PITCH PERCEPTION IN INDIVIDUALS WITH SENSORINEURAL HEARING LOSS WITH AND WITHOUT DEAD REGION

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DEDICATED
TO
MY DEAR

PARENTS

For What I am Today

&

My Revered Guide

Dr. K. Rajalakshmi

For her teaching, guidance, love and affection

CERTIFICATE

This is to certify that this dissertation entitled ***"Pitch Perception in Individuals with Sensorineural Hearing Loss with and without Dead Region"*** is the bonaflde work submitted in part fulfillment for the degree of Master of Science (Audiology) of the student **(Registration No. 05AUD012).** This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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This is to certify that the dissertation entitled ***"Pitch Perception in Individuals with Sensorineural Hearing Loss with and without Dead Region"*** has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier in any other University for the award of any Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled "***Pitch Perception in Individuals with Sensorineural Hearing Loss with and without Dead Region***" is the result of my own study and has not been submitted in any other university for the award of any diploma or degree.

Mysore

April, 2007 **Register No. 05AUD012**

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"Gratitude is the hardest of all emotions to express.
There is no word capable of conveying all that one feels.
Until we reach a world where thoughts can be adequately expressed in words.
'Thank you (will have to do). "

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CHAPTER 1

INTRODUCTION

A sinusoid is usually perceived by people with normal hearing as having clear tonal quality and a distinct single pitch; hence sinusoids are often called pure tones. However, some people with hearing impairment report that pure tones sound highly distorted and noise like (Florentine & Houtsma, 1983; Moore et al. 1985; 1977b; Murry & Byrere, 1986; Huss & Moore, 2005). Whether or not a person will experience such a percept is difficult to predict from the audiogram. It has been suspected that a pure tone might be perceived as noise like when the tone produces maximum excitation in a region of the cochlea where there is extensive or complete loss of inner hair cell (IHC) and/or neural function, which is sometimes referred to as a dead region (DR) (Florentine & Houtsma, 1983; Moore et al, 1985; Huss & Moore, 2005). A DR can be defined as a region in the cochlea where IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening (i.e. the tone is detected at a place where the amount of basilar-membrane vibration is lower, but the IHCs and neurons are functioning more effectively) (Moore, 2004). The extent of a DR can be defined in terms of the characteristic frequencies (CFs) of the IHCs and/or neurons immediately adjacent to the DR (Moore, 2001). DRs can be diagnosed and localized using psychophysical tuning curves (PTCs) (Florentine & Houtsma, 1983; Turner et al. 1983; Moore et al. 2000; Moore & Alcantara, 2001; Huss & Moore, 2003; Kluk &

Moore, 2005) and using the threshold-equalizing noise (TEN) test (Moore et al, 2000; 2004; Huss and Moore, 2003).

The Pitch of a pure tone may be determined by the auditory system from the distribution of activity or excitation along the basilar membrane or in the auditory nerve (place theory) (Helmholtz, 1863; von Bekesy, 1960; Siebert, 1968, 1970) or from temporal information derived from patterns of phase locking in the auditory nerve (Siebert, 1970; Moore, 1973; Goldstein & Srulovicz, 1977; Srulovicz & Goldstein, 1983).

In principle, theories of pitch perception can be evaluated by studying pitch perception for people with hearing impairment (Moore & Carlyon, 2005).

Studies investigating pitch perception in subjects with low-frequency DRs have suggested that a tone with a frequency falling in a DR is often perceived with a low pitch that is roughly "normal" (Florentine and Houtsma, 1983; Turner et al., 1983). Pitch shifts were much smaller than would be predicted based on the place where the tone was assumed to be detected (Just outside, the boundary of the DR). The results were interpreted as indicating that the pitch of a low frequency tone is predominantly derived from the temporal pattern of neural firing evoked by the tone.

The results obtained by Florentine & Houtsma (1983) and by Turner et al. (1983) were mostly based on pitch matches using tones at and within about 2 octaves of the edge frequency of the DR. It is possible that the analysis of information about pitch carried by interspike intervals is optimized when place and temporal information is consistent (Evans, 1978). For example, the analysis of temporal information may depend upon differences in the phase of the response at different points along the basilar membrane (Loeb et al., 1983; Shamma & Klein, 2000; Carney et al., 2002). The processing of temporal information could be disrupted when the propagation time of the traveling wave along the basilar membrane deviates from normal, as may happen in hearing impaired ears (Ruggero et al., 1996). When a tone produces peak vibration in a DR, perception of the tone depends on the spread of vibration to an adjacent functioning region of the cochlea. At that region, the traveling wave pattern, and specifically the relative phase of the response at different places, might differ markedly from the pattern occurring around the place where peak vibration occurs. This might markedly disrupt the processing of temporal information.

Need for the study

i. It remains unclear to what determines the pitch when either temporal and place information become weaker and what happens when temporal and place codes give conflicting information about pitch.

ii. The presence or absence of dead regions can have serious implications for the fitting of hearing aids. Amplification over a frequency range corresponding to a dead region may not be beneficial because amplified frequency components would be detected and analyzed in frequency channels that normally respond to other frequencies.

Aim of the study

i. To study the pitch perception in individual with & without dead regions in subjects with sensorineural hearing loss.

ii. To study whether there is relationship between dead region and perceived pitch,

iii. To see whether there is any relationship between the extent of DRs and pitch shift.

Review of Literature

CHAPTER 2

REVIEW OF LITERATURE

Hearing loss caused by damage to the cochlea (inner ear) is probably the most common form of hearing loss in developed countries. The most obvious symptom is a loss of ability to detect weak sounds. However, it is accompanied by a variety of other changes in the way that sound is perceived. Cochlear damage can arise in many ways for example by exposure to intense sounds or to ototoxic chemicals (such as certain antibiotics drugs used to treat high blood pressure or solvents) by infection, by metabolic disturbances by some forms of allergies and as a result of genetic factors. These agents can produce a variety of types of damage to the cochlea, and to complicate matters further the damage may not be restricted to the cochlea. Although hearing loss can involve structures other than the cochlea, it is common for the most serious damage to occur within the cochlea.

The inner ear is also known as the cochlea. It is filled with almost incompressible fluids and it also has bony rigid walls. It is divided along its length by two membranes Reissners membrane and the basilar membrane. The start of the cochlea where the oval window is situated is known as the base while the other end the inner tip is known as apex. It is also common to talk about the basal end and the apical end. At the apex there is a small opening (the helicotrema) between the basilar membrane(BM) and the walls of the cochlea which connects the two outer chambers of the cochlea, the scala vestibule and the scala tympani.

A second membrane called the tectorial membrane lies above the BM and also runs along the length of the cochlea. Between the BM and tectorial membrane are hair cells, which form part of a structure called the organ of corti. They are called hair cells because they appear to have tufts of hairs, called stereocilia at their apexes. The hair cells are divided into 2 groups by an arch known as tunnel of corti. Those on the side of the arch closet to the outside of the cochlea are known as outer hair cells (OHC), they are arranged upto five rows in humans. The hair cells on the other side of the arch form a single row and are known as inner hair cells (IHCs). There are about 25000 OHCs, each about 140 stereocilia protruding from it while there are about 3500 IHCs, each with about 40 stereocilia.

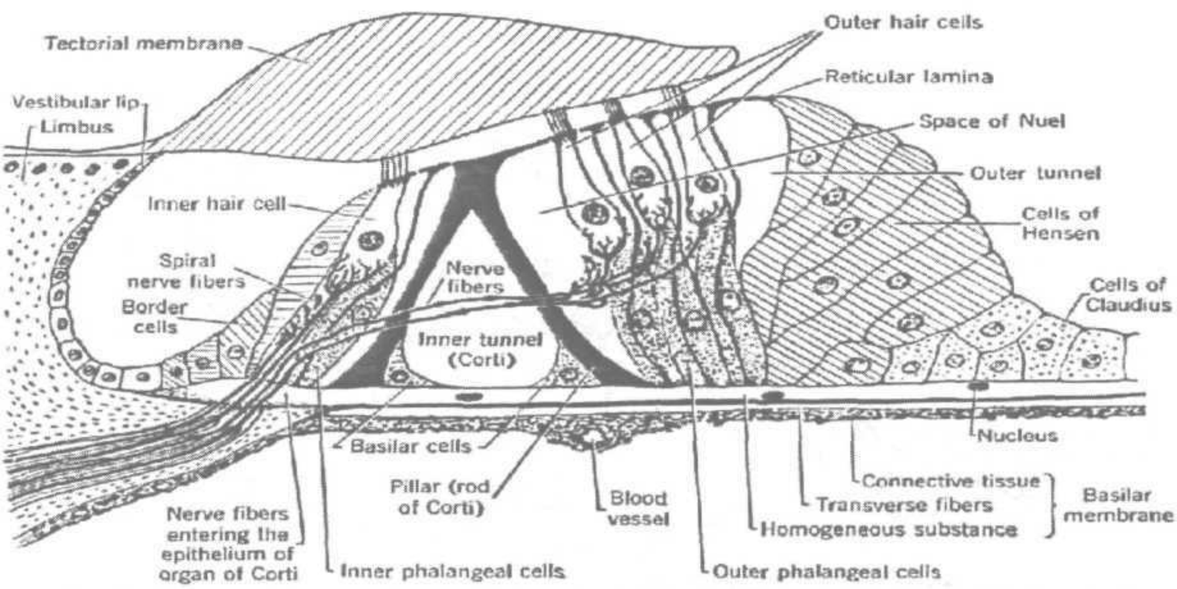


FIG. 2. Diagrammatic cross section of the organ of Corti. The outer hair cells are supported by their respective phalangeal cells, which rest in turn on the movable basilar membrane. The phalangeal cells supporting the inner hair cells rest on bone. Motion of the basilar membrane presumably distorts the hair cells. (From Rasmussen, 1943.)

Figure 1: Cross section of the organ of Corti

When the oval window is set in motion by an incoming sound, a pressure difference occurs across the BM. The pressure wave travels almost instantly through the incompressible fluids of the cochlea. Consequently, the pressure difference is applied essentially simultaneously along the whole length of the BM. This causes a pattern of motion to develop on the BM. The pattern does not depend on which end of the cochlea is stimulated. Sounds which reach the cochlea via the bones of the head rather than through the air do not produce atypical responses.

The response of the BM to sounds of different frequencies is strongly affected by its mechanical properties, which vary progressively from base to apex. At the base it is relatively narrow and stiff while at the apex it is wider and much less stiff. As a result, the position of the peak in the pattern of vibration differs according to the frequency of the stimulation. High frequency sounds produce a maximum displacement of the BM near the base while low frequency sounds produce a maximum near the apex. If two or more sinusoids with different frequencies are presented simultaneously each produces maximum displacement at its appropriate place on the BM. Thus, in effect, the cochlea behaves like frequency analyzer although with a less than perfect resolution.

A number of different methods may be used to specify the sharpness of tuning of the patterns of vibration on the BM. Most of the recent data are based on measurements of the responses of a single point on the BM to sinusoids of differing frequency. Each point on the BM can be considered as a band pass filter with certain centre frequency or characteristic frequency(CF) and bandwidth and certain slopes outside the pass band. Thus measures such as the 3- dB bandwidth, and slopes in dB/octave, can be applied to the responses of the specific points on the BM. Often it is difficult to measure the 3 dB bandwidth accurately and a measure taken further down from the pass band is used . The commonest measure is the 10 dB bandwidth, which is the difference between the two frequencies at which the response has fallen by 10 dB. It is sometime useful to use the relative bandwidth which is the bandwidth divided by the CF. The reciprocal of the relative bandwidth gives a measure of the sharpness of tuning known as Q. A larger Q value indicates a sharply tuned filter. Normally it is assumed that the 3 dB bandwidth is used to define Q. However, it is quite common in measurements of BM responses, and neural responses to use the 10 dB bandwidth. The measure of sharpness of tuning is described as QlOdB.O

Results using various techniques in live animals have shown that the sharpness of tuning of the BM depends on the physiological condition of the animal; the better the condition the sharper is the tuning(Khanna and Leonard 1982;Sellick et al.l982;Leonard and Khanna 1984;Robles et al 1986;Ruggero 1992). In a normal healthy ear each point on the BM is sharply tuned, responding with high sensitivity to limited range of frequencies, and requiring higher and higher sound intensities to produce a response as the frequency is moved beyond the range. It also seems likely that sharp tuning and high sensitivity reflect the active process.

The OHCs appear to be responsible for the sharp tips of tuning curves. When the OHCs are damaged the sharp tip becomes elevated, or may disappear together. This can cause a threshold elevation around the tip of the tuning curve of (40-50) dB. The condition of the OHCs determines the ratio of tip-to-tail thresholds. Damage to the IHCs causes an overall loss of sensitivity. This is apparent in the tail of the tuning curve whether or not the OHCs are damaged. Pure OHC damage either leaves the tail unaffected or causes hypersensitivity (lower thresholds in the tail). When both OHCs and IHCs are damaged, thresholds are usually greatly elevated, by 80 dB or more and tuning curve is broad, without any sign of a sharp tip. Damage to the IHCs can also result in a reduction in phase locking; the precision with which neural impulses are synchronized to the cochlear- filtered stimulating waveform is reduced. The reason why this occurs is unclear, but it may have important perceptual consequences.

The concept of dead regions

The concept of dead regions is quite old. Schuknecht et al(1993) performed extensive studies of the temporal bones of people with hearing loss and the hearing loss often associated with damage the sensory cells(both IHCs and outer hair cells)and /or neurons. A relatively small number of functioning IHCs and neurons is sufficient for detection of a weak stimulus. However, discrimination of sounds, including speech, may be strongly adversely affected when the loss of IHCs and /or neurons exceeds 50% (Schuknecht and Gacek, 1993;Schuknecht And Woelner,1953)

Diagnosis of dead region

DRs can be diagnosed and localized using psychophysical tuning curves (PTCs) (Florentine and Houstsma, 1983; Turner et al. 1983; Moore et al. 2000; Moore and Alcantara, 2001; Huss and Moore, 2003; Kluk and Moore, 2005) and using the threshold equalizing noise (TEN) test. Also a dead region can be present when the audiogram has a shallow slope.

Psychophysical Tuning Curves (PTCs)

Moore B. C. J., Alcantara. J. J. (2001) studied the use of psychophysical tuning curves to explore dead regions in the cochlea. PTCs were measured for five subjects with sensorineural hearing loss who were suspected of having dead regions. For each PTC, the level and frequency of the sinusoidal signal were fixed and the level of a narrow band noise masker needed just to mask the signal was determined as a function of the masker frequency. When the signal falls in a frequency region that is not "dead", the signal is detected via IHCs, with characteristic frequencies (CFs) at or close to the signal frequency. In such a case, the tip of the PTC (the masker frequency at which the masker level is lowest) lies at or close to the signal frequency. When a dead region is present, the signal is detected via IHCs with CFs different from that of the signal frequency. In such case, the tip of the PTC is shifted away from the signal frequency.

The results of the study shows that PTCs with frequency shifted tips (indicative of dead region) were found for all subjects. The frequencies at the tips sometimes decreased slightly with increasing signal level. A PTC with a tip at 5000 Hz was found for a signal frequency of 6000 Hz. These results suggest that this subject has an "island" of surviving IHCs and neurons with CFs ranging from 3000 to 5000 Hz. With extensive dead regions on either side. For the subjects with a mid-frequency loss, the pattern of results suggested a mid frequency dead region. For the subjects with high frequency loss, the results suggested the presence of high frequency dead regions, in one case starting at a frequency where absolute thresholds were only slightly higher than normal, Zwicker (1974) employed a procedure originally used by both Small (1959) and Chistovich (1957) in which low level probe tone of fixed frequency and intensity was masked by other pure tones of variable frequency and intensity. The resulting masking functions were called "psychoacoustical" or "psychophysical" tuning curves, since their general shapes closely resembled the single unit frequency threshold curve (FTCs) obtained in neurophysiological studies of the eighth nerve (eg. Kiang et al. 1965).

More recently, investigators have begun examining the frequency-resolving capabilities of impaired auditory systems by obtaining simultaneous tuning curves from listeners with sensorineural hearing loss of cochlear origin. (Leshowitz et al.1975; 1976; Carney and Nelson, 1976; Carney, 1977; Hockstra and Ritsma, 1977; Schorn et al l977; McGee, 1978; Zwicker and Schorn, 1978; Florentine, 1978; Florentine et al. 1980). In general, those investigators found that simultaneous tuning curves associated with sensorineural sensitivity losses greater than 40 dB were broader than normal. In some listeners with flat hearing losses above 50 dB or so, W-shaped tuning curves were found (Leshowitz et al., 1975; Carney and Nelson, 1976; Hoekstra and Ritsma, 1977). All of the previous studies of simultaneous tuning curves from hearing-impaired listeners used low SL probe tones, just as had previously been employed in normal hearing listeners. However, low SL probe tones in hearing impaired listeners must by necessity be presented at relatively high SPL's depending of course on the amount of hearing loss.

Carney. A. E; Nelson. D. A (1983) studied simultaneous psychophysical tuning curves obtained from normal hearing and hearing impaired listeners, using probe tones that were either at similar sound pressure levels or at similar sensation levels for the two types of listeners. Tuning curves from the hearing-impaired listeners were flat, erratic, broad and/or inverted, depending upon the frequency region of the probe tone and frequency characteristics of the hearing loss. Tuning curves from the normal hearing listeners at low- SPL were sharp as expected; tuning curves at high- SPL's were discontinuous. An analysis of high-SPL tuning curves suggests that tuning curves from normal hearing listeners reflect low pass filter characteristics instead of the sharp band pass filter characteristics seen with low SPL probe tones. Tuning curves from hearing-impaired listeners at high SPL probe levels appear to reflect similar low pass filter characteristics, but with much more gradual high-frequency slopes than in the normal ear. This appeared as abnormal downward spread of masking. Relatively good temporal resolution and broader tuning mechanisms were proposed to explain tuning curves in the hearing impaired.

Some of the differences between simultaneous and forward masking are quite dramatic (Houtgast, 1972, 1973; Sharnon, 1976), there has been some disagreement over the extent and nature of the differences between psychophysical tuning curves measured with the two techniques. Houtgast (1974) and Vogten (1974) have each reported data for one subject showing steeper, slopes for the forward masking technique, particularly on the high frequency side, but the psychophysical data obtained by McGee et al (1976) for the chilchilla reveal no significant difference. Robenburg et al (1974) found similar slopes for the two masking techniques, except for masker frequencies less than 0.8 of the probe frequency. However, they used a relatively high probe level and attributed this difference to combination tones. Wightman et al (1977) found steeper slopes in forward masking, particularly on the high frequency side of the curves, but found that the differences were reduced for listeners with hearing losses of cochlear origin. A number of other workers have determined psychophysical tuning curves in hearing impaired listeners (Hoekstra and Ritsma, 1977; Leshowitz and Lindstrom, 1977; Zwicker and Schorn, 1977), but only using the simultaneous masking technique.

Moore, B.CJ (1978) studied psychophysical tuning curves measured in simultaneous and forward masking. Parameters investigated include the level of the probe tone and the frequency of the probe tone. The general form of the psychophysical tuning curves obtained in this way is quite similar to that of single neurone tuning curves, when low level probe tones are used. However, the curves obtained in forward masking generally show sharper tips and steeper slopes than those found in simultaneous masking and they are also generally sharper than neurophysiological tuning curves. For frequencies of the masker close to that of the probe a simultaneous masker was sometimes less effective than a forward masker. The results are discussed in relation to possible lateral suppression effects in simultaneous masking and in relation to the observer's use of pitch cues in forward masking. It is concluded that neither the simultaneous- masking curves nor the forward masking curves are likely to give an accurate representation of human neural tuning curves.

Zwicker (1970) explained psychophysical tuning curves interms of the interaction between the excitation patterns produced by the signal and masker. For convenience the excitation pattern produced by a tone was assumed to be an asymmetric triangle whose low frequency side is steeper than its high- frequency side.

Davies, D.J and Patterson, R.D (1979) studied psychophysical tuning curves for 3 listeners by determining threshold for a 2.0 kHz sinusoid fixed at 20 dB SPL as a function of the level and frequency of a narrow band noise masker. Then the listening band available to the listeners was restricted by inserting a low level (~ 18 dB SPL) stationary masker at 1.8 kHz. The stationary masker alone did not mask the signal but it depressed the upper branch of the tuning curve by as much as 20 dB. The lower branch of the curve was essentially unaffected. When the low level stationary masker was repositioned to 2.2 kHz the effect was reversed; the lower branch of the tuning curve was depressed but the upper branch was little changed. The combined results show that the thresholds on the two branches of the tuning curve are based on information in different frequency regions and indicate that even at reasonably low signal levels the traditional psychophysical tuning curve overestimates the frequency selectivity of the ear.

Thornton and Abbas (1980) found that the tips of psychoacoustical tuning curves were displaced to higher frequencies in three of four listeners with moderate, low, frequency, sensory neural hearing losses. They interpreted their results as evidence that low frequency signals near threshold were being detected by high-frequency fibers in their listeners with displaced tuning curve tips. This interpretation is consistent with the animal data of Schuknecht and Neff (1952) and Sutton and Schuknecht (1954). The histology's on their animals with maximum low frequency hearing losses of 50 dB revealed a complete loss of apical hair cells and nerve fibers.

Problems with PTCs

1) Combination tones

PTCs are often considered the "gold standard" for diagnosing dead regions. (Summers, et al. 2003). However, several factors complicate the interpretation of PTCs; One such factor is combination tone detection. Under some circumstances, a combination tone produced by the interaction of the signal and the masker may be more detectable than the signal itself; when the masker is a band of noise then a "combination band" maybe detected than the signal itself; when the masker is a band of noise then a combination band may be detected; for simplicity author will describe this also **as** a combination tone. For normally hearing subjects, two types of combination tones maybe audible. For primary frequencies fl and f2, the most easily heard combination tone has a frequency corresponding to 2fl-f2. This combination tone, often referred to as the cubic difference tone, appears to reflect an inherent nonlinearity in the cochlea which depends on the active mechanism. Goldstein, 1967; Leshowitz and Lindstrom, 1977; Plomp, 1965; Smoorenburg, 1972). Detection of this combination tone may significantly affect masked thresholds of normally hearing subjects when the signal frequency lies just above the masker frequency (Alcantara, Moore and Vickers, 2000; Greenwood, 1971; Moore, Alcantara and Dau, 1998). However, the audibility of this combination tone is reduced by cochlear damage (Leshowitz and Lindstrom, 1977) (specifically OHC damage), and it appears to have little influence on masked thresholds for hearing-impaired subjects (Alcantara and Moore, 2002).

When the low pass noise was present, the tip of the PTC was only slightly shifted and the masker level at the tip was only 2 dB below the masker level at the signal frequency. However, in other similar cases it is found that the addition of a weak low pass noise resulted in more distinct shifts in the tip frequency.

It seems likely that PTCs will be affected by detection of the simple difference tone whenever the subject has relatively good low frequency hearing and poor high frequency hearing. Many of the subjects tested by Summers et al (2003) fall into this category; hearing losses of their subjects were typically in the range 5-30 dB at low frequencies, rising to 65-105 dB at higher frequencies. Thus, the PTCs of their subjects were probably affected to some extent by combination tone detection. In this context, it is noteworthy that PTCs with double tips occurred several times in their results, especially when the signal frequency was high.

2) Beat detection

Another factor that can influence the shapes of PTCs is beat detection (Alcantara and Moore, 2002; Alcantara, et al. 2000; Egan and Hake, 1950; Moore and Alcantara, 2001; Moore, et al. 1998; Wegel and Lane, 1924). When the signal frequency is close to the masker frequency, the signal and the masker interact and amplitude fluctuations occur at a rate corresponding to the frequency difference between the two. These beats are most clearly heard when both the signal and masker are sinusoids. Beats are much less salient when the masker is a narrow band noise because the inherent random amplitude fluctuations in the noise make the beats harder to detect (Dau, Kollmeier and Kohlrausch, 1997). However beats can be heard to some extent (Alcantara and Moore, 2002; Alcantara, et al., 2000; Derleth and Dau, 2000; Moore and Alcantara, 2001; Moore et al. 1998). Beats can provide a salient detection cue, and the result for a PTC, is that the masker level required to mask the signal is greater than would be the case if beats were not audible. Beats do not occur when the signal frequency is equal to the masker frequency and this result in a local minimum (a tip) in the PTC at the signal frequency. Thus, beat detection can lead to a minimum in the PTC at the signal frequency even when the signal frequency falls within a dead region. Beats are most salient when the beat rate is relatively low, below about 120 Hz (Kohlrausch, Fassel and Dau, 2000; Moore and Glasberg, 2001), but beats can be detected and may influence the detection of a signal for beat rates up to several hundred Hertz (Alcantara and Moore, 2002; Alcantara, et al., 2000)

3) **Noise bandwidth**

When noise maskers were used, there were still minimums in the PTCs close to the signal frequency, but they were much less distinct than for the tone masker. This happened because the masker level required to mask the signal for masker frequencies adjacent to the signal frequency was 20-30 dB lower for the noise maskers than for the tone masker. This is consistent with the idea that the salience of beats is reduced when noise maskers are used.

The masker level required for threshold for frequencies just below the signal frequency (specifically, 2650, 2700 and 2750 Hz) decreased with increasing noise bandwidth, by 3-5 dB. As a result the PTC for the widest bandwidth showed a relatively clear tip at 2650 Hz. This is consistent with the idea that the subject had a high-frequency dead region starting at 2650 Hz.

The masker level required for threshold for masker frequencies well below the signal frequency was higher for the noise maskers than for the tone masker. Similar effects have been observed previously (Buus, 1985; Moore, et al.1998; Mott and Feth, 1986). They can be explained by : (1) The lack of ability to use beating cues when the masker and signal frequencies differ by 500 Hz or more; and (2) the ability to "listen in the dips" of the masker envelope for the noise masker (Buus, 1985; Moore,et al., 1998; Moore and Glasberg,1987; Mott and Feth, 1986). It is noteworthy that the masker level required for threshold actually increased with increasing masker bandwidth for the masker centered at 2000 Hz. This is difficult to explain, and may just reflect random variability in the data.

In summary, PTCs determined for hearing-impaired subjects can be affected by the detection of simple difference tones and by the detection of beats. Both of these can give rise to a tip (a minimum) at the signal frequency, even when the signal frequency falls in a dead region. Also, when the main tip of the PTC is shifted away from the signal frequency, the detection of simple difference tones and beats may influence the tip frequency, and hence the estimate of the edge frequency of the dead region. To minimize the influence of these factors, the following procedures are recommended when using PTCs to diagnose dead regions:

(1) When the subject has good hearing at low frequencies and poorer hearing at high frequencies, a low pass noise should be presented with the main masker to mask the simple difference tone.

(2) To minimize beat detection, the masker should be a noise with a reasonably large bandwidth. However, the use of a very large bandwidth may lead to a loss of resolution in the frequency domain, making it harder to determine the exact tip frequency. For signal frequencies of 2000 Hz and above, the band- width of the auditory filters in normal ears is 240 Hz or more (Glasberg and Moore, 1990). For hearing-impaired ears, the bandwidths are larger (Glasberg and Moore, 1986; Tyler, 1986). Thus, a noise bandwidth of 320 Hz will be less than the auditory filter bandwidth and should not result in a significant loss of resolution in the frequency domain. For signal frequencies below 2000 Hz, a bandwidth of 16-20% of the signal frequency would seem reasonable.

(3) Detection of beats is most likely to influence the tip frequency of the PTC when the signal frequency falls just inside a dead region (Moore and Alcantara, 2001). Thus, if a high frequency dead region is suspected, the signal frequency should be chosen to be as high as possible with the constraint that the signal level at

absolute threshold should not be successively high. A practical limit for the absolute threshold is about 90 dB SPL, which would mean that a signal level of about 10 dB SPL would be used.

Although PTCs provide a useful tool for investigating dead regions, they are time-consuming measure, particularly if it is desired to define precisely the frequency at the tip. Some researchers have used a fast method for determining PTC using a masker that sweeps in frequency and procedure similar to Bekesy tracking to control the masker level (Sek, Skrodzka and Moore, 2003; Summers, et al.2003; Zwicker, 1974). We are currently exploring the use of such a method for identifying dead regions and defining their limits.

Florentine and Houtsma (1983) tested a subject who was diagnosed, using psychophysical tuning curves (PTCs) as having a unilateral low frequency DR with an edge frequency of about 2 kHz. He described tones with frequencies below 2 kHz (i.e. within the DR) as sounding 'hollow', without a body, 'very soft', and as if they were simultaneously combined with a narrow band masker in the frequency range of the tone.

Moore et al (1985) described results for a subject with a high frequency hearing loss with a steeply sloping audiogram, who was suspected of having a high frequency DR. The subject was tested in a frequency discrimination task. He was able to discriminate low frequencies reasonably well, but could not discriminate high frequencies at all. He stated that he was unable to do the task since tones at high frequencies sounded noise like. Very poor frequency discrimination of tones falling in a suspected DR has also been reported by Mc Dermott et al (1998) and by Thai-Van et al (2003).

Huss M, Moore, B.C.J 2005 assessed whether hearing impaired subjects report pure tone as sounding highly distorted and noise like that the tone frequency falls inside a dead region (DR). Nine hearing impaired and four normally hearing subject rated pure tones on a scale froml to 7, where 1 indicates clear tone and 7 indicates noise. A white noise was presented as a reference for a sound that should be rated as 7. Stimuli covered the whole audible range of frequencies and levels. The noisiness ratings were on average, higher for hearing impaired subjects than for normally hearing subjects. For the former, the ratings were not markedly different for tones with frequencies just outside or inside a DR. The results indicate that judgement of a tone as sounding noise like does not reliably indicate that the tone frequency falls in a DR. Both normal hearing and hearing impaired subjects rated 0.125 kHz and 12 kHz tones as somewhat noise-like, independently of the existence of a DR

TEN test

A clinical test for the identification of dead regions has been described by Moore et al (2000). The test is based upon the detection of pure tones in the presence of a broadband noise which is designed to produce almost equal masked thresholds (in decibels sound pressure level, dBSPL) for listeners without dead regions. The noise is called threshold- equalising noise (TEN), and the test is called the TEN test.

To assess the validity of the TEN test Moore et al (2000) measured psychophysical tuning curves (PTCs) using the same hearing impaired listeners as tested with the TEN. It is commonly assumed that, when the tip of the tuning curve is shifted away from the signal frequency, this indicates that the signal frequency falls in a dead region (Thorhton and Abbas, 1980; Florentine and Houtsma, 1983; Turner et al, 1983; Moore, 1998, 2001, Moore et al, 2000; Moore and Alcantara, 2001). Generally there was good correspondence between the results obtained using the TEN test and the PTCs. If for a given signal frequency, the masked threshold in the TEN was 10 dB or higher than normal and the TEN produced at least 10 dB of masking (i.e. the masked threshold was 10 dB or more above the absolute threshold), then the tip of the PTC was shifted. Hence, the following rule was formulated; if the threshold in TEN is 10 dB or more above the threshold in quiet, and at least lOdB above the level of the TEN, this is taken as indicative of a dead region at the signal frequency.

Moore et al (2003) used the TEN test to assess the presence of dead regions in 33 teenagers with long standing severe to profound hearing impairment. For the majority of ears, the results were inconclusive at some frequencies because the severity of the impairment meant that it was not possible to determine threshold in quiet and/or to produce at least 10 dB of masking by the TEN. However, for 23 (70%) participants the criteria for a dead region at medium or high frequencies were met in at least one ear. For eight (35%) of these participants, the criteria were only just met.

Reassessment of cochlear dead regions in hearing-impaired teenagers with severe to profound hearing loss was done by Munro K.J., Felthouse. C, Moore. B.C.J, Kapadia. S., (2005). The aim of the study was to reassess cochlear dead regions after an interval of twelve months, using the threshold equalising noise (TEN) test. Thirty- four ears of 24 teenagers (mean age of 14 years) with longstanding severe to profound sensorineural hearing impairment were tested. Testing was repeated after an interval of 12 months using the same experimental set up. A total of eight (23.5%) out of 34 ears changed category on retest,this decreased to two (7.1%) out of 27 ears when the inconclusive category was removed from the analysis. In both of these ears (of the same participant) the criteria were met at a single frequency, and the masked threshold was onlylOdB above the TEN level per ERBN (Equivalent Rectangular Bandwidth). The result shows that there was no statistically significant difference between the mean data obtained initially and those obtained twelve months later on two-factor repeated measures ANOVA. More than 90% of the threshold values at retest were within 10 dB of the initial value.

Rationale behind the TEN test

The amplitude of basilar-membrane vibration at the remote place will generally be less than the amplitude in the dead region. Therefore, a broadband noise may mask that tone much more effectively than would normally be the case, as the noise only has to mask the reduced response at the remote place. Thus, if the threshold for detecting a tone in broadband noise is markedly higher than normal, this indicates a lack of surviving IHCs/neurones with CFs corresponding to the frequency of the tone i.e. a dead region. To make the test easy to administer and interpret, like Langenbeck (1965) the test designed a masking noise that would produce equal masked thresholds at all frequencies, for normally hearing listeners. They refer to this noise as 'threshold equalizing noise' (TEN).

For listeners with cochlear hearing loss, but without a dead region at the signal frequency, the masked thresholds in the noise are expected to be only slightly higher than for normally hearing listeners. Damage to the OHCs is associated with loss of frequency selectivity (broadening of the auditory filer) (Pick et al., 1977; Glasberg and Moore, 1986; Tyler, 1986; Moore, 1998). Thus on average, masked threshold in the TEN for hearing-impaired listeners without dead regions would be only (2-3) dB higher than normal. To assess the validity of assumption that markedly higher than normal thresholds in the TEN indicate that the signal is being detected via neurones tuned away from the signal frequency.

A new version of the TEN test with calibration in dBHL was developed by Moore. B.C.J, Glasberg, B.R; Stone. M.A. for the diagnosis of dead regions. The result, of their study shows that the mean masked thresholds were almost constant across frequency when expressed in dBHL and were within 0.5 dB of the noise level per ERBN. For a single noise level, the test takes approximately 5 minutes per ear to administer.

The new TEN test has the following advantages over the original version (which used levels calibrated in dB SPL): (1) All levels are expressed in dB HL. Thus absolute thresholds only need to be measured once (2) Calibration is such that both the noise level/ERBN and the test tone levels correspond to the values indicated on the audiometer. This makes the test simpler to apply and reduces the likelihood of errors. (3) The noise bandwidth is restricted, and the noise has a low crest factor. This allows the noise level/ERBN to be increased while avoiding distortion, excessive loudness and possible further damage to hearing.

Limitations of the TEN **test**

The TEN test has several problems and limitations associated with it. These are outlined below:

(1) The TEN-test criteria (requiring 10 dB of masking and a masked threshold that is 10 dB higher than normal for diagnosis of a dead region) were developed using a relatively small sample of adults with moderate to severe cochlear hearing loss (Moore, et al. 2000). These criteria may not be appropriate for other populations, eg., those with profound hearing loss or younger people (Moore, Killen and Munro, 2003). In addition, there may be individual cases where the criteria are inappropriate. Whether a tone in noise is detected or not depends both on the signal to noise ratio at the place on the basilar membrane where the signal is detected and on the efficiency of the subject, which depends at least partly on relatively central mechanisms; some subjects require a relatively high signal to masker ratio at threshold, while others require a relatively low ratio. Individual variations in efficiency can occur even in subjects with normal hearing; the standard deviation is typically 2-3 dB around the mean value (Patterson and Moore, 1986). An exceptionally efficient subject might not meet the criteria for a dead region when the signal frequency falls just inside a dead region. Conversely, an exceptionally inefficient subject might just meet the criteria when the signal frequency does not fall in a dead region. Efficiency tends to decrease with increasing age, with elderly subjects requiring signal-to-noise ratios 2-3 dB higher

than young subjects (Patterson, Nimmo-Smith, Weber and Milroy, 1982; Peters and Moore, 1992a; Peters and Moore, 1992b). Some subjects show higher than normal masked thresholds at all frequencies; they may need to hear the tone very clearly before indicating that they detect it at all. Alternatively, the high thresholds may be indicative of a problem in the central auditory system (Langenbeck, 1965). Such cases need to be treated with caution. A reasonable policy in cases where masked thresholds are in the range 5 to 10 dB higher than normal (i.e. 5 to 10 dB above the TEN level/ERB_N), even for frequencies where the hearing loss is mild or moderate (for which a dead region is unlikely to be present), is to adopt a more stringent criterion for diagnosis of a dead region, e.g., requiring thresholds in the TEN to be 15 or more dB higher than normal.

The suitability of the criteria is also affected by the method used to measure absolute and masked thresholds, since the method affects the signal- to-noise ratio required for threshold (Marshall and Jesteadt, 1986). The TEN test criteria were established using a threshold measurement method similar to that used for manual audiometry (Carhart and Jerger, 1959). Different methods may require different criteria. In clinical audiology, thresholds are often measured to the nearest 5 dB. This can lead to problems when using the TEN test, since there may often be cases that fall exactly on the boundary defined by the criteria. For example, the masked threshold may be exactly 10 dB above the noise level per ERBN- For this reason, it is recommended that both masked and absolute thresholds be measured with as much precision as possible. Preferably, a step size of 5 or 10 dB should be used to determine the approximate level corresponding to threshold, and then a smaller step size of 2 dB should be used to define the threshold more precisely.

(2) The test gives only a rough indication of the edge frequency of a dead region; the test frequencies on the CD used to administer the test are spaced roughly at one-half octave intervals which inherently limits the precision (although test CDs with more finely spaced frequencies can easily be produced). Also, when the signal frequency falls just inside a dead region, the threshold in the TEN may be less than 10 dB higher than the TEN level per ERBN, and a dead region may be missed.

(3) The test depends on there being some degree of residual frequency selectivity in the cochlea. If the tuning in the cochlea is very poor, as a result of structural abnormalities, for example, then when the signal frequency falls in a dead region the amount of basilar-membrane vibration at the place where the signal is detected may be only a little less than the amount of vibration at the peak of the pattern, and the TEN test criteria may not be met.

(4) For frequencies at which a hearing loss is severe or profound it may be difficult to make the TEN sufficiently intense to produce 10 dB of masking. In such cases, the outcome of the test must be regarded as inconclusive. For example, Moore et al (2003) tested 13 female and 20 male teenagers with severe or profound hearing loss. For the majority of ears, the results were inconclusive at some frequencies because of the maximum output of the audiometer being reached when measuring the absolute or masked threshold. In almost all cases, the diagnosis was uncertain at some frequencies because the TEN could not be made sufficiently intense to

produce significant masking. The newer version of the test, the TEN (HL) test, allows higher noise levels to be used without overloading the audiometer because the noise bandwidth is reduced and the noise is synthesized so as to have minimal amplitude fluctuations.

(5) The TEN test does not take into account the non-flat frequency response of the earphone at the eardrum. Hence, the outcome may vary somewhat depending on which earphone is used. It seems reasonable to assume that minor irregularities in the frequency response of the earphone have only a small effect on the outcome of the test. For example, if the response of the earphone shows a peak at 2800 Hz, that peak will boost the effective level both of a 2800 Hz signal and of the noise components around 2800 Hz. The peak will not alter the local signal-to-noise ratio, and hence should not alter the masked threshold. However, this will not be the case if the response of the earphone changes rapidly with frequency. In practice, this means that the outcome of the test may not be reliable for very low or very high frequencies where the response of most audiometric earphones tends to roll off markedly. The TEN (HL) test does allow for the non-flat response of the earphones typically used for audiometry, but that version of the test only includes test frequencies from 500 to 4000 Hz, which is the range of greatest clinical interest.

Dead regions and the audiogram

When a dead region is present the audiogram will give a misleading impression of the amount of hearing loss, for a tone whose frequency falls in the dead region

(Gravendeel and Plomp,1960;Halpin,2002;Halpin,Thornton and Hasso, 1994).The true hearing loss in a dead region is effectively infinite, but the audiogram may sometimes indicate only a moderate hearing loss, especially when the tone frequency is close to the boundary of the dead region. The audiogram does not provide a reliable indication of whether or not a patient has a dead region. Halpin et al (1994) described two patients with similar audiograms both having a low frequency hearing loss with nearly normal mid frequency hearing. Post-mortem examination showed that one had no survival of the organ of corti in the apical region, while the other had an organ of corti which was present and of normal appearance (Moore et al;2000) suggests that high frequency hearing loss and a steeply slopping audiogram may be associated with dead region, but this is not always the case. Also a dead region can be present when the audiogram has a shallow slope.

DRs can be diagnosed and localized using psychophysical tuning curves (PTCs) (Florentine and Houstsma, 1983; Turner et al. 1983; Moore et al. 2000; Moore and Alcantara, 2001; Huss and Moore, 2003; Kluk and Moore, 2005) and using the threshold equalizing noise (TEN) test. Also a dead region can be present when the audiogram has a shallow slope.

A. General principle of pitch perception

The principle which was found to be essential for an explanation of the phenomena around the pitch of complex tones is the distinction between two kinds of pitch: spectral pitch and virtual pitch. The pitch of a pure tone, for example, is a spectral pitch. The pitch of a complex tone is a virtual pitch. There are two modes of pitch perception: an analytic mode, resulting in spectral pitch and a synthetic mode, resulting in virtual pitch.

Both kinds of pitch are derived from spectral cues. However, the principles by which they are derived are basically different. In particular virtual pitch is considered as an attribute which is the product of auditory Gestalt perception. In contrast to the spectral pitch cues, the virtual pitch cues can be generated only if a learning process previously has been performed. This learning process assumed to be a part of the learning process which is essential for acquiring the ability to identify speech sounds, hi that process, the correlations between the spectral pitch cues of voiced speech sounds (i.e. of harmonic complex tones) are recognized and stored. The knowledge about harmonic pitch relations that is acquired in this way is employed by the system to generate virtual pitch.

B. Pitch perception in the analytic mode

Due to certain non-linear interactions, the precise position of a particular cue depends not only on the frequency of the corresponding pure tone, but also on its sound pressure level and on the presence or absence of adjacent partials. By these influences, pitch shifts of spectral pitches are induced.

C. Explanation of some phenomena related to pitch perception

1. The ambiguity of pitch of complex tones

The true pitch of a complex tone (i.e. the pitch corresponding to the fundamental frequency) is sometimes confused with another pitch which usually differs by an octave- or fifth- interval from the "true" pitch (Ritsma and Engel, 1964, Ritsma, 1966).

2. The "residue" phenomenon-

"Residue" phenomenon, i.e. for the fact that a complex tone produces a pitch corresponding to its fundamental although the fundamental is lacking (Seeback, 1841; Schouten, 1940; Ritsma, 1962, 1963; Walliser, 1969b; Smoorenburg, 1970; Houtsma and Goldstein, 1972.

3. The pitch of an inharmonic "residue"-

A "residue" which originally is harmonic, but whose partials are shifted by one and the same frequency distance.

If the "residue" is shifted by 50 Hz and thus made strongly inharmonic, the distribution of virtual- pitch cues becomes completely ambiguous. Thus, no particular virtual pitch can be detected by the final recognition system.

These predictions agree well with related psychoacoustic observation (DeBoes, 1956; Schouten etal 1962; Walliser, 1969b, Smoorenburg, 1970).

A new approach has been formalized in a mathematical model, the "pattern transformation model",in which pitch perception is treated as a sequence of transformations of what are called "patterns of neural activity (Frederic.L Wightman, 1973). The heart of the model is the initial transformation from acoustic waveform to a hypothetical "peripheral" activity pattern, which is thought to represent the principle features of the power spectrum of the waveform. This pattern is then assumed to be Fourier transformed by the nervous system, yielding another pattern which has much in common with the autocorrelation function of the stimulus. In contrast with earlier models of pitch, the pattern transformation model is phase insensitive. Details of the temporal fine structure of the stimulus are important only to the extent that they influence the peripheral activity pattern. Pitch is assumed to be related to the positions of maximal activity in the transformed, autocorrelation like pattern.

While the model appears to be successful in accounting for the pitch of a wide variety of stimuli, two kinds of problems are encountered when the predictions of the model are compared with available data. First, most available data come from pitch matching experiments. Without extending the model considerably it is difficult to formulate an objective rule by which the model can derive a "pitch match" prediction. Second, the model makes specific predictions about another aspect of the pitch perfect, namely pitch strength. It is most important advantage over earlier models of pitch is that it is a formal mathematical model that can make specific, testable predictions.

Pitch is derived from the temporal fine structure of the stimulus waveform. The usual assertion is that pitch is given by the inverse of the time between the major positive peaks in the stimulus fine structure, eg. Ritsma and Engel (1964) explain their pitch matching results as follows: "The pitch values found are in good agreement with the hypothesis that the distance between two positive peaks in the fine structure hear two adjacent crests of the envelope constitutes a measure of the pitch of the complex."

Such theories might be called "peak picker" or "fine structure" theories of pitch.

Fine-structure theories are phase sensitive. That is since the relative phases of the spectral components of a waveform determine its temporal fine structure, changes in these phase relations are expected to affect pitch. More recent experimental evidence (Wightman, 1973) indicates that pitch is generally insensitive to such phase changes. The data suggest that within limits, all stimuli made up of the same spectral components have the same pitch, regardless of the relative phases of the components.

Thus fine structure theories appear to be inadequate. The model outlined here is one possible alternative to the fine structure theories.

If pitch perception is based on the excitation patter,. It might be expected that a pitch will be perceived which corresponds to the frequency of the tips of the psychoacoustical tuning curve, at lest low intensities. On the other hand, if the perception of pitch is based on the temporal pattern of neural firings in each active unit, then each unit responding to a 1 kHz tone is expected to be phase locked to that tone in both the normal and impaired ears. Therefore, pitch matches between the ears should yield results closer to identity matches.

Tuning curves and pitch matches in a listener with a unilateral, low frequency hearing loss was studied by Florentine.M and Houtsma, A.J. (1983). Psychoacoustical tuning curves were measured monaurally with a simultaneous tone on tone masking paradigm. Approximately 300ms, after the onset of the masker, a 250 ms probe tone was presented. Tuning curves were measured at 1 kHz for probe levels of 4.5 -, 7- and 13 dB SL in his impaired ear and for a probe level of 7 dB SL in his normal ear. The results from his left ear show a normal tuning curve when compared to data from listeners with normal hearing using a similar paradigm (i.e. Zwicker and Schorn, 1978; Florentine et al l980). The results from his right ear show tuning curves clearly displaced to the higher frequencies. As the level of the probe was increased from 4.5 to 13 dB SL, the tips of the tuning curves decreased from approximately 2.85 to approximately 2.20 kHz. Furthermore, for only an 8.5 dB increase in the level of the probe, the tips of the tuning curves increase in level from approximately 49 to 83 dB SPL. The results show a clearly shifted tuning curve tip for the 13 dB SL probe. The results of the control experiment which employed the low pass noise to mask possible combination tones, indicating no significant influence of combination tones.

In pitch matches experiment interaural pitch matches were made for ten frequencies ranging from 0.5 to 6 kHz. The subject was instructed to adjust the frequency of the comparison tone to match the pitch of the standard. The listener was instructed to use a bracketing procedure i.e. to adjust the comparison alternately higher and lower in pitch than the standard, reducing the difference until he perceived equal pitch. The most impressive feature of these results is the very large variability below 2 kHz, despite the large variability it is clear that, on the average, the matching frequencies differ between the ears.

Pitch intensity functions and psychophysical tuning curves (PTCs) were measured in ten listeners with sensorineural impairments of presumed cochlear origin, (Edward M Burns, Christpher, Turner, 1986). Masking patterns, frequency JND's, diplacusis measurements and octave adjustment were also obtained for selected conditions in selected listeners. The results showed a tendency for increased frequency JND's and increased pitch matching variability in frequency regions where frequency resolution, as determined by PTC estimates, was degraded. The results also showed exaggerated pitch level effects, both in regions where frequency resolution was degraded and in many cases, in regions where thresholds and frequency resolution were degraded and in many cases, in regions where thresholds and frequency resolution were apparently normal. The usual manifestation of exaggerated pitch level effect was an abnormally large negative pitch shift with increasing level, particularly at low frequencies. The limited data from diplacusis measurements and octave adjustments suggest that the exaggerated negative pitch shifts are the consequence of a large increase in pitch at low stimulus levels which recruit is at higher levels. These results are difficult to explain with simple tonotopic models, or presently formulated temporal models, of pure tone pitch encoding.

Pitch perception for pure tones was investigated in a group of listeners with low frequency sensorineural hearing loss(Turner et al,2000). Pitch judgements from each listener were compared with results from psycho-acoustic tasks which provide information on the "place" of cochlear response. The pitch measures employed were (1) binaural pure- tone pitch matching in a listener with unilateral hearing loss (2) octave judgements in listeners with musical ability, and (3) pitch-intensity functions in other listeners. Cochlear place for response was inferred from psychophysical tuning curves (PTCs). Two distinct types of PTC's for low frequency probe tones were observed. Three listeners demonstrated "abnormally tuned" PTCs. For these listeners the frequencies that were most effective at masking the probe were considerably higher than the probe frequency. The three remaining listeners demonstrated "normally tuned" PTC's. Listeners with abnormally tuned PTCs were suspected of having an extremely abnormal place of response for low frequency tones; this response pattern being located more toward the base of the cochlea than in the listeners with normally tuned PTCs. Sensitivity thresholds measured in the presence of high pass masking noise supported this hypothesis. Small pitch frequency irregularities were observed in many listeners, although they were not consistently related to the inferred place of response for that frequency. The individual listeners pitch judgements failed to distinguish between two types of PTCs. In particular, listeners who demonstrated abnormally tuned PTCs did not exhibit corresponding large pitch irregularities. These results are difficult to explain on the basis of a classic place theory of pitch perception.

Perception of the low pitch of frequency shifted complexes studied by Moore and Moore (2003) where all the components in a harmonic complex tone are shifted in frequency by Af, the pitch of the complex shifts roughly in proportion to Af .For tones with a small number of components, the shift is usually somewhat larger than predicted from pitch theories, which has been attributed to the influence of combination tone (Smooreburg, 1970). In experiment I assessed whether combination tones influence the pitch of complex tones with more than five harmonics, by using noise to mask the combination tones. The matching stimulus was a harmonic complex. Test complex were band pass filtered with pass bands centered on harmonic numbers 5 (resolved), 11 (intermediated) or 16 (unresolved) and fundamental frequencies (Fos) were 100, 200, 400 Hz. For the intermediate and unresolved conditions, the matching stimuli were filtered with the same pass band to minimize differences in the excitation patterns of the test and matching stimuli. For the resolved condition, the matching stimulus had a pass band centred above that of the test stimulus, to avoid common partials. For resolved and intermediate conditions, pitch shifts were observed that could generally be predicted from the frequencies of the partials. The shifts were unaffected by addition of noise to mask combination tones. For the unresolved condition, no pitch shift was observed, which suggests that pitch is not based on temporal fine structure for stimuli containing only high unresolved harmonics. In experiment 2 used three component complexes resembling those of Schouten (1962). Nominal harmonic numbers were 3,4, 5 (resolved), 8, 9, 10 (intermediate) or 13,14,15 (unresolved) and Fos were 50, 100, 200 or 400 Hz .Clear shifts in the matches were found for all conditions, including unresolved. For, the latter, subjects may have matched the "center of gravity" of the excitation patterns of the test and matching stimuli.

Method

CHAPTER 3

METHOD

Subjects: Subjects were divided into 2 groups

A) Subjects having Sensorineural hearing loss without dead region -

No. of subjects: 7

B) Subjects having Sensorineural hearing loss with dead region -

No. of Subjects: 6

Subject selection criteria

(A) **Sensorineural hearing loss**

> No significant history of neurological disorders.

> Pure tone threshold, more than 40dBHL in frequency ranges (250Hz to 4000Hz)

> Immittance screening revealing no middle ear pathology.

> An air bone gap was less than 10 dBHL at all frequencies (250Hz to 4000Hz).

(B) Sensorineural hearing loss with dead region

> No significant history of neurological disorders.

> Pure tone average more than or equal to moderate degree of hearing loss. An air bone gap of less than 10 dBHL at all frequencies from 250-4000Hz.

> Immittance screening revealing no middle ear pathology.

Instrumentation

> A calibrated two channel diagnostic audiometer MA-53 was used for testing the subjects.

> An immittance audiometer (GSI-33) used for evaluation of middle ear function.

> Tape recorder with CD for TEN test connected to a two channel diagnostic audiometer for presenting the stimulus.

Test environment

Test was carried out in an air - conditioined sound treated double room set up with ambient noise levels within permissible limits (Re: ANSI 1991, as cited in wilber,1994).

Test materials

TEN test CD was used for the purpose of diagnosing dead region in subjects wirh sensorineural hearing loss.

Procedure

1) PTA: Pure tone thresholds were obtained at octave frequencies between 250 Hz and 8000 Hz for air conduction stimuli and between 250 Hz to 4000 Hz for bone conduction stimuli using modified Hughson Westlake method (Carhart & Jerger, 1959).

2) Tympanometry: Tympanometry and reflexometry were carried out to rule out any middle ear pathology.

3) Psychophysical tuning curves: Psychophysical tuning curves (PTCs) (Chistovich, 1957; Small, 1959) were measured using a procedure which is similar to the physiological determination of a tuning curve on the basilar membrane (Sellick, et al., 1982) or in the auditory nerve (Kiang, Watanabe, Thomas & Clark, 1965). The signal was a sinusoid which was presented at a level 10 dB above the absolute threshold. In a given run, the signal frequency was fixed. The masker was an 80 Hz wide band of noise with variable center frequency. The exact masker frequencies were chosen individually for each subject, so as to define the position of the tip of the tuning curve with reasonable accuracy. Several signal frequencies were used for each subject; they were chosen to cover a range including any suspected dead region. For each of several masker center frequencies, the level of the masker needed just to mask the signal is determined.

4) TEN test: For detection of dead regions TEN test was used which is relatively fast and simple test (Moore, et al. 2000). The test makes use of a masking noise, called "threshold-equalizing noise" (TEN) which is spectrally shaped.

Absolute thresholds and masked thresholds in TEN were measured using manual audiometry, with the procedure proposed by Carhart & Jerger (1959). The TEN from the CDR was fed to one of the tape inputs on OB 922 audiometer and the sinusoidal test signal was fed to the other. TEN and signal levels were controlled by the use of the level controls on the audiometer. The noise and sinusoidal signal were mixed using the audiometer, and stimuli were delivered using TDH - 39 earphones supplied with audiometer. Each ear of each subject was tested separately.

Pitch-matching Procedure

For the pitch matching task, subjects were asked to match the perceived pitch of a variable pure tone with that of another pure tone that was fixed in frequency. The two tones were presented alternatively. Matches were made within the same ear, to estimate the reliability of matching. The subject was instructed to say 'same' or 'different' in the perceived pitch of variable tone with that of fixed frequency tone. The procedure was carried out for frequencies at 250Hz, 500Hz, 1000Hz, 2000Hz & 4000Hz. Data was tabulated in terms of the perceived pitch at the above frequencies. The extent of pitch matching was noted down for each frequency in all the subjects.

Results

CHAPTER 4

RESULTS

There were 10 sensorineural hearing losses with dead region subjects and 7 sensorineural hearing losses without dead region in the present study. Number of subjects perceived each fixed frequency and variable frequency are presented as a cross table for both the groups and both the ears.

Since we are dealing with frequency data, test of significance were not suitable and there was possibility of one person perceiving in more than one frequency because of this constraint the analysis were restricted to graphical representation and study of each subject.

A) Group analysis

Table 1: Cross tabulation with respect to fixed frequency and variable frequency in sensorineural hearing loss without dead region

(a) Right ear

	250Hz	500Hz	1000Hz	2000Hz	4000Hz
250Hz	7	0	0	0	0
500Hz	0	7	0	0	0
1000 Hz	0	0	7	0	0
2000Hz	0	0	0	7	0
4000Hz	0	0	0	0	7

Fixed frequency is shown in the first column and variable frequencies in other 5 columns.

(b) Left ear

	250Hz	500Hz	1000Hz	2000Hz	4000Hz
250Hz	7	0	0	0	0
500Hz	0	7	0	0	0
1000Hz	0	0	7	0	0
2000Hz	0	0	0	7	0
4000Hz	0	0	0	0	7

Fixed frequency is shown in the first column and variable frequencies in other 5 columns.

Table 2: Cross tabulation with respect to fixed frequency and variable frequency in sensorineural hearing loss with dead region

(a) Right ear

	250Hz	500Hz	1000Hz	2000Hz	4000Hz
250Hz	10	1	1	-	-
500Hz	-	10	1	-	-
1000Hz	1	2	9	4	2
2000Hz	1	2	4	10	9
4000Hz	-	1	3	8	9

Fixed frequency is shown in the first column and variable frequencies in other 5 columns.

(b) Left ear

	250Hz	500Hz	1000Hz	2000Hz	4000Hz
250Hz	10	1	1	-	-
500Hz	-	10	2	-	-
1000Hz	-	1	10	4	3
2000Hz	1	1	3	9	7
4000Hz	-	1	3	7	9

Fixed frequency is shown in the first column and variable frequencies in other 5 columns.

Number of subjects was converted as percentage since the subject size was not similar in both the groups. For the first group sensorineural hearing loss without dead region 7 subjects were taken and for second group sensorineural hearing loss with dead region 10 subjects were taken.

1) Sensorineural hearing loss without dead region right ear group and left ear group

It can be observed from the graph that all 7 subject with sensorineural hearing loss without dead region in both right ear and left ear fixed frequency same as variable frequencies at all frequency levels. None of the subject perceived in any other frequency level.

Figure 2: Sensorineural hearing loss without dead region (Right ear)

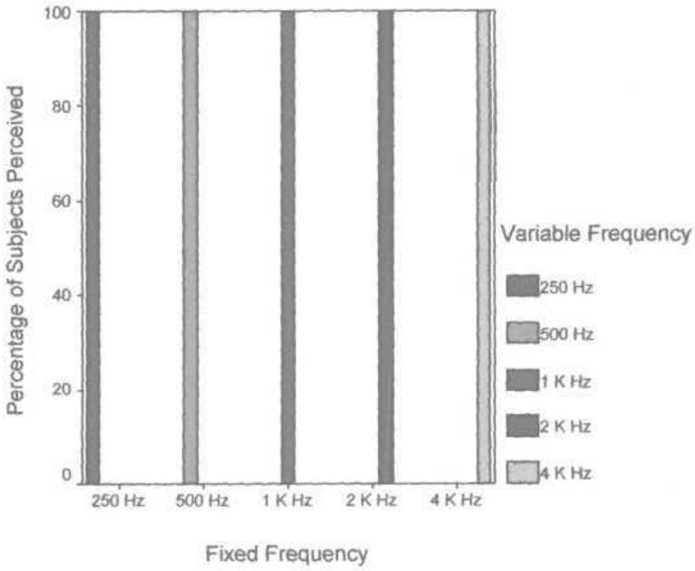
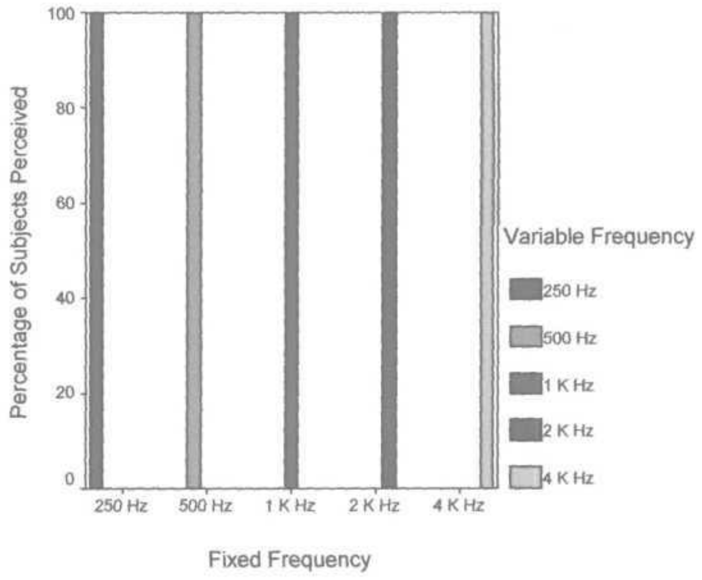


Figure 3:- Sensorineural hearing loss without dead region (Left ear)



2) Sensorineural hearing loss with dead region right ear group and left ear group

Figure 4: Sensorineural hearing loss with dead region (Right ear)

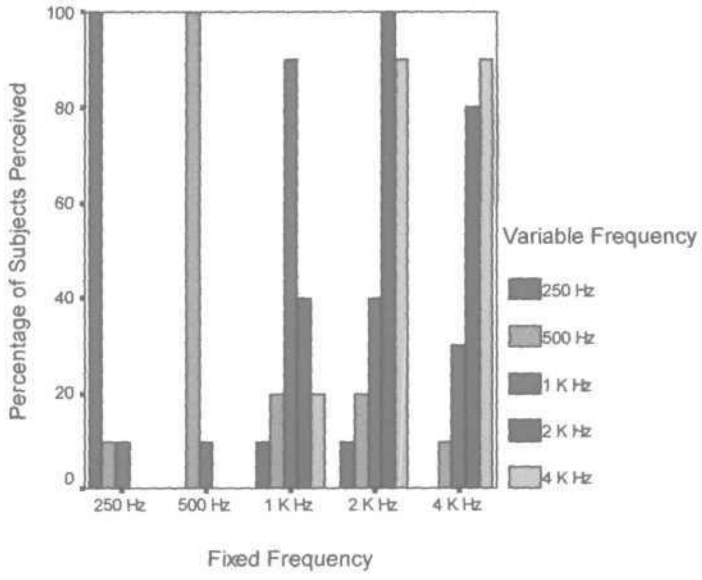
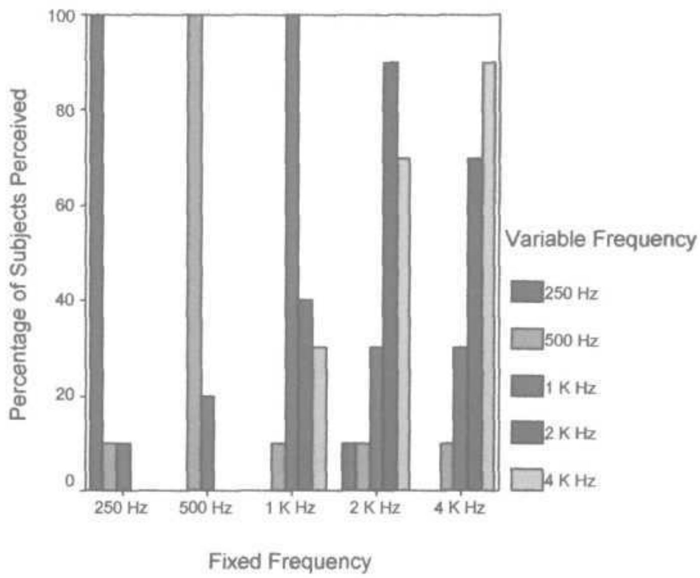


Figure 5: Sensorineural hearing loss with dead region (Left ear)



It can be noticed that in each fixed frequency we can find subjects who perceived in other variable frequencies but most of the subjects could perceive at the same frequency.

Since it was frequency data there is no analysis hence it is represented in subjective way.

B) Subject wise analysis

Table 3: Pitch matching by sensorineural hearing loss without dead region subjects

Subject Number	Frequency in Hz	Right ear					Left ear				
		250	500	1000	2000	4000	250	500	1000	2000	4000
Nl	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S
N2	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S
N3	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S
N4	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S
N5	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S
N6	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S
N7	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S					S	
	4000					S					S

Nl, N2, N3, N4, N5, N6, N7 are the subjects having sensorineural hearing loss without dead region. S indicates that the pitch was judged to be the same.

Fixed frequency is shown in the second column and variable frequency in other column.

Table 4: Pitch matching by sensorineural hearing loss with dead region subjects

Subject number	Frequency in Hz	Right ear					Left ear				
		250	500	1000	2000	4000	250	500	1000	2000	4000
SI	250	S	S				S	S	S		
	500		S	S				S			
	1000	S	S	S				S	S		
	2000	S	S	S	S			S	S	S	
	4000			S	S	S	S	S	S	S	S
S2	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S	S				S	S
	4000				S	S				S	S
S3	250	S					S				
	500		S					S			
	1000				S	S			S	S	S
	2000				S	S					S
	4000				S	S					S
S4	250	S					S				
	500		S	S				S			
	1000		S	S					S		
	2000		S	S	S	S				S	S
	4000		S	S	S	S	NR	NR	NR	NR	NR
S5	250	S					S				
	500		S					S	S		
	1000			S	S				S	S	S
	2000			S	S	S			S	S	S
	4000			S	S	S				S	S
S6	250	S					S				
	500		S					S			
	1000			S	S	S			S	S	S
	2000			S	S	S			S	S	S
	4000	NR	NR	NR	NR	NR			S	S	S
S7	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S	S				S	S
	4000				S	S				S	S
S8	250	S					S				
	500		S					S			
	1000			S					S		
	2000				S	S				S	S
	4000				S	S				S	S
S9	250	S					S				
	500		S					S			
	1000			S	S				S	S	
	2000				S	S				S	S
	4000				S	S				S	S
S10	250	S					S				
	500		S					S	S		
	1000			S					S		
	2000				S					S	
	4000					S					S

#Sl,S2,S3,S4,S5,S6,S7,S8,S9,S10 are the subjects having sensorineural hearing loss with dead region. #S indicates that the pitch was judged to be the same. #Fixed frequency is shown in the second column and variable frequencies in other column.#NR indicates no response.

The results of the present study indicated that the subjects with sensorineural hearing loss without dead region could match the pitch of 250Hz to 4000Hz precisely with the fixed frequency tones.

Table 5: Pitch matching and edge frequency for subjects with sensorineural hearing loss with dead region

Subject with dead region and edge frequency(EF)	Right ear					Left ear				
	250	500	1000 ~	2000	4000	250	500	1000	2000	4000
SI EF-1000Hz	250-500	500-1000	250-1000	250-2000	1000-4000	250-1000	500	500-1000	250-2000	500-4000
S2 EF-2000Hz	250Hz	500Hz	1000HZ	2000-4000	500-4000	250	500	1000	2000	2000-4000
S3 EF-l500Hz	250	500	2000-4000	2000-4000	2000-4000	250	500	1000-4000	4000	4000
S4 EF-1500Hz	250Hz	500-1000	500-1000	500-4000	500-4000	250	500	1000	2000-4000	NR
S5 EF-1500Hz	250	500	1000-2000	1000-4000	1000-4000	250	500-1000	1000-4000	1000-4000	2000-4000
S6 EF-2000Hz	250	500	1000-4000	1000-4000	NR	250	500	1000-4000	1000-4000	1000-4000
S7 EF-3000Hz	250	500	1000	2000-4000	2000-4000	250	500	1000	2000-4000	2000-4000
S8 EF-4KHz	250	500	1000	2000	2000-4000	250	500	1000	2000-4000	2000-4000
S9 EF-3000Hz	250	500	1000	2000-4000	2000-4000	250	500	1000-2000	2000-4000	1000-4000
S10 EF-4KHZ	250	500	1000	2000	4000	250	500	1000	2000	4000

Estimated auditory filter in subjects with sensorineural hearing loss without Dead region

Total number of subject (N) -7

It can be inferred from the results that the subject had narrower auditory filter indicating good frequency resolution and absence of dead region (DR).

250Hz N=7

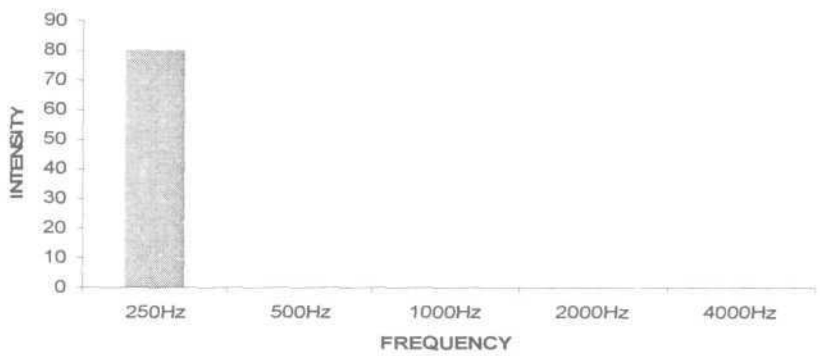


Figure 6: Estimated auditory filter shape for 250Hz

Figure indicates estimated auditory filter in subject with sensorineural hearing loss without dead region in 250Hz

500Hz N=7

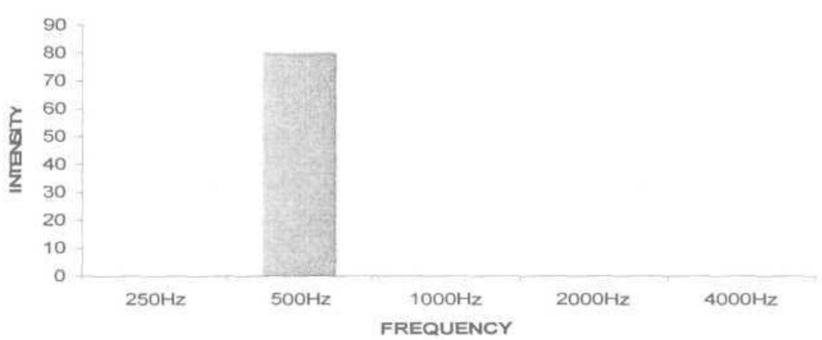


Figure 7: Estimated auditory filter shape for 500Hz

Figure indicates estimated auditory filter in subject with sensorineural hearing loss without dead region in 500Hz.

- * marks indicate edge frequency of the subjects. From that marks dead region started.
- The value in the first row indicates TEN test levels and the value in the second row indicate the masked thresholds in TEN test.

PTCs were carried out on a few subjects in order to check the validity of TEN test in detecting DR in subjects with sensorineural hearing loss.

For the subject SI PTCs are shown in the following figure -

For 1000Hz

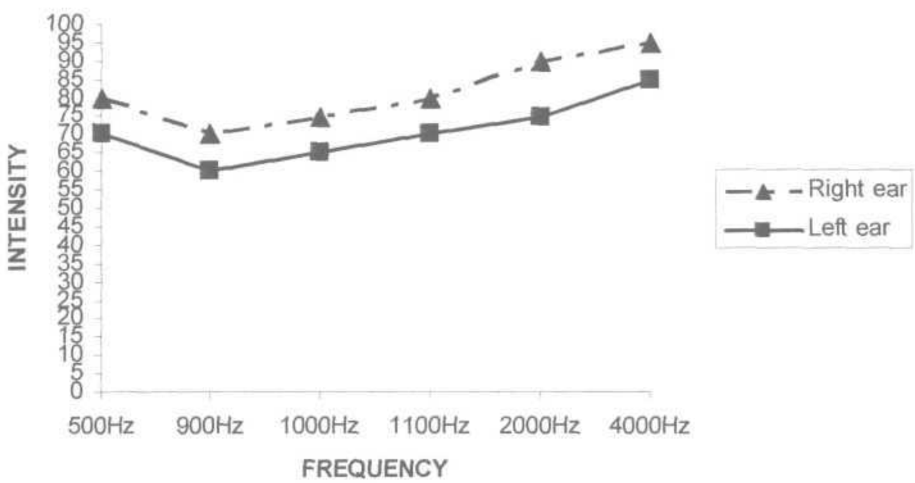


Figure 11: PTC for 1000Hz

It can be noted from the figure that the tip of the PTC for 1000Hz is not at 1000Hz instead it is at 900Hz.

From the above figure it can be observed that the tip of PTC for 1000Hz indicating intact frequency resolution.
For 2000Hz

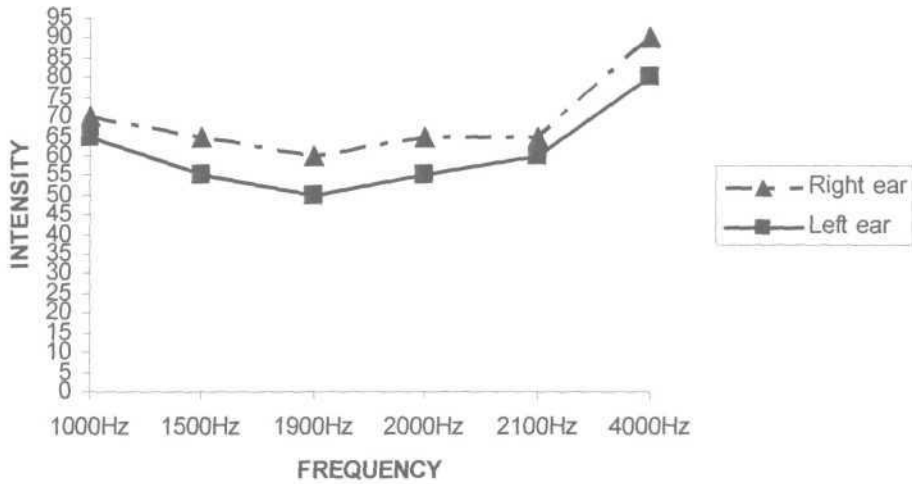


Figure 14: PTC for 2000Hz

From the above figure it can be observed that the tip of PTC for the frequencies 2000Hz shifted to 1900Hz.

For 4000Hz

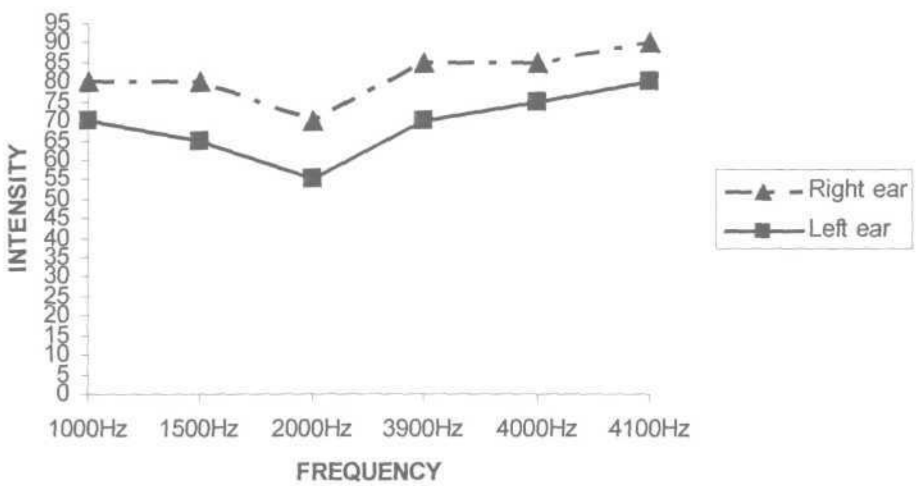


Figure 15: PTC for 4000Hz

From the above figure it can be observed that the tip of PTC for the 4000Hz PTC tip is shifted to 2000Hz. So there is shifting of frequency towards lower frequency side respectively.

For the subject S5 PTCs shows following result:

For 2000Hz

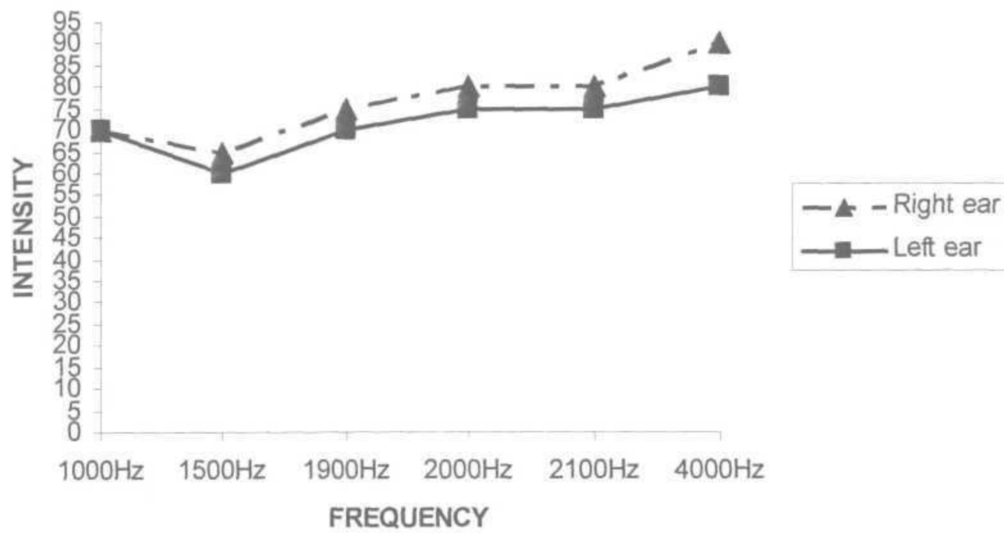


Figure 16: PTC for 2000Hz

From the figure it can be noted that the shift is towards 1500Hz for the subject S5. It denotes that there is a dead region.

So there is good correlation between the TEN test and PTC.

Auditory Filter shape for subjects with dead region

Following figure indicates subject S1 having dead region with 1000 Hz as edge frequency in both ears. From the figure it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

Right ear :
For 250Hz

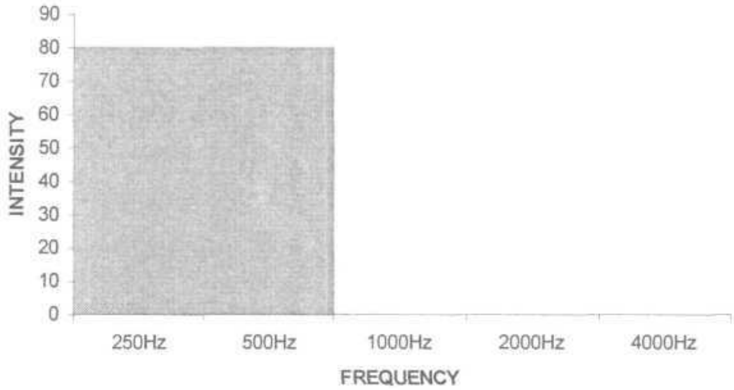


Figure 17: Estimated auditory filter shape for 250Hz

From the above figure it can be observed that for 250 Hz subject 1, there is widened auditory filter.

For 500Hz

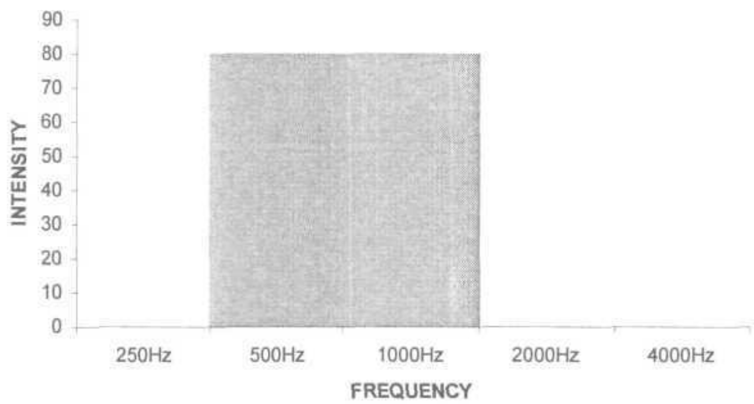


Figure 18: Estimated auditory filter shape for 500Hz

From the above figure it can be observed that For 500 Hz subject 1, there is widened auditory filter

For 1000Hz

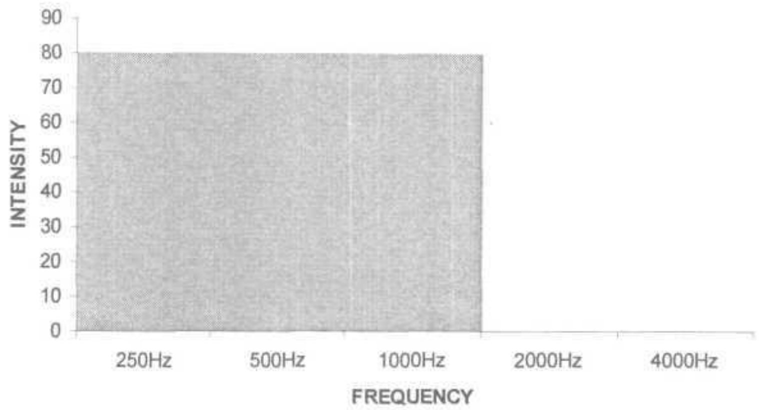


Figure 19: Estimated auditory filter shape for lOOOHz

From the above figure it can be observed that for 1000 Hz subject 1, there is widened auditory filter it started from 250Hz to lOOOHz.

For 2000Hz

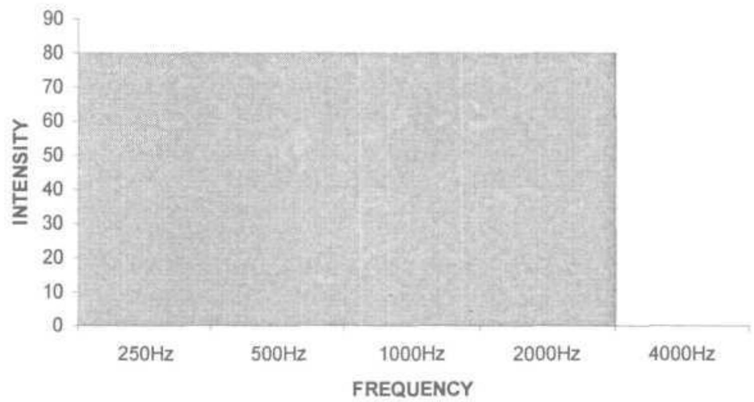


Figure 20: Estimated auditory filter shape for 2000Hz

From the above figure it can be observed that for 2000 Hz subject 1, there is widened auditory filter.

For 4000Hz

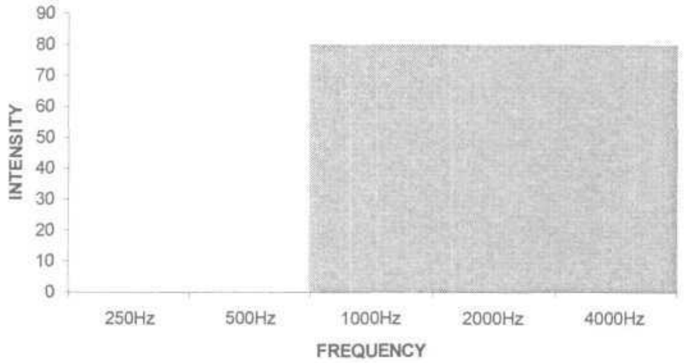


Figure 21: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000 Hz subject 1, there is widened auditory filter

Left ear :
For 250Hz

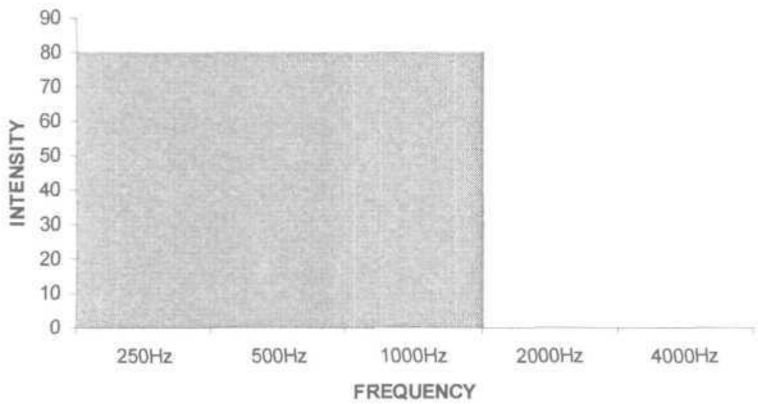


Figure 22: Estimated auditory filter shape for 250Hz

For 250 Hz subject 1, there is widened auditory filter

For 500Hz

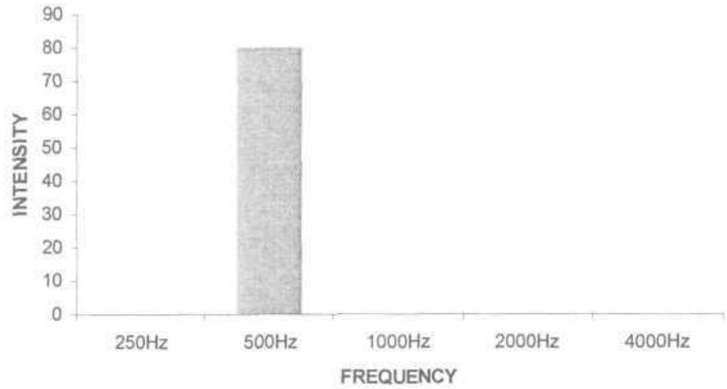


Figure 23: Estimated auditory filter shape for 500Hz

From the above figure it can be observed that for 500Hz subject 1, there is narrow auditory filter which indicates that there is no dead region

For 1000Hz

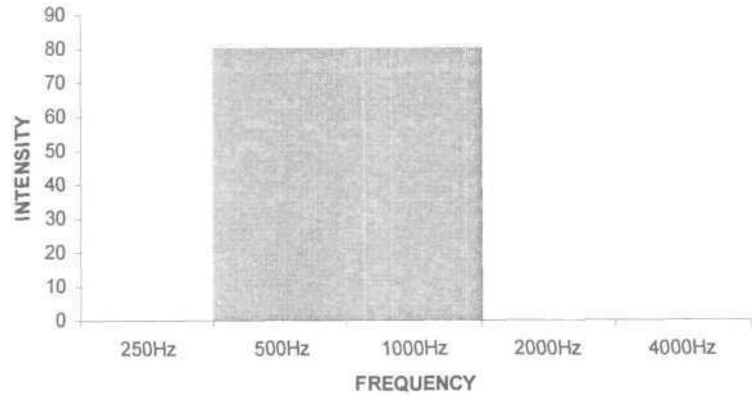


Figure 24: Estimated auditory filter shape for 1000Hz

From the above figure it can be observed that for 1000 Hz subject 1, there is widened auditory filter which indicates that dead region is present in that frequency region.

For 2000Hz

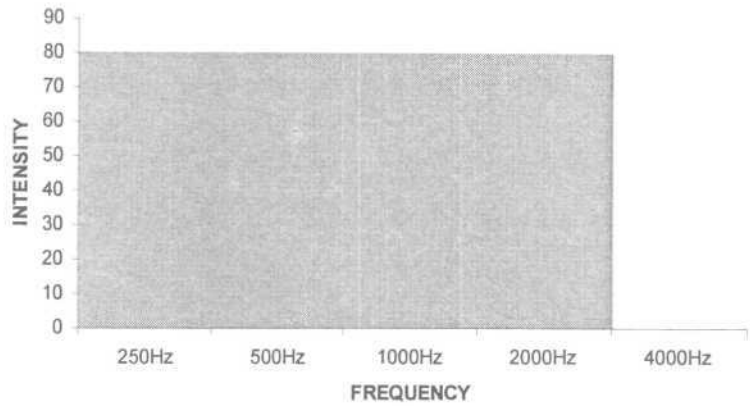


Figure 25: Estimated auditory filter shape for 2000Hz

From the above figure it can be observed that for 2000 Hz subject 1, there is widened auditory filter which indicates that dead region is present in that frequency region.

For 4000Hz

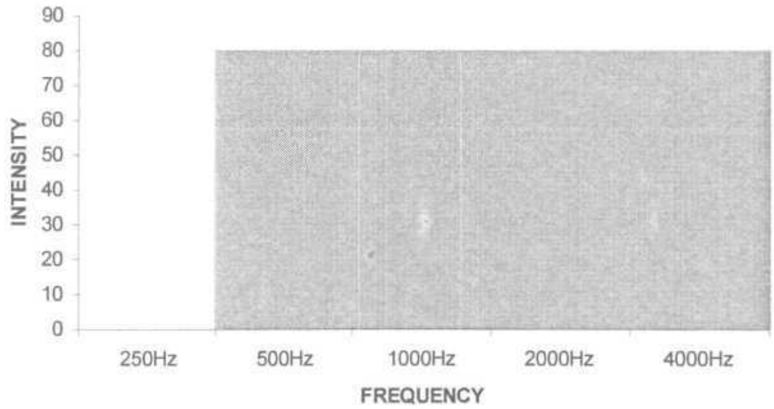


Figure 26: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000 Hz subject 1, there is widened auditory filter which indicates that dead region is present in that frequency region

From the above figure it can be observed that for subject S1 there is broadening of auditory filters for 250 Hz, 500Hz, 1 KHz, 2 KHz and 4 KHz for right ear and 250 Hz, 1 KHz, 2 KHz and 4 KHz for left ear.

Following figure indicate subjects S2 having dead region with 2000 Hz as edge frequency in both ears. From the figure it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For 250Hz, 500Hz, 1000Hz in both right and left ear shows auditory filter is narrow so there is no dead region.

For 250Hz

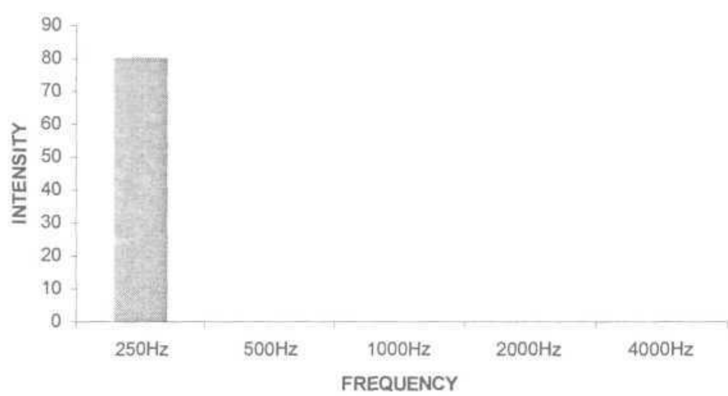


Figure 27: Estimated auditory filter shape for 250Hz

From the above figure it can be observed that for 250Hz subject 2, there is narrow auditory filter which indicates that there is no dead region.

For 500Hz

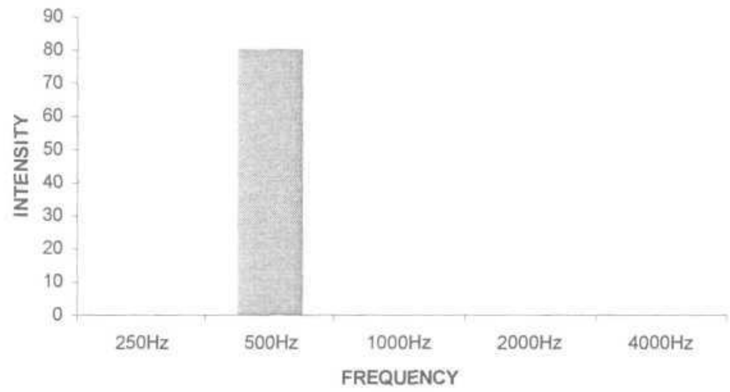


Figure 28: Estimated auditory filter shape for 500Hz

From the above figure it can be observed that for 500Hz subject 2, there is narrow auditory filter which indicates that there is no dead region

For 1000Hz

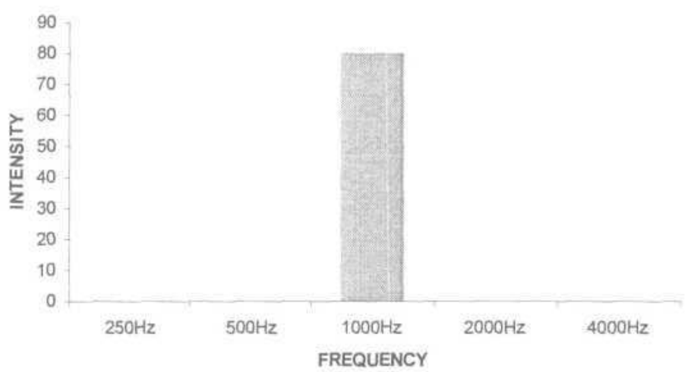


Figure 29: Estimated auditory filter shape for 1000Hz

For 1000Hz subject 2, there is narrow auditory filter which indicates that there is no dead region

Right ear:
For 2000Hz

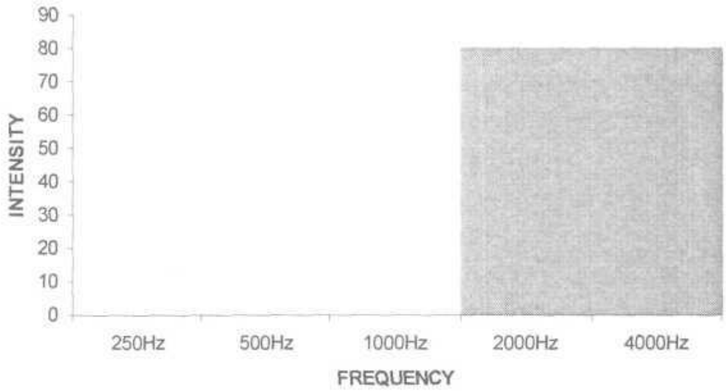


Figure 30: Estimated auditory filter shape for 2000Hz

From the above figure it can be observed that for 2000Hz subject 2, there is widened auditory filter which indicates that dead region is present in that region.

For 4000Hz

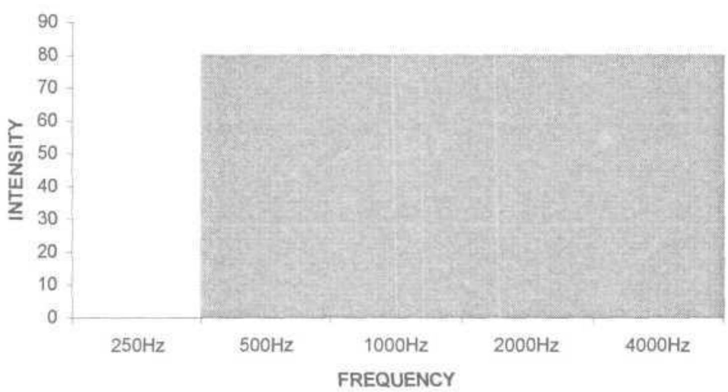


Figure 31: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000Hz subject 2, there is widened auditory filter which indicates dead region is present in that region.

Left ear:
For 2000Hz

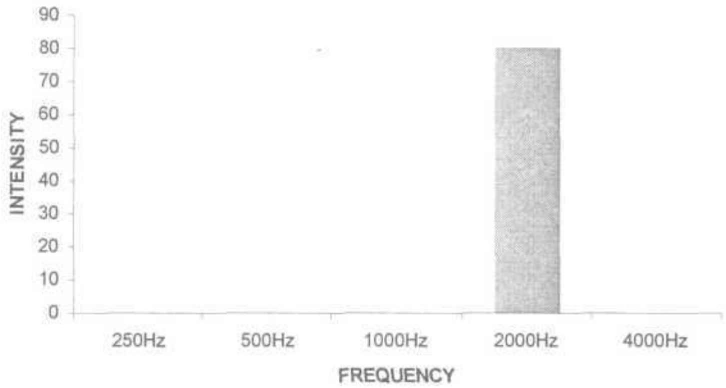


Figure 32: Estimated auditory filter shape for 2000Hz

From the above figure it can be observed that for 2000Hz subject 2, there is narrow auditory filter which indicates that there is no dead region.

For4000Hz

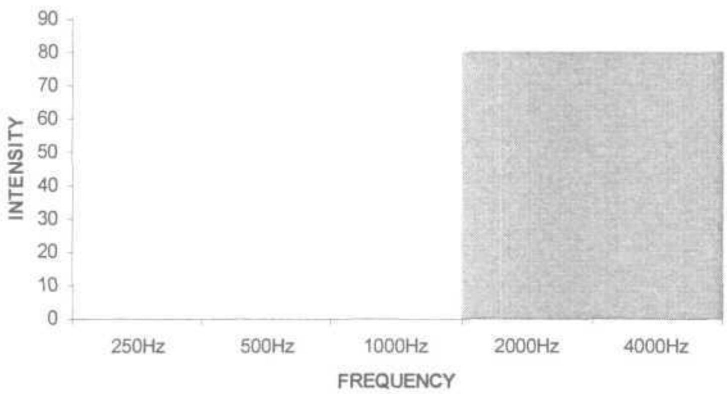


Figure 33: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000Hz subject 2, there is widened auditory filter which indicates dead region is present in that region.

From the above figure it can be observed that for subject S2 there is broadening of auditory filters for 2 KHz and 4 KHz for right ear and 4 KHz for left ear.

Following figure indicate subjects S3 having dead region with 1500 Hz as edge frequency in both ears. From the figure it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For 250Hz, 500Hz in right and left ear shows auditory filter is narrow so there is no dead region. But in right ear 1000Hz, 2000Hz, 4000Hz shows similar widening of auditory filter. The figure shown as follows:

Right ear:

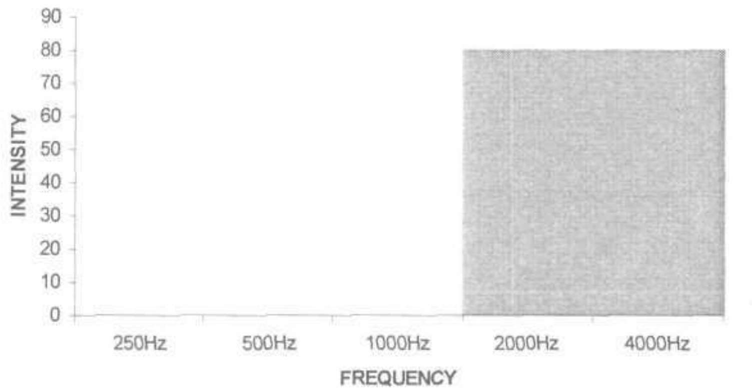


Figure 34: Estimated auditory filter shape for 1000Hz, 2000Hz, and 4000Hz.

From the above figure it can be observed that for 1000Hz, 2000Hz, 4000Hz subject 3, there is widened auditory filter which indicates dead region is present in that region.

Left ear:
For 1000Hz

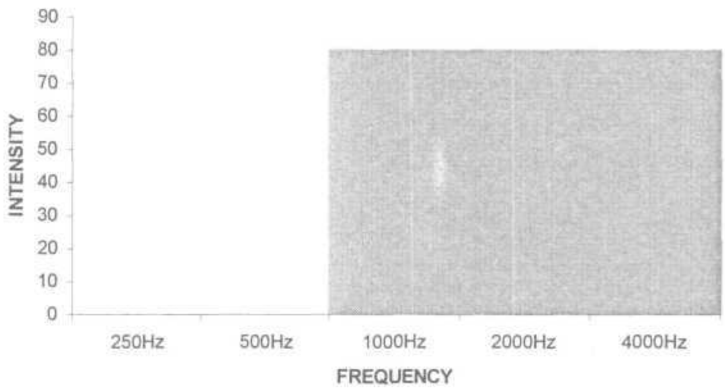


Figure 35: Estimated auditory filter shape for 1000Hz

For 1000Hz subject 3, there is widened auditory filter which indicates dead region is present in that region.

For 2000Hz, 4000Hz shows similar widen of auditory filter. The figure shown as follows:

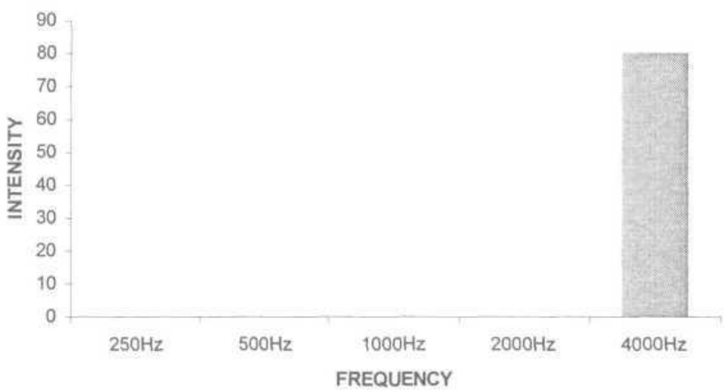


Figure 36: Estimated auditory filter shape for 2000Hz, 4000Hz

For 2000Hz, 4000Hz subject 3; there is narrow auditory filter which indicates that there is no dead region.

From the above figure it can be observed that for subject S3 there is broadening of auditory filters for 1 KHz, 2 KHz and 4 KHz for right ear and 1 KHz for left ear.

Following figure indicate subjects S4 having dead region with 1500 Hz as edge frequency in both ears. From the graph it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For the 250Hz in both right ear and left ear shows auditory filter is narrow so there is no dead region. Similarly in 500Hz and 1000Hz in left ear shows auditory filter is narrow.

Right ear:
500Hz and 1000Hz shows similar graphs

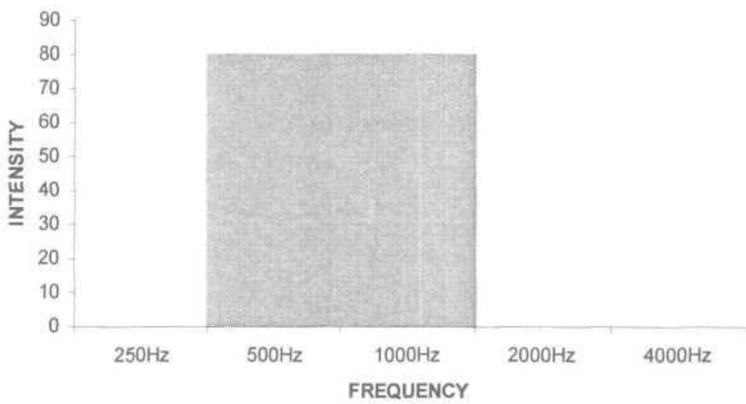


Figure 37: Estimated auditory filter shape for 500 Hz, 1000Hz

From the above figure it can be observed that for 500Hz and 1000Hz subject 4, there is widened auditory filter which indicates dead region is present in that region.

For 2000Hz and 4000Hz shows similar figure that is shown in bellow:

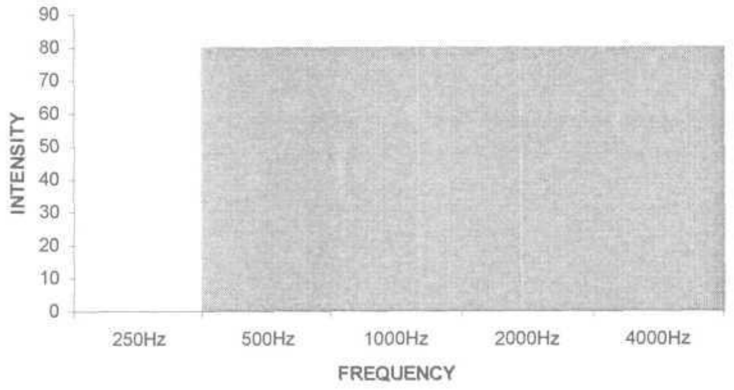


Figure 38: Estimated auditory filter shape for 2000Hz, 4000Hz

For 2000Hz and 4000Hz subject 4, there is widened auditory filter which indicates dead region is present in that region.

Left ear:

For 4000Hz there was no response but for 2000Hz figure is shown in bellow:
2000Hz

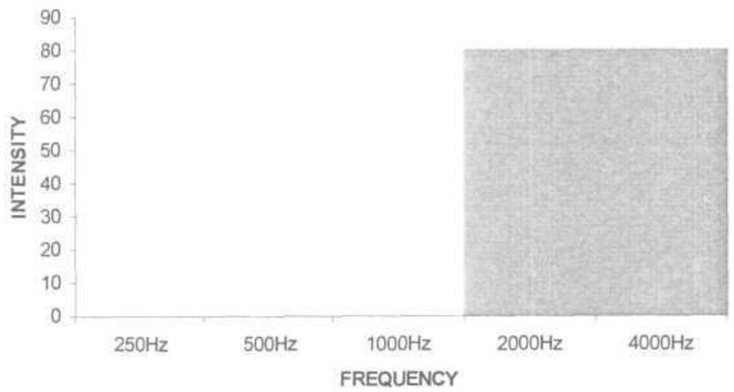


Figure 39: Estimated auditory filter shape for 2000Hz

From the above figure it can be observed that for 2000Hz subject 4, there is widened auditory filter which indicates dead region is present in that region.

From the above figures it can be observed that for subject S4 there is broadening of auditory filters for 250 Hz, 1000Hz, 2000Hz and 4000Hz for right ear and 2000Hz and 4000Hz for left ear.

Following figure indicate subjects S5 having dead region with 1500 Hz as edge frequency in both ears. From the graph it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For the 250Hz in both right ear and left ear shows auditory filter is narrow so there is no dead region and for right ear it is narrow for 500Hz also.

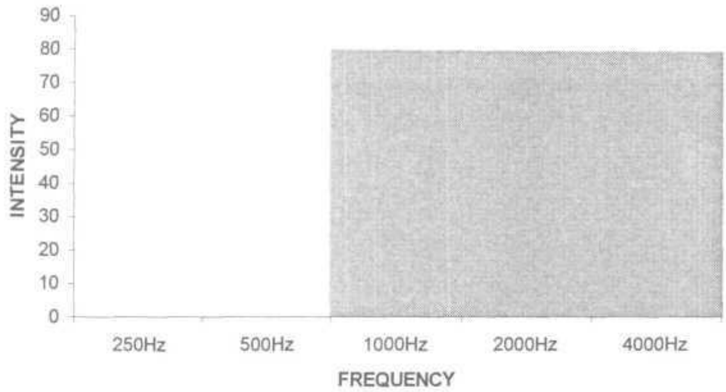
Right ear-

1000Hz-

Figure 40: Estimated auditory filter shape for 1000Hz

From the above figure it can be observed that for 1000Hz subject 5, there is widened auditory filter which indicates dead region is present in that region.

For 2000Hz and 4000Hz shows similar figure. The figure is bellow-



FREQUENCY

Figure 41: Estimated auditory filter shape for 2000Hz, 4000Hz

From the above figure it can be observed that for 2000Hz and 4000Hz subject 5, there is widened auditory filter which indicates dead region is present in that region.

Left ear :

For 500Hz

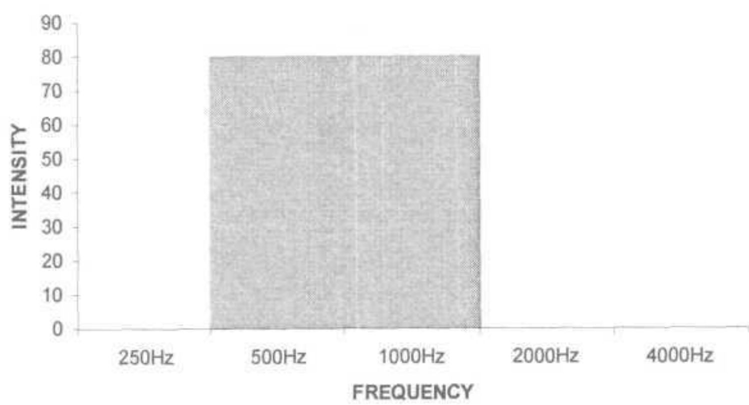


Figure 42: Estimated auditory filter shape for 500Hz

For 500Hz subject 5, there is widened auditory filter which indicates dead region is present in that region.

Left ear:
For 1000Hz and 2000Hz shows similar figure. The figure is bellow:

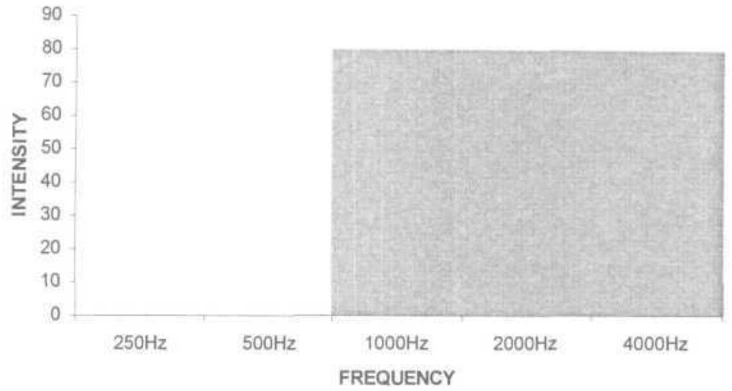


Figure 43: Estimated auditory filter shape for 1000Hz, 2000Hz

From the above figure it can be observed that for 1000Hz and 2000Hz subject 5, there is widened auditory filter which indicates dead region is present in that region.

For 4000Hz :

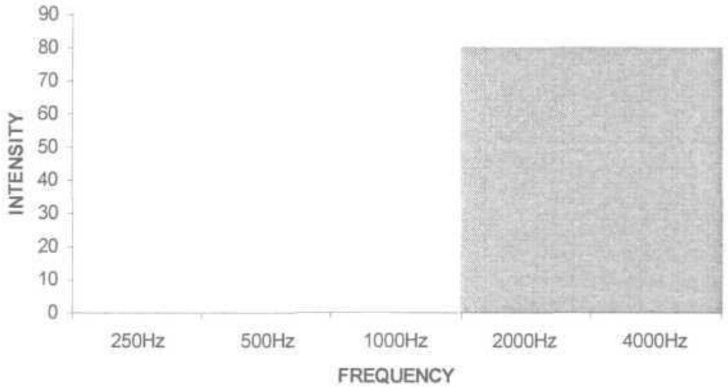


Figure 44: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000Hz subject 5, there is widened auditory filter which indicates dead region is present in that region.

From the above figures it can be observed that for subject S5 there is broadening of auditory filters for 1000Hz, 2000Hz and 4000Hz for right ear and 500Hz, 1000Hz, 2000Hz and 4000Hz for left ear.

Following figure indicate subjects S6 having dead region with 2000 Hz as edge frequency in both ears. From the graph it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR)

For the 250Hz and 500Hz in both right ear and left ear shows auditory filter is narrow so there is no dead region.

Right ear:

For 1000Hz and 2000Hz, shows similar figure but 4000Hz there is no response. The figure is below:

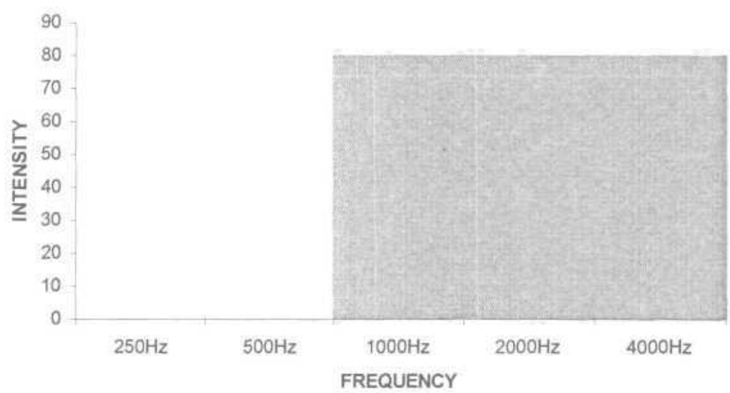


Figure 45: Estimated auditory filter shape for 1000Hz, 2000Hz

From the above figure it can be observed that for 1000Hz and 2000Hz subject 6, there is widened auditory filter which indicates dead region is present in that region.

Left ear:

For 1000Hz, 2000Hz and 4000Hz shows similar figure. The figure is below:

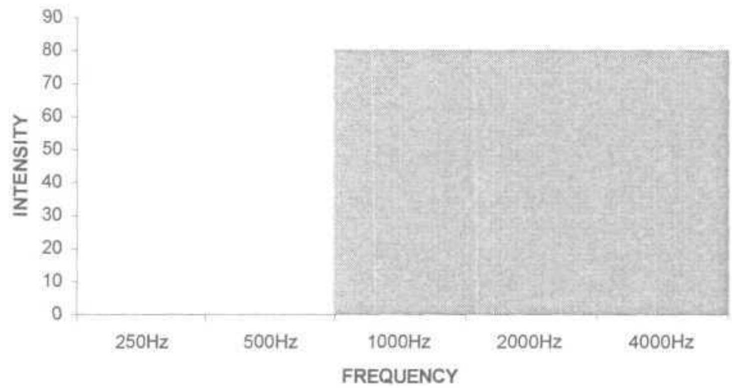


Figure 46: Estimated auditory filter shape for 1000Hz, 2000Hz, 4000Hz

For 1000Hz, 2000Hz and 4000Hz subject 6, there is widened auditory filter which indicates dead region is present in that region.

From the above figures it can be observed that for subject S6 there is broadening of auditory filters for 1000Hz, 2000Hz for right ear and 1000Hz, 2000Hz and 4000Hz for left ear.

Following figure indicate subjects S7 having dead region with 3000 Hz as edge frequency in both ears. From the figure it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For the 250Hz, 500Hz and 1000Hz in both right ear and left ear shows auditory filter is narrow so there is no dead region .For 2000Hz and 4000Hz in both ear shows similar figures. The figure is shown below:

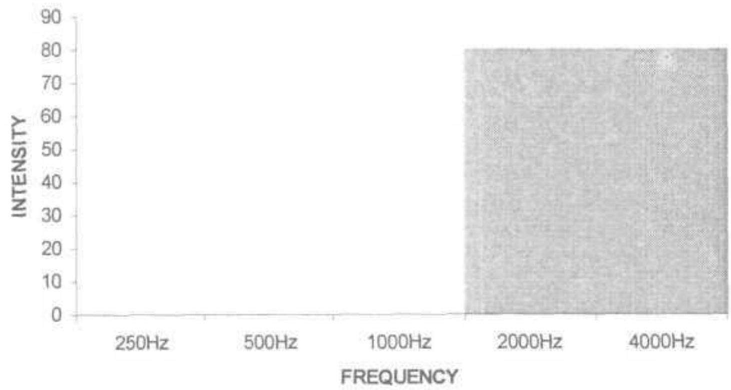


Figure 47: Estimated auditory filter shape for 2000Hz, 4000Hz

For 1000Hz, 2000Hz and 4000Hz subject 7, there is widened auditory filter which indicates dead region is present in that region.

From the above figures it can be observed that for subject S7 there is broadening of auditory filters for 2000Hz and 4000Hz for both ears.

Following figure indicate subjects S8 having dead region with 4000 Hz as edge frequency in both ears. From the figure it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For the 250Hz, 500Hz, 1000Hz in both right ear and left ear shows auditory filter is narrow and for 2000Hz right ear shows auditory filter is narrow so there is no dead region.

Right ear:

For 4000Hz

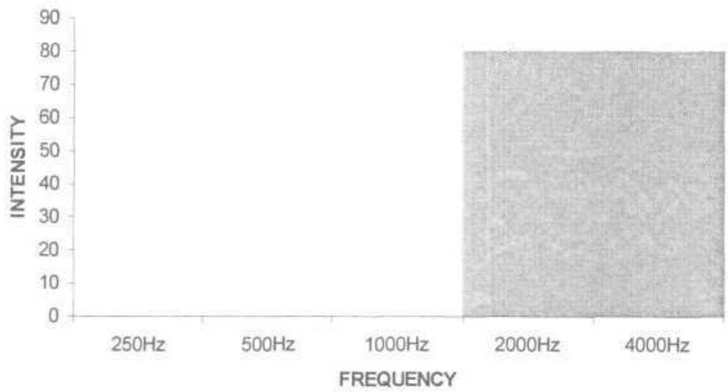


Figure 48: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000Hz subject 8, there is widened auditory filter which indicates dead region is present in that region.

Left ear:

For 2000Hz and 4000Hz shows similar figure. The figure is below:

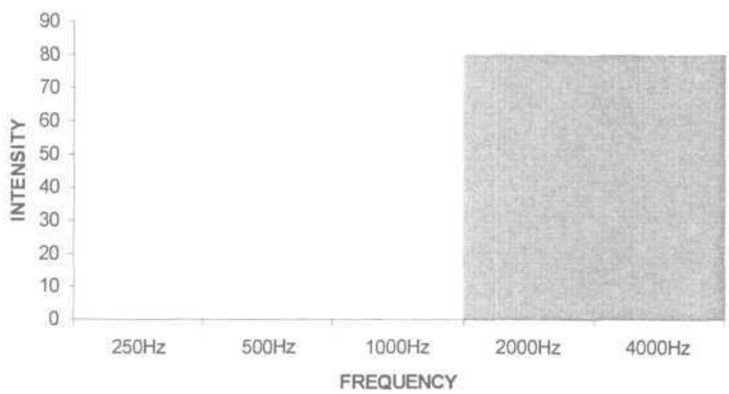


Figure 49: Estimated auditory filter shape for 2000Hz, 4000Hz

From the above figure it can be observed that for 2000Hz and 4000Hz subject 8, there is widened auditory filter which indicates dead region is present in that region.

From the above figures it can be observed that for subject S8 there is broadening of auditory filters for 2000Hz and 4000Hz for left ears and 4000Hz for right ear.

Following figure indicate subjects S9 having dead region with 3000 Hz as edge frequency in both ears. From the figure it can be inferred in the present subject the auditory filter is widen/narrow indicates of presence/absence of dead region (DR).

For the 250Hz, 500Hz and 1000Hz right ear and for the 250Hz and 500Hz left ear shows auditory filter is narrow so there is no dead region.

Right ear:

For 2000Hz, and 4000Hz shows similar figure. The figure is below:

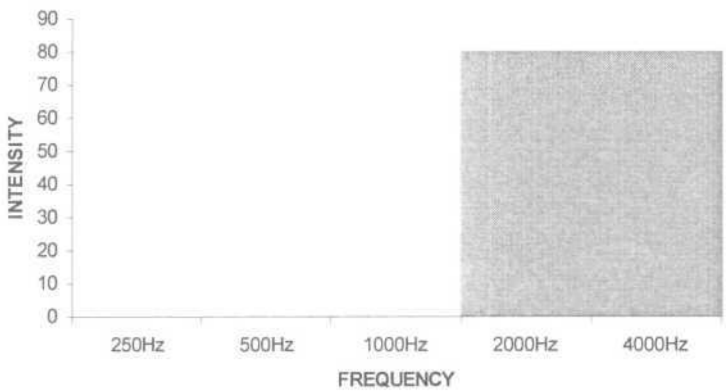


Figure 50: Estimated auditory filter shape for 2000Hz, 4000Hz

From the above figure it can be observed that for 2000Hz and 4000Hz subject 9, there is widened auditory filter which indicates dead region is present in that region.

Left ear:

For 1000Hz

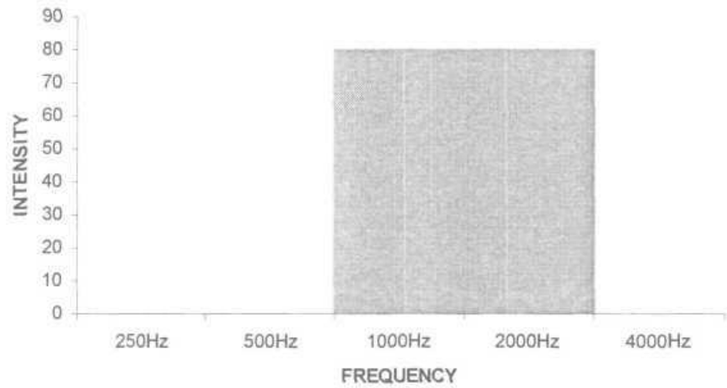


Figure 51: Estimated auditory filter shape for 1000Hz

From the above figure it can be observed that for 1000Hz subject 9, there is widened auditory filter which indicates dead region is present in that region.

For 2000Hz

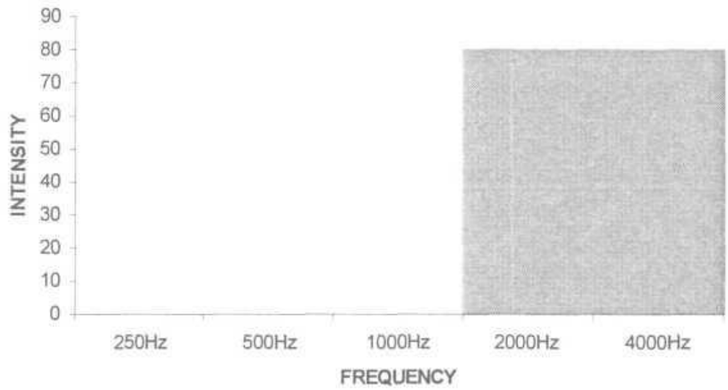


Figure 52: Estimated auditory filter shape for 2000Hz

From the above figure it can be observed that for 2000Hz subject 9, there is widened auditory filter which indicates dead region is present in that region.

For 4000Hz

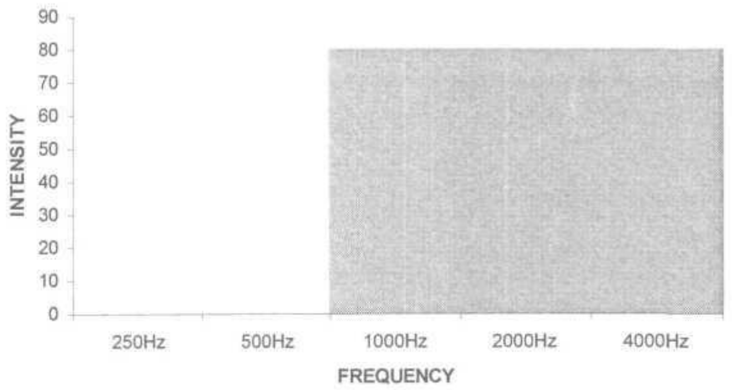


Figure 53: Estimated auditory filter shape for 4000Hz

From the above figure it can be observed that for 4000Hz subject *9*, there is widened auditory filter which indicates dead region is present in that region.

From the above figures it can be observed that for subject S9 there is broadening of auditory filters for 2000Hz and 4000Hz for right ears and 1000Hz, 2000Hz and 4000Hz for right ears.

The subjects S10 having dead region with 4000 Hz as edge frequency in both ears. For the 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz for the both ear shows auditory filter is narrow so there is no dead region in those frequency region.

Discussion

CHAPTER 5

DISCUSSION

Cochlear hearing loss results in a variety of changes in the way that sounds are represented in the auditory system. For such changes are especially relevant for the perception of pitch. There may be regions within the cochlea where the inner hair cells (IHCs) and/or neurons are completely nonfunctional. These are referred to as dead regions. The peak in the neural excitation pattern may occur at a place very different from that normally associated with that frequency. The place theory predicts that the perceived pitch of the tone in such a case should be very different from normal.

The result of present study indicated that pitch perception in individual with sensorineural hearing loss with dead region is different than the sensorineural hearing loss without dead region. The result in pitch shifts are for two reasons. The first applies when the amount of hearing loss varies with frequency and especially when the amount of inner hair cell (IHC) damaged varies with characteristic frequency. When the IHC transduction efficiency is reduced and so a given amount of basilar membrane (BM) vibration leads to less neural activity than when the IHCs are intact. When IHC damage varies with characteristic frequency the peak in the neural excitation pattern evoked by a tone will shift away from a region of greater IHC loss. Hence the perceived pitch is predicted to shift away from that region. Early studies of diplacusis (De Mare, 1948;Webster and Schubert, 1954)were generally consistent with this prediction, showing that when a sinusoidal tone is presented in a frequency region of hearing loss, the pitch shifts towards a frequency region where there is less hearing loss. An alternative way in which pitch shifts might occur is by shifts in the position of the peak excitation on the BM.

The results of the present study indicated that the tips of tuning curves shifted towards lower frequencies in case of sensorineural hearing loss with dead region. This means that the maximum excitation at a given place is produced by a lower frequency. The results also showed that shift of pitch toward higher frequency (upward) but some cases showed that shift to be towards lower frequency. The peak of the BM response in an impaired cochlea would be shifted towards the base -i.e toward place normally responding to higher frequencies. Gaeth and Norris (1965)and Schoeny and Carhart (1971) reported that pitch shifts were generally upwards regardless of the configuration of loss. However it is also clear that individual differences can be substantial and subjects with similar patterns of hearing loss (absolute thresholds as a function of frequency) can show quite different pitch shifts. Huss, et al. (2001) and Huss & Moore (2005) obtained pitch matches and octave matches for subject with an extensive high frequency dead region. For tones whose frequency fell well within the dead region, the perceived pitch was shifted upwards, although it was also unclear.

The result of the present study indicated that frequency discrimination is poor for the individual with sensorineural hearing loss with dead region. The frequency of pure tones may be represented in terms of phase locking (a temporal representation) for frequencies below about 5000 Hz, and purely, spectrally (a place representation) for higher frequencies.

The precision of phase locking can be reduced (Wolf et al. 1981; Miller, et al. 1999), although this has not always been found. According to temporal theory, reduced precision of phase locking should adversely affect frequency discrimination.

The propagation time of the traveling wave along the basilar membrane and the relative phase of the response at different places may differ from normal, because of loss of the active "mechanism", structural abnormalities, or both (Ruggero, 1994; Ruggero et al. 1996). This could adversely affect mechanisms for pitch perception based on cross-correlation of the outputs of different points on the basilar membrane (Loeb et al. 1983; Shamma, 1985; Shamma and Klein, 2000).

It has been proposed that the frequency discrimination of steady pulsed tones by normally hearing listeners is largely based on temporal information (cues desired from phase locking) for frequencies upto 4 to 5 kHz (Moore, 1973, 1974, 2003; Goldstein and Srulovicz, 1977; Sek and Moore, 1995; Micheyl, et al. 1998, Heinz, et al. 2001). Above 4 to 5 kHz, frequency discrimination is thought to depend mainly on place based changes in the excitation pattern (Moore, 1973b; Sek and Moore, 1995), although residual phase locking may play some role (Heinz, et al. 2001).

The results clearly indicated that if sensorineural hearing loss is accompanied with dead region (DR.) then there is broader auditory filter. If there is no dead region the auditory filter shape is narrow which might indicate that hair cell in that region could be functioning. It can be expected that the perception of pitch might be more affected by the relative phase of the component in a dead region than the without dead region.

For such DR cases frequency selectivity is reduced. Auditory filters are broader than normal (Pick et al. 1977; Glasberg and Moore, 1986; Moore, 1998). Hence the excitation pattern evoked by a sinusoid is also broader than normal. According to place theory this should lead to impaired frequency discrimination of sinusoids. Reduced frequency selectivity also presumably leads to a reduced ability to resolve partials in complex tones, and this might adversely affect the perception of the pitch of complex tones and also pure tone. For subjects with broad auditory filters, even the lower harmonics would interact at the outputs of the auditory filters, giving a potential for strong phase effects. Changes in phase locking and in cochlear traveling wave phase could also lead to less clear pitches and poorer discrimination of pitch.

In the present study subjects of sensorineural hearing loss with dead region reported that they did not perceive distinct pitch, but sounded like noises. There have been a few studies of pitch perception in people with hearing losses that increase abruptly at high frequencies, who probably had dead regions at high frequencies. These subjects often report that high frequency sinusoids do not have distinct pitch, but sound like noises or buzzes (Villchur, 1973; Moore et al. 1985b; Murray & Byrne, 1986). Subjective reports that pure tones sound noise like may be taken as a hint that a dead region is present, but ratings of the clarity of the tonal percept cannot be used as a reliable indicator of dead regions.

A sensorineural hearing loss involves not only a reduction of sensitivity but also a set of supra threshold impairments that distort the perception of sounds: listeners may suffer increased susceptibility to forward and backward masking, making it more likely that vowels will mask energy in weaker adjacent consonants; auditory filters are often broader than normal, leading to increased masking by background noises and by echoes in reverberant rooms; in extreme cases, even in quiet anechoic environments, difficulties may be experienced in detecting changes in the pitch of a talker's voice and in determining the spectral shape of speech sounds; the ability to analyze the temporal fine structure of the output of auditory filters may also be reduced, leading to difficulties in following rapid changes in amplitude, frequency, and pitch, and exacerbating the effects of noise.

Summary And Conclusions

CHAPTER 6

SUMMARY AND CONCLUSIONS

It has been suspected that a pure tone might be perceived as noise like when the tone produces maximum excitation in a region of the cochlea where there is extensive or complete loss of inner hair cell (IHC) and /or neural function, which is referred to as a dead region.(DR). It is defined as region in the cochlea where IHCs and /or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off place listening (i.e. the tone is detected at a place where the amount of basilar membrane vibration is lower but IHCs and neurons are functioning more effectively), (Moore, 2004). DRs can be diagnosed and localized using psychophysical tuning curves (PTCs).(Florentine and Houtsma,1983;Turner et al ,1983;Moore et al ,2000;Kluk and Moore,2005)and using the threshold -equalizing noise (TEN)(Moore et al,2000;2004;Huss and Moore,2003).

The objective of the present study was to study the pitch perception in individual with & without dead regions and whether there is relationship between dead region and perceived pitch and to see whether there is any relationship between the extent of DRs and pitch shift.

To study the objectives total 17 sensorineural hearing loss individuals with and without dead region were divided into two groups:

(a) Subjects having sensorineural hearing loss without dead region.

(b) Subjects having sensorineural hearing loss with dead region.

Group -1 Subjects having sensorineural hearing loss without dead region

In this group the subjects were selected based on the following criteria

- No significant history of neurological disorders.
- Pure tone threshold, more than 40dBHLin frequency ranges (250Hz to 4000Hz)
- Immittance screening revealing no middle ear pathology.
- An air bone gap of less than 10 dB HL at all frequencies (250Hz to 4000Hz).

Group -2 Subjects having sensorineural hearing loss with dead region

- No significant history of neurological disorders.
- Pure tone average more than or equal to moderate degree hearing loss. An air-bone gap of less than 10 dBHL at all frequencies from 250-4000Hz.
- Immittance screening revealing no middle ear pathology.

For detection of dead regions psychophysical tuning curves (PTCs) was established using a procedure which is similar to the physiological determination of a tuning curve on the basilar membrane (Sekkick et al, 1982) or in the auditory nerve (Kiang, Watanabe, Thomas and Clark, 1965). TEN test was also used which is relatively fast and simple test. If the subjects had dead region or not then pitch-matching experiment was carried out. For the pitch matching task, subjects were asked to match the perceived pitch of a variable pure tone with that of another pure tone that was fixed in frequency. The subject was instructed to say 'same' or 'different' for perceived pitch of variable tone with that of fixed frequency tone.

The results reveal that

- Pitch perception in individual with sensorineural hearing loss with dead region is different than in those individuals having sensorineural hearing loss without dead region.
- The tips of tuning curves shifted towards lower frequencies in case of sensorineural hearing loss with dead region.
- If sensorineural hearing loss is accompanied with dead region (DR) then there is broader auditory filter and hence pitch matching is difficult.

From the above result we can conclude that

- Pitch matches are often erratic and frequency discrimination is poor, for tones with frequencies falling in a dead region. This indicates that such tones do not evoke a clear pitch sensation.
- The shifted pitches found for some subjects indicate that the pitch of low frequency tones is not represented solely by a temporal code. Possibly, there needs to be a correspondence between place and temporal information for a "normal" pitch to be perceived.

Clinical implications

a) The presence or absence of dead regions has important implications for the fitting of hearing aids.

b) Counseling about the likely benefit from frequency transposition on hearing aids.

c) To help in the choice of hearing aid type if there are medical contraindication for cochlear implant.

Future suggestion for research

1. To study the speech perception and factors affecting speech perception in subjects with dead region.

2. To study the perception of music and factors affecting music perception in subjects with dead region.

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