
Title: Handbook of clinical neurology.
ArticleTitle: Decreased sound tolerance: hyperacusis, misophonia, diplacousis, and polyacousis.
ArticleAuthor: Jastreboff, Pawel J
Vol: 129 Date: 2015 Pages: 375-387
ISSN - 00729752;
Publisher: 2015
Source: Entrez:PubMed

Handbook of Clinical Neurology, Vol. 129 (3rd series)
The Human Auditory System
G.G. Celesia and G. Hickok, Editors

Chapter 21

Decreased sound tolerance: hyperacusis, misophonia, diplacousis, and polyacousis

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INTRODUCTION

Decreased sound tolerance, diplacousis, and polyacousis are dysfunctions of auditory perception. Decreased sound tolerance can be subdivided into hyperacusis and misophonia (Jastreboff and Jastreboff, 2002, 2013). While both phenomena are frequently observed in otolaryngologic and audiologic clinics, our knowledge of decreased sound tolerance is very limited and its proposed mechanisms are unproven and speculative. Nevertheless, available information suggests that decreased sound tolerance results from dysfunction of the central auditory pathways and their connections with the central nervous system rather than from dysfunction of the inner ear.

There is no consensus on the testing of decreased sound tolerance. Limited information is available regarding normative data for loudness discomfort levels (LDLs), which are typically used to assess the presence of hyperacusis (Sherlock and Formby, 2005). Questionnaires have been proposed to evaluate hyperacusis severity (Khalfa et al., 2002; Dauman and Bouscau-Faure, 2005); however, their validity needs to be confirmed. Moreover, the questionnaires do not address the presence and extent of misophonia. Reported data on the prevalence and epidemiology of hyperacusis are highly diverse. Hyperacusis can occur alone or as an adjunct to complex medical conditions (Jastreboff and Jastreboff, 2009). In spite of all the limitations listed above, the treatment of decreased sound tolerance can be highly successful (Jastreboff and Jastreboff, 2000, 2013; Jastreboff and Hazell, 2004; Formby, 2007; Formby et al., 2007).

Diplacousis was first reported in 1907 by Shambaugh, Sr. (Albers and Wilson, 1968a) and is much less frequently diagnosed than decreased sound tolerance. Diplacousis occurs when a subject who is exposed to a single-frequency tone perceives multiple tones, roughness, and beats (Ward, 1952, 1955; Flottorp, 1953; Zurek, 1981; Bacon and Viemeister, 1985). A characteristic feature of diplacousis is that the distortions are perceived only for low levels of sound. When the intensity of the external tone increases, the distortions disappear and the subject perceives a single pure tone. The mechanism of diplacousis is linked to dysfunction of the inner ear (Knight, 2004), and only single reports link it to dysfunction of the central auditory pathways (Ghosh, 1990). Polyacousis occurs when more than two tones are perceived. This term is seldom used and only one paper on the subject can be found in MedLine (Corliss et al., 1968). An internet search, using various search engines, yielded no hits for polyacousis.

DEFINITIONS

A variety of terms (e.g., hyperacousia, auditory hyperesthesia, recruitment, dysacousis, auditory dysesthesia, odynacusis, and auditory allodynia) (Baguley and McFerran, 2010) have been proposed to describe decreased sound tolerance, with the word "hyperacusis" used most frequently (Jastreboff and Jastreboff, 2004). One approach proposes further dividing hyperacusis into loudness hyperacusis, annoyance hyperacusis, and fear hyperacusis (Tyler et al., 2009).

Stedman's Medical Dictionary defines hyperacusis as "Abnormal acuteness of hearing due to increased

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irritability of the sensory neural mechanism. Syn: auditory hyperesthesia," with hyperesthesia defined as "Abnormal acuteness of sensitivity to touch, pain, or other sensory stimuli" (Anon., 1997). *American Heritage Dictionary* defines hyperacusis as "An abnormal or pathological increase in sensitivity to sensory stimuli, [as of the skin to touch or] the ear to sound" (Anon., 1994).

The definitions promoted in this chapter are based on reports from patients and on potential physiologic mechanisms, in which the auditory system (both peripheral and central parts) and the limbic and autonomic nervous systems are the main systems involved. An analysis of the negative reactions of subjects who suffer from decreased sound tolerance points to the involvement of the limbic and autonomic nervous systems in cases of clinically significant decreased sound tolerance (i.e., where a subject's difficulty with this condition is substantial enough to seek professional help). A wide spectrum of emotional reactions is observed (e.g., discomfort, dislike, distress, annoyance, anxiety, and fear), as well as a variety of negative sensations (e.g., pain, physical discomfort, fullness in the ear) and reactions associated with the overstimulation of the sympathetic part of the autonomic nervous system (e.g., anxiety, panic, decreased ability to enjoy life activities, sleep problems, problem with digestion) (Jastreboff and Hazell, 2004; Jastreboff and Jastreboff, 2004, 2009, 2013; Schroder et al., 2013).

Decreased sound tolerance is defined as present when a subject exhibits negative reactions when exposed to sound that would not evoke the same response in an average listener (Jastreboff and Jastreboff, 2002, 2013; Jastreboff and Hazell, 2004). These negative reactions can be observed when the subject is exposed to low-, moderate-, or high-level sound. The notion that sound must be loud, or louder than a certain level, is not a prerequisite for, and is not used as a criterion to, diagnose decreased sound tolerance. A patient's negative reactions may occur in response to any (including low) level of sound. It is postulated that decreased sound tolerance consists of two components: hyperacusis and misophonia, which frequently occur together.

Hyperacusis is defined as present when negative reactions to a sound depend only on its physical characteristics (i.e., its spectrum and intensity). The sound's meaning and the context in which it occurs are irrelevant (Jastreboff and Jastreboff, 2002, 2013; Jastreboff and Hazell, 2004).

Misophonia is defined as an abnormally strong reaction to a sound with a specific pattern and meaning to a given subject. The physical characteristics of the sound are secondary. Reactions to the sound depend on the subject's past history and on non-auditory factors such as the subject's previous evaluation of the sound, his/her belief that the sound is a potential threat or that exposure to it will be harmful, the subject's psychologic profile, and the context in which the sound is presented (Jastreboff and Jastreboff, 2002, 2013; Jastreboff and Hazell, 2004). The strength of the reaction is only partially determined by the sound's physical characteristics. A specific category of misophonia occurs when fear is the dominant emotion and patients are afraid of the sound (i.e., phonophobia: *phobia* = fear) (Jastreboff and Jastreboff, 2002, 2013; Jastreboff and Hazell, 2004).

Neither hyperacusis nor misophonia has any relation to the threshold of hearing, which can be normal or can involve hearing loss. Therefore, the term "recruitment" is not related to decreased sound tolerance. Recruitment refers to an unusually rapid growth of loudness as the level of a tone is increased. It occurs in association with hearing loss and is a purely cochlear-based phenomenon (Moore, 1995). Recruitment might coexist with decreased sound tolerance, but there is no functional link between the two conditions (Jastreboff and Jastreboff, 2004). Out of 740 patients treated at the Emory Tinnitus and Hyperacusis Center, during the first visit 497 patients reported a problem with decreased sound tolerance and 73% of patients in this group reported a problem with hearing as well. A total of 126 patients (17%) had hyperacusis that required specific treatment and out of that group of patients, 84 (67%) had concurrent problems with hearing. On the other hand, 476 out of 740 patients (64%) reported a problem with hearing. In all, 362 patients (76%) from this group also reported a problem with decreased sound tolerance and 70 patients (15%) required specific treatment for hyperacusis.

There is more than one definition of diplacousis (the spelling "diplacusis" is also used). One of the older definitions is that diplacousis is a perception of rough or noisy sound, or the perception of two or more sounds when a subject is exposed to a single pure tone (Ward, 1952). Currently, diplacousis is defined as an "abnormal perception of sound either in time or in pitch, such that one sound is heard as two" (Anon., 1997). The name originates from a combination of two Greek words: *diplous*, meaning double and *akousis*, meaning hearing. While specific epidemiologic studies are lacking, it is believed that diplacousis is present in many people; however, if the pitch difference is less than a half-tone and the subject does not have musical training it is not noticed. Diplacousis predominantly affects musicians as they are often trained to distinguish between small pitch differences.

A broader definition is that diplacousis is present when exposure to a pure tone results in the perception of several tones in addition to the presented tone (Ward, 1955). A tone may be perceived as harmonics

of a fundamental sound or the subject's voice (Brookler, 2009). Diplacousis depends on the frequency of the evoking sound (Brookler, 2009) and on the sound's intensity. When the intensity increases, diplacousis decreases (Burns, 1982).

Several subtypes of diplacousis can be distinguished (Bauman, 2013). Diplacousis binauralis occurs when one sound is perceived dissimilarly in each ear and may differ in pitch or in time. Diplacousis dysharmonica occurs when the sound is perceived normally in one ear and at a different pitch in the other ear (i.e., an interaural pitch difference (IPD)). Diplacousis echoica occurs when exposure to a sound results in the perception of the sound followed by the repetition or echo of the sound. Diplacousis monauralis occurs when exposure to a sound results in the perception of two different sounds in one ear. Diplacousis dysharmonica/IPD ($d_{L)}$ is the most common type of diplacousis. IPD is defined as $d_L = (f_R - f_L)/f_L = f_R/f_L - 1$, where f_R/f_L denotes the frequencies at the left and right ear, obtained by the adjustment of either frequency to achieve the pitch match (Terhardt, 2000). Diplacousis is typically associated with hearing loss. A variety of presumed mechanisms for diplacousis are associated with its different subtypes and are discussed below.

Polyacousis is a specific case of diplacousis that occurs when more than two tones are perceived. This term is rarely used.

DECREASED SOUND TOLERANCE (HYPERACUSIS AND MISOPHONIA), DIPLACOUSIS, AND POLYACOUSIS AS A PROBLEM

Decreased sound tolerance can have an extremely strong impact on patients' lives. Any sound can become offensive and evoke a negative reaction. With hyperacusis, any sound which is louder than acceptable to a patient evokes negative reactions. For misophonia, a broad variety of sounds have been reported to create problems. These sounds can be loud or soft, such as street sounds, car brakes, lawnmower, vacuum cleaner, garbage disposal, flushing toilet, cutlery and plates, keys rattling, hair dryer, school bell, announcements in a metro station or on a train or airplane, typing on a computer keyboard, the sound of a computer, refrigerator, supermarket freezer, the hum of electricity, a swimming-pool pump, shoveling cement, a husband/wife breathing in bed, snoring, sounds of eating, one's own voice, a crying baby, a musical instrument, singing, other people's headphones, fetal heart sounds, or the sound of drawing with a felt-tipped pen (Hazell et al., 2002; Jastreboff and Jastreboff, 2004, 2013). On the other hand, sounds such as bird song, running water, wind, and rain are rarely reported as negative (Hazell et al., 2002).

Decreased sound tolerance can prevent people from working and interacting socially. In extreme cases, patients do not leave their homes, and their lives and their family's lives revolve around (and are controlled by) the avoidance of offensive sounds. Misophonia evokes the same reactions as hyperacusis and further enhances the effects of hyperacusis.

Diplacousis and polyacousis are rare and are infrequently reported as causing a problem for subjects who experience them. The exception is some musicians, as diplacousis may have an impact on their ability to work by decreasing their perception of music (Kaharit et al., 2003; Jansen et al., 2009). Jansen et al. (2009) performed a study on 241 professional musicians in a symphony orchestra, aged from 23 to 64 years, and assessed their hearing loss and other hearing-related complaints. They found that musicians often complained about hyperacusis and tinnitus (79% and 51%, respectively), while diplacousis diagnosed by the presence of IPD > 1% was measured in 44% of musicians, but reported as a problem for only 7%. Interestingly, 24% of subjects complained about the distortion of tones.

Considering that differences in pitch sensation between 1.6% and 2.3% are common in non-musicians (Brink van den, 1970; Burns, 1982), it is notable in this study of diplacousis that IPD larger than 2% was observed in 18% of subjects and IPD larger than 3% was present in 3% of subjects.

Jansen et al. (2009) reported only a few very sensitive people who experienced diplacousis. This postulate is further corroborated by their finding that, when the subjective results on diplacousis were compared to the results of diplacousis matching, no significant correlation was found for any of the tested frequencies. Consequently, even when diplacousis is documented by IPD, it may neither be noticed nor create a problem, even for musicians.

Kaharit et al. (2003) evaluated 139 rock/jazz musicians for hearing disorders (Table 21.1). The presence of tinnitus, hyperacusis, distortion, or diplacousis was established by the subject's answers on a questionnaire. The authors defined tinnitus, hyperacusis, distortion, and diplacousis in the following non-standard manner:

> *Tinnitus was defined as a spontaneous or evoked sensation of sounds, e.g. ringing or buzzing, often combined with pure tones that occur in the absence of an external sound source. The different sounds could be uni- or bilaterally located in the ears, or experienced and located somewhere in the head. Hyperacusis was defined as hypersensitivity to the loudness of sounds, including a*

Table 21.1

Type of hearing disorders reported in 103 affected musicians

Groups of single or >1 hearing disorder	Hearing loss *n* (%)	Tinnitus *n* (%)	Hyperacusis *n* (%)	Distortion *n* (%)	Diplacusis *n* (%)
Single hearing disorder	11 (10.7)	7 (6.8)	9 (8.7)	1 (1)	0 (0)
>1 Hearing disorder	57 (55.3)	60 (58.3)	54 (52.4)	24 (23.3)	4 (3.9)

Data modified from Kaharit et al. (2003).

decreased pure tone and uncomfortable loudness level of specific sounds normally not experienced as loud, uncomfortable or annoying. Distortion was defined as frequencies, overtones and/or harmonics that were not experienced in their true original form but as distorted, unclear, fuzzy and out of tune. Diplacusis was defined as a pathological matching of frequency and pitch that may involve dissonance or a sudden change of pitch when a change in loudness occurs.

On the basis of audiometry and the questionnaire, to determine the presence of hearing loss the subjects were first divided into two subgroups: those who were not affected by tinnitus, hyperacusis, distortion, or diplacousis ($n = 36$ or 26%) and those who were affected by at least one of these disorders ($n = 103$ or 74%). The latter group was further subdivided into a group that had one of these disorders and a group that had more than one disorder, as shown in Table 21.1.

Hearing disorders have been observed in 74% of subjects, with tinnitus, hyperacusis, distortion, and diplacousis reported either as a single or combined disorder (Table 21.1).

DIAGNOSIS

Diagnosis of decreased sound tolerance is complex and there is no agreement on how it should be done. For hyperacusis, there is a general agreement that pure-tone LDLs must have decreased values. Low values by themselves, however, do not prove the presence of hyperacusis as these values may be due to misophonia.

There is no consensus on how LDLs should be evaluated. Varied results depend on the specific method used to administer LDLs (e.g., stimuli: pure tone, warble tone, noise; presentation: free field, insert earphones, headphones) and the instructions given to patients (Hawkins et al., 1987; Byrne and Dirks, 1996; Ricketts and Bentler, 1996; Cox et al., 1997; Sherlock and Formby, 2005). Several studies indicate LDLs are in the range of 90–110 dB sound pressure level (SPL) in the normal population. The results tend to cluster within 95–110 dB SPL for frequencies from 500 to 8000 Hz, which corresponds to approximately 90–100 dB hearing level (HL) (Hood and Poole, 1966; Stephens and Anderson, 1971; Sherlock and Formby, 2005). A study aimed specifically at this issue showed that the average LDL value for subjects who do not have a sound tolerance problem was 100 dB HL (Sherlock and Formby, 2005). The study has been performed on 59 adults with normal hearing and no problem with sound tolerance. In addition to evaluating LDLs, loudness growth function was measured by categoric scaling judgments on a subgroup of 18 subjects. There were no differences between absolute (LDL) and relative (categoric scaling) judgment of loudness discomfort, intersubject variability, or intrasubject test–retest reliability. The authors concluded that administering LDLs to estimate loudness discomfort is an efficient and valid clinical measure to characterize the "threshold of discomfort."

When hyperacusis is present, LDLs are lower, typically in the 60–85 dB HL range (Jastreboff and Jastreboff, 2002). In cases of pure misophonia, LDL values from 30 to 120 dB HL can be observed. Therefore, LDLs alone are insufficient to diagnose hyperacusis or misophonia, and a specific detailed interview is crucial to diagnose and assess the relative contribution of hyperacusis and misophonia to decreased sound tolerance. Notably, hyperacusis and misophonia frequently occur together. Indeed, misophonia is inevitable in cases of severe hyperacusis. However, misophonia does not induce hyperacusis.

When interviewing prospective patients, it is important for the clinician to identify sounds that evoke negative reactions as well as sounds that are well tolerated in order to detect any discrepancies between reactions and the intensity of the sound. While a patient with normal LDLs does not have hyperacusis, decreased sound tolerance can still be present due to misophonia. Consequently, diagnosis of decreased sound tolerance is subjective and based predominantly on the patient's report.

To decrease the impact of misophonia on LDLs, we promote a modification of the standard procedure for administering LDLs (Hood and Poole, 1966) so that the results are dominated by hyperacusis and the effects

of the misophonic component of decreased sound tolerance are kept to a minimum. To achieve this, patients are provided full control during testing and given the power to stop it at any time (Jastreboff et al., 1996; Jastreboff and Jastreboff, 2004).

There are no established and validated questionnaires to determine the severity of decreased sound tolerance. Two questionnaires have been proposed to assess the extent of hyperacusis – the Hyperacusis Questionnaire (Table 21.2) (Khalfa et al., 2002) and the Multiple-Activity Scale for Hyperacusis (MASH) (Table 21.3) (Dauman and Bouscau-Faure, 2005) – but their specificity and selectivity need to be further evaluated. The Hyperacusis Questionnaire was created by testing that was performed only on the general population of subjects who did not complain of hyperacusis. The questionnaire focuses on the psychologic and social aspects of hearing rather than on an indication of hyperacusis. Only four of 14 questions (rated on a scale from 1 to 4) are related to hyperacusis while the remaining questions appear to be related to other aspects, including hearing loss ("5. Do you have difficulty listening to conversations in noisy places?") (Khalfa et al., 2002). MASH consists of a list of 14 activities, and patients are asked to indicate their level of annoyance related to a given activity on a scale from 0 to 10 (Dauman and Bouscau-Faure, 2005). Both questionnaires have been reported to be effective in the evaluation of hyperacusis, but interestingly, there was no correlation of their scores with audiologic measurements of discomfort levels (i.e., LDL and speech discomfort level) (Dauman and Bouscau-Faure, 2005). Notably, neither of these questionnaires differentiates between hyperacusis and misophonia. There is no validated questionnaire for misophonia.

Diagnosis of diplacousis and polyacousis is based on an interview with the patient and on pitch matching of

Table 21.2

Khalfa's Hyperacusis Questionnaire

Surname, first name:
Sex:
Age:
Profession or studies:
Place (town or area) of residence:
Telephone:
Are you or have you been exposed to noise?
Do you tolerate noise less well as compared to a few years ago?
Have you ever had hearing problems? If so, of what kind?
In the following questionnaire, put a cross in the box corresponding to the answer which best applies to you: No; Yes, a little; Yes, quite a lot; Yes, a lot

1. Do you ever use earplugs or earmuffs to reduce your noise perception (do not consider the use of hearing protection during abnormally high noise exposure situations)?
2. Do you find it harder to ignore sounds around you in everyday situations?
3. Do you have trouble reading in a noisy or loud environment?
4. Do you have trouble concentrating in noisy surroundings?
5. Do you have difficulty listening to conversations in noisy places?
6. Has anyone you know ever told you that you tolerate noise or certain kinds of sound badly?
7. Are you particularly sensitive to or bothered by street noise?
8. Do you find the noise unpleasant in certain social situations (e.g., night clubs, pubs or bars, concerts, firework displays, cocktail receptions)?
9. When someone suggests doing something (going out, to the cinema, to a concert, etc.), do you immediately think about the noise you are going to have to put up with?
10. Do you ever turn down an invitation or not go out because of the noise you would have to face?
11. Do noises or particular sounds bother you more in a quiet place than in a slightly noisy room?
12. Do stress and tiredness reduce your ability to concentrate in noise?
13. Are you less able to concentrate in noise towards the end of the day?
14. Do noise and certain sounds cause you stress and irritation?

Table 21.3

The Multiple-Activity Scale for Hyperacusis (MASH)

Concert
Shopping center
Cinema/TV
Work
Restaurant
Driving a car
Sport
Church
Housework
Children
Social activities
Pottering about
Gardening
Others

For each individual activity the patient was asked to provide a score from 0 to 10 to indicate the level of annoyance caused. If the subject did not attend concerts, because of a dislike of or lack of interest in live music, his/her reaction to loud music was taken into consideration. When the scores for cinema and TV differed, the highest was selected. When the patient felt unable to indicate a score for a given item, the item was deleted, even though the activity may have been relevant to him/her. The most frequently mentioned "other" noises (open-set) were small motorcycles and emergency vehicle sirens. The mean MASH score was calculated by dividing the total score by the number of relevant activities.

the perceived tone in both ears (Kaharit et al., 2003; Ogura et al., 2003; Jansen et al., 2009). For example, Jansen et al. (2009) used an adaptive procedure to compare the pitch of pure tones presented alternatively to the right and left ear by headphones using three different frequencies: 1, 2, and 4 kHz. Specifically, in the first step, subjects were asked to match the loudness of a tone in the left ear to a 60-dB HL tone presented in the right ear using increments of 1 dB. Subjects were then asked to match the pitch of the tone in the left ear to that in the right ear using increments of 1 Hz. The procedure was repeated by alternating ears and changing the frequency of the test tone. The result of diplacousis matching was determined by the deviation between the ears and was expressed as a percentage of the measured frequency (Jansen et al., 2009). There are no reported methods to assess the severity and impact of diplacousis and polyacousis on a patient's life; severity is judged only on the basis of the patient's report.

PREVALENCE AND EPIDEMIOLOGY

The lack of an objective method to determine the presence of decreased sound tolerance and the variety of epidemiologically oriented questionnaires used to do so yield limited data on the prevalence of decreased sound tolerance in the general population. Notably, the data obtained from 10 349 randomly selected subjects showed that 15.3% reported hyperacusis (Fabijanska et al., 1999). Diagnosis of hyperacusis is made even more complex because LDL measurements are not part of a routine audiologic evaluation. Moreover, a careful inspection of the reports revealed that, in some cases, misophonia rather than hyperacusis was present (e.g., reports on Williams syndrome) (Klein et al., 1990; Blomberg et al., 2006).

An estimation of the prevalence of decreased sound tolerance can be obtained by analyzing its co-appearance with tinnitus, and more detailed and extensive data are available in that regard. Approximately 60% of tinnitus patients have significant decreased sound tolerance. Of these, about 30% of patients suffer from hyperacusis and require treatment for it (Jastreboff et al., 1999; Jastreboff and Jastreboff, 2002; Jastreboff and Hazell, 2004). Since, on average, the prevalence of bothersome tinnitus reported in the literature is about 4% (Hoffman and Reed, 2004), it is possible to estimate that 1.2% of the general population has tinnitus and hyperacusis. On the other hand, it has been reported that 86% of patients with hyperacusis suffer from tinnitus (Anari et al., 1999). It is therefore possible to calculate that 14% of subjects with hyperacusis (i.e., 0.56% of the general population) do not have tinnitus. Taking the above information into account, it is possible to estimate that clinically significant hyperacusis exists in approximately 1.75% of the general population. As the data indicate that about half the patients with decreased sound tolerance have hyperacusis, the prevalence of decreased sound tolerance in the general population can be estimated at 3.5%.

Limited data exist on the prevalence of diplacousis and polyacousis. A wide variety of ototoxic factors have been linked to diplacousis, with noise exposure being the most common (Albers and Wilson, 1968b). Nevertheless, clinical observations indicate that diplacousis is reported infrequently, and mainly by musicians or people to whom the accurate perception of music is crucial for their work. To date, only a couple of studies in the literature report on the epidemiology of diplacousis and both studies analyze the population of musicians. In the first study, performed on 139 rock/jazz musicians and described earlier in this chapter, 4 subjects (2.9%) reported diplacousis (Kaharit et al., 2003). A more recent study of diplacousis prevalence amongst 241 symphony orchestra musicians revealed that diplacousis was generally not reported as a problem and affected only 7% of subjects (Jansen et al., 2009). Subjects in this study mainly complained about tinnitus and hyperacusis. A total of 79% of the musicians complained about hyperacusis, 51% complained about tinnitus, and 24% complained about tone distortion (Jansen et al., 2009). Interestingly, while only 7% of the musicians perceived an interaural difference in pitch perception as a problem, the results of diplacousis matching revealed that 18% experienced an IPD of more than 2%. Notably, the subjective perception of diplacousis did not correlate with the extent of differences in pitch matching and there was no difference between males and females with regard to the subjective rating of diplacousis (Jansen et al., 2009).

MECHANISMS

The mechanisms of hyperacusis are speculative. The lack of an animal model of hyperacusis makes it difficult to prove the validity of any postulated mechanisms responsible for this condition. Existing theories suggest a potential involvement of both peripheral and/or central mechanisms (Wrinch, 1909; Jastreboff and Jastreboff, 2004; Baguley and Andersson, 2007; Niu et al., 2013).

At the peripheral level, the abnormal enhancement of cochlear basilar membrane vibration by the outer hair cells (OHCs) might result in the overstimulation of the inner hair cells, and therefore result in hyperacusis (Jastreboff, 1990; Jastreboff and Hazell, 2004). Indeed, in rare cases, it is possible to observe high-amplitude distortion product otoacoustic emissions and distortion products evoked by low-level primaries (Jastreboff and Mattox, 1998). The presence of asymmetric

hyperacusis would indicate a peripheral mechanism because the involvement of central mechanisms would more likely act similarly on both sides. However, in nearly all cases decreased sound tolerance is symmetric, which argues against the dominant role of the peripheral mechanisms (Jastreboff et al., 1999).

Substantial data support the presence of central mechanisms in hyperacusis. Animal research has shown that damage to the cochlea or a decrease in auditory input results in a decrease of the response threshold in a significant proportion of neurons in the ventral cochlear nucleus and inferior colliculus (Boettcher and Salvi, 1993). Studies on evoked potentials indicate an abnormal increase of gain in the auditory pathways after such manipulations are applied (Gerken, 1993). The notion of increased gain within the central part of the auditory pathways has been discussed and promoted in recent approaches to the mechanisms of tinnitus and hyperacusis (Norena and Farley, 2013).

A number of medical conditions have been linked to decreased sound tolerance (e.g., tinnitus, Williams syndrome, Bell's palsy, Lyme disease, Ramsay Hunt syndrome, poststapedectomy, perilymphatic fistula, head injury, migraine, depression, withdrawal from benzodiazepines, cerebrospinal fluid high pressure, Addison's disease, translabyrinthine excision of a vestibular schwannoma) (Adour and Wingerd, 1974; Klein et al., 1990; Wayman et al., 1990; Lader, 1994; Nields et al., 1999; Gopal et al., 2000; Jastreboff and Hazell, 2004; Blomberg et al., 2006). These conditions can be linked to the central processing of signals and to the modification of the level of neuromodulators as possible factors that induce or enhance hyperacusis. Moreover, serotonin has been implicated in hyperacusis on the basis of indirect reasoning that some conditions occur with hyperacusis as a symptom (e.g., migraine, depression, pyridoxine deficiency, benzodiazepine dependence, and postviral fatigue syndrome) and involve a disturbance in serotonin activity (Marriage and Barnes, 1995). These authors speculated that, as serotonin is considered to have an inhibitory role in sensory modulation at a central level, a reduction in forebrain serotonin activity is therefore the most likely underlying pathology that causes central hyperacusis. The authors have not proposed any more specific mechanisms of serotonin involvement, and have stated that the increase or decrease of serotonin may be linked to hyperacusis. Additionally, they labeled decreased sound tolerance as hyperacusis, with stress on phonophobia, which may have different mechanisms than hyperacusis, and is inconsistent with current classifications (Jastreboff and Jastreboff, 2002, 2013; Tyler et al., 2009).

Serotonin involvement in hyperacusis has not been confirmed. There is only one case presentation which supports the proposed hypothesis by showing an improvement in hyperacusis, difficulty understanding speech, withdrawn depression, lethargy, and hypersensitivity to touch, pressure, and light after following treatment with selective serotonin reuptake inhibitors (Gopal et al., 2000).

A high prevalence of decreased sound tolerance in people with Williams syndrome (over 80%) suggests a genetic basis of decreased sound tolerance in those subjects (Nigam and Samuel, 1994; Gothelf et al., 2006).

The mechanisms of misophonia could involve the enhancement of the functional links between the auditory and limbic systems at both the cognitive and subconscious levels (Jastreboff, 1990; Jastreboff and Hazell, 2004). Alternatively, a tonic high level of activation of the limbic and autonomic nervous systems may result in strong behavioral reactions to moderate sounds (Jastreboff and Hazell, 2004). A recent study supported the proposed mechanisms of misophonia by showing the enhanced autonomic reactivity to a sound, but not to other sensory stimuli in misophonic patients (Edelstein et al., 2013). In January 2013, Schroder et al. redefined misophonia based on their work in a psychiatric center and proposed to classify the condition as a new psychiatric disorder. In our opinion, Schroder et al. studied a population of psychiatric patients who happened to have misophonia as well. In our clinical work, we have seen 318 misophonic patients (compared to 42 cases reported by Schroder et al.), all evaluated by physicians, and in only 7 cases (2.2%) did patients exhibit psychiatric problems. Moreover, our misophonic patients showed significant improvement when treated with a combination of counseling and a specific version of sound therapy (described below), without any need for psychiatric intervention.

The mechanisms of diplacousis are hypothetic. Nearly all the proposed mechanisms of diplacousis involve the cochlea, and only one paper describes diplacousis of (presumably) central origin linked to a lesion in the posterior thalamus (Ghosh, 1990). The first class of proposed mechanisms links diplacousis to hearing loss and OHC damage in the cochlea. OHCs work as a mechanical amplifier within the cochlea and are responsible for sharp tuning of the traveling wave in the cochlea. Notably, the OHCs amplify sounds of lower intensities only – below 60 dB SPL – which corresponds roughly to half the dynamic range of hearing. OHCs provide gradually less amplification when the level of a sound increases and become inactive for sound intensities higher than 60 dB SPL.

The mechanism for diplacousis linked to hearing loss is discussed below. The hypothesis is based on basic science regarding the functioning of the cochlea and the mechanisms of pitch perception. There is a strict relationship between a given place on the cochlea's basilar

membrane and the frequency of tone that evokes it. Neuronal activity in the auditory nerve is correlated with the phase of the incoming pure tone only for frequencies below 1000 Hz. For higher frequencies, the place on the basilar membrane where the maximal amplitude of the traveling wave develops determines the perceived pitch (Moore, 1995). When a group of OHCs is damaged, the tuning curve becomes broader and its peak shifts in frequency. When compared to an ear with undamaged OHCs for this specific frequency region, the shift in place occurs where maximal stimulation of the basilar membrane occurs. Consequently, the subject perceives a different pitch in one ear than in the other ear. Note that, as OHCs do not function for sound intensities higher than 60 dB SPL, diplacousis based on this mechanism decreases with the increase of a sound's intensity and disappears when the intensity exceeds 60 dB SPL. Diplacousis may or may not appear depending on the difference in the damage of OHC systems in one ear versus the other ear for a given frequency range.

This theory explains the clinical observation that diplacousis is particularly linked to unilateral/asymmetric hearing loss, the intensity of a sound to which a subject is exposed, and the relation of the affected pitch to the regions of hearing loss. The theory also explains instances of temporal or permanent diplacousis evoked by a loud noise, as reported in the literature (Knight, 2004; Jansen et al., 2009). The temporal dysfunction of OHCs occurs following exposure to a loud noise (i.e., the cilia of the OHC becomes disorganized, making a cell temporarily dysfunctional). Depending on the asymmetry of damage and pre-existing damage of the OHC system, diplacousis may temporarily appear. If the exposure to a sound results in permanent damage to a group of OHCs, permanent diplacousis emerges. Local damage of OHCs causes a loss of sharp tuning of stimulation of IHCs and a shift of frequency where maximal stimulation occurs. This results in the perception of a different frequency than the one to which the subject is exposed (Fig. 21.1). Broadening of the curve may result in the perception of a fuzzy sound.

A question arises regarding the mechanisms of diplacousis in subjects without hearing loss. First, a normal audiogram can be seen in subjects who lost up to 30% of their OHCs (Harding and Bohne, 2007, 2009; Chen et al., 2008), and yet for these subjects the proposed mechanisms described above are still applicable. An evaluation of the functional status of OHCs by high-frequency resolution distortion product otoacoustic emissions (DPOAE) measurement is needed to determine whether groups of OHCs are damaged. A study of a sudden hearing loss case supports the proposed mechanisms: while there was no clear relation of diplacousis with hearing threshold and transient otoacoustic

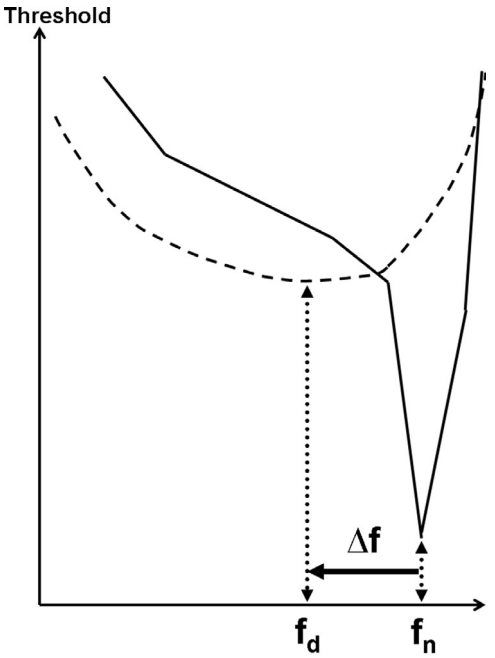

Fig. 21.1. Potential mechanisms of diplacousis as a result of outer hair cell (OHC) dysfunction or loss. Damage of OHC results in a broadening response curve and shifting frequency where maximal stimulation occurs. Horizontal axis, frequency; vertical axis, threshold of stimulation of inner hair cell (IHC); solid line, intact OHC; dashed line, OHC are dysfunctional or damaged in an area on the basilar membrane; f_n perceived frequency in normal cochlea; f_d perceived diplacousis frequency in cochlear with dysfunctional OHC; Δf diplacousis frequency shift.

emissions, the observed frequency shifts in the DPAOE fine structure were in close agreement with the changes in diplacousis (Knight, 2004).

Another mechanism may be involved in subjects with diplacousis who have normal hearing. This mechanism may also explain the presence of monaural diplacousis. An indication for this mechanism arises from two observations: (1) in diplacousis related to hearing loss, the pitch shift is pronounced and exists in a broad frequency range, while in subjects with normal hearing the shift is typically only ±2% and is distributed in a random manner with a mean shift close to zero; (2) spontaneous otoacoustic emissions (SPOAE) are commonly observed in people with normal hearing; these emissions consist of a number of pure-tone/very narrow noise bands and may have relatively high intensity.

If a person with SPOAE is exposed to a low-level tone, then due to the non-linear properties of the cochlea, the tone will interact with SPOAE idiotones and create a number of distortions with frequencies that follow the equation $f_d = \pm mf_{et} \pm nf_{SPi}$, where f denotes the frequency, subscript d denotes distortion, et refers to an

external tone, SPi is an "i" component of SPOAE, and n and m are natural numbers (i.e., 1, 2, 3, etc.). The condition $f_d > 0$ has to be fulfilled. As SPOAE may contain many frequencies, the resulting perception of a sound can be complex. Reported properties of diplacousis support this hypothesis, while pointing to the complex nature of the proposed interactions (Formby and Gjerdingen, 1981; Long, 1998).

THE NEUROPHYSIOLOGICAL MODEL OF DECREASED SOUND TOLERANCE

The neurophysiologic model of tinnitus, decreased sound tolerance, and the treatment approach based on the model, known as tinnitus retraining therapy (TRT), were introduced in 1990 (Jastreboff, 2000, 2007b, 2010; Jastreboff and Jastreboff, 2001, 2006). An analysis of negative reactions experienced by patients led to the proposition that the auditory system plays a secondary role in clinically significant decreased sound tolerance, and that other systems in the brain are dominant. While a number of systems in the brain are important (e.g., prefrontal cortex, attention networks, systems involved in memory), the limbic and autonomic nervous systems seem to be crucial. The block diagram of the neurophysiological model of tinnitus as applied to decreased sound tolerance has been described in detail elsewhere (Jastreboff, 2004; Jastreboff and Hazell, 2004; Jastreboff and Jastreboff, 2004).

The model can be used to discuss the potential mechanisms of hyperacusis and misophonia. First, the reactions experienced by patients are the same in both hyperacusis and misophonia. This supports the postulate that the same systems in the brain are responsible for these reactions. In turn, the type of negative reactions supports the notion that the limbic and autonomic nervous systems are dominant in the emergence of these reactions. The activation of these systems in the brain occurs in a different manner for hyperacusis than it does for misophonia. With hyperacusis, the presumed mechanism is an abnormally high amplification occurring within the auditory pathways (predominantly at the subconscious level) that yields a strong neuronal activation evoked by moderate or weak sound. Similar activation is evoked in a normal subject following exposure to a high level of sound. The limbic and autonomic nervous systems are activated as a consequence of the high level of auditory system activation. Thus, patients with hyperacusis experience the same problems while exposed to moderate or weak sound that a person without hyperacusis does when subjected to a very high level of sound (Fig. 21.2A) (Jastreboff and Jastreboff, 2004).

Proposed mechanisms of misophonia involve a high level of activation of the limbic and autonomic nervous systems due to enhanced functional connections between the auditory system and other systems in the brain (mainly the limbic and autonomic nervous systems for specific patterns of a sound only) (Jastreboff and Jastreboff, 2009, 2013). At the same time, the auditory system functions normally (Fig. 21.2B). Note that the presumed neurophysiological mechanisms are distinctively dissimilar for hyperacusis and misophonia, and consequently the treatments are different as well. Therefore, it is important to assess the presence and extent of both phenomena in a patient as each condition needs to be treated using different approaches. Audiologic evaluation provides only partial help in this regard and therefore a detailed interview is crucial.

TREATMENTS

Treatment for hyperacusis has taken two opposite directions. The most common approach is to advise patients to avoid sounds and use ear protection. This is based on the reasoning that, because patients became sensitive to a sound, they are supposedly more susceptible to sound exposure and consequently need extra protection. Patients easily embrace this reasoning and begin to

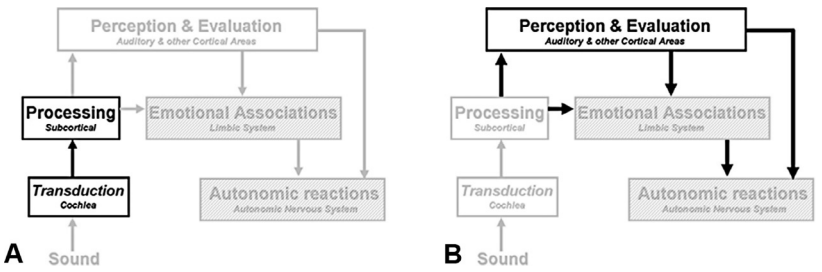

Fig. 21.2. Block diagram of potential mechanisms responsible for decreased sound tolerance. (**A**) Block diagram of potential mechanisms responsible for hyperacusis. Hyperacusis results from an abnormal amplification of sound-evoked activity occurring within the auditory pathways (marked by black lines). (**B**) Block diagram of potential mechanisms responsible for misophonia. Misophonia results from enhanced functional connections between the auditory and the limbic and autonomic nervous systems for a specific pattern of sound-evoked activity (marked by black lines). Note the overamplification of the limbic and autonomic system occurring in both conditions and marked by cross pattern. (Modified from Jastreboff and Jastreboff, 2004.)

protect their ears, even to the extent of using earplugs in quiet environments. Unfortunately, this well-intended approach makes the auditory system even more sensitive to sound and further exacerbates hyperacusis (Vernon and Press, 1998; Formby et al., 2003, 2007, 2013; Hawley et al., 2007).

The opposite approach to treating hyperacusis involves desensitization, wherein patients are exposed to a variety of sounds. The desensitization approach has been promoted for some time with a number of protocols and types of sounds used. For example, sounds with certain frequencies removed, short exposure to moderately loud sound, or prolonged exposure to relatively low-level sounds have been used (Vernon and Press, 1998; Jastreboff and Jastreboff, 2000). "Pink noise therapy," as proposed by Vernon and Press (1998), has gained some recognition. In this approach, patients were advised to stop ear overprotection and to listen to pink noise through headphones set to the highest comfortable level for 2 hours a day. A group of patients were provided with pink-noise cassette tapes and questionnaires were mailed to 30 participants. Out of 20 patients who responded, 13 reported using these tapes in a systematic manner and 7 (54%) reported improvement in their hyperacusis (Vernon and Press, 1998). A version of pink-noise therapy has also recently been proposed for tinnitus and hyperacusis by Johnson (2014). The protocol combines the use of pink noise with a 16-week cognitive exercise program divided into sections devoted to different topics, such as recognition and relief. To date, no results have been published in the peer-reviewed literature regarding the effectiveness of this approach.

There are no published treatments for diplacousis and polyacousis. In one patient's case, the use of aspirin resulted in a reduction of SPOAE into the noise floor and eliminated monaural diplacousis (Long, 1998).

Tinnitus retraining therapy (TRT) for decreased sound tolerance

TRT can help patients with tinnitus and hyperacusis. The presence of hyperacusis is one of the key factors in the categorization of TRT patients and in determining the protocol for treatment (Jastreboff, 1999, 2010; Jastreboff and Hazell, 2004). It is recommended that if hyperacusis is present it must be treated first. For some patients with decreased sound tolerance, it is possible to completely remove hyperacusis and misophonia and to effectively provide a cure for these conditions (Jastreboff and Jastreboff, 2001, 2013).

According to the principles of the neurophysiological model of tinnitus, prolonged exposure to relatively low-level sound is recommended and is used as a part of TRT. Independent results support the use of TRT for the treatment of hyperacusis and have shown that the desensitization approach used in TRT has a statistically and clinically significant impact on hyperacusis (Formby, 2007; Formby et al., 2007, 2013). Therefore, for hyperacusis patients, avoiding silence and being continually exposed to sound are crucially important. The sound level should be well controlled during treatment and should never induce discomfort or annoyance. Ear-level, wearable sound generators, which facilitate keeping the sound at a constant, well-controlled level, are often employed.

Unfortunately, patients with decreased sound tolerance (particularly misophonia) tend to set the sound level of their devices close to or at the threshold of hearing, and this is considerably less efficient for tinnitus and hyperacusis treatment. The use of real-ear measurements as a guide in setting and checking the sound level for all patients who use instrumentation to treat decreased sound tolerance is very helpful to patients and should be performed during their initial and follow-up visits with the TRT clinician. The recommended range of sound is from 6 to 16 dB sensation level (SL).

Desensitization works on the auditory system. Therefore, this approach will not affect misophonia, which needs to be addressed via the active extinction of conditioned reflexes between the auditory system and the limbic and autonomic nervous systems. This can be achieved by specific counseling and protocols for working with sound (Jastreboff, 2007a; Jastreboff and Jastreboff, 2002, 2004, 2013). In particular, patients are advised to systematically engage in pleasant activities they enjoy where sounds play an indispensable role, such as listening actively to one's favorite music or to audiobooks following a specific protocol (Jastreboff and Jastreboff, 2002). Other activities include shopping in a mall, going to parties, dining in restaurants, and attending movies. The main idea is to create an association of a given sound with a pleasant situation (implementing the active extinction of conditioned reflexes).

There are four classes of protocols for misophonia. The specific protocol used is tailored to the individual patient. Frequently, more than one protocol is used to treat misophonia. Each protocol is geared to create a positive association with a sound, but the protocols differ with respect to the extent of control the patient has over the sound environment and, in the case of protocol category 4, employ the use of sounds with a positive association together with bothersome sounds which evoke negative reactions (Jastreboff and Jastreboff, 2013).

Protocol category 1 provides the patient with full control over the selection of sound, its level, and duration. As such, it can be used even in cases of coexisting significant hyperacusis and can be implemented from the start of treatment.

Protocol category 2 affords the patient full control over the type of sound, but only partial, indirect control over the sound level, by yielding control to someone close to the patient who is instructed to set the sound volume to a level he or she thinks the patient will accept. After a listening session, the patient should provide feedback as to whether the sound level was too high, too low, or just fine.

Protocol category 3 enables the patient to select the type of sound, but the sound level is fully out of the patient's control. This protocol can be used only when significant hyperacusis is absent or has been eliminated by treatment. Therefore, the introduction of this protocol is frequently delayed.

Protocol category 4 uses the concept of complex conditioned stimuli and combines the exposure to sounds which evoke negative reactions with the simultaneous exposure to sound the patient regards as highly positive and enjoyable. The ratio of sound levels of positive-to-negative sound is gradually decreased. The environment where this protocol is used is taken into account, as many patients react differently depending on where they are exposed to a bothersome sound (i.e., home, school, a public place, a restaurant, a friend's home). The multisensory aspect of stimuli is also taken into account, as some patients react even to seeing someone produce offensive sounds (e.g., eating).

An analysis was made of 201 consecutive patients diagnosed with decreased sound tolerance and treated with TRT at Emory Tinnitus and Hyperacusis Center. A total of 184 patients (92%) had misophonia; 17 patients (8%) had hyperacusis alone, and 56 patients (28%) had hyperacusis and misophonia concurrently. The proportion of patients with significant hyperacusis (with or without misophonia) who required specific treatment is similar to the 25–30% reported in the literature (Jastreboff et al., 1999; Hazell et al., 2002; Herraiz et al., 2003, 2006; Jastreboff and Jastreboff, 2004) and to the 26% we have reported previously (Jastreboff and Jastreboff, 2002).

Improvement in hyperacusis was judged on the basis of changes in LDLs combined with responses obtained during the structured interviews, while improvement in misophonia was solely based on the interviews. This decision was based on the observation that, in cases of misophonia, any LDL values could be seen and the values were not correlated with patients' judgment of the problems due to decreased sound tolerance.

Of 201 patients with decreased sound tolerance, 165 patients (82%) showed significant improvement. For 56 patients with hyperacusis (with or without misophonia), 45 patients (80%) showed significant improvement. The effectiveness of treatment for misophonia with or without hyperacusis was identical (152 of 184 patients with misophonia accompanied by hyperacusis, or 83%, and 139 of 167 patients with misophonia alone, or 83%). As noted earlier, in some cases it is possible to achieve a cure for misophonia as well as for hyperacusis (Jastreboff and Jastreboff, 2001, 2013). Furthermore, our clinical observations demonstrated that treatment of misophonia is crucial to achieving a successful outcome for tinnitus treatment (Jastreboff and Jastreboff, 2012).

CONCLUSIONS

Decreased sound tolerance (hyperacusis and misophonia) remains a challenging topic to study and to treat. Many questions are unanswered. The mechanisms are speculative and unproven. Even less is known about diplacousis and polyacousis.

The neurophysiological model of tinnitus and TRT provide an approach that helps patients and may ultimately result in a better understanding of decreased sound tolerance. There is a need to investigate the potential mechanisms of diplacousis and polyacousis as our knowledge of these phenomena is severely limited and effective treatments for these problems have not been established.

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