

A theory to explain some physiological effects of the infrasonic emissions at some wind farm sites

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For at least four decades, there have been reports in scientific literature of people experiencing motion sickness-like symptoms attributed to low-frequency sound and infrasound. In the last several years, there have been an increasing number of such reports with respect to wind turbines; this corresponds to wind turbines becoming more prevalent. A study in Shirley, WI, has led to interesting findings that include: (1) To induce major effects, it appears that the source must be at a very low frequency, about 0.8 Hz and below with maximum effects at about 0.2 Hz; (2) the largest, newest wind turbines are moving down in frequency into this range; (3) the symptoms of motion sickness and wind turbine acoustic emissions “sickness” are very similar; [REDACTED]

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I. INTRODUCTION

For at least four decades there have been reports in the scientific literature of people experiencing motion sickness-like symptoms attributed to low-frequency sound and infrasound. For example, Dawson (1982) makes the following points:

“Apart from the matter of acoustic fatigue in buildings and other structures, the main problem arising from excessive low frequency noise concerns people who can be disturbed, annoyed, made wretched or ill by acoustic insult to a degree which can be disruptive on a local scale and which nationally produces significant economic and social penalties.”

He adds that: “[With] low frequency noise some people can be distressed to an extreme degree while others remain quite unaffected.”

“Once a person has displayed some sensitivity to low frequency noise, further exposure lowers the sensitivity threshold.”

“Any sensitivity is exacerbated by the presence of other stresses. The low frequency sensitivity syndrome includes: Feelings of irritation, unease, stress, undue fatigue, headache, nausea, vomiting, heart palpitations, disorientation, swooning, prostration.”

Fifteen years later, Tesarz *et al.* (1997) reports much the same scenario: “In case studies of persons sensitive to low frequency noise, symptoms such as [REDACTED]

or a pulsating feeling on the eardrum have been the most consistent result. Other symptoms that have been reported in both field and experimental studies are tiredness, irritation and uneasiness, difficulties to concentrate, headache, nausea and dizziness....”

Adopting the conclusions of Tesarz, Annex C, Clause C.1 of ISO 1996-1 (2003) states “...that the perception and the effects of sounds differ considerably at low frequencies as compared to mid or high frequencies.” The text goes on to list six reasons for these differences. Two of these reasons are: (1) [REDACTED]) “complaints about feelings of ear pressure.” These are the same two effects as those listed in the preceding text by Tesarz as “most consistent.”

Now these same problems are appearing in the vicinity of wind farms, and as in 1982 and earlier, nobody understands how these problems arise; nor is it understood why only a fraction of the population is affected.

The purpose of this paper is to provide a foundation upon which the reported effects of infrasound from wind turbines may be investigated. This paper presents a theory upon which needed investigations can go forward. The Appendix outlines some elements of a research statement.

II. DATA FROM A PROBLEM SITE

A. Observations from people affected by the installation of wind turbines

One wind farm that is experiencing these problems is in Shirley, WI. Here three families have abandoned their homes

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because family members who became ill after installation of the turbines could not acclimate to the situation.¹ Because of these conditions in Shirley, a study was conducted with the proposed test plan calling for the wind farm owner to cooperate fully in supplying operational data and by turning off the units for short intervals so the true ON/OFF impact of turbine emissions could be documented. The owner declined this request citing the cost burden of lost generation from the eight turbines at the Shirley site.

Four acoustical consulting firms cooperated to jointly conduct this study: (1) Channel Islands Acoustics (ChIA), (2) Hessler Associates, Inc., (3) Rand Acoustics, and (4) Schomer and Associates, Inc.

This study was conducted during a 3-day period in December, 2012. The first task accomplished was to meet with residents having problems with the wind turbine acoustic emissions including members of the three families who had abandoned their homes. These discussions with the residents yielded the following observations:

- (1) At most locations where these various symptoms occurred, the wind turbines were generally not audible. That is, these problematic symptoms are devoid of noise problems and concomitant noise annoyance issues. The wind turbines could only be heard distinctly at one of the three residences examined, and they could not even be heard indoors at this one residence during high wind conditions.
- (2) Some residents reported that they could sense when the turbines turned on and off; this was independent of hearing or seeing the turbines. This assertion by the residents is readily testable, and a plan to test this assertion is briefly summarized in the Appendix.
- (3) The residents reported “bad spots” in their homes but pointed out that these locations were as likely to be “bad” because of the time they spent at those locations as because of the “acoustic” (inaudible) environment. The residents did not report large changes from one part of their residences to another.
- (4) The residents reported little or no change to the effects based on any directional factors. Effects were unchanged by the orientation of the rotor with respect to the house; the house could be upwind, downwind, or crosswind of the source.
- (5) Many of the residents reported motion sickness like symptoms [REDACTED]

Two of the major implications of these five findings are:

- (1) Because these residents largely report wind turbines as inaudible, it seems that suggestions some have made that these conditions are being caused by extreme annoyance can be ruled out and (2) the lack of change with orientation of the turbine with respect to the house and the lack of change with position in the house suggest that we are dealing with very low frequencies; frequencies such that the wavelength is a large fraction of the wind-turbine diameter (i.e., about 3 Hz or lower).

It should be mentioned that there are about 120 residences within about 5000 ft of the closest turbine; this suggests

that there are about 275 residents. Of these 275 residents, 50 have described adverse effects that they have experienced after the introduction of the wind turbines. It is not known how many of the 120 residences are “participating,” but most agreements for participating residences include some form of confidentiality and non-complaint clauses.²

The most common complaints are feelings of pressure and pulsations in the ears. And this is very much in accordance with ISO 1996-1 (2003) where, as discussed in the preceding text, these two factors are listed as the most common effects of low-frequency noise. However, in this paper, we are concentrating on sea-sickness like symptoms.

B. Physical measurements

Figure 1 is an aerial photo of the Shirley wind farm. This figure shows the positions of five of the eight wind turbines that make up this site, Nordex N-100s, and the position of the three abandoned residences. Primary measurements were made at residences 1–3 on consecutive days.

Bruce Walker of Channel Island Acoustics employed a custom designed multi-channel data acquisition system to measure sound pressure in the time domain at a sampling rate of 4000/s where all signals are collected under the same clock. The system is calibrated to be accurate from 0.1 Hz thru 10 000 Hz. Measurements were made both inside and outside the house to gather sufficient data for applying advanced signal processing techniques.

George and David Hessler of Hessler Associates, Inc., employed four off-the-shelf type 1 precision sound level meter/frequency analyzers with a rated accuracy of ± 1 dB from 5 to 10 000 Hz. Two of the meters were used as continuous monitors to record statistical metrics for every 10-min interval over the 3-day period.

Robert Rand of Rand Acoustics observed measurements and documented neighbor reports and [REDACTED] including nausea, dizziness, and headache. He used a highly accurate microbarograph to detect infrasonic pressure modulations from wind turbine to residences.

Paul Schomer of Schomer and Associates, Inc., observed all measurements. Among other things the following observations are made based on the results of the physical measurements. In particular, these observations are based upon the coherence calculations by Bruce Walker. Figure 2 shows the coherence between the outdoor ground plane microphone and four indoor spaces at residence 2: The living room, the master bedroom, behind the kitchen, and in the basement. The data collected at residence 2 were measured with only 58% of turbine power, although the wind conditions were optimal for turbine operation, and the power was much less than 58% during the measurement periods at R1 and R3.

It is inferred from the residents’ observations that the important effects result from very low frequency infrasound of about 3 Hz or lower. We can test this assertion with the data collected at the three residences at Shirley. Only residence 2 was tested during a time when significant power was being generated, so it is the only source of data used herein. Figure 2 shows the coherence between the outdoor ground plane microphone and the four indoor spaces listed above

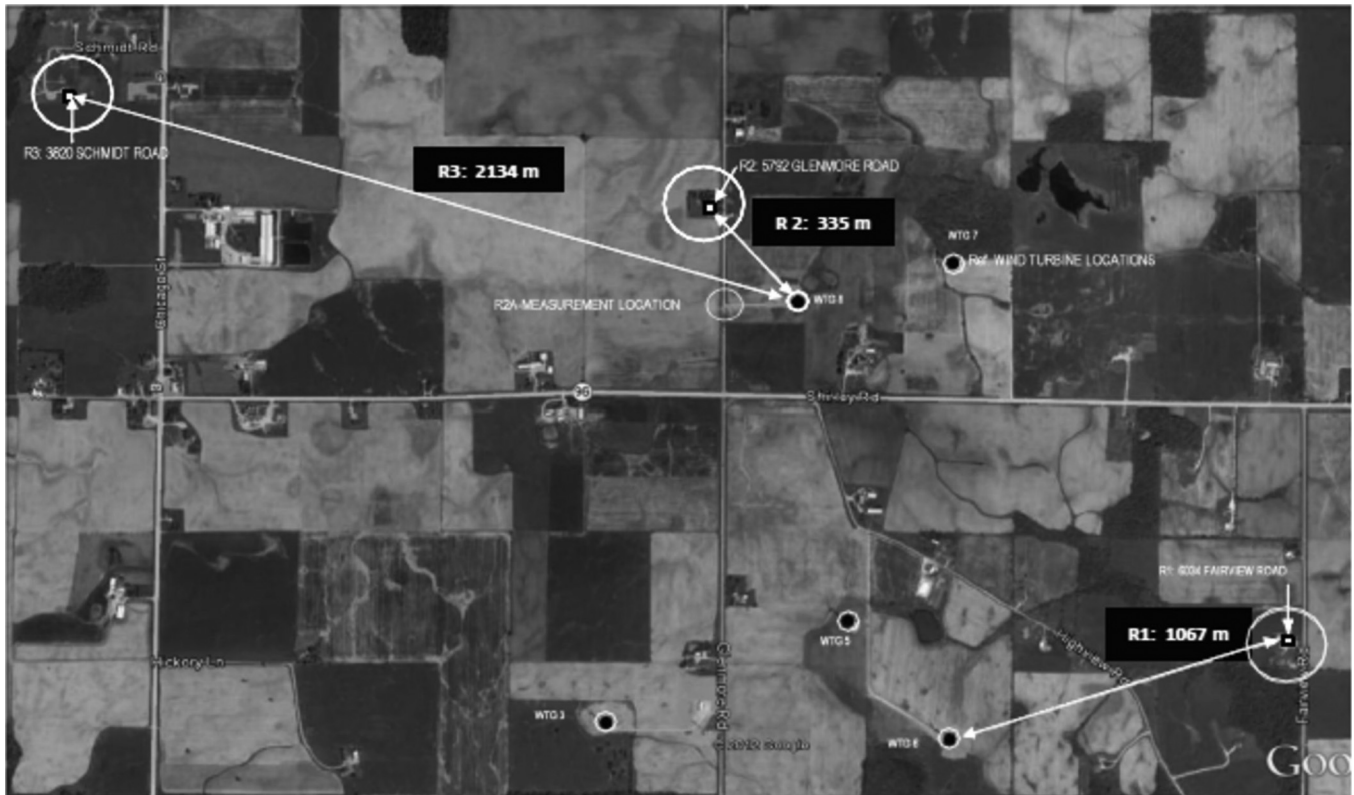


FIG. 1. Aerial photograph of the site showing the three residences and the five closest wind turbines.

for the frequency range from 0.5 to 7 Hz. All of the four spaces exhibit coherence at 0.7, 1.4, 2.1, 2.8, and 3.5 Hz, and in this range, there is no coherence indicated except for these five frequencies. The basement continues, with coherence exhibited at these higher harmonically related frequencies of 4.2, 4.9, 5.6, 6.3, and 7 Hz. The three indoor microphones situated on the first floor exhibit only random zones of high and low coherence as a function of frequency but not so as to correspond to other microphones in the house. That is, above 5 Hz the three indoor microphones exhibit only random periods of coherence, and above 7 Hz the basement microphone exhibits only random periods of coherence. But all four microphones are lock step together in their coherence with the outdoor microphone below about 4 Hz.

As an analysis that is complementary to the coherence plots of Fig. 2, Fig. 3 shows spectral plots of data collected

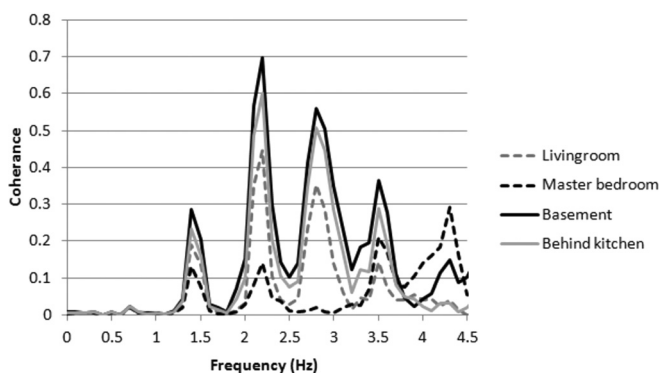


FIG. 2. Coherence between the each of the four indicated rooms with the outdoor-ground plane microphone.

at residence 2. As in the coherence plots, one can see the first several harmonics of the wind-turbine blade-passage frequency, 0.7 Hz, and nothing notable above about 7 Hz. Two channels of measurement are shown on Fig. 3, the outside, ground plane microphone (upper curve), and the indoor microphone in the living room (lower curve). Note that the pressures that result from the acoustic emissions of the wind turbines, when measured indoors, keep growing as the frequency goes lower because the entire house is behaving like a closed cavity.

Based on this analysis of the spectral and coherence data, we conclude that the only wind turbine-related data

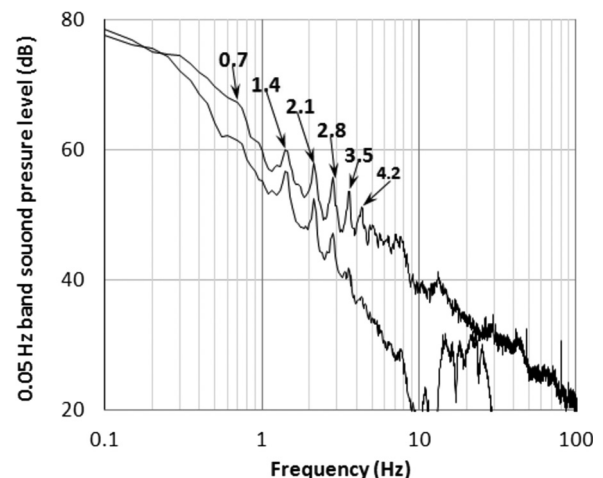


FIG. 3. Spectral plot of the ground-plane outdoor microphone data (upper trace) and indoor data measured in the living room of Residence 2 (lower trace).

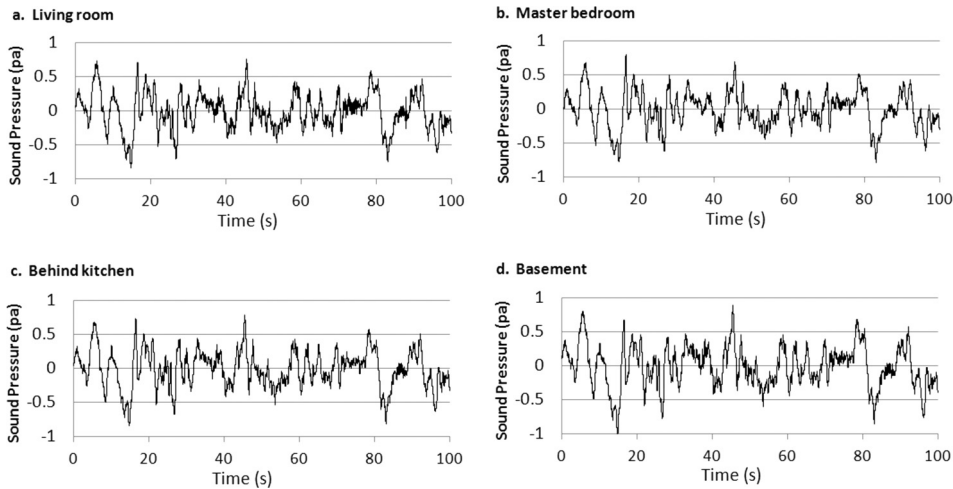


FIG. 4. Sound pressure versus time for of the data collected at the four indoor measurement locations indicated in Fig. 2 and for the first minute of data from the data set used for Fig. 2. Note that the sound pressure versus time is very similar for all indoor locations.

evident in the measurements at residence 2 are the very low frequencies ranging from the blade passage frequency of 0.7 Hz to up to about 7 Hz. This conclusion is consistent with the residents' reports that the effects were similar from one space to another but a little to somewhat improved in the basement, the effects were independent of the direction of the rotor and generally not related to audible sound.

Figure 4 shows the sound pressure level for the first minute of the 10 min represented on Fig. 2, above. This figure, which is sensitive to the lowest frequencies, shows that at these very low frequencies, the sound pressure levels in all four spaces are quite similar. The small changes from different positions in the house also suggests that the house is small compared to the wavelength so that the insides of the house are acting like a closed cavity with uniform pressure throughout being driven by very low-frequency infrasound.

The measurements support the hypothesis developed in the preceding text that the primary frequencies are very low, in the range of several tenths of a hertz up to several hertz. The coherence analysis shows that only the very low frequencies appear throughout the house and are clearly related to the blade passage frequency of the turbine. As Fig. 4 shows, the house is acting like a cavity and indeed at 5 Hz and below, where the wavelength is 60 m or greater, the house is small compared to the wavelength.

While we would have liked to have been able to draw conclusions on measurements at all three sites, that was not possible because the energy company was not generating much power during the measurements of R1 and R3, and even just over 50% during the measurements at R2.³

III. THE MOTION SICKNESS HYPOTHESIS

A. The Navy's nauseogenic region

As a starting point we consider a paper by Kennedy *et al.* (1987) entitled: "Motion sickness symptoms and postural changes following flights in motion-based flight trainers." This paper was motivated by Navy pilots becoming ill from using flight simulators. The problems encountered by the Navy pilots appear to be similar to those reported by about five of the Shirley residents. This 1987 paper focused on whether the accelerations in a simulator might cause

symptoms similar to those caused by motion sickness or seasickness. Figure 5 (Fig. 1 from the reference) shows the advent of motion sickness in relation to frequency, acceleration level and duration of exposure. To develop these data, subjects were exposed to various frequencies, acceleration levels, and exposure durations, and the Motion Sickness Incidence (MSI) was developed as the percentage of subjects who vomited. Figure 5 shows two delineated regions. The lower region is for an MSI of 10%. The top end of this region is for an exposure duration of 30 min and the bottom end is for 8 hr of exposure. The upper delineated region has the same duration limits but is for an MSI of 50%.

What is important here is the range encompassed by the delineated regions of Fig. 5. Essentially, this condition appears to occur primarily below 1 Hz. Note that the Navy criteria are for acceleration, while in Shirley we are dealing with pressures in a closed cavity, the house.

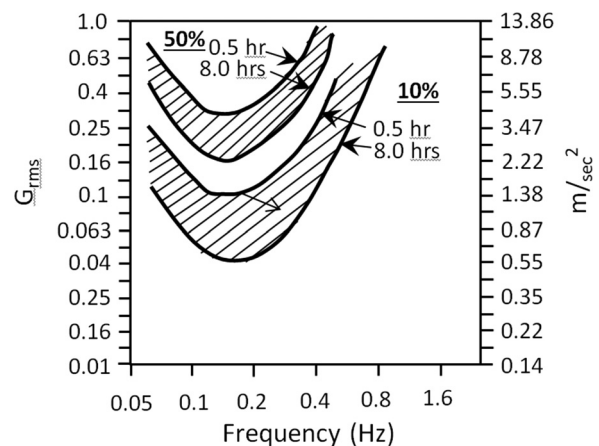
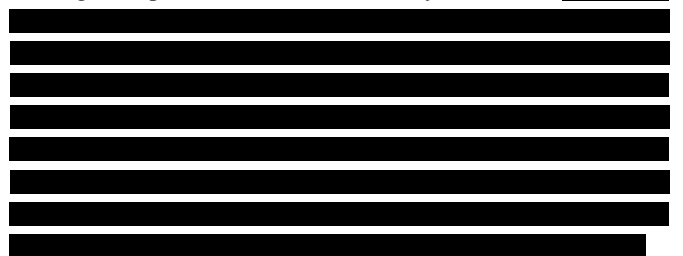


FIG. 5. The nauseogenic region as developed by the U.S. Navy (after Kennedy *et al.*, 1987).

As the generated electric power of a wind turbine doubles, the sound power doubles and the blade passage frequency decreases by about 1/3 of an octave (Møller and Pedersen, 2011).⁴ The wind turbines at Shirley have a blade passage frequency of about 0.7 Hz. This suggests that a wind turbine producing 1 MW would have a blade passage frequency of about 0.9 Hz, and on Fig. 5, a change from 0.7 to 0.9 Hz requires a doubling of the acceleration for the same level of response.

[REDACTED] s not appeared frequently heretofore because older wind farms were built with smaller wind turbines.

B. Motion sickness like symptoms and their implications

We systematically listed the symptoms of low frequency noise, as given by the two papers cited in the preceding text (Dawson, 1982; Tesarz *et al.*, 1997), and on the same basis, we listed the symptoms of sea-sickness, using two journal papers (Stevens and Parsons, 2002; Bittner and Guignard, 1988) and the symptoms listed by the National Health Service (2014) and C-Health (2013). Table I compares the various frequencies of the indicated symptoms of seasickness and low-frequency infrasound sickness from this published literature. The two sets of symptoms are strikingly similar.

[REDACTED]

[REDACTED] us motion sickness is not really a sickness but rather is a natural reaction to unusual input information.

At the start of this analysis, the working hypothesis was that wind turbine noise somehow, [REDACTED] created symptoms that were similar to those of motion sickness. We now have a much simpler hypothesis—just as some people experience motion sickness

TABLE I. Percent of references citing symptom indicated.⁵

	Composite of four sea sickness studies or information papers	Composite of two low frequency “sound” sickness studies
Not feeling well	100	100
Dizziness	100	100
Headache	100	100
Nausea and vomiting	100	100
Sleepiness, drowsiness, and sleep disturbance	75	100
Fatigue and tiredness	75	100
Difficulty thinking	25	50
Irritation	25	100
Sweating	100	0
Pale	75	0

when watching movies and videos, wind-turbine acoustic emissions trigger motion sickness in those who are susceptible; it is another form of *pseudo-kinetosis*.

At Shirley, of the 50 people who reported symptoms after the introduction of wind turbines to the area, 5 of those 50 people reported symptoms similar to motion sickness. We simply have no information on other area residents, except for these 50, and do not know how many of the other residents are participating.³ Based on the sample of 5 of 50, we can say that the incidence of motion sickness symptoms at Shirley is 10% or less, a figure that is clearly in line with the expected percentage of those in the general population affected by motion sickness.⁶ In fact, Montavit (2014) indicates that “about 5% to 10% of the population is extremely sensitive to motion sickness; 5% to 15% are relatively insensitive; and about 75% are only subject to it to a ‘normal,’ i.e., limited degree.”

[REDACTED] The same is true for Rob Rand and Steve Ambrose, who are two acoustical researchers who have themselves reported suffering strong symptoms from low frequency wind-turbine emissions.

[REDACTED]

■ . EXCITATION OF THE OTOLITH

A. The middle ear and inner ear

As shown on Fig. 5, the Navy criteria for the likelihood of sea sickness are functions of three factors: (1) Duration of exposure to the motion, (2), amplitude of the acceleration, and (3) frequency of the acceleration. Moreover, because the blade passage frequency has been decreasing and the acoustic power has been increasing as the turbines get larger, one can imagine a future with greater, more frequent problems like those in Shirley (Møller and Pedersen, 2011) (footnote 4). There is one main question that greatly affects the likelihood of this eventuality. This main question relates to the fact that the Navy criteria are based on acceleration, while the wind-turbine acoustic emissions are very low frequency acoustic pressure waves.

In the following, we show only that it appears that an acoustic wave at 0.5–0.7 Hz can generate a similar response as the signal generated by acceleration at 0.5–0.7 Hz.

[REDACTED]

[REDACTED]

B. Classical model of the otolith

[REDACTED]

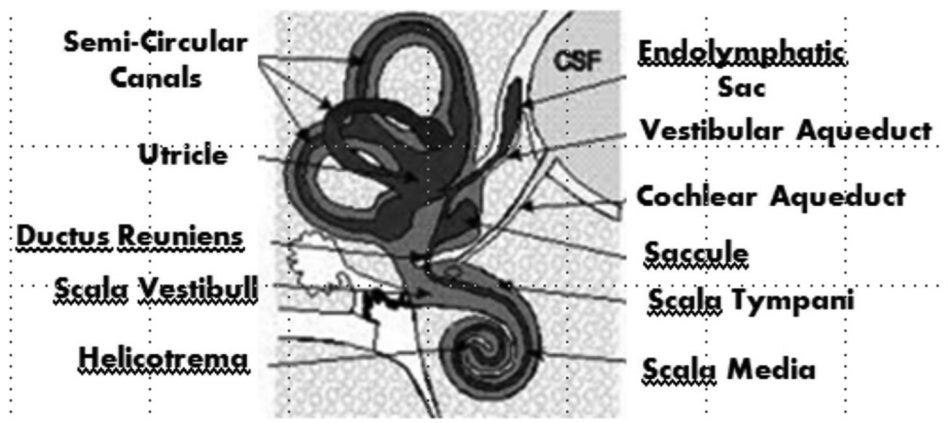


FIG. 6. The inner ear (after Salt, unpublished data).

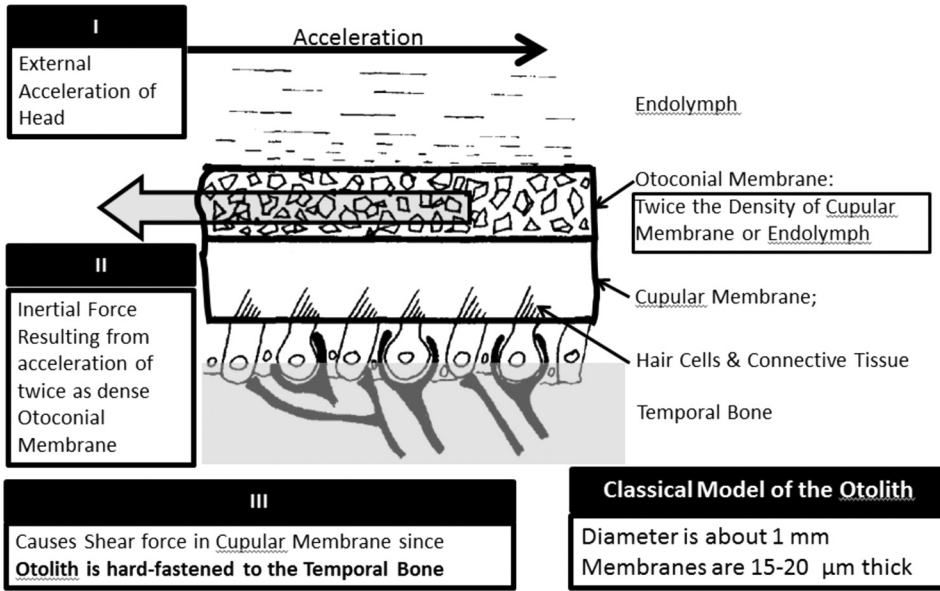


FIG. 7. Schematic sectional drawing of the classical model for the otolith.

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

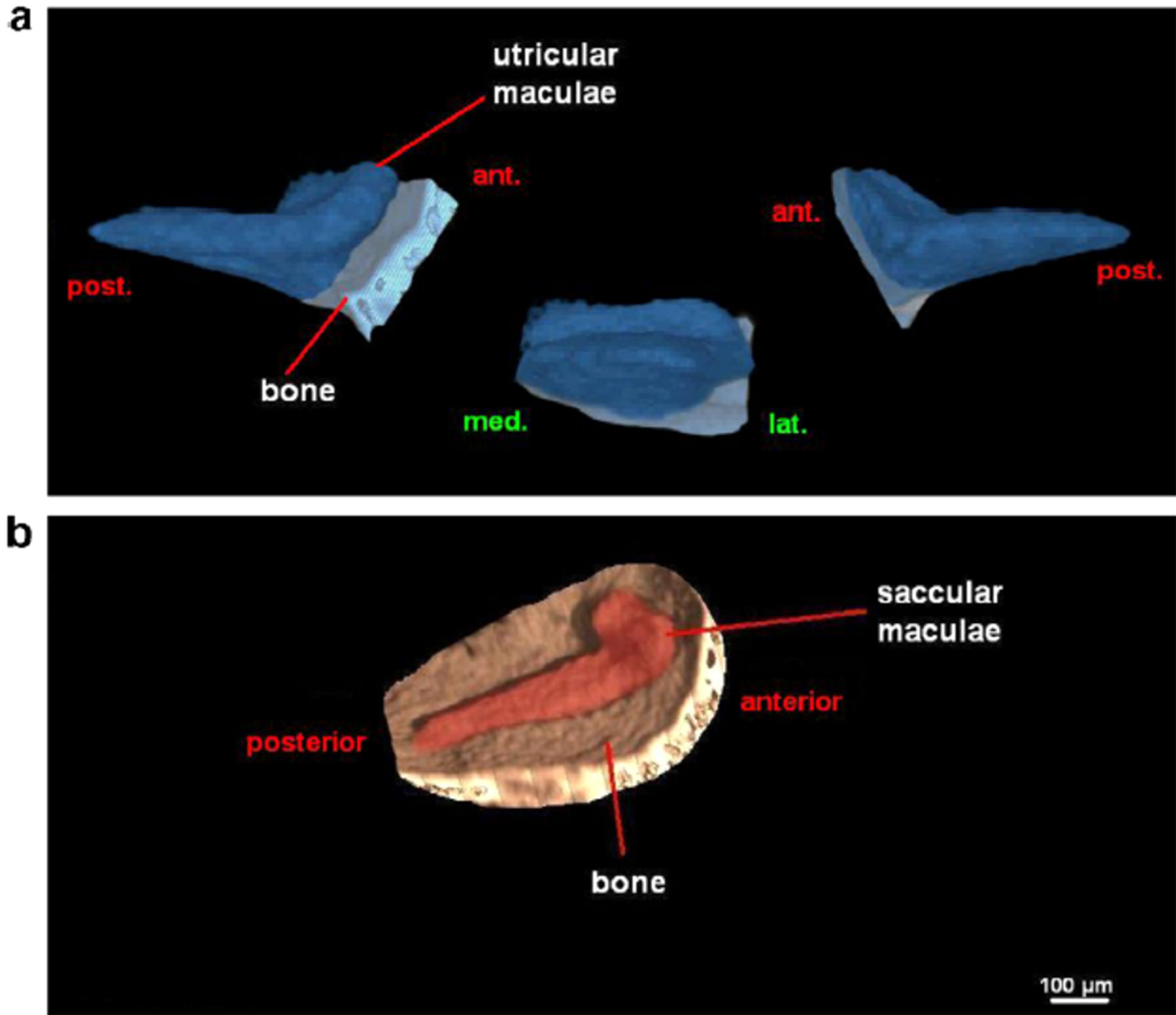


FIG. 8. (Color online) Artist rendered three-dimensional images of the utricular and the saccular maculae of a guinea pig (from Uzun-Coruhlu *et al.*, 2007).

[REDACTED]

E. An example that indicates these theories may be correct

[REDACTED]

[REDACTED]

[REDACTED] d this is exactly what both Steve Ambrose and Rob Rand, who are both acousticians, each experienced. Rob Rand, one of the acoustical researchers on this project, the one who is sensitive to wind turbine acoustic emissions, said of his work in Falmouth, MA in April 2011: “I went outside hoping to feel better. I looked straight at a tree with my eyes, and my brain said the tree was about 20 to 30 degrees elevated and about 20 to 30 degrees to the right. Then I tried to focus on a bush looking straight at it, and again my brain said the bush was off to the right and elevated at about the same angle as before; and the same for the house. For everything I looked at, immediately my brain would say it was elevated and off to the right.” Steve Ambrose had exactly the same experience, only not the same angles.

V. CONCLUSIONS

The wind turbine clearly emits acoustic energy at the blade passage frequency, which for the Nordex N100 is

0.7 Hz and about the first six harmonics of 0.7 Hz. This very low infrasound was only found at R2, but that was the only day in which significant power was being generated (about 58%).

Most residents do not hear the wind-turbine sound; noise annoyance is not an issue. The issue is physiological responses that result from the very low frequency infrasound and that appears to trigger motion sickness mainly in some of those who are susceptible to it. These results suggest a relation between wind turbines and motion sickness symptoms in what appears to be a small fraction of those exposed. [REDACTED]

[REDACTED]

Finally, it is shown that the force generated [REDACTED] by the pressure from the infrasonic emissions of the wind turbines is perhaps three times larger than the force that would be generated by an acceleration that was in accordance with the U.S. Navy's nauseogenic criteria (Fig. 5 herein). That is, a 0.7 Hz "tone" at 54 dB produces about the same to three times the force as does a 5 m/s² acceleration.

VI. ADDITIONAL RESEARCH AND DATA COLLECTION RECOMMENDATIONS

Research to date has not tended to study the effects on humans reported anecdotally in what is probably a minority of wind farms even though these reports are exactly what is to be expected in accordance with ISO 1996-1 (2003). This paper provides part of the foundation upon which such research could be accomplished. Some of the necessary research is listed below. The first item in the list, perform sensing, is discussed in more detail in the Appendix.

- (a) Perform the "sensing" tests outlined in the Appendix of this paper.
- (b) Demonstrate electric signals going to the brain that emanate from the otoliths; signals that are in sync with the wind turbine emissions, where depending on method this testing would be done with surrogate species.
- (c) Develop an understanding of why this phenomenon seems to affect residents near only a small minority of wind farms.
- (d) Establish who is and who is not affected by wind turbine infrasonic emissions in various ways.
- (e) Establish why this all occurs.

Currently the wind turbine industry presents only A-weighted octave-band⁷ data down to 31 Hz, or, frequently 63 Hz, as a minimum. They have stated that the wind turbines do not produce low frequency sound energies. The measurements at Shirley have shown that low frequency infrasound is clearly present and relevant. As indicated by

ISO 1996-1 (2003), A-weighting is inadequate and inappropriate for description of infrasound.

ACKNOWLEDGMENTS

The authors wish to acknowledge the extraordinary effort and trust that went into making the testing at the Shirley wind farm possible. First, there is the extraordinary effort of David and George Hessler and their client, Clean Wisconsin, who made these tests happen at the Shirley wind farm. Coupled with this effort were the extraordinary efforts by Glen Reynolds and Forest Voice who also made this test happen. Additionally, our acknowledgment goes to George Hessler for repeated reviews of the paper with helpful inputs and questions, and much credit is due to Bruce Walker for his development of a custom multi-channel time-domain very low frequency, 0.1 Hz, measurement system necessary for advanced signal processing and analysis between and among channels and his custom reprinting of the coherence and spectral plots herein from Shirley. Additionally, credit goes to Robert Rand for repeatedly being a firsthand source of knowledge about the effects of wind turbine emissions and for general thoughts and ideas. Our acknowledgment goes to Dr. Sarah Laurie (Southern Australia), Dr. Robert McMurtry (Ontario, Canada), and Dr. Jay Tibbitts (central Wisconsin); three physicians from around the world who searched their records to provide information on symptoms and histories. And finally, acknowledgments, Alec Salt for providing key references about the otoliths that led us in the right direction; Sumuk Sundarum, MD Ph.D. internal medicine, for review of an early draft; Stephen Chadwick, MD otolaryngology, for initial ideas and review of an early draft; Paul Schomer's good friend Michael Rosnick, MD family medicine, for correcting a misconception about the Eustachian Tube; and to Paul Schomer's daughter Beth Miller, Ph.D., for initial lessons and information on the anatomy and physiology of the ear.

APPENDIX: A TEST FOR PERCEPTION OF THE ACOUSTIC EMISSIONS FROM WIND TURBINES

In Shirley, residents stated that some of them could sense the turning on and off of the wind turbines without any visual or audible clue. This assertion is readily tested; however, it requires the cooperation of the energy company.

Consider the two houses at Shirley where there is no audible sound; the R-1 house and the R-3 house. The residents of the houses, and others who would be subjects, would arrive at the house with the wind turbines off. The test itself would take something like 2 h to perform. Sometime during the first hour, the wind turbine(s) that had been designated by the residents as the turbines they could sense, might or might not be turned on. It would be the residents' task to sense this "turn on" within some reasonable time designated by the residents—say 10 or 30 min. Correct responses (hits) would be sensing a "turn on" when the turbines were turned on, or sensing no change if they were not turned on. Incorrect responses (misses) would be failure to sense a turn on when the turbines were turned on, or (false alarms) would be "sensing" a turn on when the turbines were not turned on.

Similar tests could not necessarily be done starting with the turbines initially on because the subjects, when sensitized find it more difficult to sense a turn off.

¹The family in the closest dwelling, R-2, reported that the wife and their then 2-yr-old son had the problems; the husband did not have problems. This totally stopped upon their leaving the vicinity of the wind turbines.

²Traditionally, participating households are those that receive a share of the proceeds in exchange for having wind turbines or ancillary facilities or equipment on their property. As a part of these agreements, these households are required to agree to not complain about the wind turbines. At Shirley, the energy company also had their “good” neighbor policy wherein all residents who were not eligible to be participating were offered payments for agreeing not to make complaints or take any legal action.

³A report, including conclusions and recommendation, was written and signed by these five Shirley technical participants. One of the many interested parties and /or legal entities did not like the conclusions and expunged these from the report without obtaining the approval of the authors while retaining the signature block as it was. Both versions were eventually placed in the record and the complete version as written and signed can be found at the following link: http://psc.wi.gov/apps40/dockets/conten/detail.aspx?dockt_id=2535-CE-100c, go to “Documents”; then to “January 2, 2013, 8:40 A.M.” (Ex. -Forest Voice-Rand2) (Last viewed 9/29/2014).

⁴Møller and Pedersen present data from 41 wind turbines. In Fig. 1, they plot the turbine sound versus power. These 41 data points form two clumps based on power; one at about 700 kW and the second at about 2 MW. Regression lines fit to two measures of the power both show that the sound level is increasing at a rate of about 12 dB for a tenfold increase in power or about 3.6 dB per decade. Normalized spectra for these same two groups exhibit about a one-third of an octave decrease in the spectrum for the higher power relative to the lower power (Sec. D, Fig. 16). There is also a third much smaller clump of 4 turbines with power ratings of about 100 kW that are not used for much in the paper.

⁵A major effort was made to logically group the “symptoms” in Table I. It is possible that this grouping should have gone further and grouped “sleepiness, drowsiness, and sleep disturbance” with “fatigue and tiredness.” That combined “symptom” would have resulted in 100% for the two categories that make up the table.

⁶Montavit (2014) states that 5%–10% of the population are “extremely sensitive” and that 5%–15% are “relatively insensitive.” So 5%–10% of the population is probably closer to the percentage that we should be using rather than 15%.

⁷One of the reviewers questioned the use of A-weighted octave band levels. The authors also question this, but the IEC standard requires that the data be reported this way and the wind farm industry concurs.

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