Infrasound, the Ear and Wind Turbines

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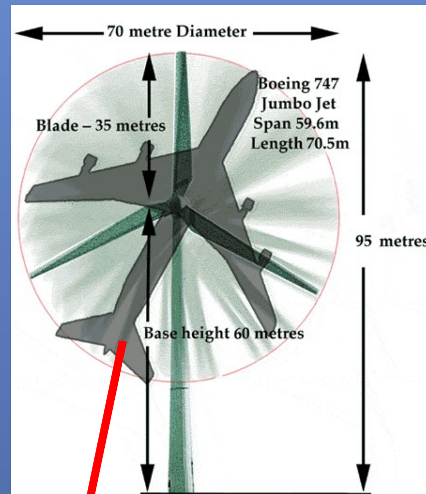
Windmills have always been Industrial Machines.

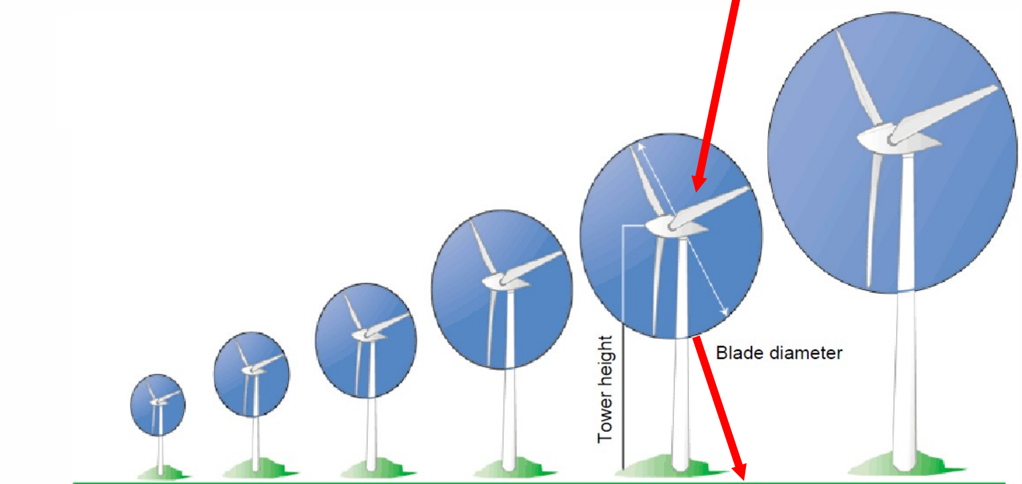
Some are beautiful and remind us of days gone by.

Modern wind farms are equally industrial but not so quaint

(unless there happens to be a castle nearby).

Wind turbines have been getting bigger and bigger….





	1980	1985	1990	1995	2000	2005
Power	: 30 kW	80 kW	250 kW	600 kW	1.500 kW	5.000 kW
Blade diameter	: 15 m	20 m	30 m	46 m	70 m	115 m
Tower height	: 30 m	40 m	50 m	78 m	100 m	120 m
Energy production per year	: 35.000 kWh	95.000 kWh	400.000 kWh	1.250.000 kWh	3.500.000 kWh	ca. 17.000.000 kWh

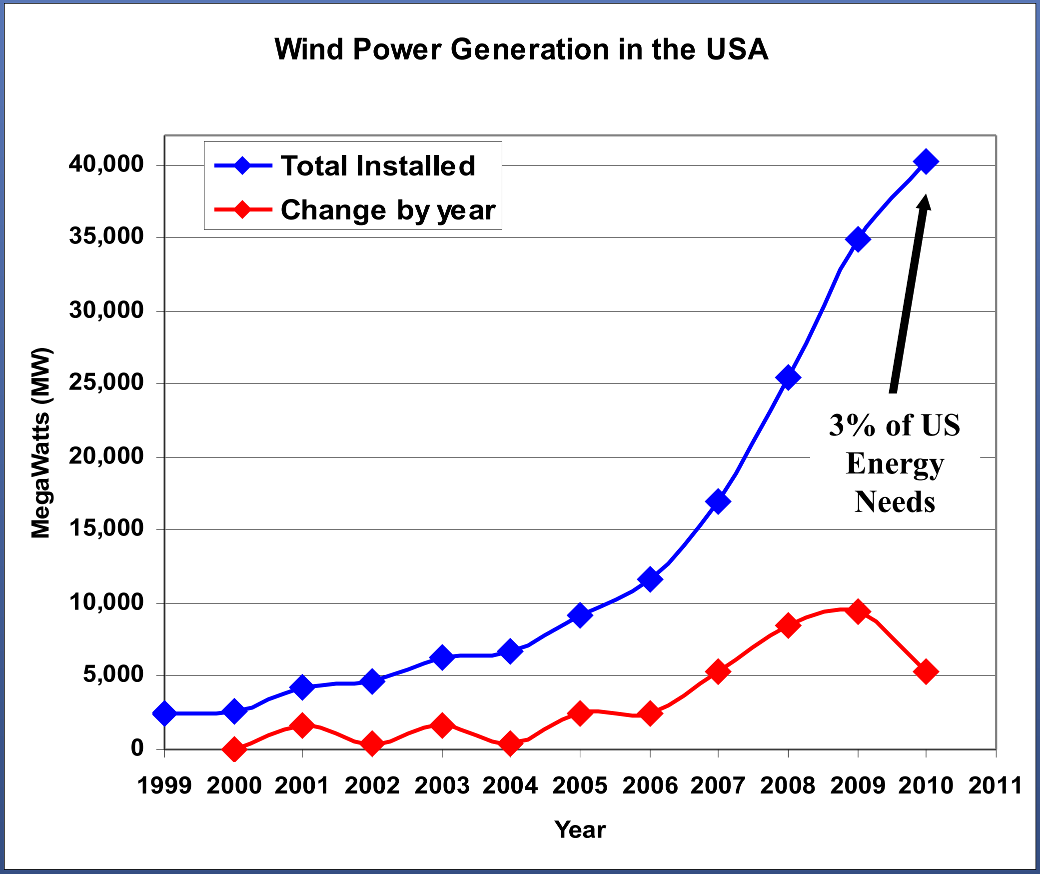
Lars Ceranna, Gernot Hartmann, and Manfred Henger.
Infrasound Workshop 2005, Tahiti

Rotor diameter (126m = 413ft) is bigger than a football field including both end zones !

The world's largest wind turbine is now the Enercon E-126. This turbine has a rotor diameter of 126 meters (413 feet). The E-126 is a more sophisticated version of the E-112, formerly the world's largest wind turbine and rated at 6 megawatts. This new

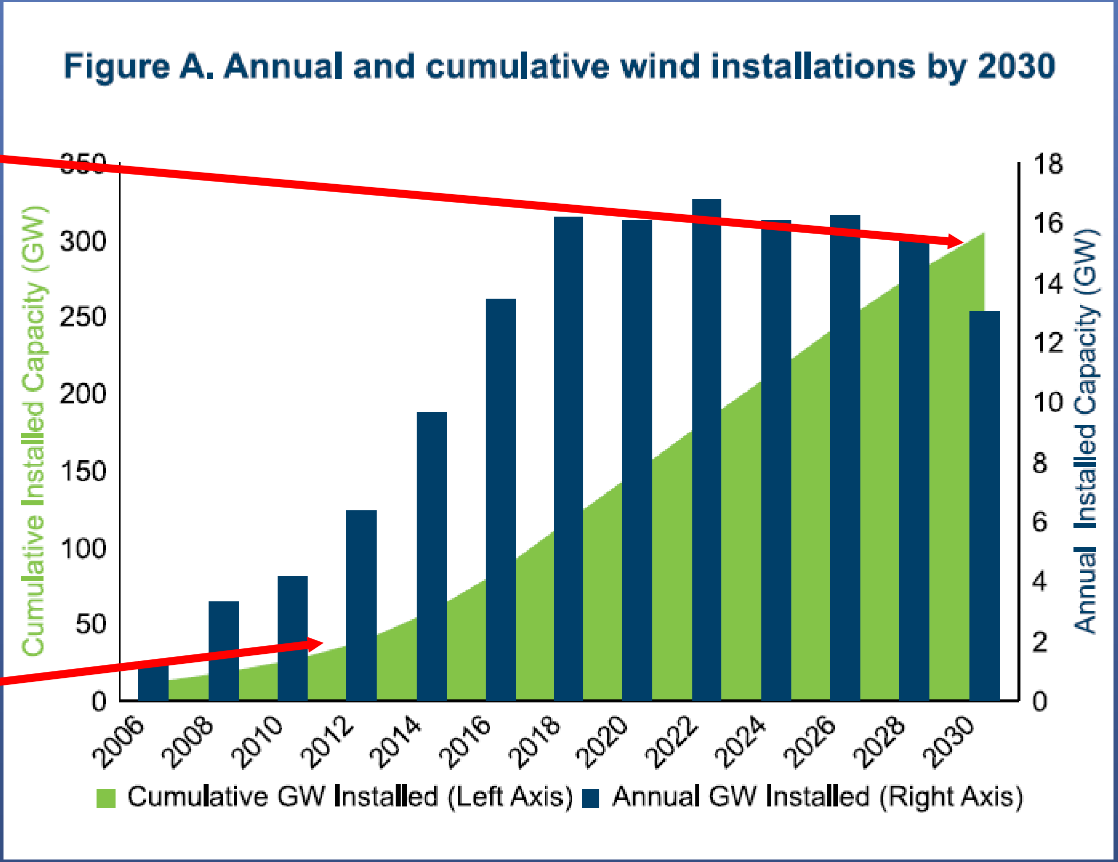
That is a shipping container !!

Wind turbines are "green" and are contributing to our energy needs



Planned installations

The goal is to generate 20% of the electricity for the USA with wind turbines



By 2030, the plan is to install 300 GW.

That is 300,000 MW

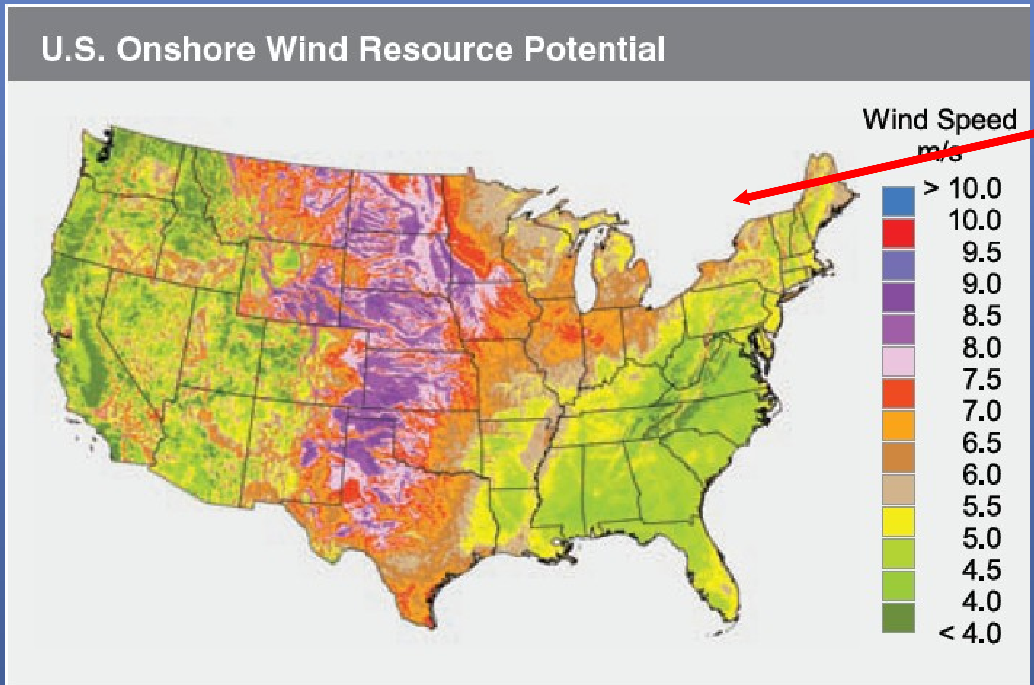
which is approximately

150,000

2 MW turbines

We are currently around here with 40 GW capacity

And they are coming to locations near you!



Data Source: AWS Truewind, LLC, for windNavigator® for the National Renewable Energy Laboratory

+ + + Ontario, Canada

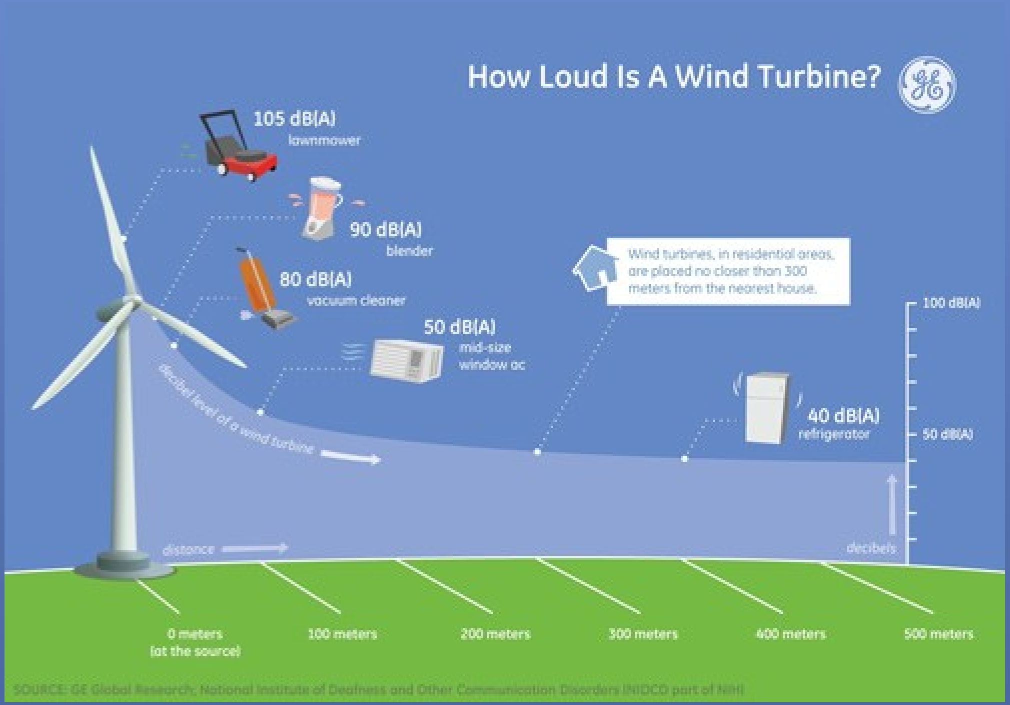
Wind farm locations depend not only on wind, but on proximity to urban centers and the electricity grid.

So far, this is all good news.

A potential problem

…..They are installing these machines as little as 300m from people's homes

Is the sound from wind turbines a problem?

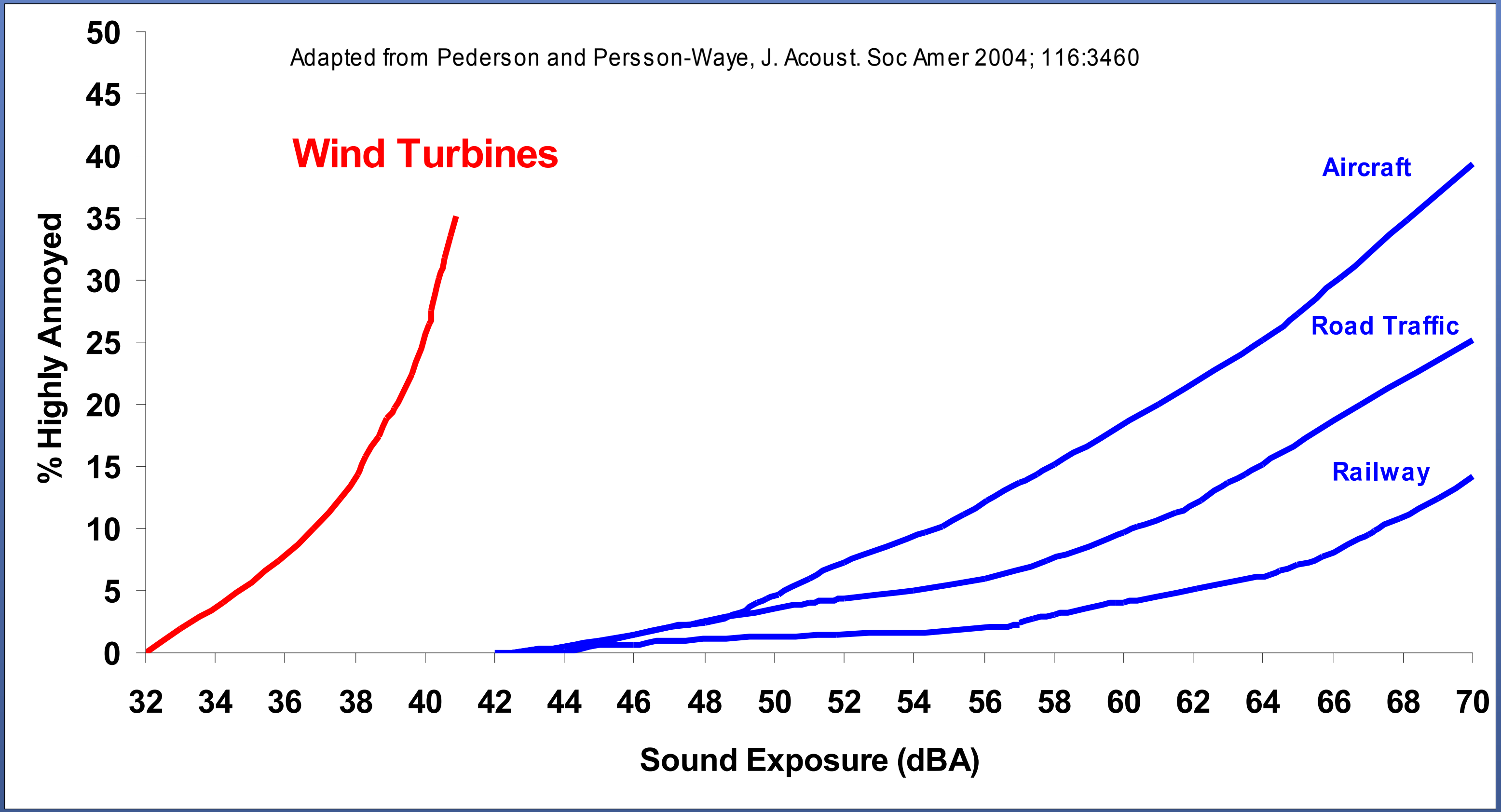


British Wind Energy Association:
Wind farm at 350m
35-45 dBA

"….the sound of a wind turbine generating electricity is likely to be **about the same level as noise from a flowing stream about 50-100 meters away or the noise of leaves rustling in a gentle breeze. This is similar to the sound level inside a typical living room with a gas fire switched on, or the reading room of a library or in an unoccupied, quiet, air-conditioned office."**

American Wind Energy Association – Tom Gray
"Wind turbine noise (at 200 m) is as loud as your refrigerator heard from the living room".

Then why is Annoyance so high?



There's something about wind turbine noise people don't like !

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Wind farms can cause noise problems finds study

The noise caused by wind farms can make some people ill, according to experts.

By Louise Gray, Environment Correspondent
Published: 7:30AM GMT 28 Jan 2010

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Wind farms have traditionally been seen by protesters as a blot on the British countryside
Photo: AFP / GETTY

The study by a panel of independent experts found that the irritation caused by the noise around wind farms can effect certain individuals.

Scientists dismissed the idea of a "wind turbine syndrome" where the vibrations in the air or the particular sound waves from wind turbines cause headaches, nausea and panic attacks.

However, they did concede that the swishing sound caused by wind turbines can "annoy" some people, keeping them awake at night and even causing

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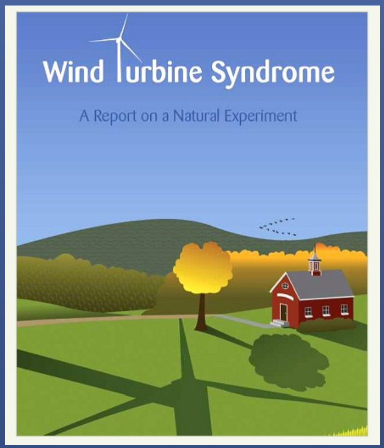
At the wateringhole

Sound from Windmills: Wind Turbine Syndrome

Clinical symptoms first formally identified by British physician Amanda Harry, MD.

sleep disturbance	89%
headache	56%
tinnitus	58%
ear pressure /pain	30%
dizziness / vertigo	59%
nausea	
visual blurring	
tachycardia (rapid heart rate)	
irritability	76%
problems with concentration and memory	93%
panic episodes	



%ages above from Pierpont

N=21 to 38 people surveyed expressing problems

Dr. Nina Pierpont, MD, 2009

(self-published book)

Epidemiology

- Harry 2007: 39 people living 300m-2 km from turbines. 81% believed their health was adversely affected.
- Pierpont 2009: 40 people self-reported as having problems****
- Nissenbaum (2010): 22 adults within 3500' compared with 27 "matched" people living about 3 miles away. Surveys of symptoms (similar to prior studies), validated surveys of sleep status and quality of life. (presently in peer review). Reports a strong correlation between sleep status and distance from the turbines **even in the control group**!!!
- Laurie (2010): Longitudinal monitoring of morning blood pressure. Found elevation on days the turbines were running.

Each has been an unfunded, volunteer study by private individual. As a result they have largely been dismissed by the wind turbine industry.

- No study yet relating symptoms to turbine noise characteristics/level.

Other reasons the problem may be real

- Many individuals now reporting symptoms were initially turbine supporters, and changed when the turbines started up. They feel they were misled by claims the turbines were quiet.

- Some people buy/rent second homes to sleep in, or abandon their homes because they cannot stand to sleep there . This is often at great financial hardship as it is difficult to sell the home near the turbine. People would not do this just to make a political point.

Health Issues / Disease / Pathology

- Not everyone affected.
- Not all turbines cause problems.
- For those affected, symptoms go away when not near turbine.
- No expected pathology / damage. ?

- In terms of health, somewhat analogous to motion sickness. Not a disease, but still very unpleasant when it affects you.

Noise /Health Issues from the Industry Perspective

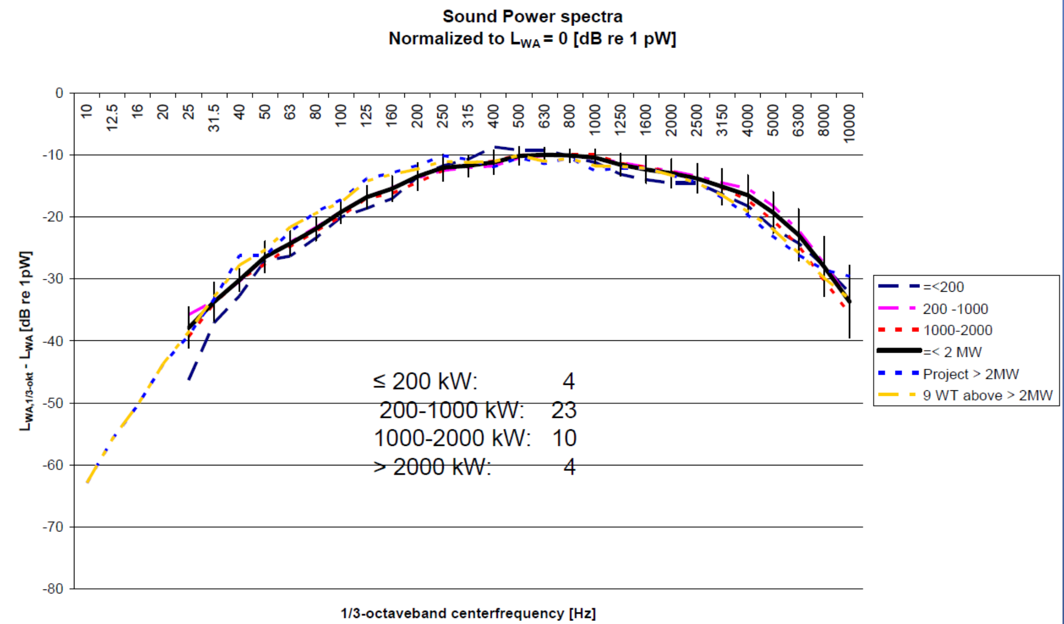
- There are no health effects of wind turbines
- People who complain are NIMBYs
- Annoyance is not a health issue. Sick and annoyed are not the same thing *(Colby)*.
- Nocebo effect (bad attitude to turbines).
- No noise monitoring is necessary.
- No further scientific studies are necessary *(Dobie)*.

Current Litigation / Hearings

- Australian Senate Commission – Hearings into the social and economic impacts of wind farms.
- Ontario, Canada. Kent Breeze environmental tribunal.
- plus many more contentious “local” planning meetings.
- Problem turbines: Falmouth, Mars Hill, Vinalhaven (USA), Toora, Cape Bridgewater, Waubra (Australia), Wolfe Island (Canada)

Sound Characteristics: Wind Turbine Spectra

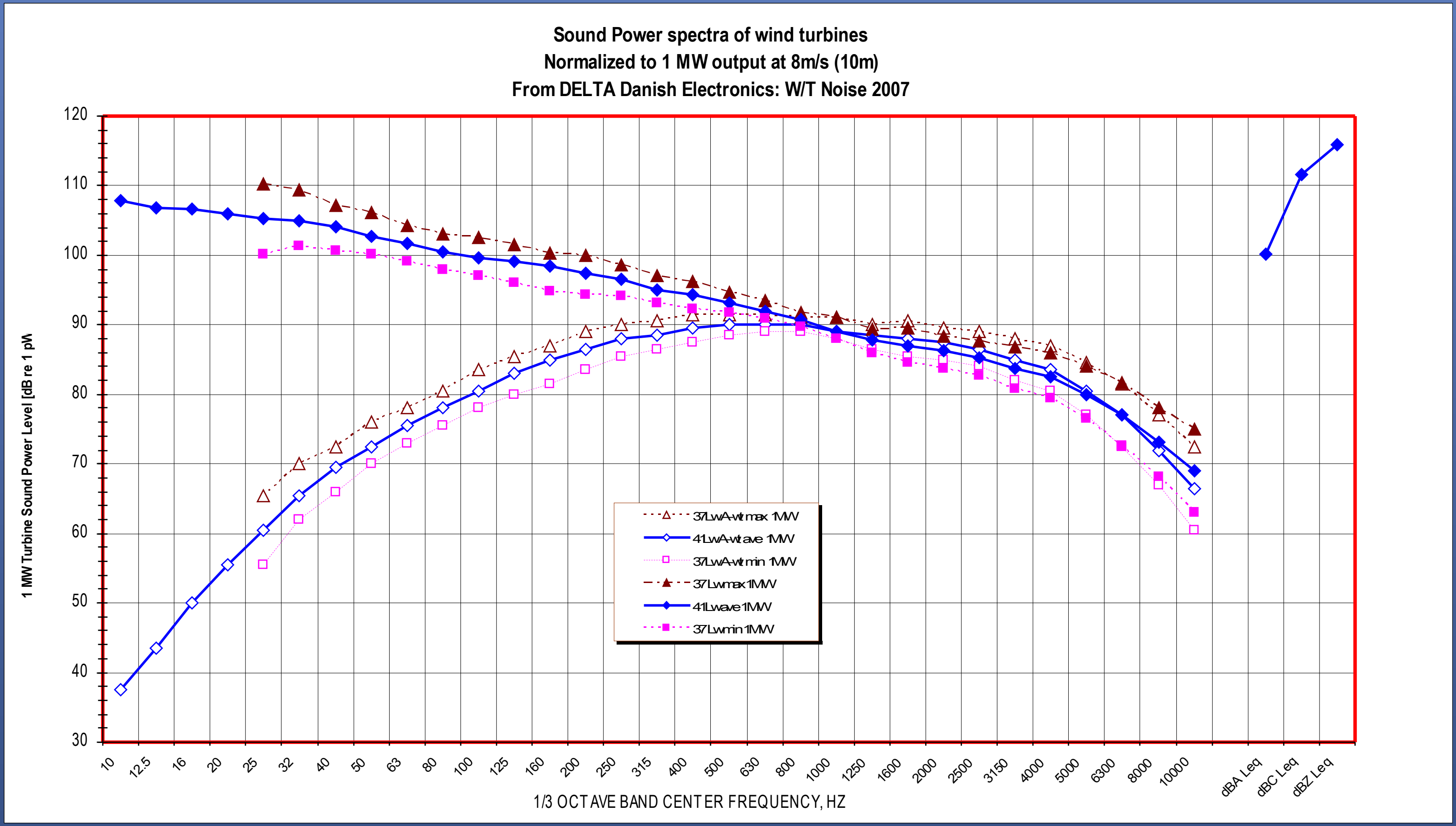
Bo Søndergaaard (2008)
Delta Report "Low Frequency Noise from Large Wind Turbines"



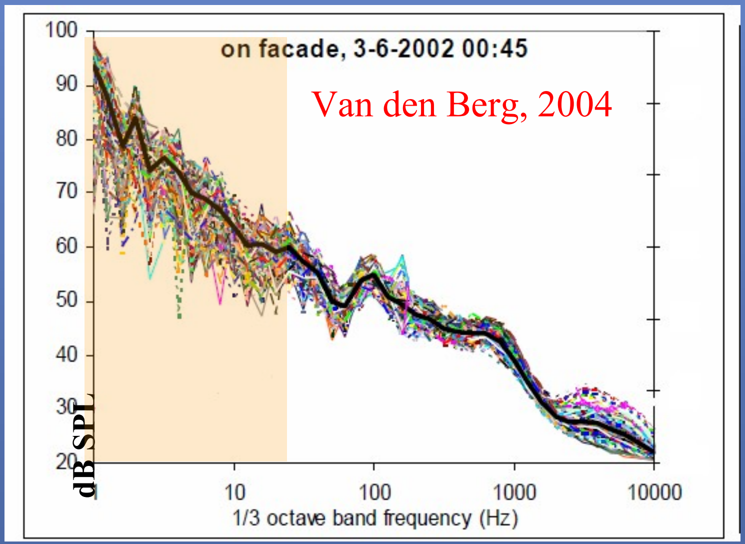
Peak energy at around 500 Hz

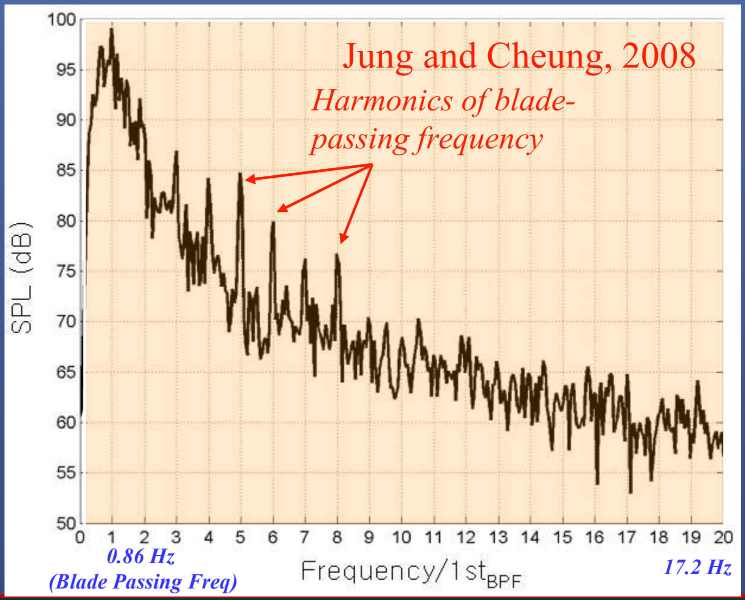
ed in the sound you can hear – these spectra
A-weighted" i.e. weighted according to
human hearing sensitivity.

Kampermann: Re-analysis of Bo Søndergaard's measurements to remove A- weighting

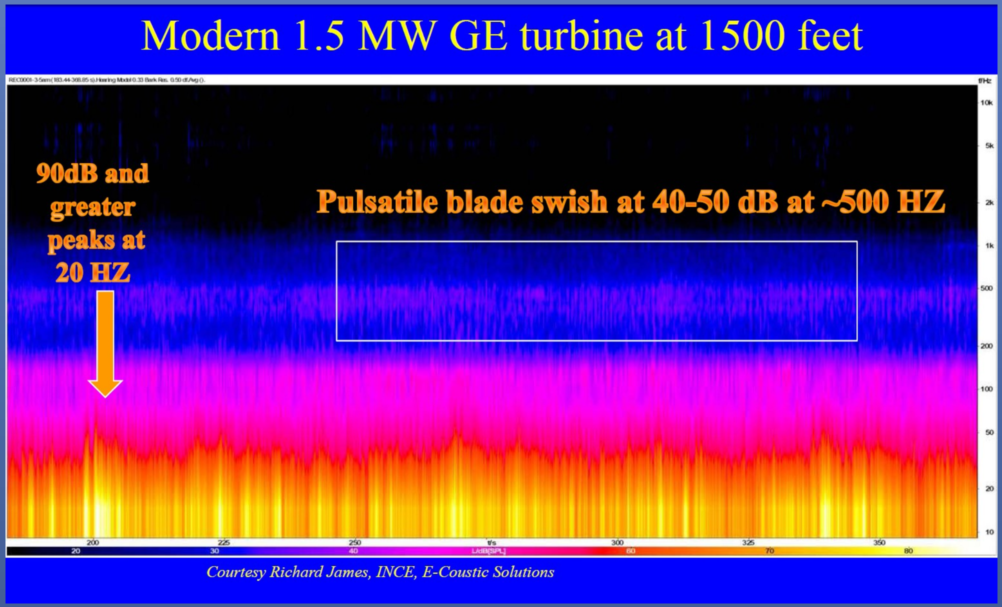


Wind Turbine noise shown as unweighted spectra





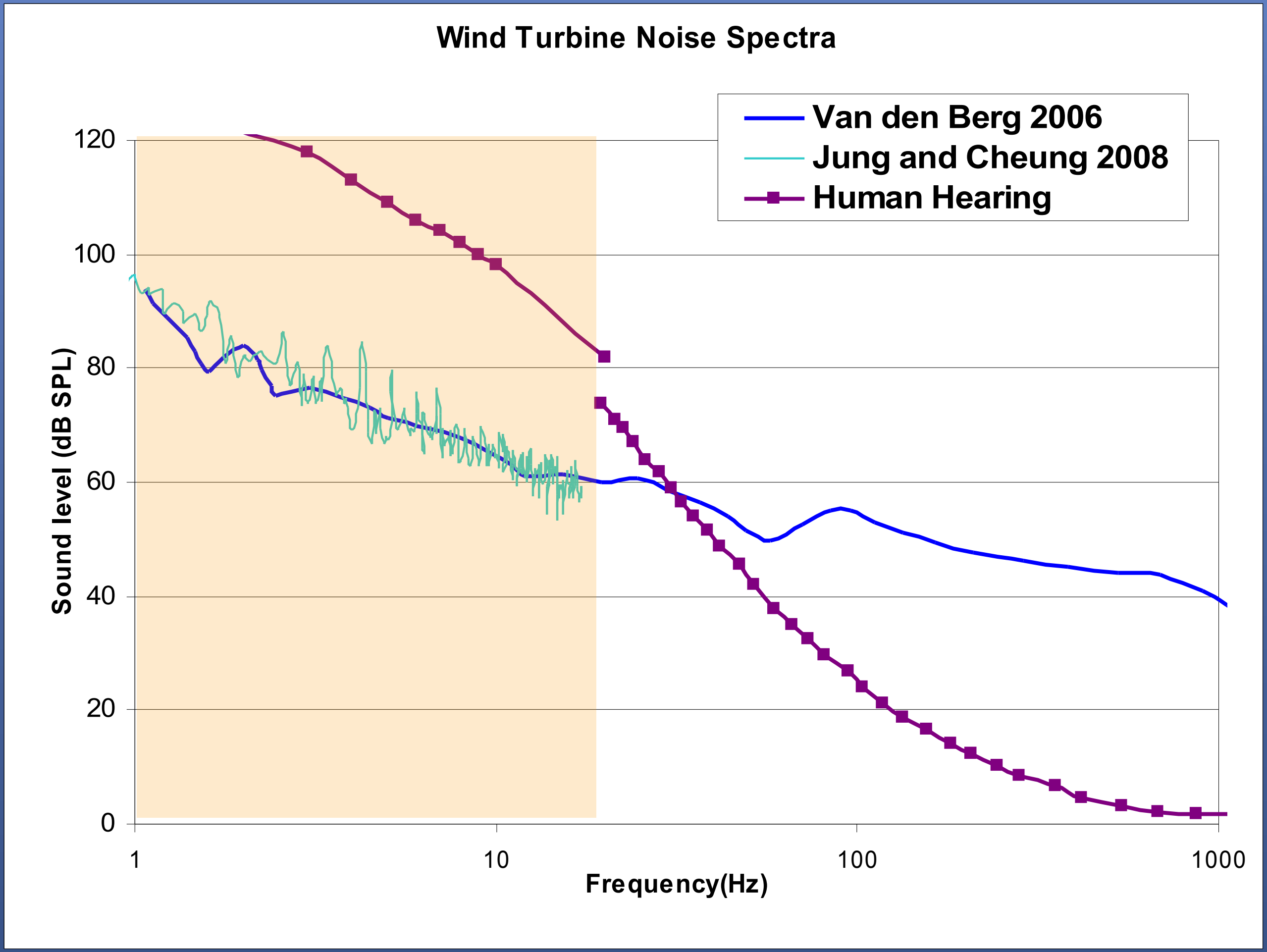
Spectrogram down to 10 Hz



Under some conditions, sound levels are over 90 dB SPL below 20 Hz.

Refrigerators do not generate infrasound to this degree!

Wind turbine infrasound is at levels that cannot be heard



The Wind Industry Position

"**Renewable UK**", the website of the **British Wind Energy Association** use this quotation from Dr. Leventhall, one of their consultants.

"I can state quite categorically that there is no significant infrasound from current designs of wind turbines"

*The critical word above is "**significant**". If you cannot hear the sound it is assumed to be insignificant.*

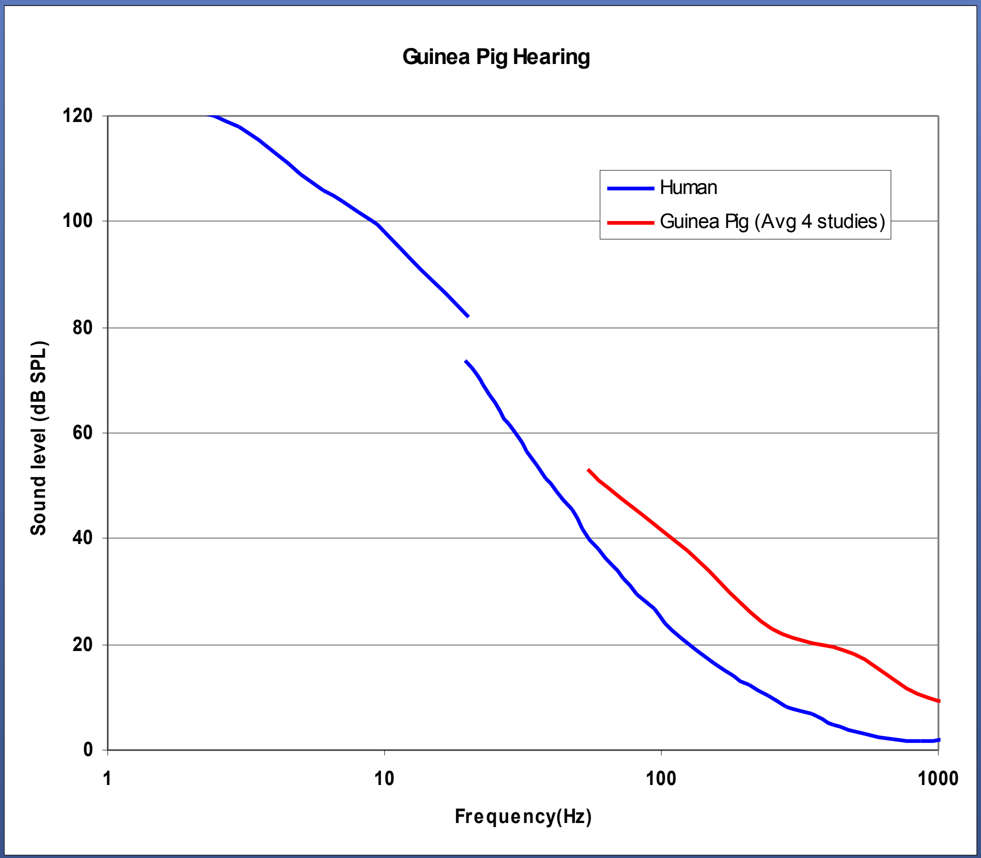
8. Unusual perception

The evidence is that the ear is the most sensitive receptor for infrasound and low-frequency sound, that if you cannot hear a sound you cannot perceive it in other ways and it does not affect you. However, unusual sensitivity is sometimes reported, for example by Feldmann and Pitten (2004). Here a family complained of disturbance at night, and consequent effects on health, allegedly caused by noise from a boiler house.

Leventhall G. What is infrasound? Progress in Biophysics and Molecular Biology 2007; 93: 130–137

If you can't hear a sound…it does not affect you

Hearing in guinea pigs compared to humans



Low frequency hearing sensitivity correlates well with cochlear length

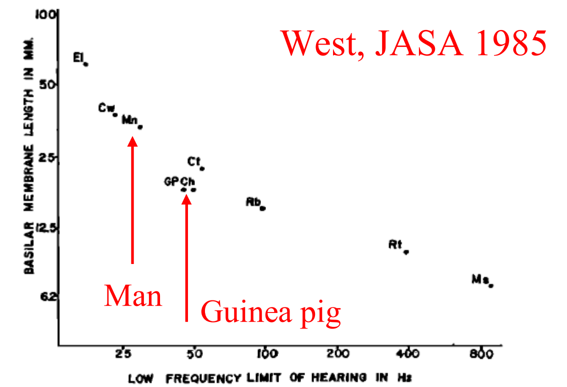


FIG. 8. Length of the basilar membrane versus the low-frequency limit of hearing for different species of ground dwelling mammals at 60 dB SPL, $r = -0.94$ ($P < 0.001$). Abbreviations: Ch—chinchilla, Ct—cat, Cw—cow, El—elephant, GP—guinea pig, Mn—man, Ms—mouse, Rb—rabbit, and Rt—rat.

The guinea pig cochlea is about half the length of the human

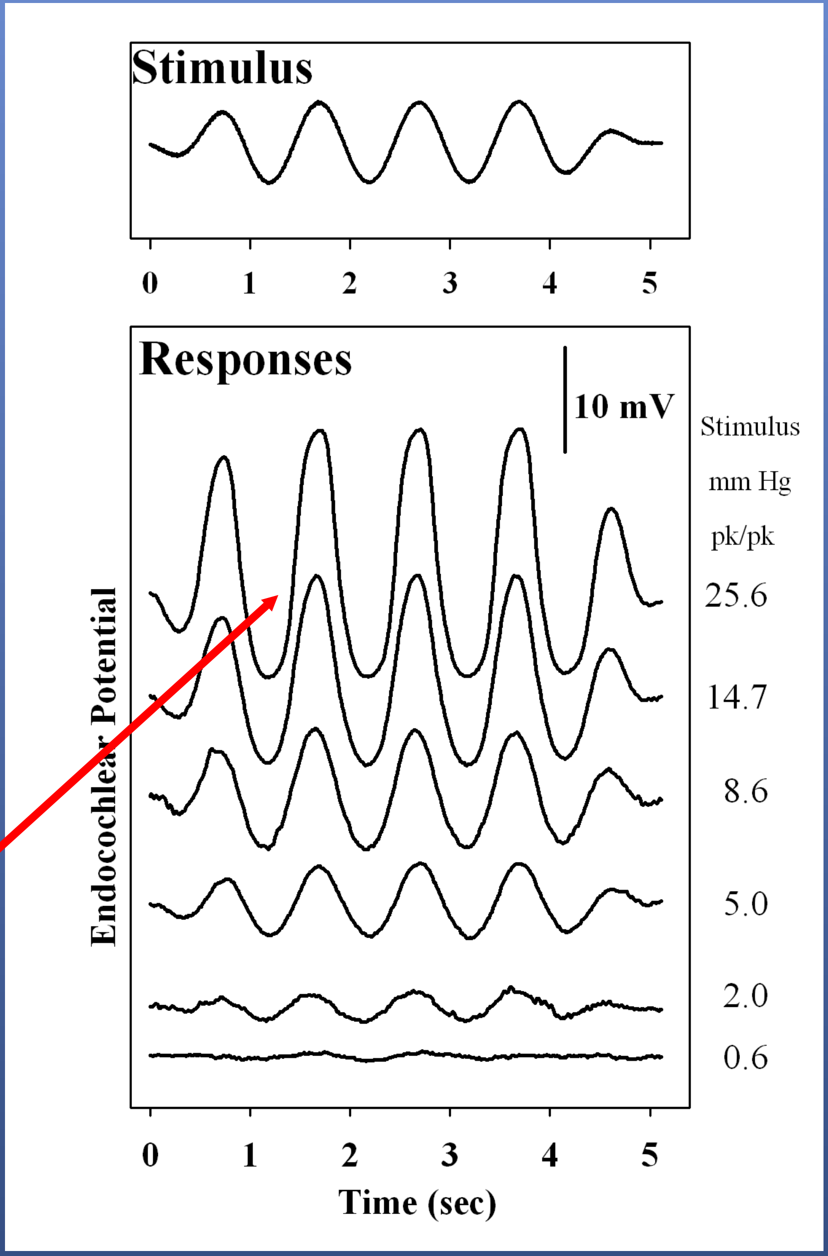
Guinea pigs are about 10-20 dB LESS sensitive than humans

Our Experience with Guinea Pigs and Infrasound

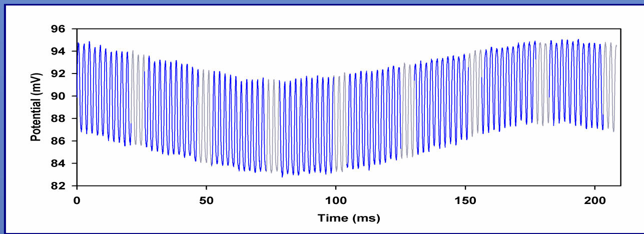
Is the ear insensitive to infrasound ?

Salt & DeMott, JASA 1999
Stimulus: Fluid pressure delivered from a pipette sealed into scala vestibuli.

Measuring potential from endolymphatic compartment of second cochlear turn.



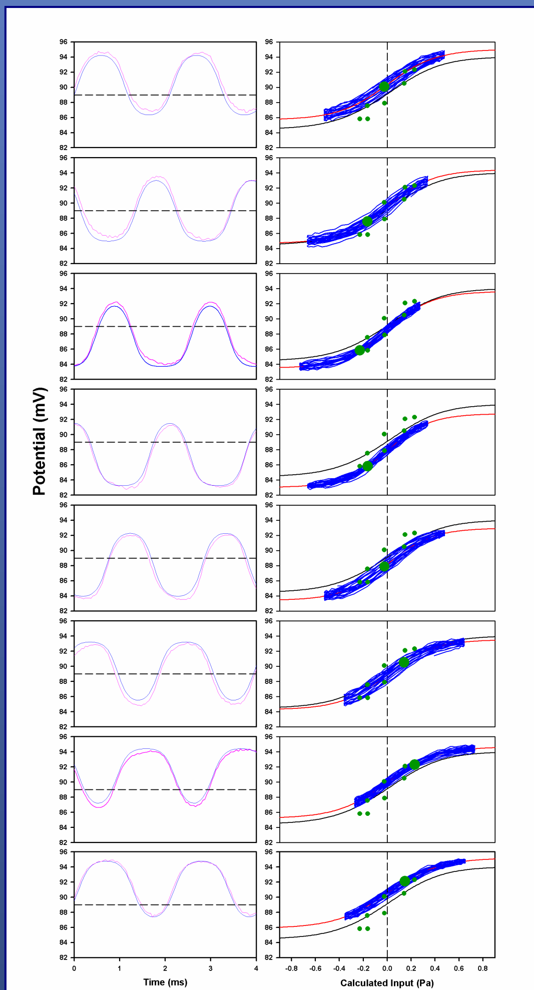
Absolutely HUGE cochlear microphonics!
24 mV pk/pk (EP was 72 mV)
(but this was not airborne sound)

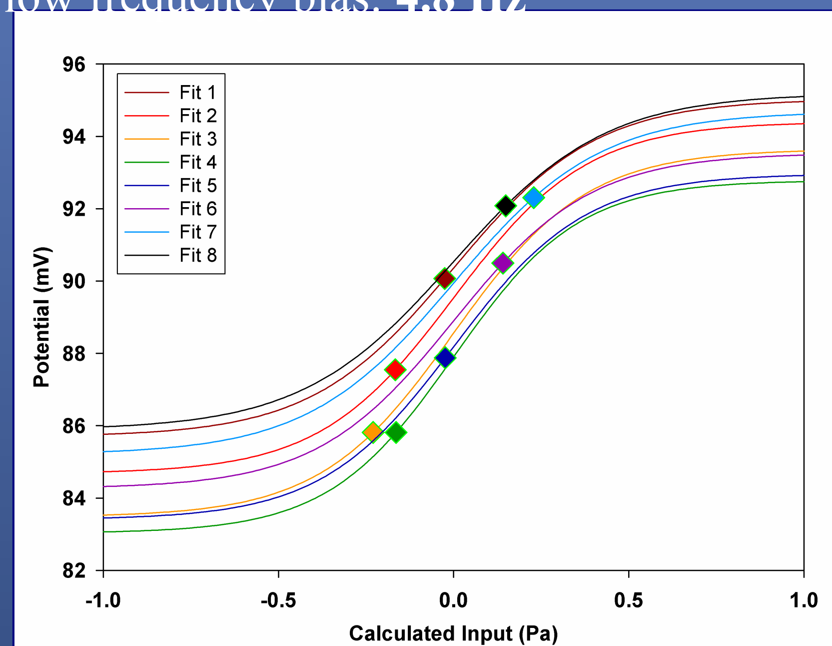


Cochlear Microphonic Biasing Experiments

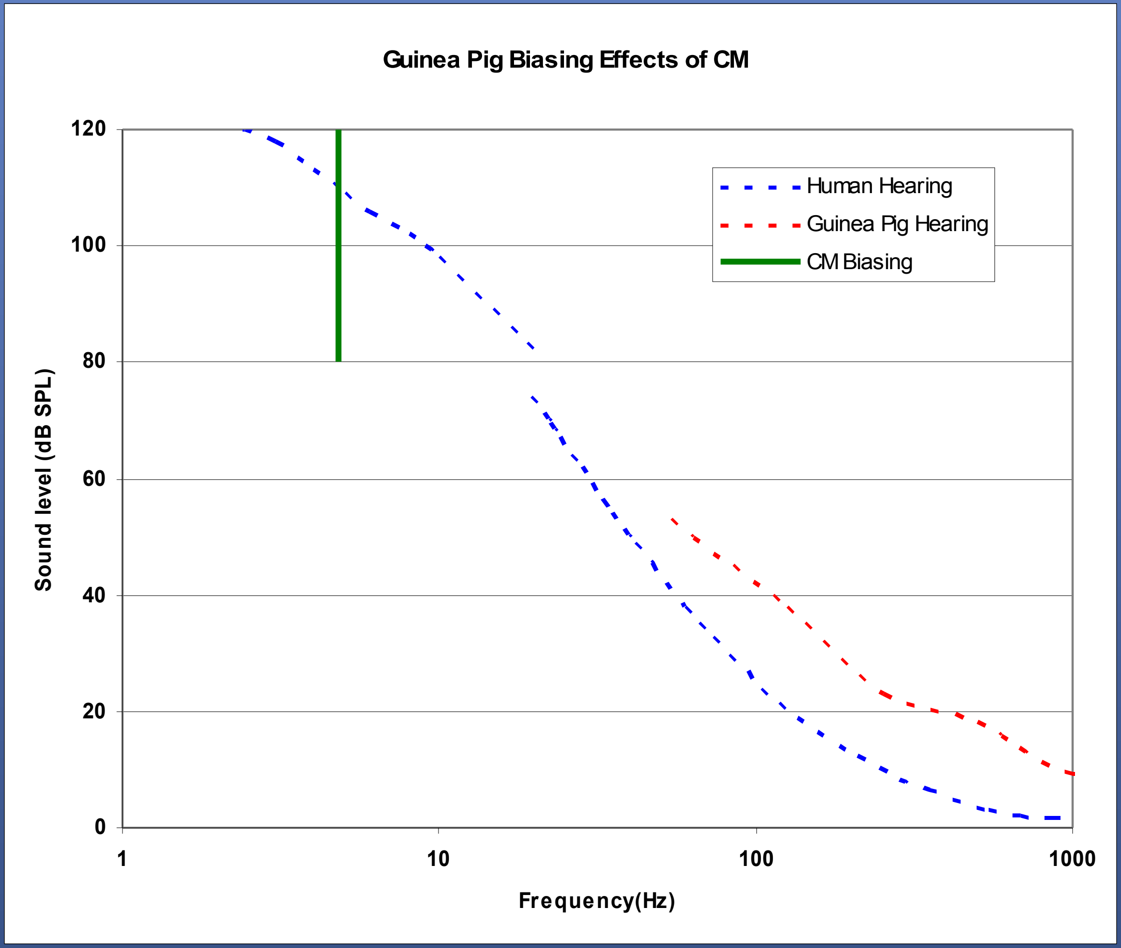
Looking at low frequency bias effects on transduction.

Because we wanted multiple “windows” we used a very low frequency bias: **4.8 Hz**





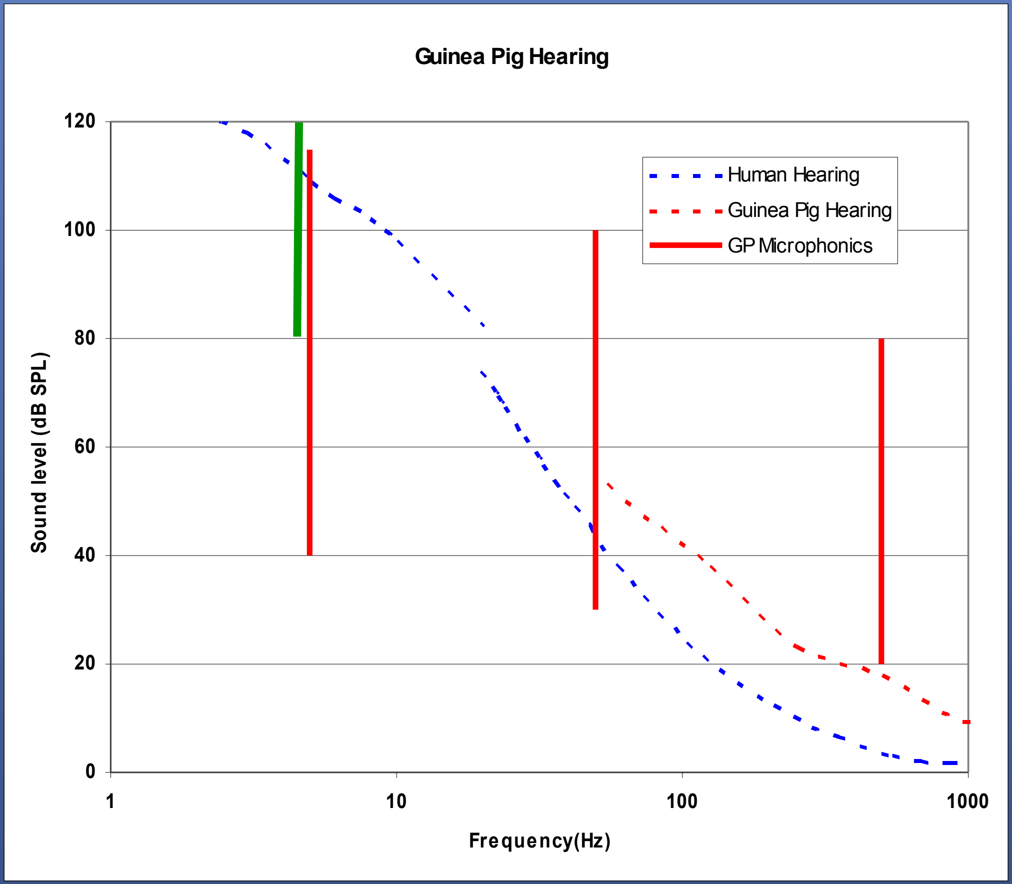
Sound Level Required for Biasing

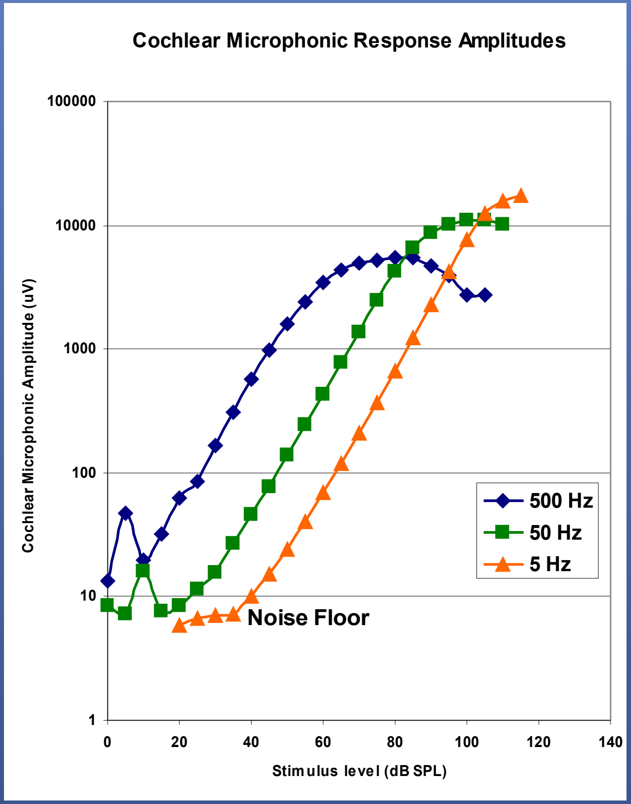


Bias tones are effective down to 80 dB SPL at 4.8 Hz !

30 – 40 dB below presumed hearing threshold.

Electrical recording from the guinea pig ear (cochlear microphonics)





Recording from scala media of the third turn of guinea pig (with averaging and band-pass filtering).

Explanation – Two types of sensory cell in the Ear

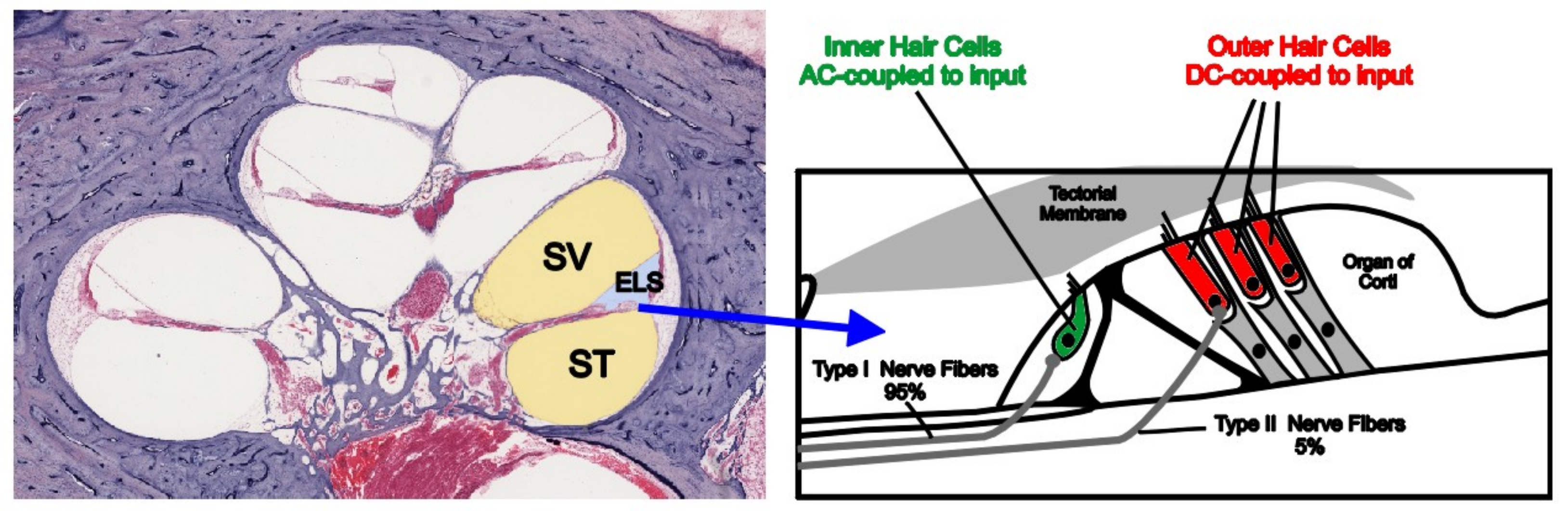


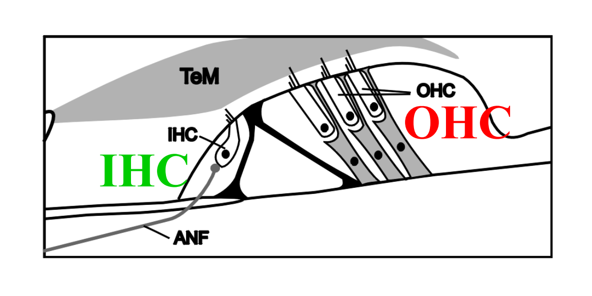
Image Courtesy of Saumil Merchant MD,
Mass Eye and Ear Infirmary, Harvard Medical School

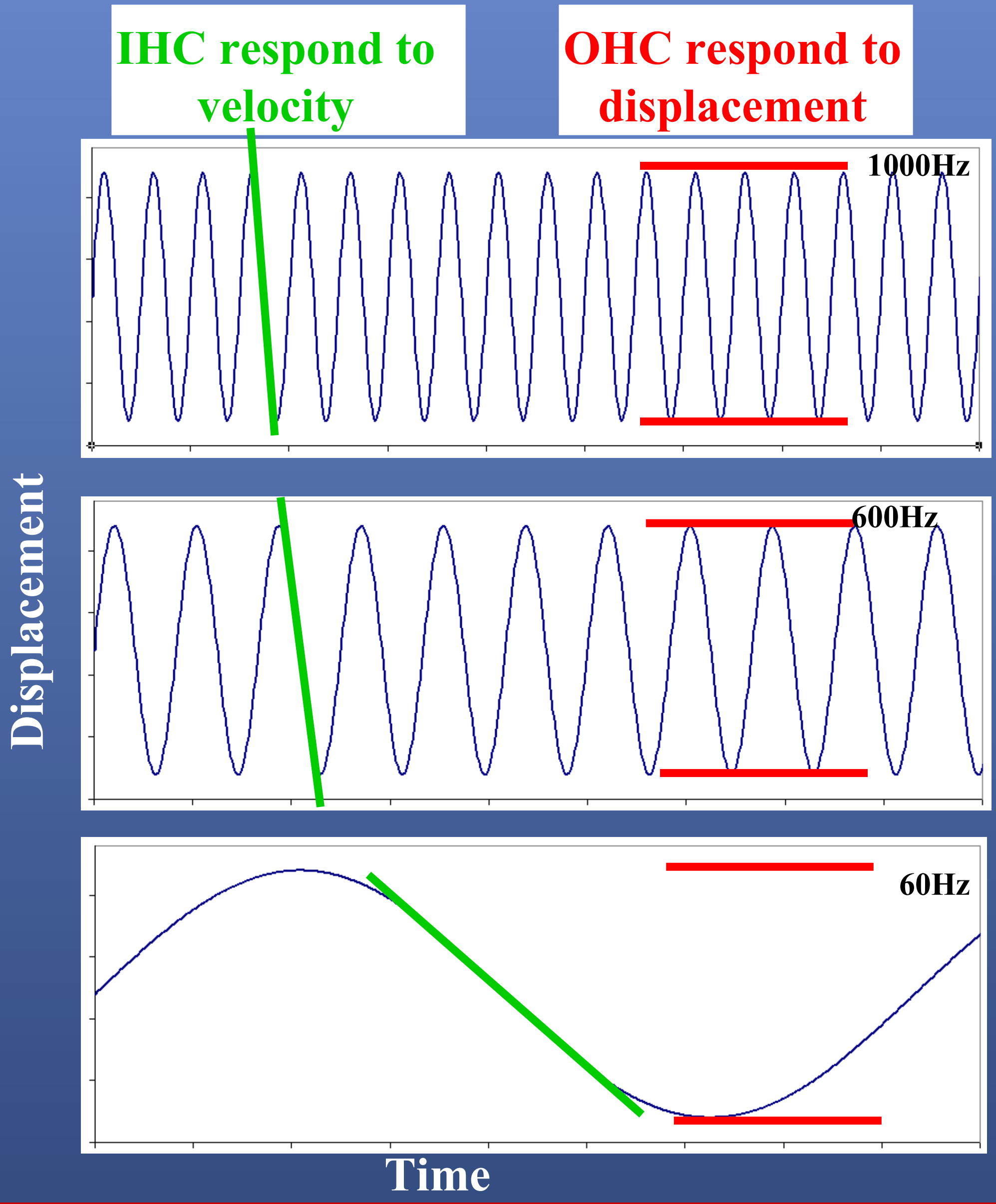
Two types of Hair Cells in the Cochlea

Inner Hair Cells (IHC)	Outer Hair Cells (OHC)
Responsible for HEARING	Generate Cochlear Microphonics
Hairs do NOT contact Tect. Memb.	Hairs Contact Tect. Memb.
*Respond to VELOCITY	*Respond to DISPLACEMENT
(velocity decreases 6 dB/oct as frequency is lowered)	*(displacement constant with frequency for fixed input level)*

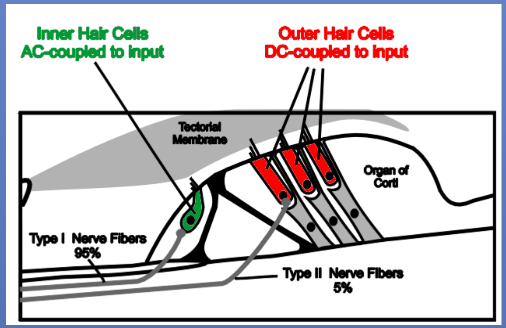
* *Based on Cheatham and Dallos, 2001*

IHC and OHC respond differently as sound frequency is changed

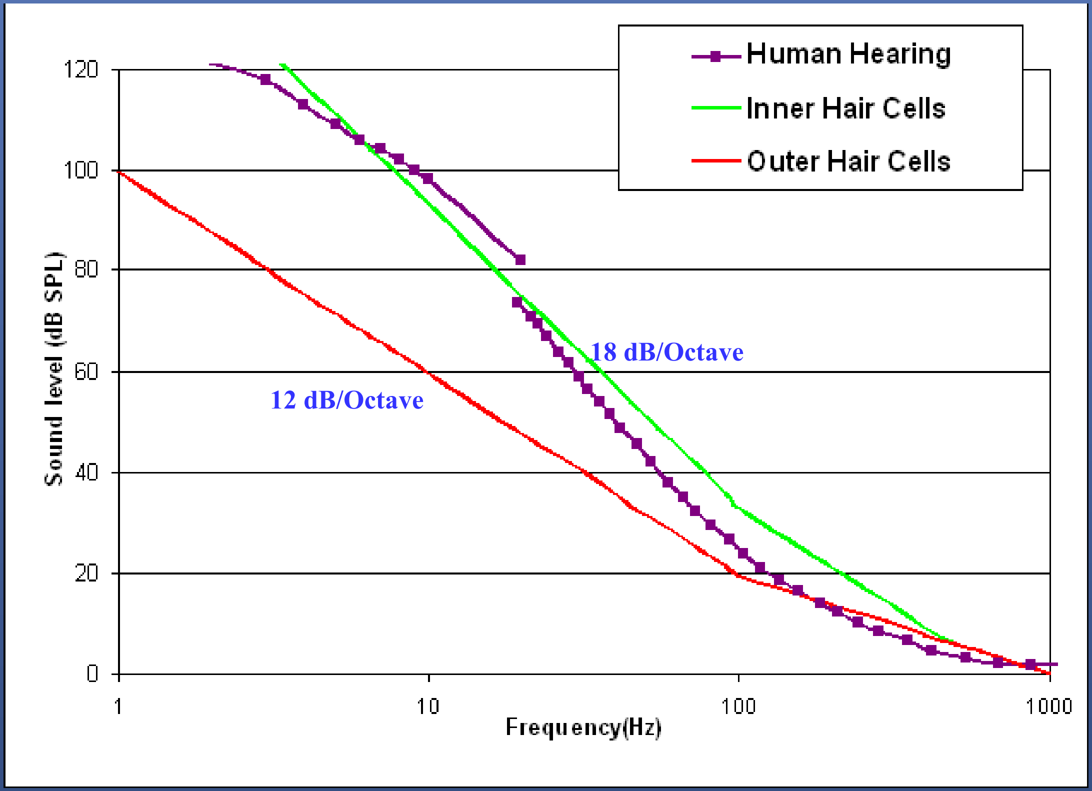




Calculated Hair Cell Sensitivity



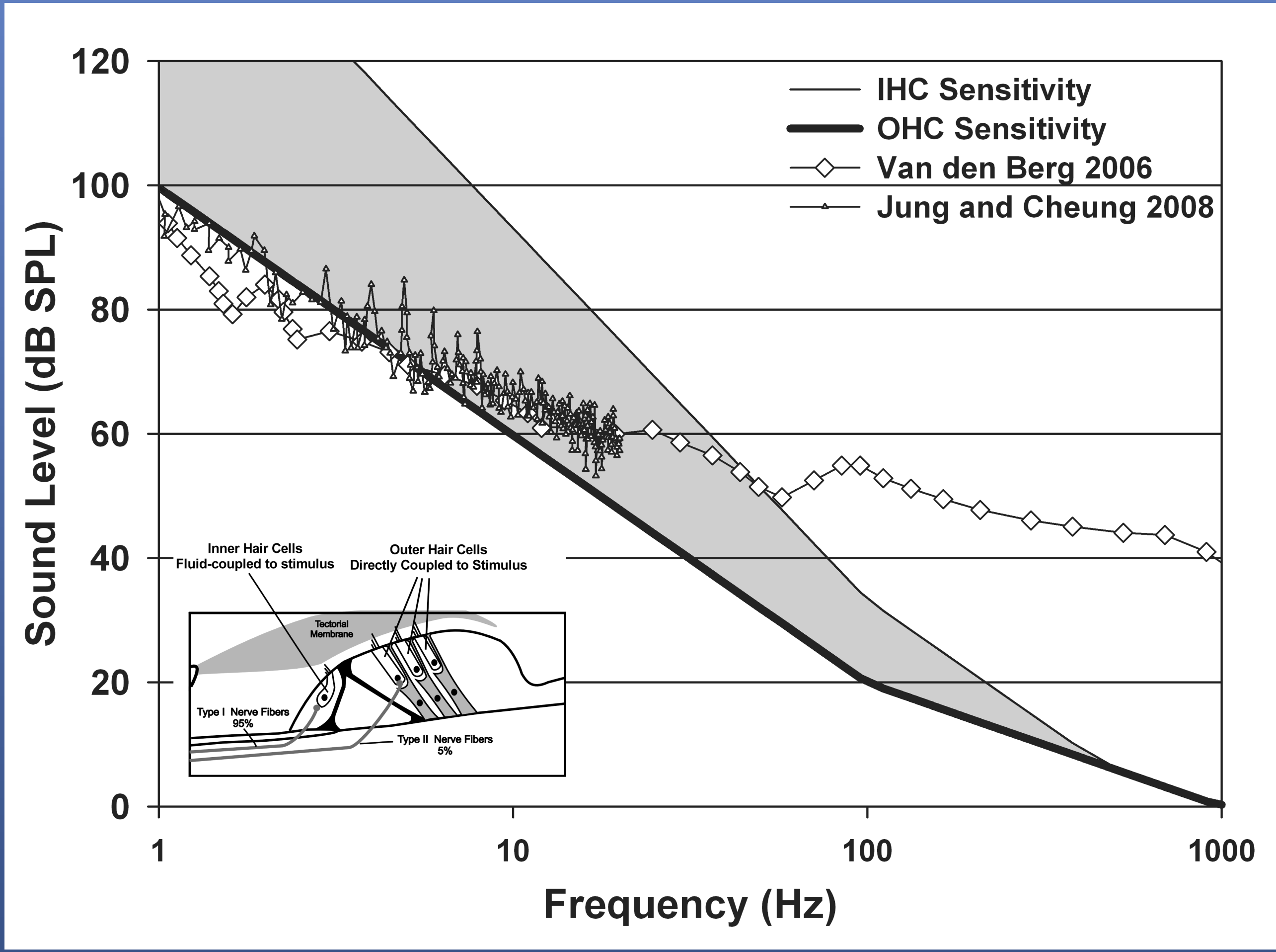
Cheatham and Dallos JASA 2001;110:2034.



We hear through our INNER HAIR CELLS. As they are insensitive to infrasound, we don't hear the infrasound.

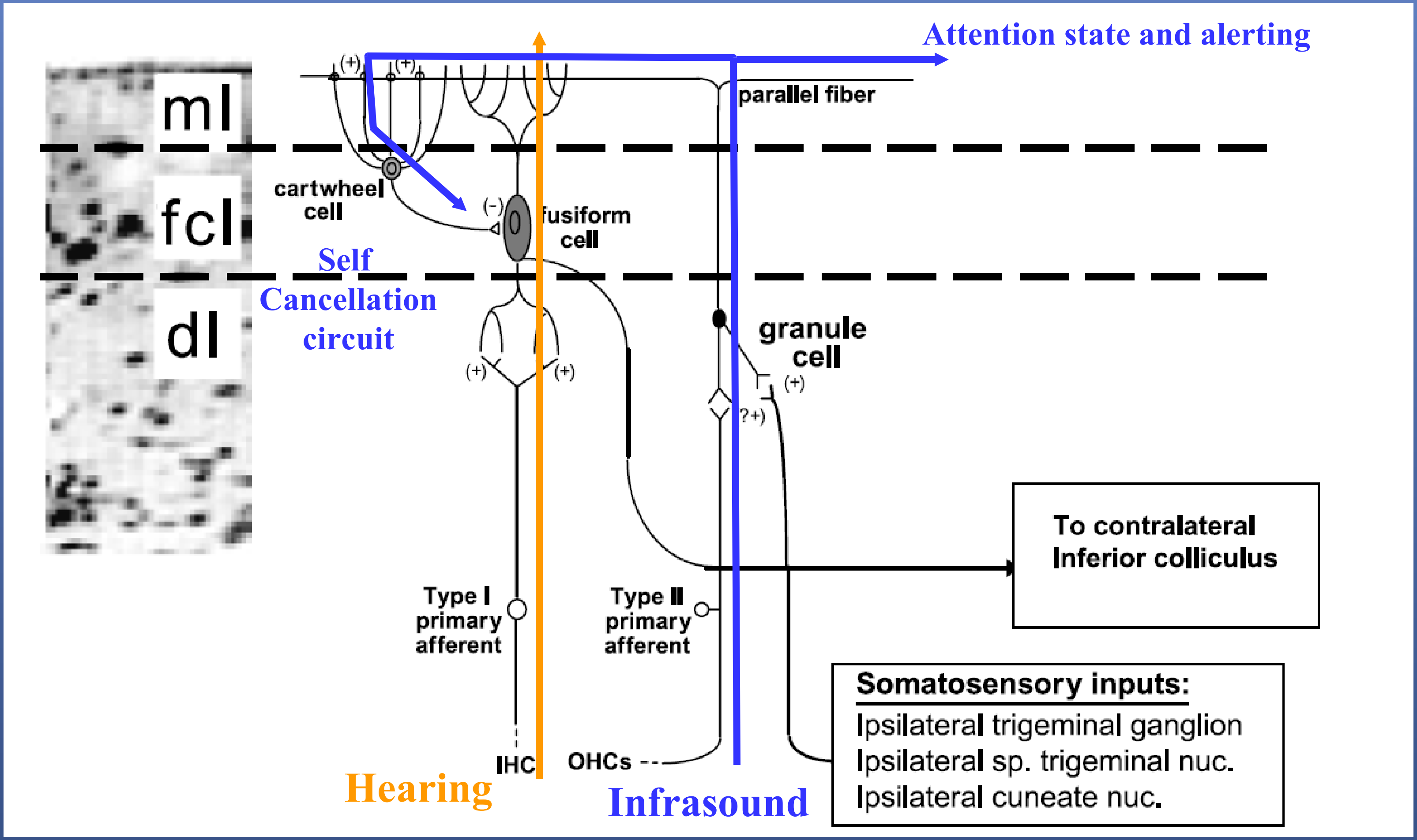
OUTER HAIR CELLS generate the cochlear microphonic response. They are stimulated at ~40 dB lower sound levels at low frequencies.

Wind Turbine Sounds you don’t Hear will stimulate the OHC



Sound in the gray, shaded area (5 – 50 Hz) will not be heard but will stimulate the OHC

Connections within the brain

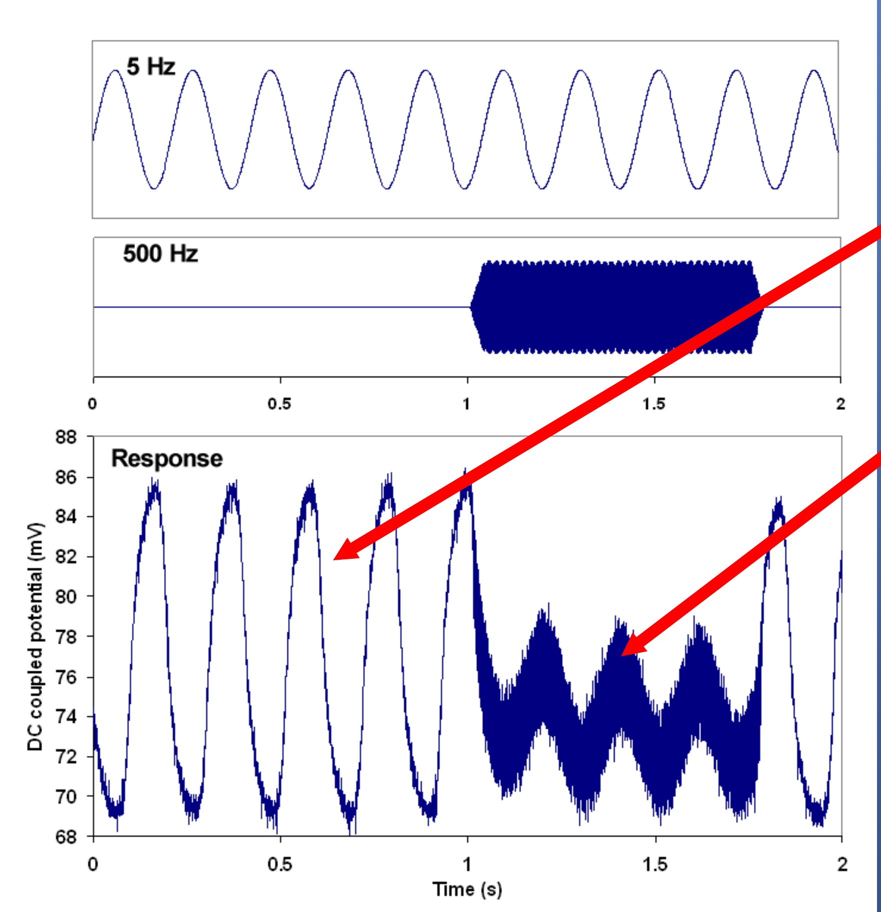


From Kaltenbach and Godfrey, 2006

Important Conclusions

- Outer Hair Cells detect and transduce low frequency sounds at levels substantially below those that are heard.
- OHC stimulation by unheard low frequency sound could cause sensations of fullness, pressure or tinnitus and may disturb sleep.
- “What you can’t hear can’t affect you” is FALSE

Infrasound responses are suppressed by higher frequency stimuli (i.e. sounds that are heard)



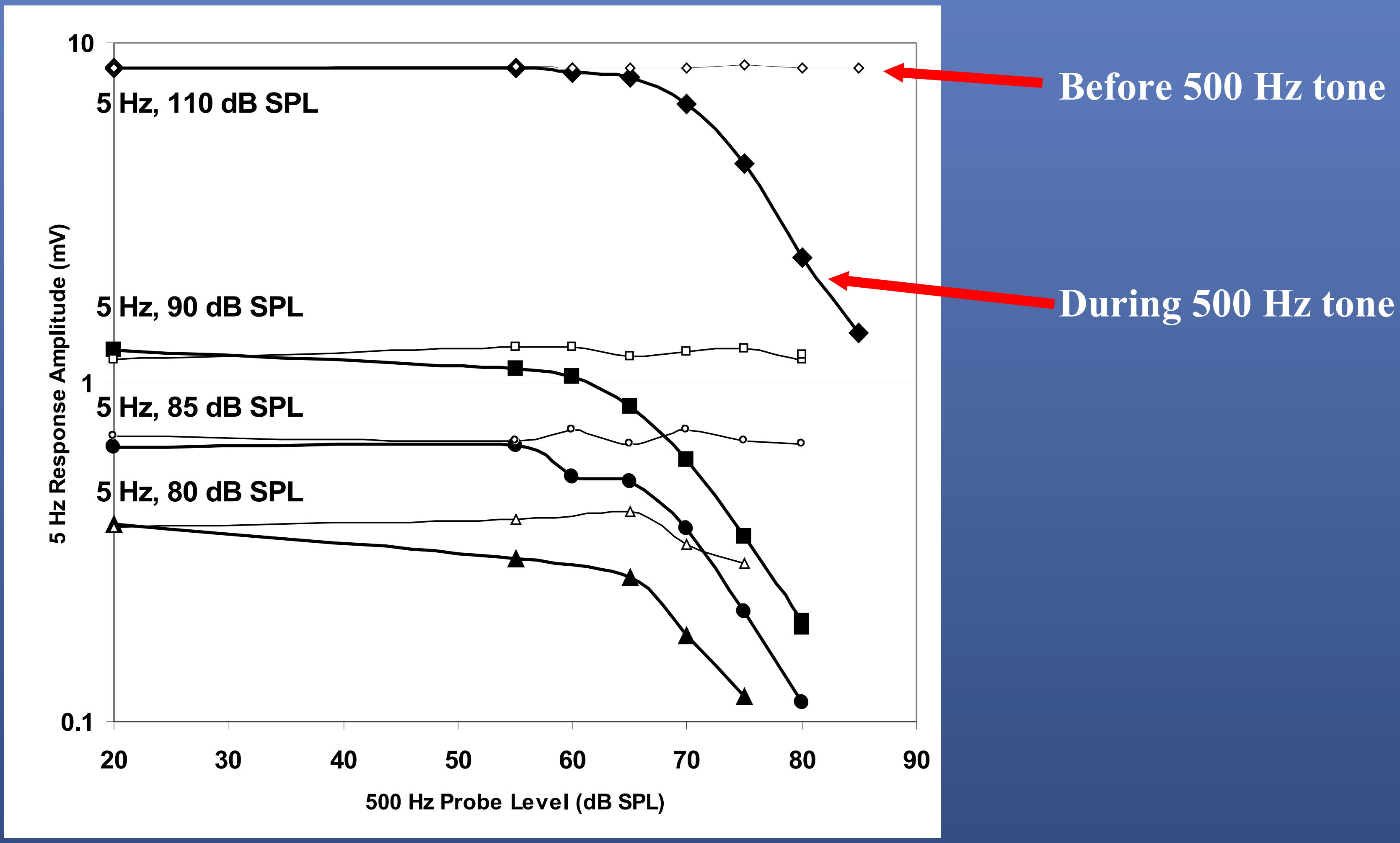
Cochlear Microphonic response (generated by outer hair cells) to a 5 Hz stimulus.

5 Hz response is suppressed by a superimposed 500 Hz tone.

Responses and sensitivity to low frequency sounds could depend on the “listening environment”.

Maximum sensitivity would occur when ambient sound levels are low

Sensitivity to infrasound is maximal in a quiet environment even at low infrasound levels



Considerations of infrasound exposure in the home.

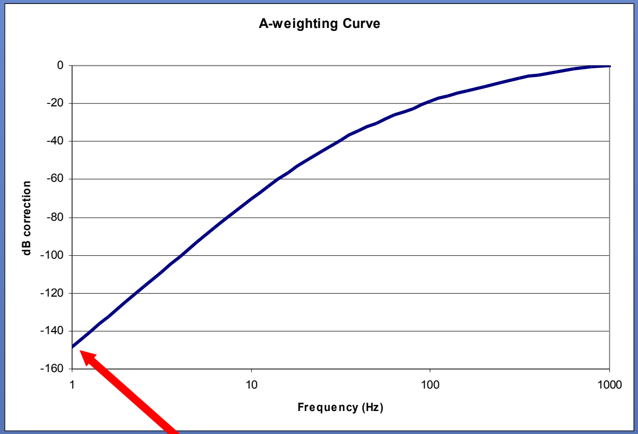
Exposure duration may be considerably longer than the work week. Includes weekends, morning, evening, nighttime. Exposure may be 24 hrs a day, 7 days a week if the person doesn’t work.

Infrasound travels further (is attenuated less with distance) than higher frequency sounds which are attenuated by vegetation, etc.

Infrasound is not attenuated by the house structure, even though audible sounds are attenuated.

The maximum influence of infrasound probably occurs while in a quiet room (e.g. sleeping in a bedroom).

A- weighting noise measurements



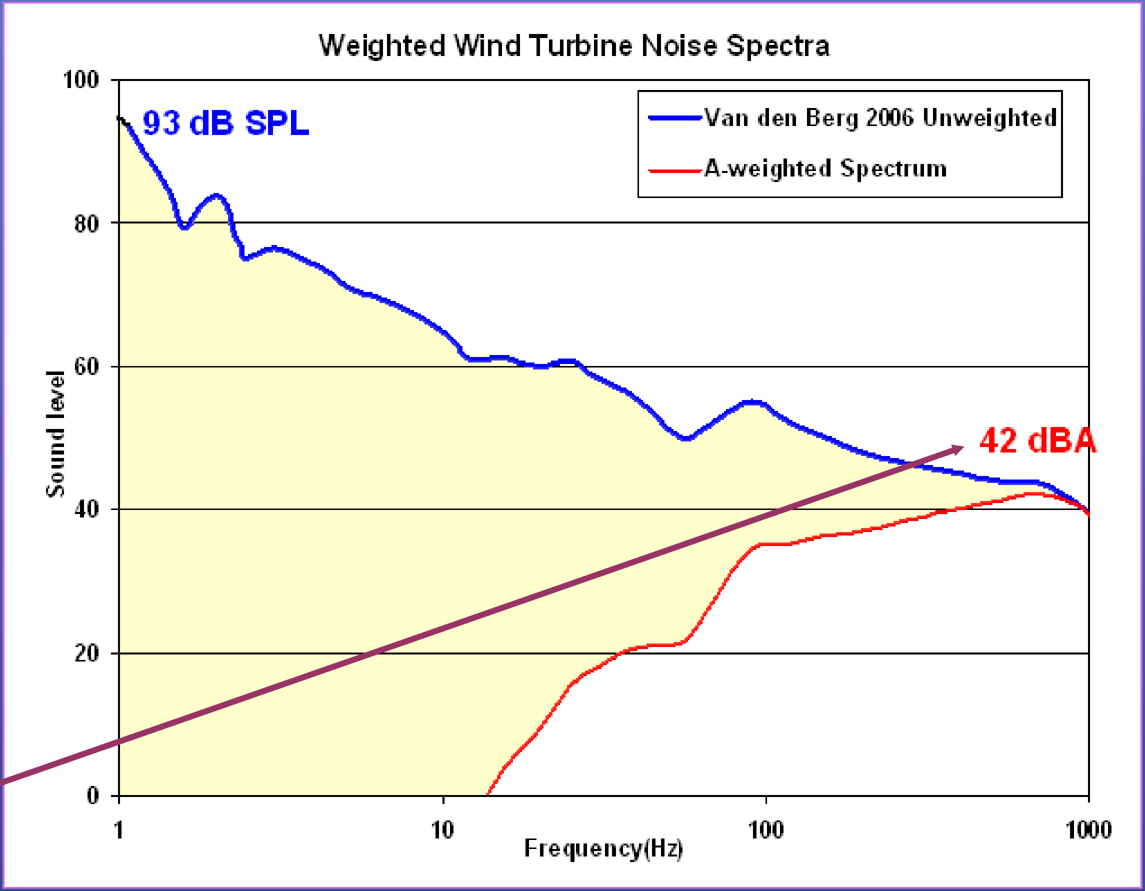
Not a "minor correction"!

Over 140 dB at 1 Hz.

Is only valid if "hearing" is the important issue.

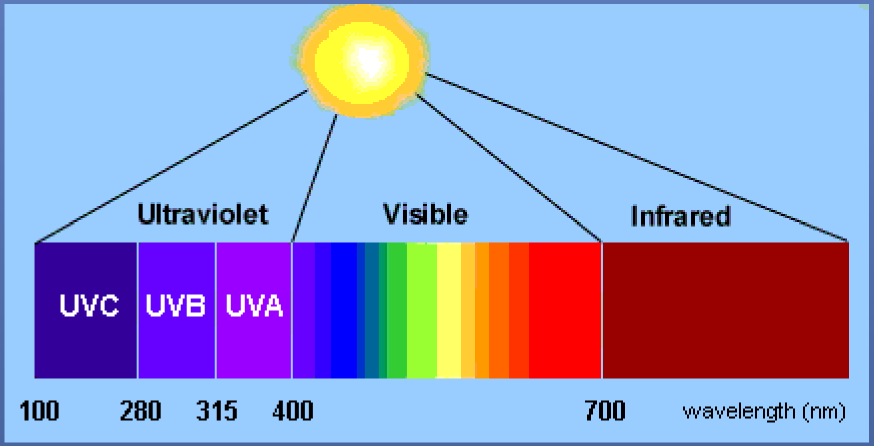
If other structures of the ear respond a levels lower than the heard level, A-weighting is inappropriate.

Rustling of Leaves ☺



Analogy with UV light filtering

Ultraviolet (UV) light is invisible…

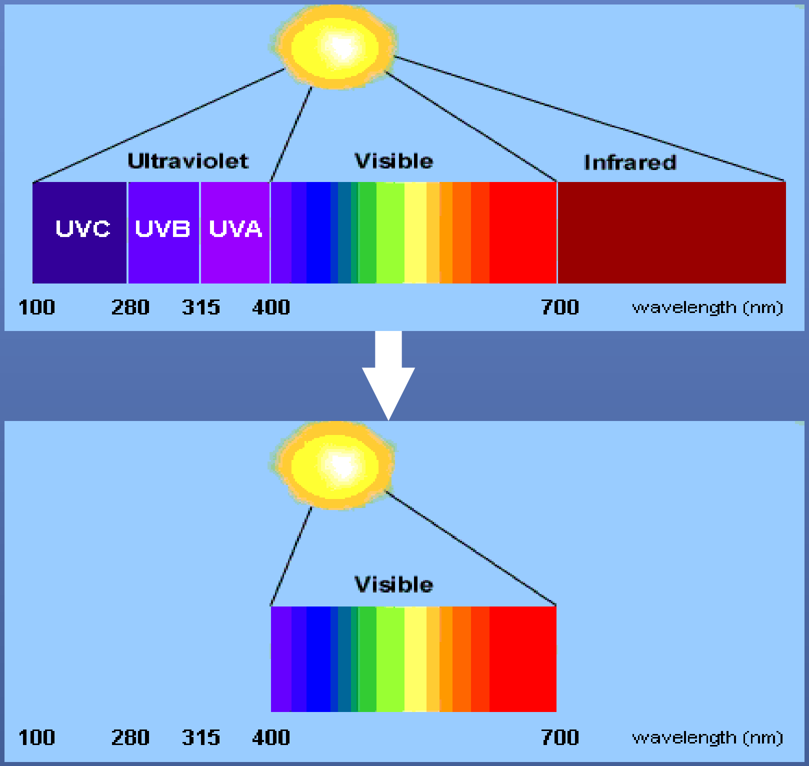


…but it can affect you.

Photokeratitis,
"snow blindness"
"welder's flash"
+
cataracts

Sunburn

“A-weighting” principle applied to UV light



Adjust sunlight spectrum to only show what is VISIBLE

Conclude that there is nothing that can harm you.
You don’t need sunscreen.
You don’t need sunglasses.
Go spend all day laying out in the sun. ☺

This approach isn’t rational when applied to light,
So how can similar logic applied to sound ???

Measuring visible light (e.g. taking photographs with a regular camera) tells you nothing about UV content.
A-weighted measurements tell you nothing about the infrasound content.

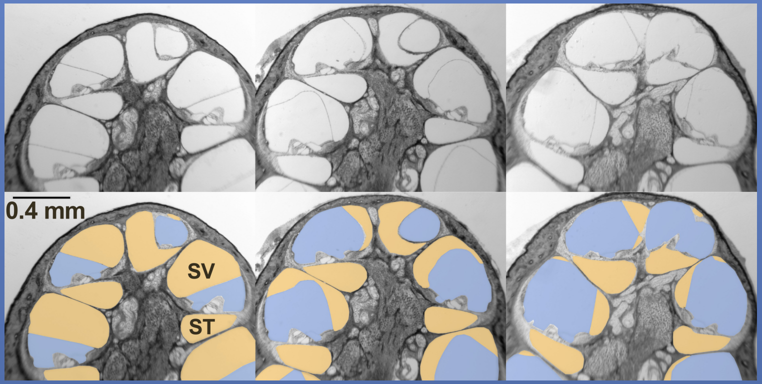
Show Me the Noise!

- Most video recorders (e.g. news crews), home camcorders, tape recorders, cellphones, etc. are incapable of detecting wind turbine infrasound.
- Most speakers will not generate sounds below 20 Hz.
- YouTube videos showing how quiet or noisy wind turbines are are meaningless.
- Radio shows cannot demonstrate what it sounds like.
- This makes it difficult to show people such as politicians and wind turbine executives what the problem is. Many people do not really understand what infrasound is. It requires a technical background to understand.

Sensitive patient groups

Meniere's disease

The helicotrema is one of the structures that Reduces the sensitivity of the ear to low frequency sounds.
Endolymphatic hydrops can plug the helicotrema.



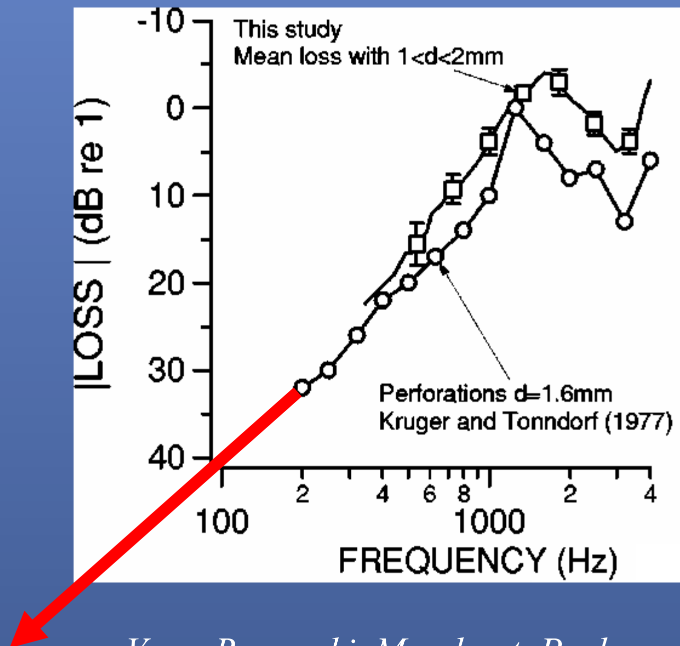
In animals with hydrops, or animals with the helicotrema plugged by injection of gel, sensitivity to infrasound (5 Hz) increases by approximately 20 dB.
(Salt et al., (2009) Hear Res 250:63–75.)

Superior canal dehiscence syndrome

"Third window" pathologies increase the sensitivity of vestibular structures to airborne low frequency sounds.

If disturbance increases with the level of infrasound (increasing OHC stimulation), then these patient groups would be expected to be more sensitive to wind turbine noise

Insensitive patient group



Voss, Rosowski, Merchant, Peake, JASA, 2001, 110, 1432.

Tympanostomy tubes attenuate the entry of infrasound into the ear by at least 50 dB
(depending on perforation size)

Montandon et al., 1988: Tympanostomy tubes as a therapy for Meniere's disease.

If infrasound affects Meniere's symptoms, this would be ameliorated by tympanostomy tubes.

Could the symptoms of some Meniere's patients have their symptoms caused or exacerbated by infrasound exposure?

Accelerated Presbyacusis ?

- In a chinchilla model of noise damage, we showed that simultaneous exposure to damaging (4 kHz) noise and low frequency sound (30 Hz) produced larger focal lesions than when the low frequency was absent.

  (Harding et al. 2007. Effect of infrasound on cochlear damage from exposure to a 4kHz octave band of noise. Hear Res. 225:128.)

- The possibility exists that over the long term, the rate of loss of hearing could be greater in a sustained low frequency sound environment.
- No studies have yet addressed this issue. It may be a mistake to assume there are no consequences of long-term low frequency sound exposure.

Conclusions with regard to wind turbines

- The ear is sensitive to low frequency sounds at the levels generated by some wind turbines.
- People disturbed by wind turbines placed near their homes don't think they are being treated fairly.
- There is considerable resistance from the wind turbine companies to accept that a problem could exist.
- There is a lack of understanding of wind turbine noise character, how best to measure it, and how it influences the ear.
- More auditory physiologists need to become active in this area. Our field has let down both the engineering community and the public by not presenting what is known about the ear in a form that those outside the auditory neuroscience community can understand.

Image from www.windturbinesyndrome.com

Conclusions regarding patients in the clinic

- Understanding the influence of wind turbine noise on the human "guinea pigs" presently living near wind turbines may contribute to our scientific understanding of the ear and its response to low frequency sounds.
- If long-term exposure to low frequency sounds, at levels that are not heard, can cause otologic symptoms such as tinnitus, fullness and unsteadiness, this may contribute to the symptoms of other patients who are unknowingly exposed to infrasound from other sources, such as air handlers, automobiles (soft top), etc. This may be more apparent if the patient has a pathologic condition that makes them more sensitive to infrasound.
- In patient histories, it may be necessary to ask if they live in the vicinity of wind turbines.

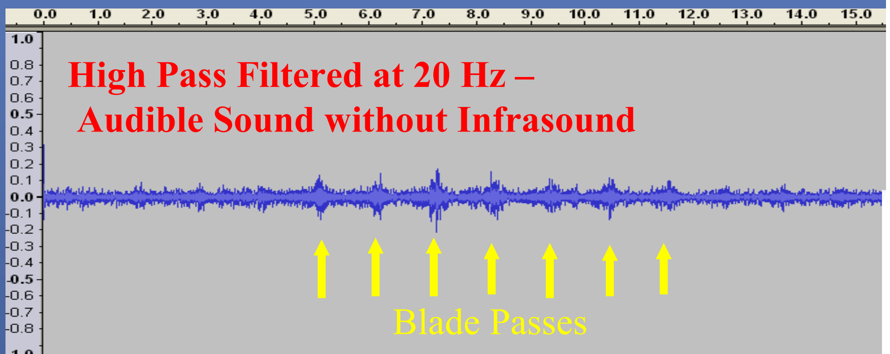
What should be done?

- Increase the “setback” distance to one where fewer people experience symptoms, e.g. 2 km, until the issue is better understood.
- Noise monitoring (not A-weighted, but including infrasound) in homes closer than the 2 km setback distance.
- Fund longitudinal epidemiological studies (blood pressure, sleep status, etc) in conjunction with noise measurements (blind to subjects) to assess whether symptoms correlate with turbine noise and/or infrasound.
- Determine whether tympanostomy tubes alleviate the symptoms of those living near wind turbines.
- Long term audiology monitoring of those living nearby (presbyacusis).
- More research in this important area.

Amplitude Modulation

- Blade "swish" and blade "thump" are perceived as a highly annoying character of wind turbine noise
- Swish: audible downstroke of blade, disappears with distance downwind, and at hub height (Bowdler 2010).
- Thump: Asymmetric waveform, more apparent with turbulent wind, more apparent downwind (Bowdler 2010).

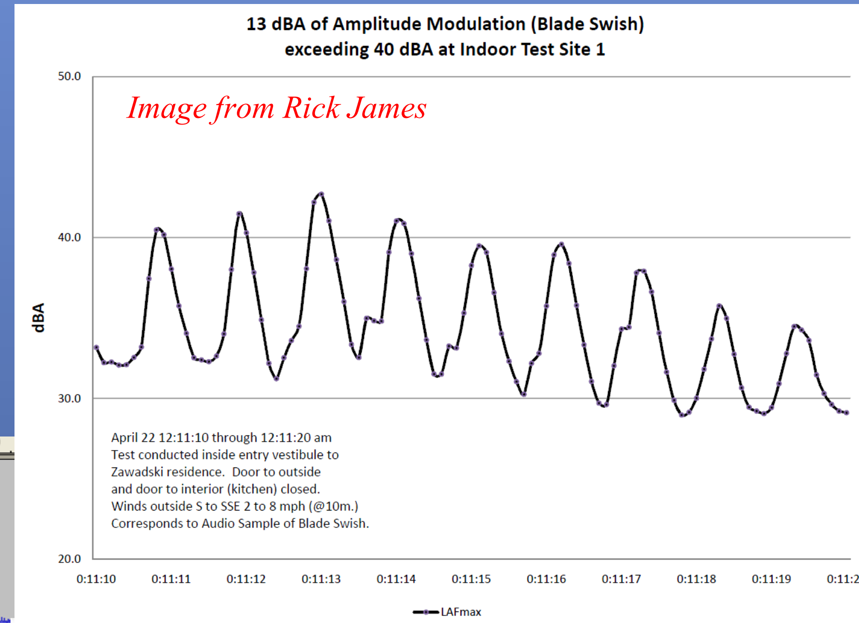
Measures of Amplitude Modulation
(Blade Swish)

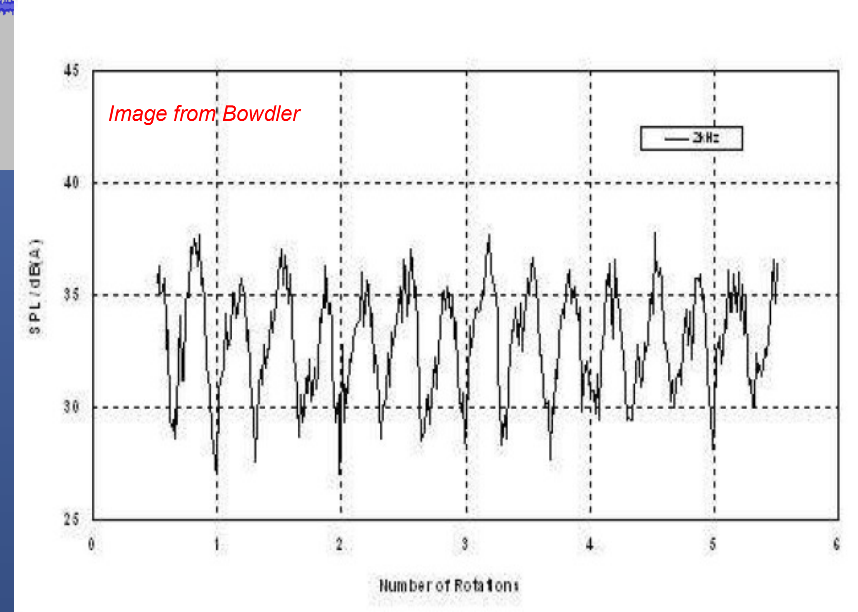


Audible sound measured with the sound level meter (A-weighted, so no infrasound) varies up and down with time.

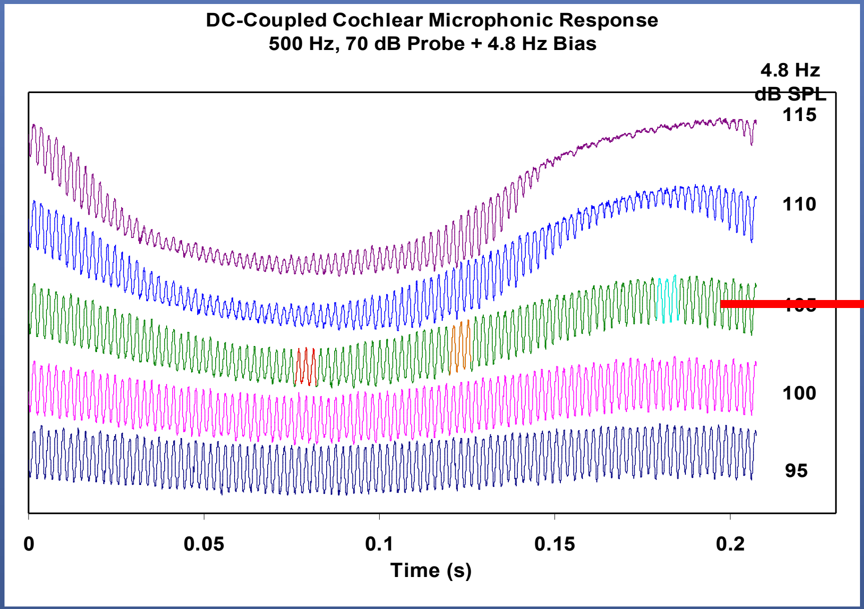
The envelope represents an infrasonic frequency.

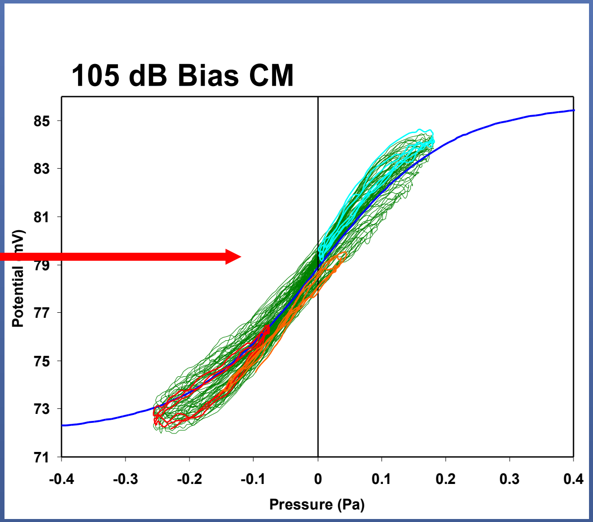
It has been assumed that this represents the modulation that annoys people.





Amplitude Modulation of Cochlear Microphonics by Infrasound

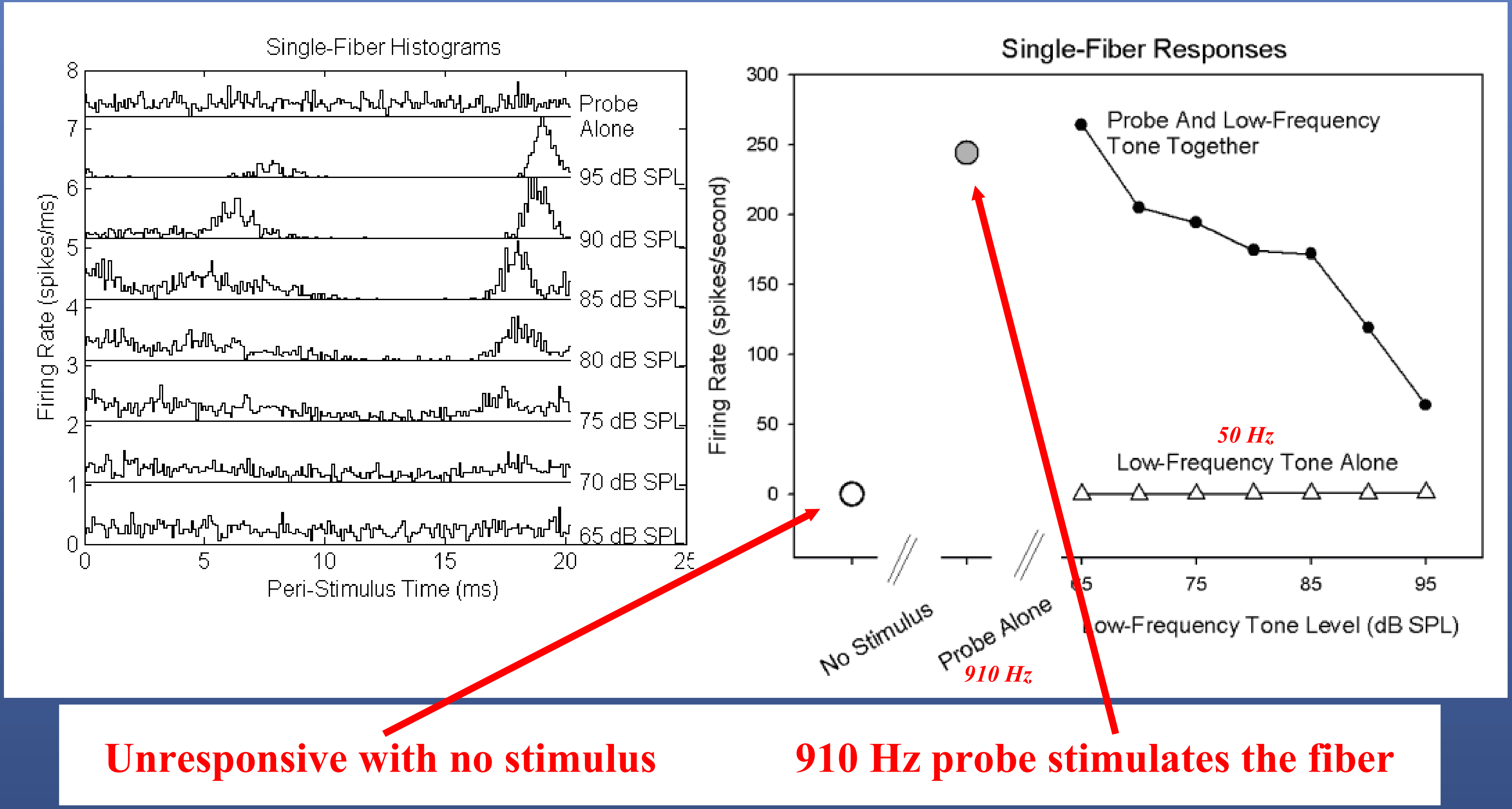




Waveform changes (altered amplitude and distortions) of the cochlear microphonic as low frequency bias tones drive the "operating point" up and down the cochlear transducer curve.

Amplitude modulation of single unit responses

Auditory nerve fiber responses from cat collected by Jeff Lichtenhan, Harvard Medical School



Amplitude modulation of single unit responses

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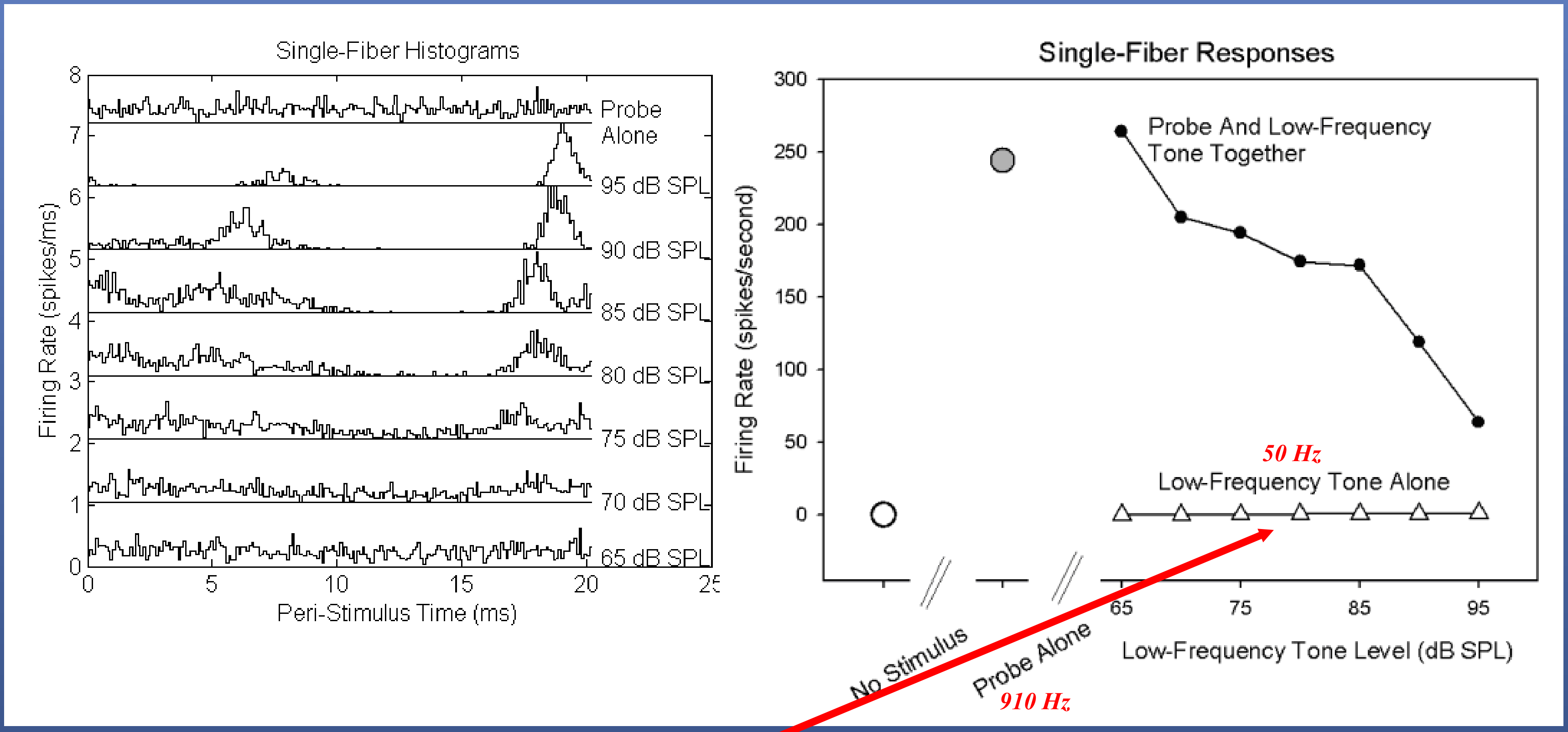

Alone, the 50 Hz tone doesn't affect the fiber at any level

Amplitude modulation of single unit responses

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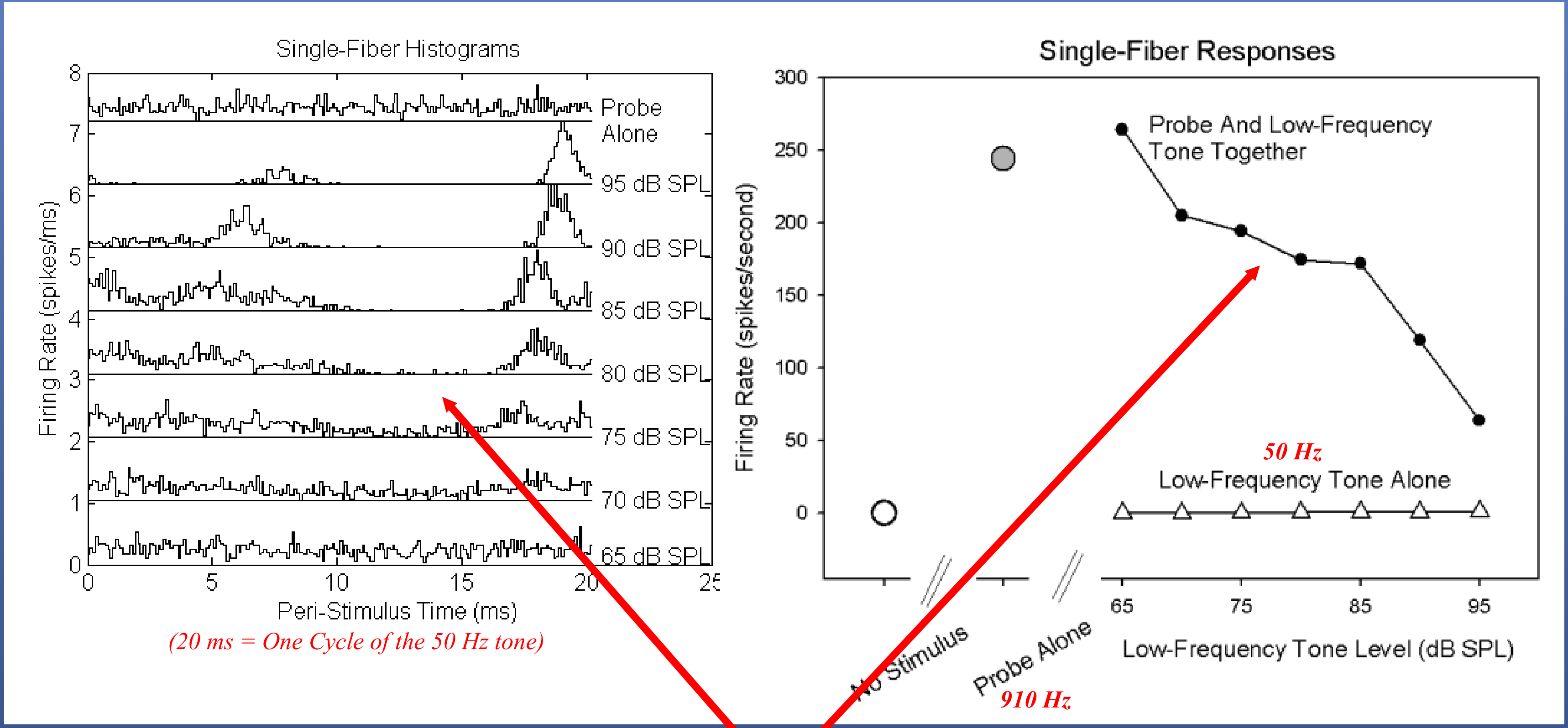
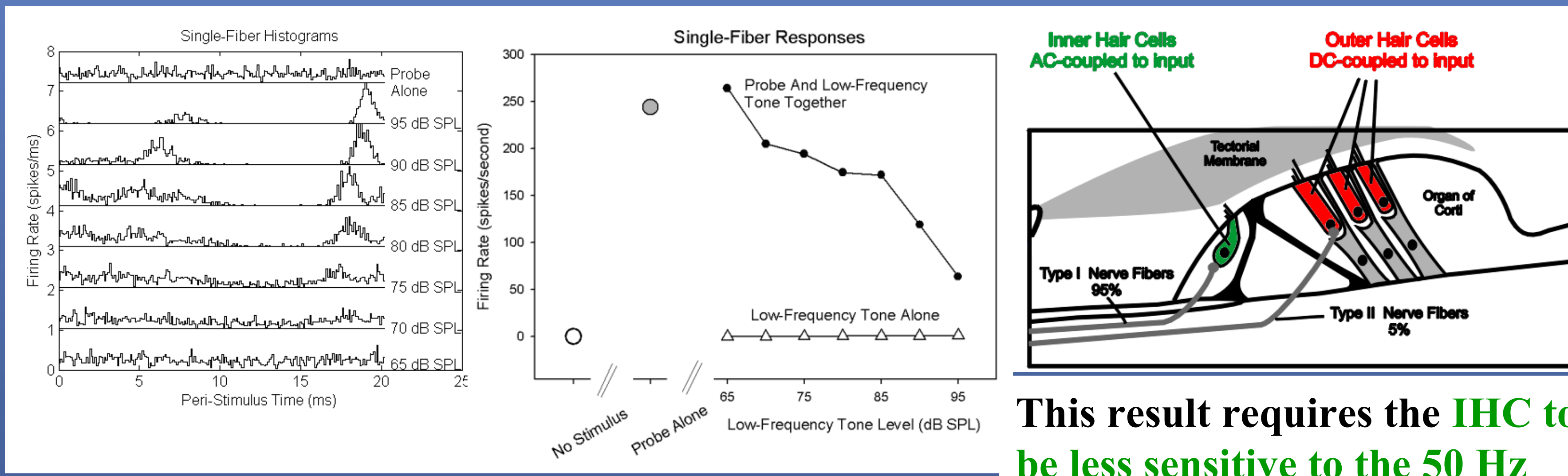


When combined, the 50 Hz tone amplitude modulates the 910 Hz responses

This form of amplitude modulation by sub-audible low frequency sounds is biological in origins and cannot be measured with a sound level meter

Amplitude modulation of single unit responses

Auditory nerve fiber responses from cat collected by Jeff Lichtenhan, Harvard Medical School



This result requires the IHC to be less sensitive to the 50 Hz tone while the OHC detect the 50 Hz at these levels and respond by changing their amplification at 910 Hz.

These data provide further confirmation that IHC and OHC have different response characteristics, with the OHC more sensitive to low frequency stimuli.

Conclusions – Amplitude Modulation

- Modulated sound levels, such as blade swish and blade thump can be measured by a sound level meter.
- In addition, there can be a BIOLOGICAL modulation of audible (higher frequency) sounds by infrasound. This is caused by the OHC gain and response characteristics changing as the operating point of the outer hair cells is displaced by the infrasound.

Note: There are many publications (> 50) related to operating point and cochlear responses. This is not a new concept.

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