Noise Exposure and Hidden Hearing Loss

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- Traditional thinking about NIHL
- Animal studies in NIHL –synaptopathy
- Clinical studies in synaptopathy and hidden hearing loss
- Translational issues
- Clinical considerations

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Incidence & prevalence

- ~25% of American work force is at risk for hearing loss due to occupational noise exposure Suter & von Gierke, 1987
- 2nd most common cause of sensorineural HL
- 10 million Americans reported to have noise-related HL Brookhouser, 1994

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Diagnosis of NIHL

- Patient history
- Audiologic evaluation
  - Otoscopy
  - Immitance
  - Standard audiometry
  - Interoctaves: 3 & 6 kHz

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Noise damages OHCs

- OHCs particularly vulnerable to noise damage Wang et al., 2002
- HC damage eventually leads to AN degeneration
- Where did this idea come from?
  - Widespread OHC loss w/in hours of noise exposure Bohne and Harding, 2000; Lawner et al. 1997; Suzuki et al., 2008; Webster and Webster, 1978
  - Loss of spiral ganglion cells not detected for weeks to months after injury and progresses over years Johnsson, 1974; Miller et al., 1997; Sugawara et al., 2005; Webster and Webster, 1978

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Noise damages OHCs

- Function of OHCs = cochlear amplifier
- Loss of OHCs → higher thresholds
- Acute incidence called a temporary thresholds shift (TTS)
- TTS is difficult to capture because of exponential decay
- Eventually, enough TTS → Permanent threshold shift (PTS)
- PTS is what is most commonly assessed by the behavioral pure-tone audiogram

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Audiometric ambiguity

- The audiogram is good at
  - Documenting loss of sensitivity
    - Frequency-specific
  - Differentiating SNHL from CHL

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Audiometric ambiguity

- The audiogram is *not* good at
  - Reflecting reported (or demonstrated) perceptual difficulties Bharadwaj et al., 2015; Gordon-Salant, 2005; Grose and Mamo, 2010; Ruggles et al., 2011
    - Difficulty understanding speech in noise
    - Auditory processing disorder
  - Differentially diagnosing site-of-lesion Bharadwaj et al., 2015; Felder and Schrott-Fischer, 1995; Halpin et al., 1994; Moore, 2004; Lobarinas et al., 2013
    - Assessing loss of IHCs and AN fibers
    - Puretone thresholds may not change until neural loss > 80-95%
      - 80% in cats Schuknecht and Woellner, 1955
      - 80% in chinchillas Lobarinas et al., 2013
      - 95% in mice Chambers et al. (2016)

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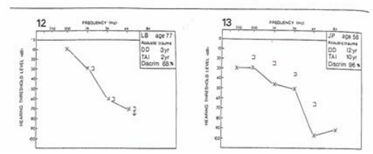

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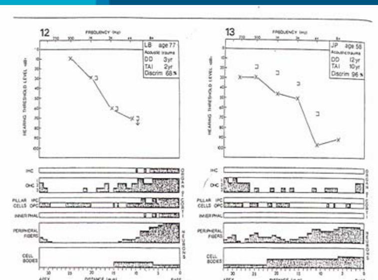

Fig. 12. Case 17, Table III, acoustic trauma. The hair cells, pillar cells, and inner phalangeal cells are degenerated in the basal 7 to 10 mm of the cochlea. There is a severe loss of dendritic fibers and a mild loss of cell bodies in this region.

Fig. 13. Case 27, Table III, acoustic trauma. There is a severe loss of neurons in the basal turn, but the inner cell complex shows no significant change.

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Hidden hearing loss

- What is hidden hearing loss
  - Selective dysacusis Narula and Mason, 1988
  - Obscure auditory dysfunction Saunders and Haggard, 1989
  - King Kopetzky syndrome Hinchcliffe, 1992
  - Auditory disability w/ normal hearing King and Stephens, 1992
  - Idiopathic discriminatory dysfunction Rappaport et al., 1993
  - Auditory processing disorder British Society of Audiology APD Special Interest Group, 2011
  - Synaptopathy Schaette and McAlpine, 2011
  - Threshold-independent hearing disorder Steve Neely's favorite
- Reported or demonstrated impairment in speech perception that is unexplained by standard clinical audiometry

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Prevalence of hidden hearing loss

- 5-8.4% of patients referred for hearing difficulties, subsequent findings of normal hearing thresholds Saunders, 1989; Stephens et al., 2003;
- 6-7% of people with normal hearing complained of having difficulty following a conversation in background noise Spehar and Lichtenhan, 2018

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Etiology of hidden hearing loss

- Central
  - Long-lasting effects of middle ear pathologies Knudsen et al. 1984; Popescu & Polley 2010; Polley et al. 2013; Gay et al. 2014
  - Degradation of tonotopic maps in cortex after noise exposure Pienkowski & Eggermont 2011, 2012; Eggermont 2014
  - APD
  - Cognitive deficit
  - Language deficit
- Peripheral
  - Auditory neuropathy
  - IHC pathology
  - Synaptopathy?

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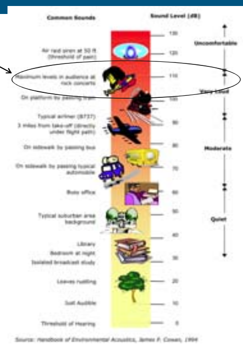
Noise exposure for 2 hrs at 110 dBSPL



Then remainder of life in quiet

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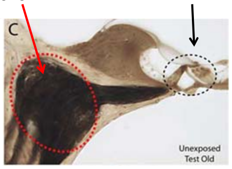
spiral ganglion, AN cell bodies

hair cells



Kujawa & Liberman (2006)

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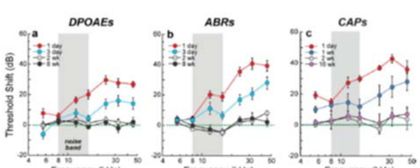
- Study repeated on TTS Kujawa and Liberman, 2009



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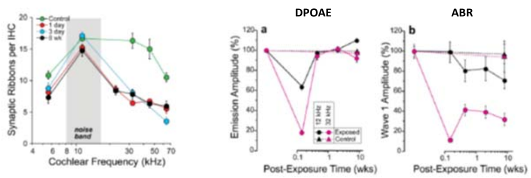

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- Immediate retraction of auditory nerve from inner hair cells
  - Loss occurs basal to frequency region of noise exposure
- Thresholds return to normal
- OAE amplitudes return to normal
- ABR wave I amplitudes reduced
- Auditory nerve fiber cell body (spiral ganglion) degenerates over weeks and years

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Translation to human hearing

- How does synaptic loss not affect threshold?
  - i.e. how can you lose 40-50% of the synapses with IHCs and have normal thresholds? Kujawa & Liberman, 2015
- Type I auditory nerve fibers have different spontaneous firing rates
  - High-spontaneous rate fibers → important for coding soft, near-threshold sound
  - Medium & low-spontaneous rate fibers → important for coding moderate to high intensity sound

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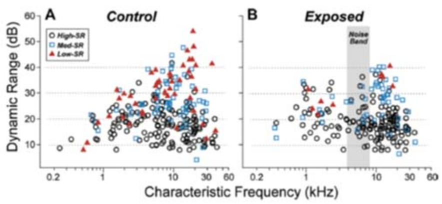
- Noise exposure selectively damages low-spontaneous rate fibers

Furman et al., 2013



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- If noise selectively damages low-spontaneous rate auditory nerve fibers
  - Present with normal audiometric thresholds
  - Poor understanding of speech, especially when spectral and temporal cues are degraded i.e. noisy environments
- Hidden hearing loss
  - Normal audiogram
  - Complaints of poor understanding of speech in noise

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- Questions to answer:
  - Does synaptopathy occur in humans?
  - Is it related to noise exposure?
  - Is it related to aging?
  - How does it affect perception?
  - Is this an etiology of hidden hearing loss?

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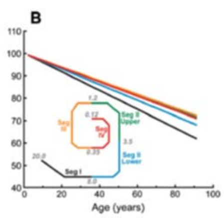
Does synaptopathy occur in humans



- 100 temporal bones
- newborn to 100 y.o.
- Normal OHC and IHC counts
- Neuronal loss in human temporal bones
- Slightly steeper loss in base than apex

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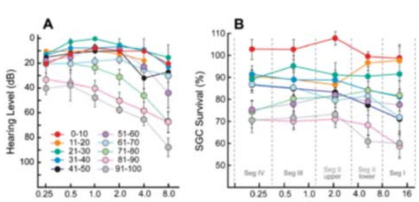
- Normal number of HCs



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Relationship between occupational noise exposure and ABR metrics

- Many studies saw increased ABR wave latencies in people with occupational noise exposure Fabiani et al., 1998; Chen, Chiang, and Chen 1992; Thakur, Anand, and Banerjee 2004; Attias and Pratt, 1984;Pushpalatha and Konadath, 2016; Noorhassim, Kaga, and Nishimura 1996
  - Most participants in these studies had hearing loss
  - Only a couple studies collected OAEs
- Majority found no effect of noise exposure on ABR wave amplitudes Samelli et al. 2012; Kamerer et al., in press
  - Lower amplitudes in those with more HL Almadori et al. 1988; Donaldson and Ruth, 1996; Noorhassim, Kaga, and Nishimura 1996; Xu et al. 1998

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Relationship between non-occupational noise exposure and ABR metrics

- A small number of studies that have revealed associations between noise exposure and deficits in the amplitude and latency of ABR Wave I Stamper and Johnson, 2015a; Bramhall et al. 2017; Valderrama et al. 2018; Liberman et al. 2016; Grose, Buss, and Hall 2017
- However, a number of studies treating noise exposure as a continuous variable, rather than dichotomising subjects into groups, failed to find any relationships between noise history and Wave I amplitude Spankovich et al., 2017; Fulbright et al., 2017; Grinn et al., 2017; Ridley et al., 2018; Guest et al. 2017; Prendergast et al. 2017; Prendergast, Millman et al.,2017b; Guest et al. 2018; Prendergast et al. 2018; Kamerer et al., In Press

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Relationship between noise exposure and speech-in-noise performance

- Most recent studies recruited normal hearing, young participants
- Most studies treating noise exposure as a continuous variable failed to find any relationships between noise history and outcomes on speech in noise tests Fulbright et al. 2017; Grinn et al. 2017; Prendergast, Millman et al. 2017; Yeend et al. 2017; Valderrama et al. 2018
- Several studies enrolling workers exposed to occupational noise, who had not yet developed significant hearing loss, revealed differences between the noise-exposed workers and controls Alvord 1983; Kujala et al. 2004; Kumar, Ameenudin, and Sangamanatha 2012; Hope, Luxon, and Bamiou 2013
- A study employing an extremely difficult speech in noise test revealed deficits associated with musical training Liberman, 2015

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TTS and ABR metrics

- Mostly older studies (1970-1986)
- Temporary reduction in ABR wave I after TTS-inducing noise exposure but no permanent changes Mills et al., 1970; Sohmer and Pratt, 1975; Botte et al., 1976, 1979; Klein and Mills, 1981; Fiakowska et al., 1983; Attias and Pratt, 1986; Nam and Won, 2004; Lichtenhan and Chertoff, 2008; Grinn et al., 2017
- Likely due to changes in OHCs or temporary synaptic swelling
  - One study measuring TTS from personal music players found decreases and subsequent recovery in DPOAE amplitude paralleled changes in threshold sensitivity Le Prell et al. 2012; Le Prell et al. 2016
  - Animal studies show recovery of both auditory nerve dendrite swelling and ABR Wave-I amplitude after noise exposure Puel et al. 1998; Yamasoba et al. 2005

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Interspecies variability

- Noise-induced synaptopathy shown in mice, guinea pigs, chinchillas, rats, & nonhuman primates
- Higher noise levels needed to induce synaptopathy in the guinea pig Lin et al., 2011 and rat Lobarinas et al., 2017
- Species differences in physiology and susceptibility of low-spontaneous rate fibers
  - Low-spontaneous rate fibers may not be critical for coding suprathreshold sound Carney et al., 2018
  - Can't measure speech-in-noise performance in animals

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Variability in measures of hearing

- No normative data for ABR wave amplitudes
  - OHC loss often occurs in parallel with neural or synaptic pathologies
  - OHC and IHC pathology degrades signal input to auditory nerve
  - Sex differences
- Speech-in-noise performance
  - Hard to separate perceptual issues that are purely HC or purely AN
  - Cognitive effects –attention, executive function, memory

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Quantifying noise exposure

- Inducing noise exposure difficult and unethical
- Alternative is self-reported noise exposure
- Many surveys developed to quantify noise exposure history

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Thorough consideration
Unclear or limited consideration
Absent or very limited consideration

	Lifetime Exposure to Noise and Solvents (Bramhall et al, 2017)	Leisure Noise Table (Carter et al, 2016)	Epidemiology of Hearing Loss Study Questionnaire (Dalton et al, 2001)	Noise Exposure Questionnaire (Johnson et al, 2017)	Exposed Noise & Hearing Disorders of Conscripts (Jokitulppo et al, 2006)	Questionnaire 1 (Liberman et al, 2016)	Questions Concerning Music Exposure (Moore et al, 2017)	First Annual Study Questionnaire (Neitzel et al, 2004)	Adolescents' Habits & Hearing Protection Use (Spankovich et al, 2017)	General Noise History (Spankovich et al, 2017)	NAL Online Noise Survey (Yeend et al, 2017)
Examines lifetime exposure?	Yes	Yes	In part[1]	No	Yes	Yes	Yes	No	Unclear[2]	No	Yes
Considers duration of each exposure?	No[3]	Yes	Yes	Yes	Yes	No	No	In part[4]	No	Yes	Yes
Considers duration of overall exposure period?	Yes	Yes	In part[1]	No	Yes	Yes	Yes	No	No	Yes	Yes
Considers frequency of occurrence of exposures?	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Allows for changing exposure habits over time?	No	No	No	In part[5]	No	No	In part[6]	No	No	No	In part[6]
Considers sound level?	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes
Includes all potential exposure activities?	No (>10)	Yes	No (>10)	No (>10)	Yes	Unclear[7]	No (<10)	No (>10)	No (>10)	No (>10)	No (>10)
Considers ear protection?	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Incorporates ear protection into exposure calculation?	Yes	Unclear	Yes	No	Unclear	Unclear	No	No	No	Unclear	Yes
Considers firearm exposure?	Yes[3]	Yes[8]	Yes[9]	Yes[8]	Yes[10]	Yes[8]	No	No	Yes	Yes[8]	Yes[8]
Specifies quantitative method for combining the data?	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

[1] Seeks information on number of years of exposure, but does not incorporate this information into the overall measure

[2] Described as a measure of lifetime exposure, but interrogates current habits ("How often do you ...?")

[3] Treats firearm peak sound level as if it were continuous sound level, causing the measure to be overwhelmingly dominated by firearm noise

[4] Assumes a 4-hour duration for most activities

[5] For occupational noise only, the respondent may report different exposure habits in term time than in the summer vacation period

[6] Allows changing exposure habits to be reported, but requires that the lifespan be divided by decade, reducing accuracy where habits have changed mid-decade

[7] Asks about noisy "hobby(s)" and "job(s)", but provides a single field for each response, making it unclear how to report data for multiple activities

[8] Gathers data on firearm noise, but does not state how these data are incorporated into the measure

[9] Gathers data on firearm noise, but does not incorporate these data into the measure

[10] Attempts to quantify firearm noise using the same methods as for continuous-type noise (combining estimated level and duration)

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Quantifying noise exposure

- What is included/left out?
  - Bias toward male-dominant activities and occupations
- Subject to memory
- Score is a noise dose
  - High variability in susceptibility
  - Highly weighted by impulse noise exposure (e.g. firearm use) Kamerer et al., in press
- # of TTS events a better measure?
  - Subjective reports of TTS more predictive of tinnitus and hearing complaints than self-reported noise exposure Brungart et al., 2019

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What is "normal hearing"

- Average puretone thresholds of healthy, normal hearing young adults, measured in quiet = 0 dB HL across all frequencies
- Standard deviations are 3 to 5 dB in the 0.1 to 8 kHz range Wilber et al. 1988; Han & Poulsen 1998; American National Standards Institute 2010
- 95% confidence intervals for thresholds are at most −10 to 10 dB HL up to 8 kHz
- Majority of people with thresholds between 10 and 20 dB HL have DPOAE amplitudes outside of the normative range, indicative of some degree of outer hair cell (OHC) dysfunction Zhao & Stephens 2006; Job et al. 2007; Dhar & Hall 2011
- Should we consider 20 dB HL normal? (4-6 SD below mean)

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OAEs

- Distortion product otoacoustic emissions are more sensitive than the audiogram to OHC dysfunction
- Recommended as part of diagnostic battery for NIHL
- DPgrams can be more sensitive to OHC dysfunction than the audiogram
- Only modestly correlated with self-reported hearing impairment Engdahl et al. 2013

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Extended high frequency thresholds

- Although OSHA regulations do not require testing at 8 kHz or above, poorer high-frequency hearing has been reported in
  - workers exposed to continuous occupational noise Hallmo, Borchgrevink, and Mair 1995; Korres et al. 2008; Riga et al. 2010; Mehrparvar et al. 2014
  - personal audio system device users Le Prell et al. 2013; Sulaiman, Husain, and Seluakumaran 2015; Kumar et al. 2017
  - musicians Schmidt et al. 1994; Gonc¸alves et al. 2013; Liberman et al. 2016
  - concert attendees Grose, Buss, and Hall 2017
  - military personnel Balatsouras, Homsioglou, and Danielidis 2005; Buchler, Kompis, and Hotz 2012
  - high non-occupational noise exposure Prendergast et al. 2017a; Yeend et al. 2017; Kamerer et al., in press
- EHF hearing is used for localization Heffner and Heffner, 2008; Best et al., 2005; Brungart and Simpson, 2009; Carlile et al., 1999; King and Oldfield, 1997
- EHF important for speech-in-speech recognition Strelcyk et al., 2014; Monson et al., 2019

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Change in regulations

- Per 29 CFR 1904.10, hearing loss is required to be reported as an occupational noise injury when
  - a standard threshold shift (STS) is documented during annual audiometric testing
    - permanent threshold change averaging 10 dB or more at the frequencies of 2, 3 and 4 kHz)
  - the average threshold at the 2, 3 and 4 kHz frequencies is 25 dB HL or poorer

Exchange Rates of NIOSH and OSHA Standards • National Institute for Occupational Safety and Health 1998; Occupational Safety and Health Administration 2009. According to each governing body, a person can safely be exposed to each decibel level for its corresponding time without risk of NIHL. For example, according to the OSHA standard, a person can withstand an environment with sound levels at 95 dBA for four hours. After four hours they are at risk for NIHL. NIOSH maintains that a person is safe in a 95 dBA environment for less than one hour.

NIOSH Standard	
Sound level (dBA)	Duration (Hours: Minutes: Seconds)
82	16:00:00
85	8:00:00
88	4:00:00
91	2:00:00
94	1:00:00
97	0:30:00
100	0:15:00
103	0:07:30
106	0:03:45
109	0:01:53
112	0:00:56
115	0:00:28
118	0:00:14
121	0:00:07
124	0:00:03
127	0:00:01

OSHA Standard	
Sound level (dBA)	Duration (Hours: Minutes: Seconds)
85	16:00:00
90	8:00:00
95	4:00:00
100	2:00:00
105	1:00:00
110	0:30:00
115	0:15:00
120	0:07:30
125	0:03:45
130	0:01:53
135	0:00:56
140	0:00:28
145	0:00:14
150	0:00:07
155	0:00:03
160	0:00:01

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Change in regulations

- OSHA & NIOSH regulate occupational exposure to both steady-state and impulse noise
  - These regulations are based off of risk for PTS
- Increased effort to understand and regulate noise injury based on TTS
  - Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) proposed a limit for exposure to impulse noise (e.g. gunfire)

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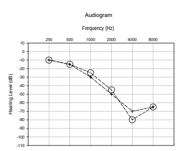
In conclusion...

- We don't really know what is going on in the ear
- We do know that the audiogram isn't giving us enough information
- Why should we care about diagnosing site-of-lesion?
  - Realistic outcome predictions for hearing aids
  - Help determine cochlear implant candidacy
  - Individualize programming
  - Pharmaceutical intervention



Speech Audiometry

Ear	SRT	%	HL
R	35	88	75
L	40	84	80

SUMMARY

Mild to moderate sloping sensorineural hearing loss. Recommend hearing aid evaluation.

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