that exceeds the travel of those emissions would aid in determining the cause of the effects.

CONCLUSION

Incontrovertible proof of causation has tended to be an elusive goal. The debate of determining causality associated with placing IWTs near family homes is similar to past controversies around the debate of causality from the use of tobacco products and from worker exposures to asbestos and coal. The "best available evidence" is the current standard, and it is our contention that the Bradford Hill criteria are that standard.

Based on our analysis of clinical, biological, and experimental evidence and its concordance with the nine BH criteria, we conclude that there is a high probability that emissions from IWTs, including infrasound and LFN, result in serious harm to health in susceptible individuals living and/or working in their proximity. These effects can be attributed to IWT-related events such as recurring sleep disturbance, anxiety and stress, and likely others.

With the growing weight of evidence indicating this causation and the rapid proliferation of IWT installations globally, preventative actions should be taken, and policies implemented that are more cautiously protective of public health, safety, and welfare rather than wait for absolute certainty. More stringent regulation is needed to recognize, monitor, analyze, and document effects on the health of local residents and animals. Of concern is the lack of determination of the safe exposure cumulative dose of noise, including LFN and infrasound, for adults, the elderly, and particularly for fetuses and young children. There are no evidence-based guidelines for setbacks of IWT; rather regulations have a wide variance across jurisdictions. The concern is compounded by the lack of centralized vigilance monitoring for those who have constant, long-term exposure while living in their homes. Our findings provide compelling evidence that there is a pressing need for risk assessment before deployment of IWT into rural community settings that consider more effective and precautionary setback distances. A margin of safety sufficient to prevent pathogenic LFN from being detected by the human vestibular system is paramount before proceeding with political or economic policies.

As written by Hill: "All scientific work is incomplete—whether it be observations or experimental. All scientific work is liable to be upset or modified by advancing knowledge. That does not confer upon us a freedom to ignore the knowledge we already have, or to postpone the action that it appears to demand at a given time."[2]

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Conflicts of interest

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APPENDIXES

Appendix 1: Reports of adverse effects on animals

Reported AHE of animals located near IWTs include the following:

- Disturbances in animal reproduction have been reported related to wind energy facilities in Wisconsin (USA).[120,121] Reported abnormalities include teratogenic effects in cattle (missing eyes and tails); health, teratogenic and reproduction problems in a formerly award-winning herd of cattle (cancer deaths, cows not calving properly, mutations such as absent eyeballs or tails, cows holding pregnancy only 1–2 weeks and then aborting, blood from nostrils); as well as teratogenic effects in chickens (crossed beaks, missing eyeballs, deformities of the skull, joints of feet/legs bent at odd angles)
- Farmers near a wind turbine development near Goderich, Ontario, Canada, observed health problems with their livestock which began shortly after the wind turbines were installed.[122] The cattle were reported to exhibit unusually aggressive and erratic behavior, "including the kicking of newborn calves, prolapsed birthing, weight loss, decline in fertility, a high incidence of mastitis, calves being deformed at birth, and a high incidence of stillbirths"
- Similar adverse health effects and excess mortalities in various animal species have been reported that were temporally coincidental with the installation of industrial wind turbines and associated generating stations, that include the following:
  - Cows: Reduced fertility (Canada);[123] fertility and structural issues (Japan);[125] and mortality (France)[127-129]
  - Goats: Reduced fertility and health problems (Canada)[123] and mortalities in 450 of 700 (Taiwan)[130,131]
  - Horses: Leg deformities (Portugal)[106]
  - Emu: Mortalities in 30 of 38 and reduced laying (Canada)[126]
  - Mink: 1600 miscarriages and birth defects (Denmark)[124]
  - Badgers: High cortisol levels, an indicator of stress (UK)[132]
  - Other effects.[133]

Appendix 2: Experimental evidence: Clinical studies associated with industrial wind turbines

Additional clinical studies

A study conducted by Smith *et al*.[156,157] examined the potential for nocturnal noise with the acoustical characteristics of wind turbine noise to contribute toward sleep disturbance (Wind Turbine Noise Effects on Sleep). Six young, healthy individuals spent five nights in a sound exposure laboratory. During the final three nights of the study, the participants were exposed to synthesized wind turbine noise, which was based on analysis of field measurements. Exposures involved periods of different amplitude modulation strengths, the presence or absence of beats, different blade rotational periods, and outdoor L_{Aeq}, 8 h = 45 or 50 dB with indoor levels based on the windows being fully closed or slightly open. Physiological measurements indicate that nights with low-frequency band amplitude modulation impacted sleep the most. The amplitude modulation and the presence of beating contributed to sleep disruption, reflected by more electrophysiological awakenings, increased light sleep and wakefulness and reduced random eye movement and deep sleep.

A study was performed by Pawlaczyk-Luszczynska *et al*., 2010 to investigate the annoyance of low-frequency noise (LFN) at levels normally at workplaces in control rooms and office-like areas.[158] Two different laboratory experiments were carried out: (1) included 55 young volunteers; (2) 70 older volunteers categorized in terms of sensitivity to noise. The subjects listened to noise samples with different spectra, including LFNs at sound pressure level (SPL) of 45–67 dBA, and evaluated annoyance using a 100-score graphical rating scale. The subjective ratings of annoyance were compared to different noise metrics. Results showed a significant influence of individual sensitivity to noise on annoyance rating for some LFNs, with no age-related difference. Generally, over half of the subjects were predicted to be highly annoyed by LFN. Low-frequency A-weighted SPL (L (LFAeq, T)) and C-weighted SPL (L (Ceq, T)) seemed to be reliable predictors of annoyance exclusively from LFN. Note that although noise limits for turbines are often regulated to be no more than an average of 40 dBA, there are fluctuations well above the level in this study.

In a U.K. experiment involving the National Physical Laboratory, back-to-back music concerts were staged in London's Purcell Hall.[159] The concerts were similar in all respects except that two different musical pieces in each concert were laced with infrasound. While hearing the infrasound-laced pieces, audience members reported significantly elevated sensations of nausea, dizziness, increased heart rates, and tingling in the neck and shoulders, among other sensations.

Effects of high-level LFN were examined by Takahashi *et al*. through measurement of human body surface vibrations at the chest and the abdomen, induced by high-level low-frequency pure tones. The subject rated the unpleasantness perceived during the exposure. Results revealed that the unpleasantness correlated closely with the vibration acceleration level of the vibration measured. The vibration acceleration level was not related to the loudness; the A-weighted SPL was not related to the vibration. It was concluded that the effects of vibration should be considered when evaluating the effects of LFN.[180]

A study by Weichenberger *et al*. investigated the brain's response toward near- and supra-threshold infrasound stimulation (sound frequency <20 Hz) under resting-state fMRI conditions. It demonstrated that infrasound near the hearing threshold may induce changes of neural activity across several brain regions which are known to be involved in auditory processing and in emotional and autonomic control.[160]

Animal studies

Mikolajczak *et al*. studied the effect of noise generated by wind turbines on stress parameters (cortisol) and the weight gain of geese. Two groups of 40 domestic geese. (Anser anser f. domestica, 5 weeks old) were studied over 12 weeks: Group I remained within 50 m from turbine; Group II within 500 m from turbine. Measurements included noise, weight gain, and the concentration of cortisol in blood. Significant differences between groups were found in both weight gain and blood cortisol levels. Geese from Group I gained less weight (10%) and had a higher concentration of cortisol in the blood, lower activity, and behavioral changes compared to individuals from Group II. Group II had elevated blood cortisol compared to control values, indicating that they were still affected by the turbines. In addition, the stress parameters (cortisol concentration) increased with the residence time in the vicinity of the wind turbine. The study indicates that the turbines induced stress in the geese that affected their health and behavior.[162]

Karwowska *et al*. assessed the effect of three different distances from a wind turbine (50, 500, and 1000 m) on the physicochemical properties and fatty acid composition of loin and neck muscles in reared pigs. Those reared in proximity to the turbines had lower muscle pH, heme iron, and C18:3n 3 fatty acid. This impacted their bulk and market value.[163]

Concerns over women aviators of childbearing age prompted the U.S. Army Aeromedical Research Laboratory to conduct a study of chicken embryos exposed to low frequency vibration. Fertilized eggs were exposed to different levels and frequencies of whole body low frequency vibration (5–50 Hz), 3 h per day, 5 days per week. There was increased mortality and birth defects with the vibration. Mortality increased with the magnitude of the exposure. Factors associated with chicken embryo mortality were frequency, amplitude, amplitude transmission, and timing of the exposure. Teratogenic effects included crossed beaks, missing eyeballs and missing bony structures in the skull, some disorientation, muscular weakness, and malformed feet.[164]

Similar effects were found by Tzvetkov *et al*. studying the effect of vibration of 150 Hz frequency for 3 h daily over 3 months on reproduction in female white rats. The rats were exposed up to the time when fertilization occurred (first experimental group) and up to the end of the first quarter of pregnancy (the 5^{th} day after fertilization) (second experimental group). They were studied throughout the prenatal period and during the postnatal development of the offspring. In the second experimental group, mortality before implantation was raised by a factor 1.5–1.8; in the first group, the weight of the placenta was lower; in both groups, the weight of the fetuses was lower, there was a higher proportion of fetuses with abnormal development of parenchymal organs and bones, and on days 20 and 60 after birth, the offspring showed less motor activity. The data indicate that exposure to high-frequency vibration before the onset of pregnancy and during the early part of pregnancy can have an adverse effect on reproduction.[165]