MODELLING OF HUMAN AUDITORY SYSTEM
AND
HEARING DEFICIENCY CLASSIFICATION

A THESIS

submitted in partial fulfilment of the
requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Measurement and Instrumentation)

By

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January, 1988

CANDIDATE'S DECLARATION

I hereby, certify that the work which is being presented in the thesis entitled, MODELLING OF HUMAN AUDITORY SYSTEM AND HEARING DEFICIENCY CLASSIFICATION, in partial fulfilment of the requirements for the award of the Degree of MASTER OF ENGINEERING IN ELECTRICAL ENGINEERING with specialization in MEASUREMENT AND INSTRUMENTATION, submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee (India), is an authentic record of my own work carried out for a period of about sixteen months, from August, 1986 to January, 1988 under the supervision of Dr. H.K. Verma, Professor, and Dr. Vinod Kumar, Reader, Department of Electrical Engineering, University of Roorkee, Roorkee, India.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

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Dated: January 16 ,1988

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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"Foot prints, that perhaps another, sailing o'er life's solemn main, A forlorn and shipwrecked brother, seeing, shall take heart again. Let us then be up and doing, with a heart for any fate; still achieving, still pursuing learn to labour and to wait."

— Long Fellow
('Psalm of life')

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INTRODUCTION

CHAPTER I

INTRODUCTION

1.1.0 Prologue

Recognition of the recent growth of interest, in the study of human sensory systems, has prompted advanced coagulation of engineering principles and applications with human physiology and bio-medicine. In a field as diffuse as biomedical engineering the sensory processes, perhaps, find the latest areas of extensive research and deep study; the most important reason being that they are quite complicated. Their complexity is worth unraveling, if for no other reason than the fact that whatever we know about the world is based on what we find out through the senses. The senses impose limits on what we know and they bias our understanding of the world. All the sensory information is analysed, changed, abstracted and finally stored in the form of knowledge in the brain. A large portion of the brain-cortex, of our nervous system is devoted to audition. Recent researchers have commented that favourite sounds, melodies and speeches not only speed up recovery of hospitalized patients but also help to a great extent in, evoking lost memories and, curing minor brain disorders. In ancient India special mantras and sutras were chanted to revive and improve concentration, cure all sorts of illness and purify the senses.

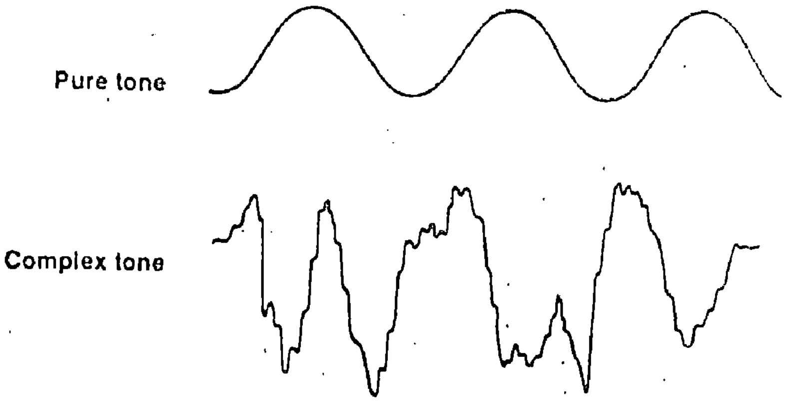

FIG. 1.1.0 PURE & COMPLEX TONES.

The sense of hearing is a fantastic, difficult and an exciting phenomenon. Alongwith being incredible, it is a wonderful receptive mechanism given to us by nature. It collects energy through its receptors, the ears, in the form of sound and converts that energy into a code, the nervous system can use. The conversion is crucial, and it is not entirely understood. This vital step is still a mystery. Our brain does not physically translate the code into sound; rather the coded information itself or some correlate of it is what we perceive as sound. The process of perceiving conscious sensations of sound is still not absolutely understood.

Sound energy is transmitted through air by a movement of air molecules. The disturbance of air molecules that makes up a sound wave consists of regions of compression, in which the air molecules are close together and the pressure is high, alternating with areas of rarefaction, where the molecules are farther apart and the pressure is lower. Anything capable of creating such disturbances or waves can serve as a sound source. A tone emitted by a sound source is said to be a pure tone when the waves of rarefaction and compression are regularly spaced. The waves of speech and many other common sounds are not regularly spaced but are complex waves made up of many frequencies of vibration. In other words, pure tone is a sound wave made up of just one frequency; and complex tones are combinations of two or more pure tones(Fig.1.1.0). If all the pure tones, that we can hear, are combined, we get an extremely complicated sound wave, which appears to be irregular, and is called noise (white noise).

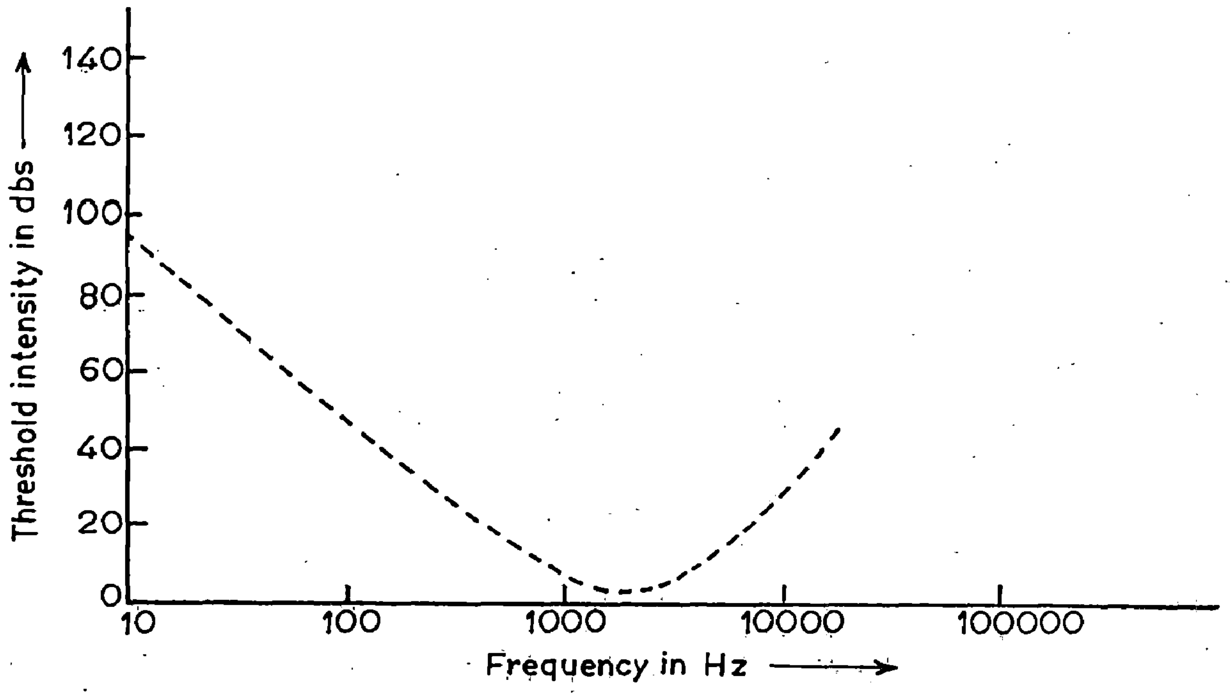

FIG.1.1.1 HUMAN AUDIBILITY CURVE.

White noise sounds like the hissing static we can pick on our radio. It has no particular pitch and is best described as a "sush" sound.

The sounds heard most keenly by human ears are those from sources vibrating at frequencies between 1000 and 4000 Hz (Fig.1.1.1), although the entire range of frequencies audible to human beings extends from 20 to 20,000 Hz. The frequency of vibration of the sound source is related to the pitch we hear; the faster the vibration, the higher the pitch. We can also detect loudness and tonal quality, or timbre, of a sound. The difference between the packing (or pressure) of air molecules in a zone of compression and a zone of rarefaction, i.e. the amplitude of the sound wave, is related to the loudness of the sound that we hear. The number of sound frequencies in addition to the fundamental tone, i.e. the lack of purity of the sound wave, is related to the timbre of the sound. We can distinguish some 400,000 different sounds; we can distinguish a note played on a piano from the same note played on a violin, and we can identify voices heard over the telephone. We can also selectively not hear sounds, tuning out the babel of a party to concentrate on a single voice.

The unit of measurement of sound intensity is called the 'bel'. Often, we work with sounds that are less than one bel and therefore we use a smaller unit of measurement called the decibel i.e. one tenth of a bel. The db ratings of some common sounds are:

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The unit of measurement of sound intensity is called the 'bel'. Often, we work with sounds that are less than one bel and therefore we use a smaller unit of measurement called the decibel i.e. one tenth of a bel. The db ratings of some common sounds are:

Rustle of leaves in gentle breeze	10 db
Quiet car, 10 feet away	50 db
Ordinary conversation	60-70 db
Pneumatic drill, 10 feet away	90 db
Phonograph putting out 10 watts, 10 feet away	110 db
Faintest audible sound	0 db
Painful sound	140 db.

Sound intensity is measured with respect to some reference. Two different reference sounds are used. One is sound pressure level (abbreviated SPL), which is defined as a wave having a pressure of 0.0002 dyne/cm^2. The other is the sensation level (abbreviated SL) which is the pressure of a sound that is at the threshold of human hearing. SPL and SL actually do not differ very much, but still these two references have their own significance.

Many a scientists and bio-medical specialists have tried to explain the remarkable and mysterious operation of audition. But the most genuine and practical results with the best convincing evidences have been obtained whenever human anatomy and physiology were combined with a few principles of electrical engineering. Scientists and anatomists like Gaspard Bauhin, Helmholtz, Alfonso Corti, Georg Von Békésy and many others, explained the mechanism of hearing, on basis of anatomical evidences and some basic laws of physics, propounding several theories of hearing. The validity and logic behind these theories was only proved and counter checked when specialized electrical engineers like Onchi, Zwislocki, Moller, Mundies and several others gave a new dimension to biomedical engineering, in the field of auditory mechanics, by formulating and simulating electrical network models of the human ear. These electrical models developed and improved upon gradually, are the only source of absolute information about the mechanism of hearing and function of the ear. How sound waves travel down the three portions of the ear and how are the sound energies screened and sorted, filed away or acted upon, these questions are answered to every specific detail by electrical modelling. Besides this, electrical modelling opens another prominent and useful field in audition. It is, the one of, hearing deficiency classification. To be precise, any deviation of the parameters of electrical model of any abnormal ear, from those of the normal one, offer direct, accurate and reliable means of detecting hearing losses.

Measurements of sensory performance of the auditory behaviour, are rarely traight-forward. First, because of the fluctuations in performance that seem to be an inherent aspect of sensory behaviour; and second, because of the influence of such largely nonsensory attributes as: listener training, motivation, fatigue, adaptation, background noise, inter-listener variability, and the way in which the measurements are organised and carried out. In the measurement of auditory pressure thresholds, for example, these attributes, if uncontrolled, may introduce uncertainties of 20 db or more. In spite of these difficulties, however, measurements of many aspects of auditory behaviour can be made with sufficient precision and stability to permit useful interactions with physiological observations. Instruments which aim to assess hearing acuity are known as audiometers. The threshold level of the intensity of sound at different frequencies of a sinusoidal wave is determined by pure tone audiometry; and the graph so obtained is called an audiogram. These instruments can either use air-conduction or bone conduction. A combination of the use of these devices, speech audiometry and other well-established tests allow a decision to be made regarding the patient's hearing ability. The instruments are particularly necessary in order to determine how far the auditory response of any individual departs from the normal. It is essential that any instrument is correctly and frequently calibrated against a standard. In case of air-conduction audiometry the standard is an artificial ear and for bone conduction audiometry an artificial mastoid is used.

1.2.0 Organisation of Thesis

The present thesis work deals with the electrical modelling of the 'Human Auditory System' and on its basis the classification of different hearing impairments. The entire work is divided into seven major topics.

Importance of the work and its study is discussed in the present chapter; and the human ear's essential anatomy and physiology in the second. The second chapter also deals with the perception of sound and the theories of hearing.

In chapter three hearing inabilities of varying degree are enumerated and the modern science of Audiology is brought into limelight. The recent techniques in Audiometry are also discussed.

Chapter IV consists of electrical modelling of the human auditory system. The model of the ear studied in this chapter is the one that has been obtained after detailed mathematical review of the many existing models. Out of the various electrical models surveyed, it is the model undertaken here which possesses the characteristics of a normal audiogram and resembles the standards of normal hearing thresholds. Therefore, it forms the foundation of disease classification on the basis of electrical modelling of the car.

The next chapter, discusses the hearing deficiency classification by audiogram. Chapter V deals with the techniques of audiogram interpretation and the international standards of minimum hearing thresholds. It also describes the clinical audiometer that was employed to record twenty normal and forty abnormal/diseased audiograms. The evaluation of these audiograms has been done with the help of physicians and experts and partly on the basis of the audiogram interpretation methods discussed in this chapter.

Chapter VI evaluates the performance of the electrical model of ear presented in Chapter IV on the basis of mathematically derived impedance function. This impedance function closely resembles the standards of normal audible thresholds, thereby justifying the model to be the desired one for hearing deficiency classification. Therefore, at this stage, all the sixty audiograms are analysed by a computer software technique and the different sets of R-L-C parameters corresponding to each audiogram are obtained. The ranges of normal ear's electrical parameters are determined by Gaussian probability curves and eventually the parameters for the hearing impaired are detected and grouped under respective hearing deficiencies.

The last Chapter (VII) gives the conclusions obtained by the entire work and stresses upon further modifications and developments that can be carried out in this field.

CHAPTER-II

ANATOMY AND PHYSIOLOGY OF HUMAN EAR

CHAPTER II

ANATOMY AND PHYSIOLOGY OF HUMAN EAR

2.1.0 Introduction

The ear is an organ concerned with the sense of hearing and equilibrium. To understand the complete concept of auditory behaviour, the knowledge of ear's anatomy and physiology is necessarily important. It is useful and conventional to divide the ear anatomically into three sections : the outer ear, the middle ear and the inner ear, as shown in Fig.2.1.0.

2.2.0 Outer And Middle Ear

The section called the outer ear consists of those structures that can be seen from outside the skull. The first and the most obvious structure is the fleshy piece of tissue known as the pinna or auricle. Although, the pinna is relatively small, flat and immobile, yet, it reflects sound waves towards the ear canal. The next structure is the ear canal, which extends from the pinna to the ear drum. The ear canal is technically known as the external auditory meatus. It carries inwards, the sound waves diffracted and shadowed, partly by the head and partly by the pinna. The eardrum, correctly called the tympanic membrane, is a thin sheet of tissue that forms the last structure in the outer ear. When sound waves travel down the external auditory meatus, they bounce up against the tympanic membrane, and it begins to vibrate. Just inside the tympanic membrane, there is a cavity

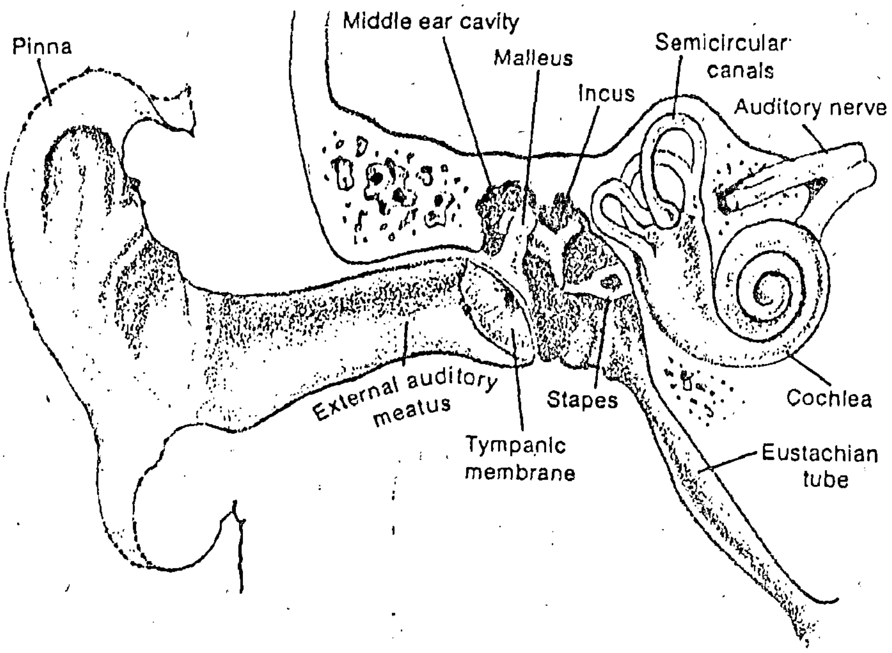


FIG. 2.1.0 STRUCTURE OF HUMAN EAR.

in the skull bone that houses the three smallest bones in the body. This is the middle ear cavity which is separated from the ear canal by the tympanic membrane, and is called the tympanic cavity. The series of the three movable bones, as a group, is called the ossicular chain and these bones are called ossicles. The ossicles are named according to their shape. The first bone called malleus (hammer) rests against the tympanic membrane. The second bone called incus (anvil),rests against the first ; and the third bone, called the stapes (stirrup) rests against the second. Whenever the tympanic membrane vibrates, the malleus begins to move. Its movements make the incus vibrate. The incus, in turn, sets the stapes into movement. In this manner, the sound vibrations are transmitted from the outer into the middle ear. The pressures in the ear canal and the tympanic cavity are normally equal. The ear canal is at atmospheric pressure, and the middle ear is exposed to atmospheric pressure only through the auditory (eustachian) tube, which connects the middle ear cavity to the throat (pharynx). The slit like ending of this tube in the pharynx is normally closed, but during yawning, swallowing , or sneezing, when muscle movements of the pharynx open the entire passage, the pressure in the middle ear equilibrates with atmospheric pressure. A difference in pressure can be produced with sudden changes in altitude, as in an elevator or, air-plane, when the pressure outside the ear changes, while the pressure within the middle ear remains constant because of the closed eustachian tube . This difference distorts the tympanic membrane and causes pain. The ossicular chain, the tympanic cavity with the eustachian tube form the middle ear [1,4,17,30].

2.2.1 Function of the Ossicular Chain

The placement of the ossicular chain between the tympanic membrane and the cochlea has a very special significance. In the presence of stimuli, the external ear receives sound signals in form of air pressure cycles. These movements of air molecules must be translated into movements of fluid molecules in the cochlea. The fluids inside the cochlea are considerably denser than air and this higher concentration of molecules in the fluids offers more resistance (or "impedance") to the movements than the relatively sparse air molecules do. Therefore, a greater force is to be applied against the fluids than against air to create equal effects on them. This mechanism of applying more force against the cochlear fluids as compared to the force created by movements of air molecules in external auditary meatus, is performed by the middle ear bones; the ossicles, thus, logically perform impedance matching. This impedance matching is accomplished when the ossicles transfer the movements of the relatively large tympanic membrane to the movements of the very small oval window. Pressures against the entire tympanic membrane are funded down, by the ossicular chain to pressures against a membrane one twentieth its size. In other words, the pressure per unit area of the oval window is some 20 times greater than the pressure per unit area of the tympanic membrane. This 20 fold increase makes up for the higher impedance of the cochlear fluids.

Sometimes, sound waves reach the cochlea without passing through the ossicular chain. This occurs when the bones of the skull vibrate, and the outer bony walls of the cochlea are set into motion. The vibrations of the cochlear wall make the fluids inside move. Sounds that reach the cochlea this way, are called bone-conducted sounds. Bone conducted sounds commonly occur when we speak, because, as the tongue and lips move and the air is expelled, the bones of the skull vibrate. This is partly the reason for the fact, that our own voice on tape appears strange from that we normally speak when we listen to the tape, we do not receive the bone-conducted sounds that are heard during speech [17,20,22,30].

2.2.2 Function of Middle Ear Muscles

Presence of very intense sound at the ear drum causes, the ossicles to amplify it further to higher intensities, in order to accomplish proper impedance matching between the air molecules of outer and middle ear, and, the fluids of the cochlea. The resulting large displacements of stapes footplate tend to drive it right through the oval window. To prevent this severe injury, there is a protective mechanism which inhibits the stapes from moving far enough to damage the oval window. This protective arrangement consists of two very small muscles in the middle ear cavity. Whenever the amplitude of a sound wave becomes sufficiently large, these muscles reflexly contract. One muscle, called the tensor tympani, connects the malleus to the wall of the middle ear cavity and the second, called the stapedious

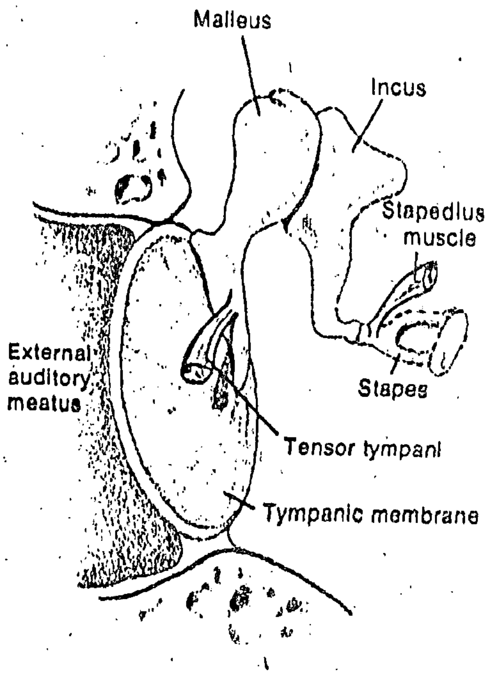


FIG. 2.2.2 MIDDLE EAR MUSCLES/BONES.

muscle connects the stapes to the wall of the cavity (Fig.2.2.2). When these muscles contract, the malleus is pulled slightly to one side, and it does not impart as much of its movement to the incus as it normally would. The result is that incus too, moves less than it otherwise would and lesser motion is imparted to the stapes. Now the stapes is no longer free to move in and out, like a piston, against the oval window. The effective result is that the oval window is not pushed or pulled to the limits of getting damaged or torn by the stapes; and the waves created in the fluids of cochlea are of lesser amplitude. As a consequence, the sound seems less intense than it actually is [1,7,30].

2.3.0 Inner Ear

The last and the most essential part of the ear is the inner ear or internal ear. The third ossicle i.e. the stapes, rests against a thin flexible membrane in the side of a coiled structure that forms the inner ear. Inside the coiled structure are the auditory receptors - the cells that transform sound information into neural information. The coiled structure looks something like a very tiny shell and it gets its name, cochlea, from a Latin word for snail. The cochlea is filled with fluids and, when the stapes move in and out against the cochlea's flexible membrane, waves are created in the fluids. From the cochlea, a collection of neural pathways (axons), called the auditory nerve, carry the neural information to the brain.

The intricacy of audition is directly related to the delicate and complicated construction of cochlea. The cochlea is

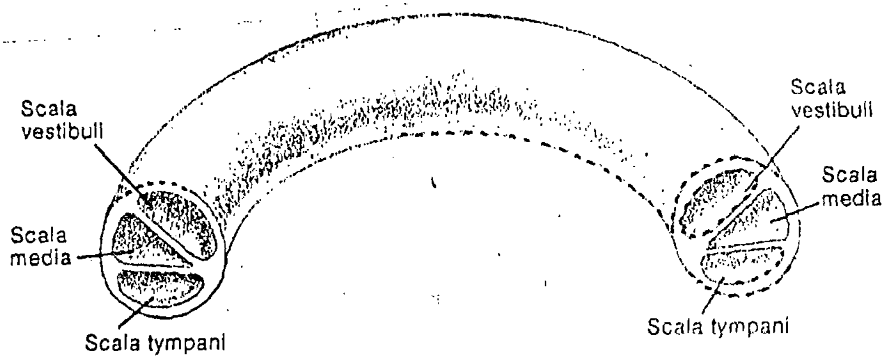


FIG. 2.3.0 CROSS SECTION OF COCHLEA.

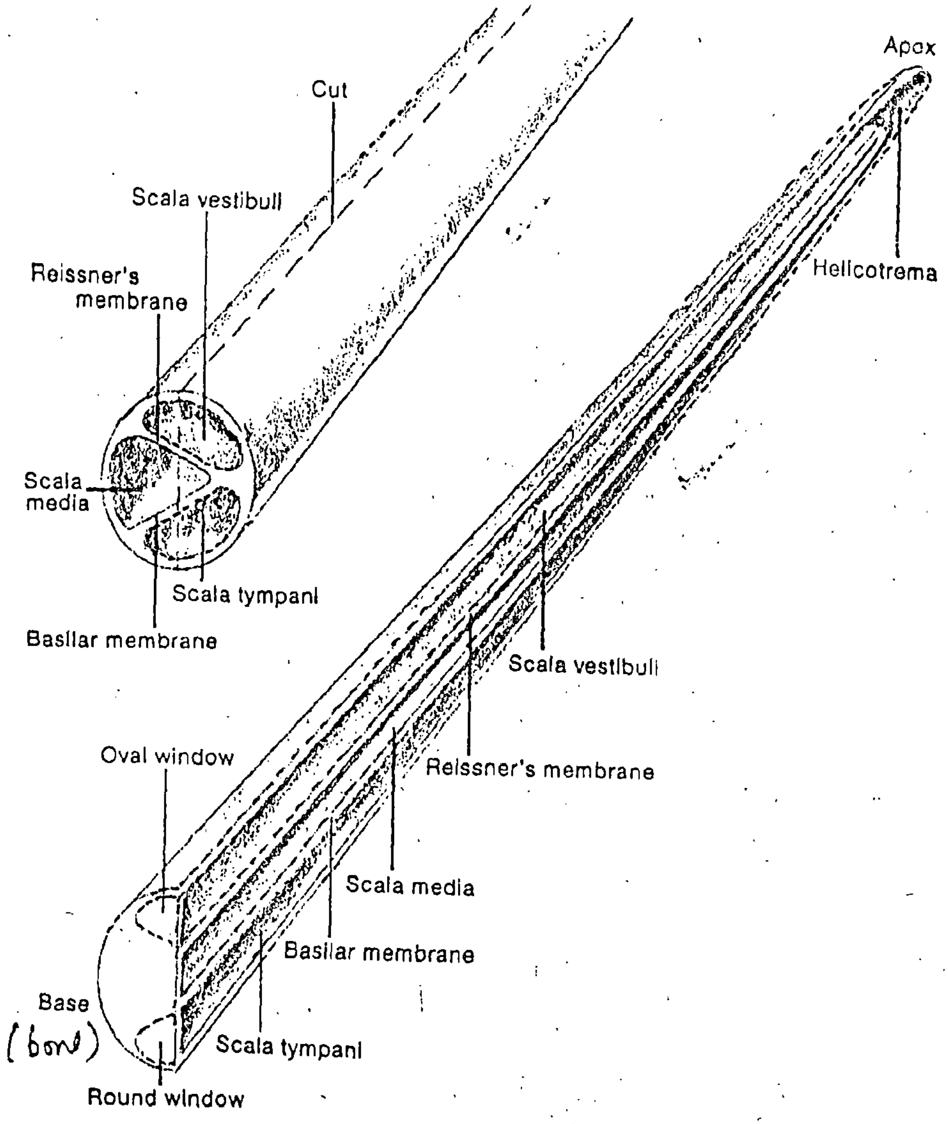


FIG. 2.3.1 INTERNAL PARTS OF COCHLEA.

a very small, snail shell shaped structure, embedded in the bone of the skull. There are, approximately, three and a half coils in the human cochlea. The complete structure, twisted in a turban fashion has a height roughly the same as the width of the tip of our smallest fingernail. The cochlea is made up of three long chambers - the scala vestibuli, scala media and the scala tympani. The first coil in the cochlea appears, in cross section, as shown in Fig.2.3.0. Each scala (chamber) is divided from the next one by a very thin membrane. Scala vestibuli is separated from scala media by Reissner's membrane; scala media is separated from scala tympani by the basilar membrane. Trying to imagine that we could untwist the cochlea, slice it, along its length, right down the middle, throw out the right half and look at the left half from the cut side we would observe something like shown in Fig.2.3.1. In the figure we see that the Reissner's membrane and the basilar membrane do not extend the length of the cochlea. At the apex they join, the opening between them that is created at the apex is called the helicotrema. The three cochlear chambers contain fluid. Because scala vestibuli and scala tympani communicate with each other at the helicotrema they contain the same fluid called perilymph. Scala media contains a slightly different fluid called the endolymph. The walls of the cochlea are made up of bone, except at two places along the cochlea's base. There we have two flexible membranes. The membrane that covers the base of scala vestibuli is called the oval window. It is the same flexible membrane pushed and pulled by the stapes, thereby creating waves in the perilymph of

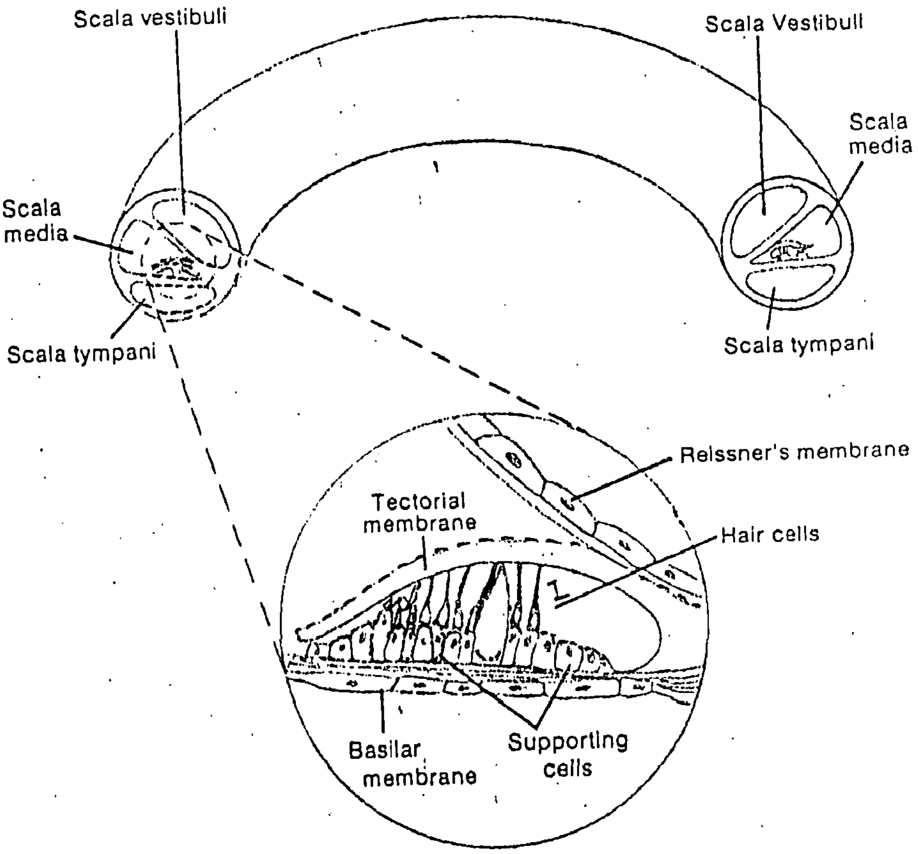


FIG. 2.3.2 CROSS SECTIONAL DETAILS OF COCHLEA.

scala vestibula. The waves travel down the length of scala vestibuli, and through the helicotrema, the waves continue into the perilymph of scala tympani. At its base, scala tympani also has a flexible membrane, called the round window. As the perilymph surges against it, the round window bulges out and in, providing a kind of damping mechanism for the waves.Reissner's membrane and the basilar membrane are extremely thin tissues. Because of this, whenever waves occur in the perilymph, waves will also occur in the endolymph. Thus, scala media will also be affected when the stapes pushes in and out against the oval window. The portion which includes Reissner's membrane, scala media and its endolymph, the auditory cell receptors and their associated structures, and the basilar membrane - has been given its own tabel; it is called the cochlear duct. The receptor cells and their associated structures are located along the entire length of the basilar membrane. The receptor cells are extremely thin and have short hairs at their tips and are therefore called hair cells. They jut up out of supporting cells that rest on the portion of the basilar membrane nearest the inner, narrow side of scala media. Resting on top of the hair cells, there is a flap of tissue called the tectorial membrane. All these structures fit into the cochlea as shown in Fig. 2.3.2. The collection of supporting cells, hair cells, and tectorial membrane is called the organ of Corti. It is this sensitive and fragile organ which is most vital and indispensible link to the brain. All the hair cells, of the organ of corti, bear very small, bristle - like endings called cilia, which touch the underside of the tectorial

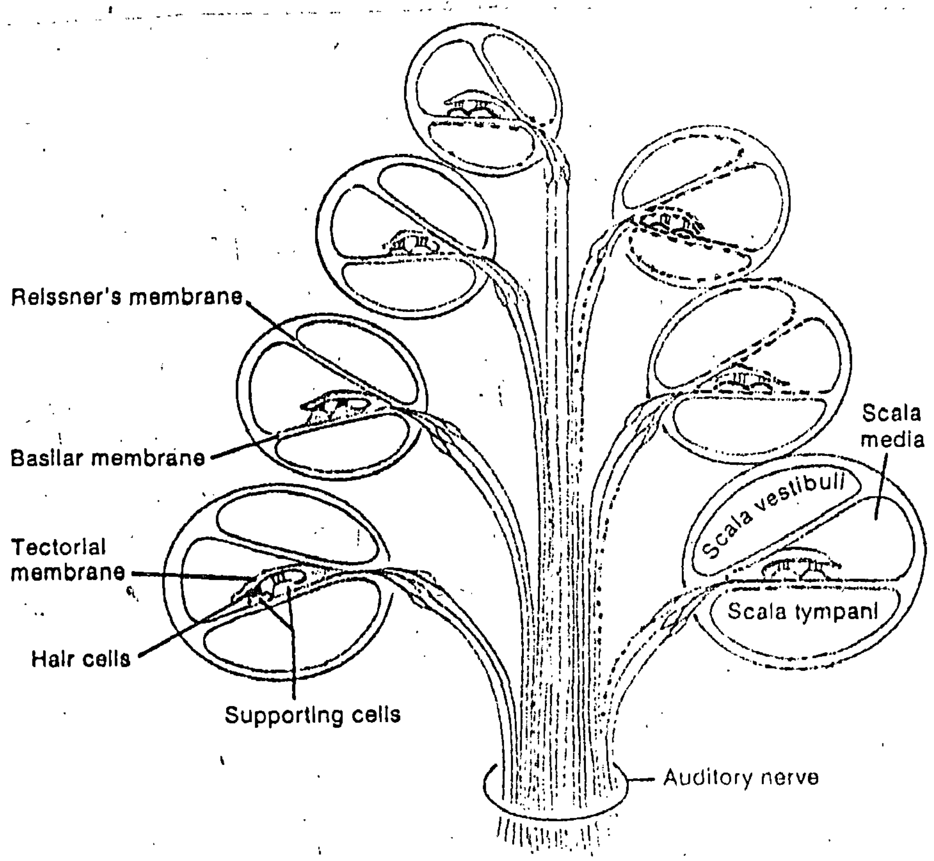


FIG. 2.3.3 BRAIN AND COCHLEA LINK.

membrane when the tectorial membrane moves relative to the cilia, the cilia are deformed by the movement. Somehow this activates the hair cells. Lying just underneath the bases of the hair cells, among the supporting cells, are dendrites of neurous. The somas of the neurous are located, in the bony, central core of the cochlea, and their axous travel together towards the brain, forming the auditory nerve (Fig.2.3.3). When the hair cells become active, they create graded potentials in the dendrites. If the graded potentials are sufficiently large by the time they reach the axon, action potentials occur.

Although once again we are in a mystery world where receptors translate physical energy into neural information, some things are known about the processes invalued. First of all, the critical step is to get the tectorial membrane to rub across the cilias causing the bending of the cilia from side to side. This is called the shearing force and it occurs because the tectorial membrane and the basilar membrane (on which the hair cells rest) move at different rates and in slightly different directions, when waves are set up in the endolymph. Part of the reason for the differences in their movements has to do with the fact, that the tectorial membrane is anchored at only one edge, while the basilar membrane is anchored along both edges. The net result is, that the tectorial membrane tends to slide (back and forth) across the basilar membrane, bending the cilia. Another important and known fact is that shearing forces causing bending in opposite directions tend to produce opposite effects. If the cilia are bent one way, the dendrites become depolarized (an excitatory response); if the cilia are bent in the opposite direction, the dendrites become hyper-polarized (an inhibitary response). Finally, it is suspected that activation of hair cells is somehow related to changes in the distribution of ions in the endolymph immediately surrounding the cilia. The precise way in which the shearing of the cilia creates ionic changes is not known. In the auditory nervous system, there are four sets of synaptic areas (nuclei) between the auditory nerve and the neurons of the auditory cortex. At each of the synaptic areas, information may be compared, modified, analysed, detected or stored. The system is bilateral, meaning thereby that information from each ear ends up being sent to both sides of the brain. At virtually every synaptic area, there is more and more mixing of the information that originated in the two ears. By the time, the information reaches the auditory cortex, there is an almost equal amount of information from each ear, arriving on each side of cortex [17,20,30,37].

2.4.0 Theories of Hearing

When the frequency of a sound wave is changed, the sound changes in pitch. The human ear can differentiate between sounds of different pitch or frequency. This ability of the ear is primarily attributed to the complicated reactions within the cochlea, whenever a change in sound's frequency is detected. Historically, there are two kinds of theories behind the reactions taking place within the cochlea: Frequency theories and place theories. These theories which seek to explain the essence of hearing, were proposed long before much was known about the structure of the cochlear duct.

2.4.1 Frequency Theories

Frequency theories hypothesise that the basilar membrane moves up and down in tune with the movements of the stapes. For a low frequency sound, the stapes move in and out against the oval window relatively few times each second; as the frequency of sound is increased, the stapes move in and out at a faster rate. And the basilar membrane vibrates at the same frequency as the stapes. In other words, the vibrations of basilar membrane are identical to those of air molecules entering the ear. The most well known frequency theory is Rutherford's Telephone theory. He proposed that the basilar membrane behaves similar to the diaphragms in telephones. The diaphragms move at the same frequency as the driving stimulus (sound for the speaker diaphragm; electrical impulses for the listening diaphragm). Ernest Rutherford, proposed that the basilar membrane works the same way: it too moves at the same frequency as its driving stimulus (the movement of the stapes). Accordingly, he meant, a sound of 25 Hz moves the basilar membrane up and down 25 times per second. A sound of 250 Hz moves it up and down 250 times per second.

2.4.2 Place Theories

In opposition to the frequency theories, all the place theories, propose that the basilar membrane does not respond as a single unitary structure. They propose that different portions of the basilar membrane react to sounds of different frequencies. These theories postulate that sounds of different frequencies each activate a particular place along the length of the basilar

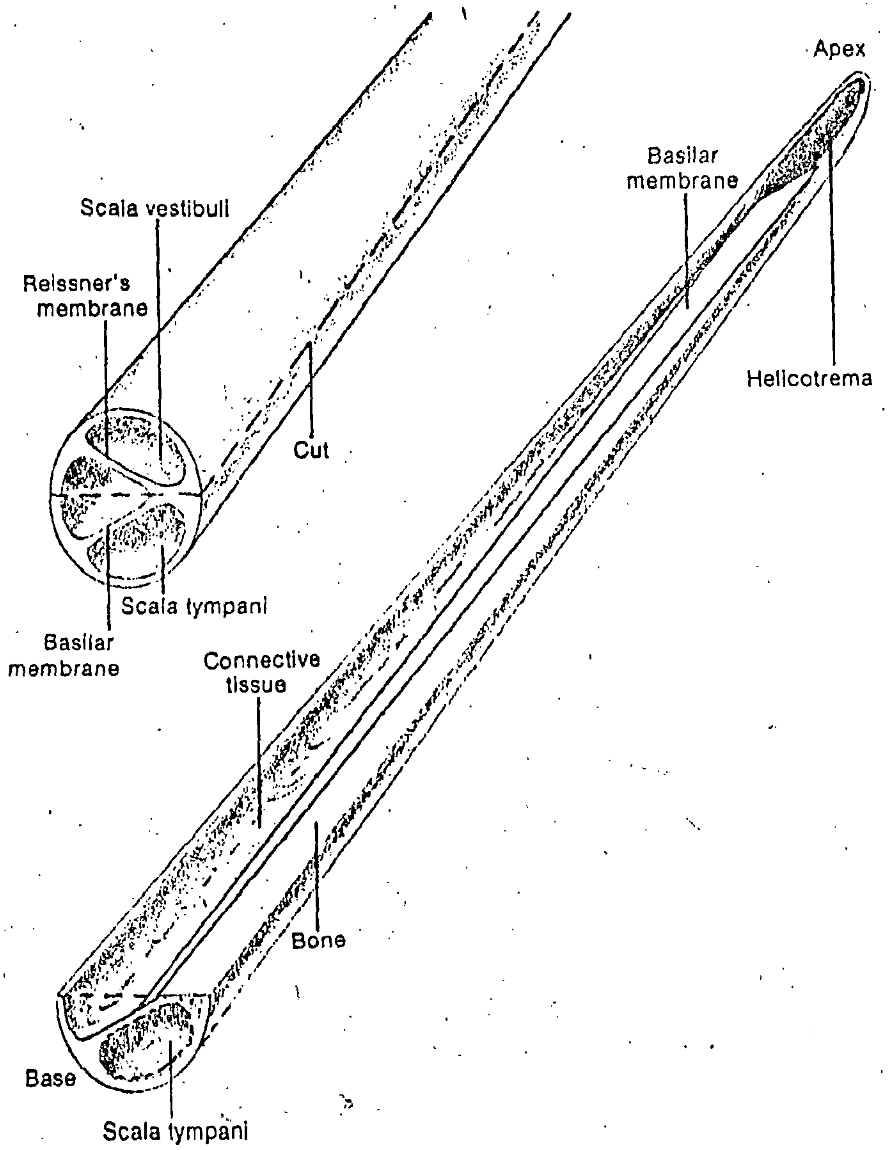


FIG. 2.4.2 SHAPE OF BASILAR MEMBRANE.

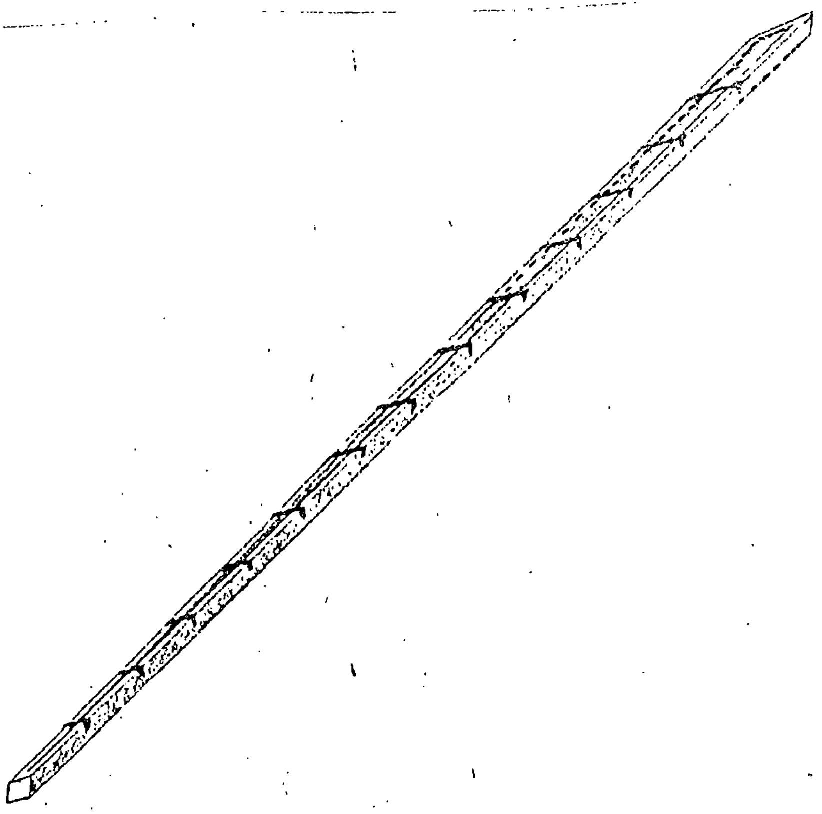
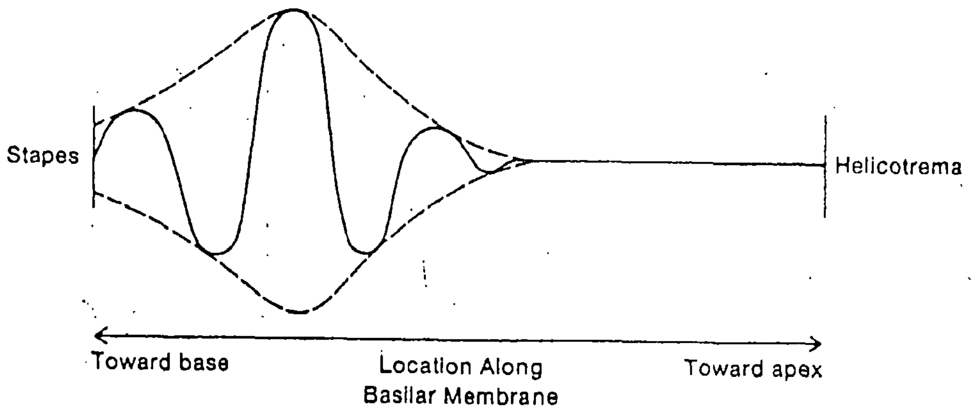


FIG. 2.4.3 HELMHOLTZ'S STRUCTURE OF BASILAR MEMBRANE

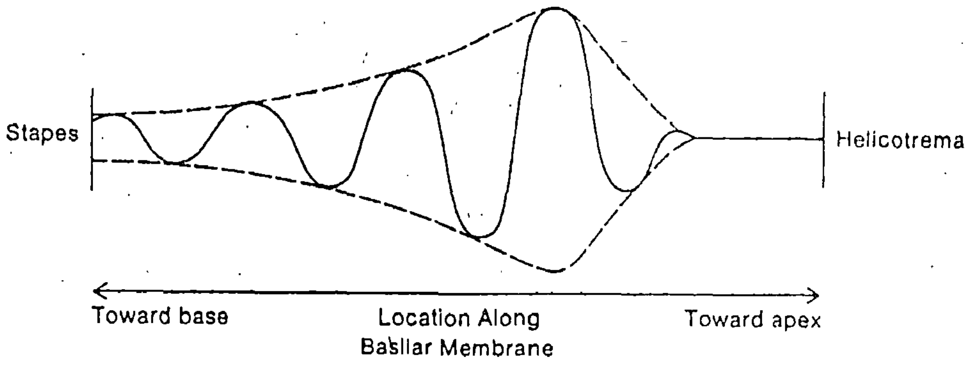
membrane. The most well known of the older place theories is Helmholtz's Resonance Theory. Hermann Von Helmholtz (1863) postulated his theory by principally concentrating on the shape of the basilar membrane. According to him, the basilar membrane is narrow at the base of the cochlea and broad at the cochlea's apex. As shown in Fig.2.4.2, we can clearly notice Helmholtz's findings. He proposed that the basilar membrane is similar to musical instruments that are made up of a series of stretched strings of various lengths Fig.2.4.3 when a short string is plucked, a high, pitched sound is produced by the string's vibration. When longer strings are plucked, low pitched sounds are produced. An identical operation is accomplished by the basilar membrane when sound pressure waves cause the selective resonance of the membrane. Thus, high frequency sounds cause vibrations in the narrow end of the basilar membrane and low frequency sounds produce vibrations in the middle or wide portions of the membrane.

For the Helmholtz's Resonance Theory to be correct, the basilar membrane must be under considerable transverse tension, i.e. if the strings of the musical instrument are slack, they would not resonate. They must be taut. Helmholtz suggested that this is also true for the basilar membrane. Many years after Helmholtz proposed his theory, a researcher named Georg Von Bekesy directly tested Helmholtz theory by making a small horizontal slit in the middle of the basilar membrane. If the membrane were under transverse tension, it should have ripped open. As it turned out, the basilar membrane did not rip open, and Von Bekesy concluded that the basilar membrane is normally quite slack.

High-frequency sound



Medium-frequency sound



Low-frequency sound

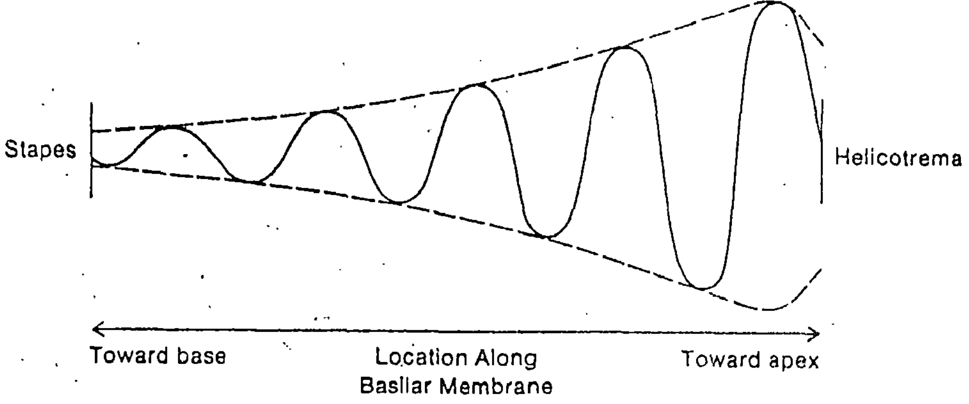


FIG. 2.4.4 TRAVELLING SOUND WAVES ALONG BM.

He proved that the Helmholtz Resonance Theory is not totally wrong, because he confirmed and accepted the notion of place theories. He, then, proposed a new theory known as the 'Travelling Wave Theory'. Von Békésy managed to drill a small hole in the wall of the cochlear duct, sprinkled some very fine shavings of aluminium on the basilar membrane, covered the hole with glass, and then watched what happened when the stapes moved at different frequencies.

The aluminium shavings were needed because the basilar membrane itself is so thin as to be virtually transparent. He discovered that the place theories are essentially correct: different portions of the basilar membrane react to sounds of different frequencies when the stapes moves at higher frequencies, the narrow end of the basilar membrane moves up and down the most. As the frequency of stapes movement is lowered the location of the maximum movement of the basilar membrane shifts towards the wider end at the apex of the cochlea. The movement of any particular location along the basilar membrane is created by very complicated waves in the fluids, which are set up by movements of the stapes and reflections of waves off the walls of the cochlea. As waves reflect off the walls, they reinforce, or cancel out, both, each other and the additional waves being generated by the movements of the stapes. The outcome is that some portions of the basilar membrane are subjected to strong waves, while other portions remain relatively still. This is schematically represented in Fig.2.4.4. Referring to the dashed "envelopes", it is clear that different portions of the basilar membrane are maximally affected by different sound frequencies. The more a region of the basilar membrane moves, the more the tectorial membrane bends the hair cells of that region. And the more the hair cells are bent, the more their associated neurons will change their firing rates. Evidently, sound frequency is signalled by the identity of the group of neurons that produces the greatest changes in firing rates, implying thereby that our auditory perceptions depend upon comparisons of the relative activity of different neurons. This approach, to understanding the cochlea, is called Von Békésy's Travelling Wave Theory, and it correctly describes the movements of the basilar membrane in response to sounds above 500 Hz. Sounds with frequencies less than 500 Hz create up and down movements equally throughout the entire length of the basilar membrane; as a result, hair cells through out the cochlea are equally affected by sounds below 500 Hz. Therefore, the principle behind frequency theories is correct when it comes to low frequency sounds, and the principle behind place theories is correct when it comes to moderate and high frequency sounds [16,17,27,30,37].

CHAPTER-III

HEARING DEFICIENCY AND AUDIOMETRY

CHAPTER III

HEARING DEFECIENCY AND AUDIOMETRY

3.1.0 Introduction

Deafness and hard of hearing have different meanings. Deafness means nearly complete or total loss of hearing. It can be congenital or acquired. An individual who is congenitally deaf is one who is either born deaf or later becomes deaf because of an inborn defect. In the acquired type, the person is born with normal hearing but becomes deaf due to an accident or illness. Hard of hearing applies to those who lose some of the ability to hear later in life, but who may have learned to speak before the loss occured. Deafness is caused by many conditions; most of these are mentioned and described in the following paragraphs. Five to ten percent of people have a hearing defect, temporarily or permanently, which is severe enough to impair their normal functioning of the ear. Hearing loss may occur at any age and produces disability depending upon the degree of loss, the age at which it occurs (interference with language and speech development), and whether one or both ears are affected [7,17].

3.2.0 Hearing Losses And Disorders of the Ear

In general we can classify hearing losses into four major categories. The first one categorizes as conduction deafness. If an individual cannot hear sounds that reach the cochlea via the tympanic membrane and ossicular chain, but can hear the bone conducted sounds say produced by resting the base of a vibrating tuning fork against the skull; the person is said to suffer from conductive hearing loss. This type of loss is associated with defects and diseases of the middle ear, ear drum or ear canal. The resultant hearing disability, as measured by pure tone audiograms, is usually fairly uniform as a function of frequency, but increases at high and low frequencies. The second, broad, category of hearing impairment is nerve deafness. In this case the suffering individual cannot hear either airborne or bone conducted sounds. It is due to disturbance or damage in the inner ear i.e. cochlea, or, some defect in the auditory nerve leading to the brain stem. This deficiency is also known as sensori-neural loss, the audiogram showing loss for usually high tones than for low ones. Two common causes of cochlear impairment are Meniere's syndrome and traumatic noise exposure. The latter typically affects the outer hair cells at the basal end of the cochlea and produces a rapidly falling high frequency hearing loss. Disorders in the auditory nerve occur due to a tumour, hemorrhage, or multiple sclerosis. Some of these disorders causing sensorineural loss are discussed, in more detail, later. The third major class of hearing loss is central in nature. This type of impairment is not, necessarily, accompanied by a decrease in auditory sensitivity but tends to manifest itself, in varying degrees, through a decrease in auditary comprehension. For example, the subject may have a normal or nearly normal audiogram, but may be unable to recognise or interpret sounds, specially speech. The state also refers to mixed type of deafness i.e. due to disturbance in both the conductive and nerve mechanisms. Lastly, adding the fourth classification we have the functional type of deafness. For this type of hearing loss, there is no known organic involvement. While this classification is said to have an undiagnosed pathology, it does properly embrace many very real cases of deafness, for which the causes are psychological or motivational rather than physiological.

Disorders of the ear occur in numerous forms. The most common of ear disorders is earache. It can be caused by a foreign body that becomes trapped in the ear resulting in its inflammation. If the foreign body plugs the auditory canal, there is a blunting of hearing or a temporary deafness which is relieved on removing the object. Earache is also caused by boils, furuncles, fungus infection, inflammation of the ear canal. But in these cases normal hearing is not affected.

Many disorders, both inflammatory and non-inflammatory affect the middle ear. These are, in most of the cases, caused by respiratory infections which invade the middle ear through the Eustachian tube. Bacteria also cause such infections, entering the middle ear cavity, through perforation(s) in the ear drum. Acute middle ear infection called otitis media, causes swelling of the Eustachian tube; and waves of deafness occur frequently. Hearing is impaired if repeated attacks of otitis media persist. A chronic middle ear infection develops as a result of persistent ear infection or from respiratory diseases. It may also be caused by diseases such as tuberculosis, measles and syphilis. One of the main symptoms of chronic middle ear infection is a ringing sensation in the affected ear. It comes at intervals in the beginning, then gradually ringing becomes constant. The sound varies both in pitch and intensity. Hearing is certainly affected, but total deafness seldom occurs. Another serious disorder of the middle ear is secretory otitis media; characterised by the collection of fluid in the middle ear. This fluid may be either clear or glue-like. The predominant symptom of the disorder is impaired hearing, which varies from slight to almost total loss of hearing. Acute draining middle ear infection is another basis of impaired hearing. It originates from the same causes as all the middle ear infections mentioned above. The chief symptom is filling of the ear with fluid, which gradually becomes puslike. Hearing is affected as long as pus remains in the middle ear. After several days, the eardrum ruptures spontaneously and, about, after three weeks time, the fluid seeps through the canal, then subsides and stops. This perforation in the drum usually, but not always, heals over.

Many cases of severely impaired hearing in adults are attributed to middle ear infections in childhood. One reason for prevalence of such infections among children is that, in infants and young children, the Eustachian tube is shorter and more nearly horizontal. Thus, the tube is more likely to become an avenue of infections in children than in adults. The easiest and most effective manner of preventing middle ear infections is to establish good hygiene habits and low resistance to respiratory diseases, since childhood. If early diagnosis of middle ear infections is not done, the infections spread easily towards the inner ear, as parts of the ear are very delicate and intricate, thus vulnerable to many diseases.

Tinnitus, or ringing in the ear, is yet another very common auditory phenomenon which is experienced occassionally, to a mild degree, by almost everyone. The disorder is caused by spontaneous discharge of hair cells or nerve fibers. The sensation of noise, also known as ear noise, is more noticeable in quiet environment. It is symptomatic of an irritation of the sense organ and is induced in many ways, such as, by excessive intake of drugs like quinine antibiotics and aspirin. The symptom may also be caused by excessive amounts of coffee, tobacco or alcohol or due to exposure to high intensity sound. The incidence of tinnitus increases with age and the ear noises occur most often in persons between the ages of 50 and 70 years. It also intensifies under conditions of stress and tension. In severe cases, it contributes significantly to the disruption of speech perception.

The eardrum (tympanic membrane) which divides the external ear and the middle ear is subject to puncture or rupture through several types of injury. Most commonly, ear drum is punctured due to insertion of a sharp object into the ear. Also, violent explosions near the ear may cause the drum to tear or rupture. Decreased air pressuring during or after descent from high attitudes, severe sneezing, diving, and increased pressure frequently, are also responsible for damaged ear drum. The damaged ear drum is usually the site of small, chalky (lime) deposits, which are formed due to repeated attacks of ear infection. There is no successful method of removing chalk deposits without seriously injuring the ear drum and thus depressing the hearing to greater extent.

Advanced age is another well known cause of impaired hearing. Changes associated with aging occur throughout the auditory system and include the degeneration of hair cells, particularly in the basal turn of the cochlea; alterations in the cochlear fluids and the loss of neurons in the ascending path ways and cells in the auditory cortex. These effects are collectively termed presbycusis and are mainly manifested as a high frequency loss that increases with age and adversely affects speech discrimination. An additional phenomenon associated with it, is a dip in the audiogram at 4 KHz. Prolonged exposure to very intense noise or industrial noise also produces this reduction in hearing sensitivity which cannot be easily distinguished from presbycusis.

Loss of sensitivity is not the only symptom of a hearing defect. Various forms of distortion or loss of clarity of the incoming sound signal are also common. Sensori-neural impairment is usually accompanied by some degree of impairment of speech discrimination. As a result of hair cell degeneration, some of the frequency-resolving power of the cochlea is lost and the hearing impaired individual experiences difficulty in making fine distinctions between speech sounds, particularly in the high frequency range. Speaker's voice is easily heard but the effected person is unable to distinguish, for example, between the words "fat" and "sat".

There is another phenomenon called recruitment that occurs in conjunction with many types of sensori - neural losses; subjecting the patient to experience an abnormally rapid growth of loudness with sudden increase in signal levels. As a result, the impaired ear has a considerably reduced dynamic range; because not only is the threshold of detection elevated, but a relatively small increase in sound level makes the sound uncomfortably loud. The abnormality called diplacusis is one, in which a tone is heard as having a harsh or buzzing quality or having more than one pitch. A common form of diplacusis is that, in which different pitches are heard by the two ears for the same sound. The disorder, rendering a nerve type of deafness is caused by local irritation, fatigue or mild injury to the organ of Corti, and sometimes is due, to prolonged exposure to a very loud sound.

Attributed for its origin to the inner ear, there is another serious malady described by Prosper Meniere named Meniere's syndroms after him. Its characteristic symptoms are sudden, severe attacks of dizzines, tinnitus, and a fluctuating hearing loss. The cause and mechanism of this order have not been definitely established, and therefore, the term "syndrome" is used generally rather than the term "disease". Persons in the middle age group are more commonly affected by this syndrome. The vertigo associated with this phemomenon may be so violent that the simplest activities become impossible. Usually, the patient has a sensation of objects whirling around. Nausea and vomiting are associated usual symptoms. The course of this syndrome is unpredictable and the patient may suffer for a very long period with the episodes of attacks occurring after gaps of a few years. The hearing loss in the ear, involved, is total. According to one theory, the syndrome is related to an unbalance of pressure between the perilymph and the endolymph. Careful and a very calculated surgical operation of the cochlea is carried out to drain out, usually, some of the endolymph fluid.

To conclude, deafness is due to many causes summarizing them, once again, following are the conditions from which poor or total loss of hearing results:

(1) Temporary or chronic infection in one or both ears;
(2) Secondary complications of disease elsewhere in the body;
(3) Direct damage or defect in some part of the hearing system;
(4) Aging; (5) Occlusion of the auditory canal; (6) Aero-otitis media; (7) Meniere's syndrome; (8) Otosclerosis; (9) Noise, and (10) Certain ototoxic drugs including Kanomycin and Streptomycin.

Associated with the above the degrees of hearing loss are:

(1) Conductive deafness which results when sound waves are not transmitted properly through the outer and middle ear.
(2) Nerve deafness results when there is a damage to the inner ear or the nerve path way to the brain. This is a greater handicap and in many cases is difficult to cure.
(3) Mixed hearing loss contains elements of both the conductive and the sensori-neural types of loss.
(4) Central type hearing loss is caused by disorders in the central nervous system.

Certainly, mixed and central types of hearing losses are most severe ones and can rarely be reversed.

Poor hearing also results when any individual suffers from severe infections during very early childhood. Head colds, fonsillitis, measles, searlet fever, mumps and meningitis are some of the infections diseases which damage to varying degrees the hearing mechanism of a child. These infections may attack one or many parts of the ear. The degree of loss of hearing is dependent on the severity of the infection. If a woman develops German measles (rubella) during the first three months of her pregnancy, the new born will, in at least, 70 percent of the cases, suffer a partial hearing defect. This congenital deafness may be masked by even more severe birth defects resulting from the mother's infection. Old age may have some bearing as a cause of hearing loss. Serious infection with damaging consequences to hearing rarely occurs after a person has passed the age of twenty. Later in life, usually after the age of fifty, changes which lead to partial loss of hearing, specially for higher tones, may occur in the auditory nerve [3,7,8,16].

3.3.0 Audiology

It is a relatively modern field which has been unraveling, since the mid nineteenth century, many baffling questions related to speech and hearing sciences; neurophysiology; psychophysics; architecture and functions of the auditory nervous system; mechanism of hearing and structure of the ear; auditory impaviements; speech perception deficiency; techniques of measuring hearing acuity; developing and progressing sensory aids for the deaf and dumb, and different methods of categorization of auditory deficiencies, the most vital being audiometry. The history of audiology, to be precise, can be traced down the year 1876 when Alexander Graham Bell discovered, while attempting to develop a speech waveform display for the deaf, the principle of driving a relatively large mass (which was an electromagnet) by a very fine, lightweight diaphragm that was sufficiently sensitive to respond to acoustic vibrations in the air. This discovery led to the development of telephone. In the years that followed, it had an enormous influence on subsequent research and study of the different aspects of audiology mentioned above. The science of audiology was utilized to the best results after the World War II. In India, its advent was even later i.e. in the mid 1960's. Since then, as a profession and research field audiology has grown considerably both in terms of the sophistication and in terms of the extent of its application. The most upgraded and versatile device used in its application fields by professionals offering audiological services, is the audiometer. Depending on their extensive and indispensible utility audiometers can be broadly classified into three main categories. In the most crude form audiometers are manually operated. Recent advent of automated and microprocessor based systems for on line computations, monitoring and control has led to the increased production and circulation of automatic and microprocessor based audiometers. Audiometers can be further classified into the following types: Screening, clinical diagnostic, Individual or group type; all having speech and pure-tone facilities. Developmental changes in the field of audiometry cover a time-span of nearly more than

100 years Advances in this field of bio-technology are summarized below [1,11,15,21.38].

Year	Type of Audiometer	Discoverer
1875	Telephone receiver (it makes possible use of earphones in audiometer)	Alexander Graham Bell
1878	A coumeter (utilized telephone receiver for the first attempt to develop puretone audiometer)	Hartman
1879	Electric Sonometer (inspired first the use of the term audiometer)	D.E. Hughes
1885	Application of binaural receiver in audio meter	Jacobson
1890	B.C. Vibrator	Gradings
1899	Audiometer with logarithmic intensity	Seashore
1904	Phonograph in audiometer	Sohrer Bryant
1914	Electric generator	Stefamine
1919	Otandian (First audiometer which could produce puretones of any described frequency and of measurable intensity)	Germans
1921	Vaccum tube audiometer (utilized interrupter switch)	Gutman
1922	First Commercial clinical audiometer	Wegel and Fowler
1924	Provision of both AC and BC made available in audiometers	Knudsen and Jones
1940 onwards	Several commercial audiometers appeared in market with vacuum tubes replaced by transistors and integrated circuits.	

3.4.0 Pure Tone Audiometry

Whether commercial or clinical diagnostic type or advanced microprocessor based - all types of audiometers employ testing the hearing acuity with the help of pure-tone sound signals of varying magnitudes and frequency. Generation of pure tones and assessment of a person's hearing ability is genuinly brought about by a combination of precisely, accurately and carefully designed electronic circuits composed of, necessarily, an oscillator, attenuator, transducer and switching mechanism - all together forming the audiometer [1,5,21,23].

(a) Oscillator: It has a range of frequencies, producing electrical signals of sinusoidal waveform either in discrete frequency steps or a continuous range. These frequencies/ frequency signals are made free from harmonic distortion, at the intensities required, by careful designing of the oscillator.

(b) Attenuator: An attenuator is needed to accurately change the power output of the oscillator. This is usually in steps of 5 db, but smaller intervals are available for more precise testing.

(c) Transducer: The signal may be presented to the patient by air-conduction either from a loudspeaker or through earphones. The latter is a more usual method as it reduces the effects of background noise. The transducer must be a high-grade moving coil device, free from distortion at the frequencies required. It is specially important to investigate the frequency response of an earphone for resonance. In bone-conduction audiometry a moving iron transducer is used as a much larger mass is to be moved. Also, this transducer must be applied to the head at the proper location by suitable means so that a definite pressing pressure is achieved.

(d) Switching: The switching mechanism is necessary for the switching of pulses to be made silently to avoid the "click" effect on the ear due to a transient response which is produced by a sudden application of pressure. The electrical pulse is allowed to build up and decay by passing it through a low pass filter before it reaches the coil.

3.4.1 The Békésy Audiometer

The recently developed audiometers are based on the principle of working of the Békésy Audiometer. The automatic clinical diagnostic type are actually Békésy Audiometers used by Pathologists, bio-engineers and medical physicists. In its original form, the audiometer has a continuously variable frequency with a range of 100-10,000 Hz. The oscillator is driven by an electric motor over the complete range in 15 minutes. The subject can change the intensity by pressing a button, which drives a motor to change an attenuator, so that the intensity decreases at about 2.5 db/min. The subject presses this button for as long as he can hear the test tone, then releases it as soon as the tone becomes inaudible.

The recording is made automatically, since the motor driving the frequency control also moves a card under a pen-recorder. The resulting audiogram is a zig-zag pattern, but shows the threshold response of the subject [1,21,23,31].

3.4.2 Calibration of Audiometers

In the case of air-conduction the power output from the transmitter, which provides the electrical signals to the earphone, can be determined. But it is difficult to determine the intensity of the signal received at the ear in terms of pressure. This can only be done by coupling the transducer to an artificial ear which is equipped with a microphone of known sensitivity. It is essential that this artificial ear is carefully designed to simulate the average human ear, i.e. so that at all frequencies it presents an acoustic load, to the sound wave, of the same magnitude as the average human ear.

In case of bone conduction the amount of vibration from a moving iron transducer can be determined, but the effect on the ear itself is not known. The calibration of these transducers is performed using an artificial mastoid that simulates the average human head in terms of mechanical impedance. The sound waves are detected by a vibration sensor instead of a sound pressure detector as in the artificial ear. This detector cannot be placed between the transducer and the mastoid as it would affect the calibration; so the detector, a piezo-electric crystal, is placed in the body of the artificial mastoid. Here it receives a fraction of the force at the surface, the applied force's resultant on the mastoid being measured independently. The response of the ear in our conductional geometry is independent of the means by which the transducer is connected to the ear, whereas, in bone conduction audiometry the response depends on the area of contact and the force of application of the transducer. A standard has been set for these conditions by the International Organisation for Standardization i.e. the static force must be 5.4 Newtons and the area of contact must be 1.75 cm^2[1].

3.4.3 Recording of Results by Audiometer

In audiometers used for screening large numbers of subjects, say in an industry, the instrument should be self recording (e.g. Békésy audiometer). Five or six discrete frequencies (e.g. 0.5,1,2,3,4 and 6 KHz) or, a continuous range of frequency is used and the intensity is allowed to vary at the rate of + 2.5 db/s or - 2.5 db/s. Consequently, the subject indicates when he hears the signal by pressing a button. A more general diagnostic instrument has more facilities and ranges of frequencies. The testing of a subject is complicated by the psychological aspects of understanding instructions and responding accordingly to the patient's ability to make a decision; whether the patient is more willing to say, "yes" when he might be wrong or vice-versa. This introduces an error in testing that can cause unreal changes of 15-20 db in either direction of the threshold level at a given frequency. The response to the signals near the threshold is not a simple "yes" or "no" response but shows a statistical relationship dependent on the intensity. Over a range of 1-2 db a subject will show a result which varies according to the level of intensity. If pulsed tones are used at high intensity the pulse will be heard every time, but there comes a point, as the intensity is lowered, at which the subject will hear only a percentage of the pulses, even though they

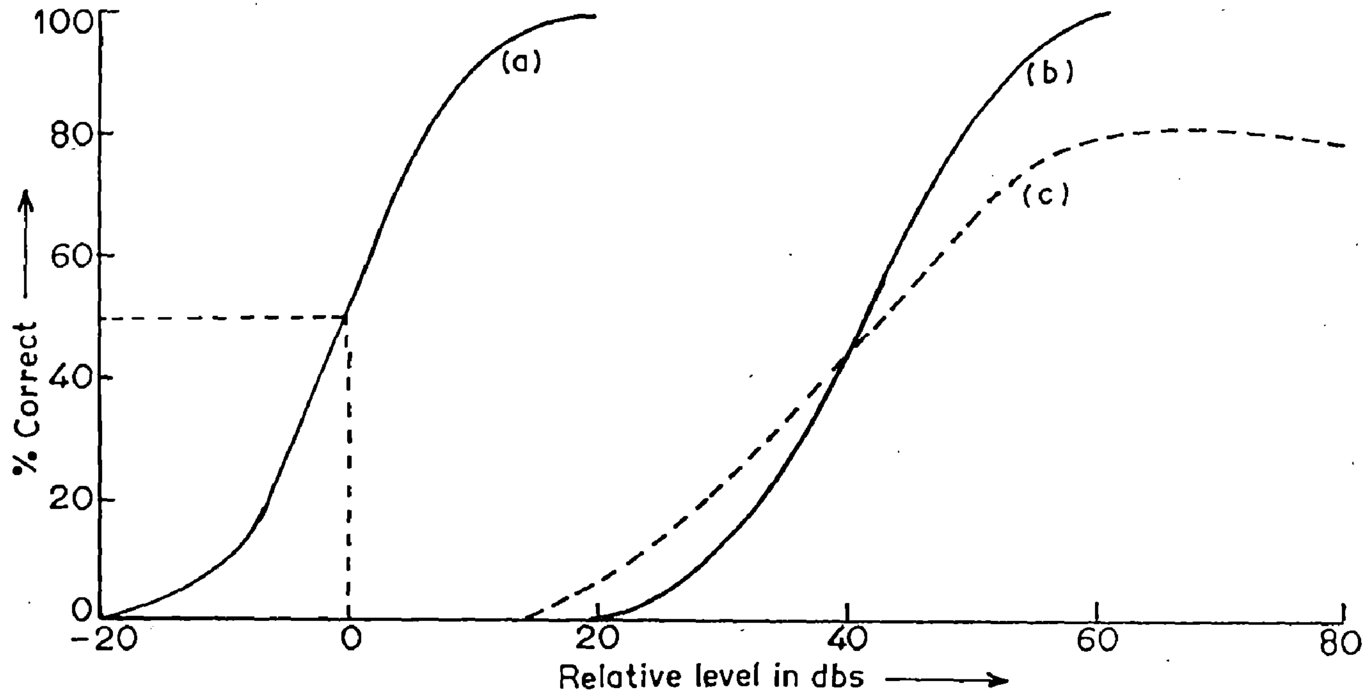


FIG.3.3.4 THE % SCORE IN PURE TONE SPEECH AUDIOMETERY FOR (a) Normal (b) Conductive deafness (c) Sensori-neural deafness.

are all of the same intensity. Detailed study shows that this response is an S-shaped curve (Fig.3.4.3). A suitable criterion for determining a precise threshold response is to use the 50% response. With the limited tune, usually available, this complete curve cannot be plotted. In practice it is found satisfactory to define the threshold as that value of sound pressure at which at least two responses are obtained for four separate stimuli of 2-second duration. This point is approached by first lowering the intensity and then raising it [1,31,38].

3.4.4 Masking

In patients with unilateral hearing loss or asymmetrical bilateral loss there is a possibility of obtaining a false threshold level for the poor ear (Test ear or T.ear) as the signal may be of such an intensity that it is transmitted across the skull to the non-test ear (N.T. ear). This produces a false diagnosis. To prevent this faulty diagnosis the technique called masking is employed. Masking consists of a noise presented to the N.T. ear to shift its threshold level upwards and effectively more intense tones can be used for the T. ear without crossover. Therefore, whenever there is a problem of the test tone (in air conduction and bone conduction tests) being heard by the N.T. ear, masking is a powerful tool. Different masking noises applied in A.C. and B.C. tests are as follows [3,4,5,10].

3.4.5 Masking Noises

(i) Complex noise: It consists of a fundamental frequency and its harmonics.

(ii) White noise: Is a continuous spectrum of frequency. The actual frequencies presented to the ear, although, depend on the frequency response of the transducer. This frequency response is reasonably flat (± 2 db) upto 6 KHz.

(iii) Narrow band noise: It is produced by passing a continuous spectrum of frequency through a band-pass filter. The pass band is described by its centre frequency (e.g. 1 KHz) and band width at -3 db (e.g. 300 Hz).

Narrow band noise is preferable to white noise, but either must be used instead of complex noise because discrete tone can produce beats with the test tone.

Masking is used in air-conduction audiometry when the signal applied to the test ear exceeds, the bone-conduction threshold in the non-test ear, by more than 40 db. In bone conduction audiometry, masking is used, whenever the test ear exhibits an air-bone gap. The procedure of masking is as follows in case of bone-conductional tests:

(i) The air-conduction threshold on the N.T. ear is determined using the masking noise.

(ii) Next, the bone conduction threshold on the test ear is determined using the pure tone.

(iii) Finally, the masking noise is increased by 10 db and step (ii) is repeated.

As the masking intensity increases, the apparent threshold level, for bone conduction, of the test ear rises. Therefore it is recorded that the true threshold of the T. ear is when the apparent threshold level remains fixed at a value.

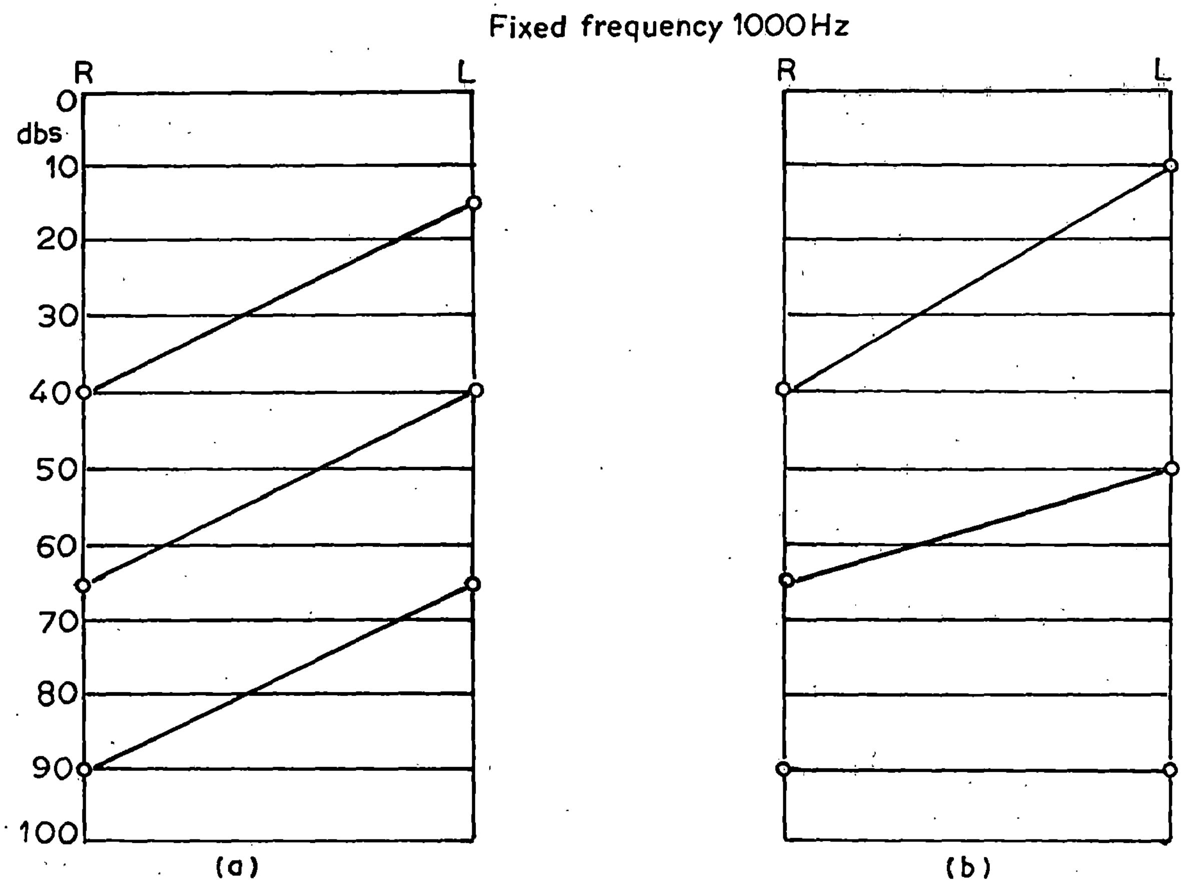


FIG.3.5.0 RECRUITMENT OF LOUDNESS (a) Conductive deafness-slope constant. (b) Sensori-neural deafness -an increase in slope at lower intensity.

3.5.0 Tests Conducted by Modern Audiometers

In general the tests, conducted by an audiometer, in recent times are classified into two well known and important groups:

Subjective tests and

Objective tests.

Subjective tests include Recruitment of Loudness, Short Increament Sensitivity Index (SISI), Threshold Tone Decay (TTD) and Speech Audiometry. Recruitment of loudness is a term associated with cochlear or perceptive deafness. Even if the bone conduction threshold is normal, there is a recruitment of loudness, meaning thereby that while near the threshold a sound is heard with less than normal loudness, at intensities quite above the threshold sounds are heard at normal loudness. The test of this consists of asking the subject to make loudness adjustments to pure tones of the same frequency applied alternately to each ear. An example, of the results of this kind of testing, is depicted in Fig. 3.5.0. The Short Increment Sensitivity Index is used in the diagnosis of cochlear disorders. In this test, a pure tone is presented to the subject at a certain intensity (usually, about, 20 db above threshold) but punctuated at random intervals by a pulse of 1/5 second duration with a small increament in intensity level (usually 1 db) which is imperceptible to the normal ear. However, the subject with loudness recruitment is likely to register this change because of the greater slope of loudness sensation against the intensity level. Therefore, the patient is asked to count the number of pulses that are heard and this score is used as a measure of the degree of disorder.

The threshold Tone Decay is the test which gives a measure of the degree to which a loss of sensitivity is produced due to prolonged exposure to a, tone/sound. The test indicates the level of the tone to be raised so that it is properly perceived. The patient is tested by comparing the effect of a continuous tone with a pulsed one. Patients suffering from retrocochlear disorders may have a normal threshold with pulsed tones, but show dramatic tone decay for the continuous tone. For patients with severe damage of the cochlear parts (may be hair cells, basilar membrane or connecting fibers to the auditory cortex) the tone is increased in intensity to 60 db over a two minutes continuous exposure! When the audiometer is used as a speech audiometer it functions as a device for reproducing speech signals, of all sorts, at a known intensity for making tests of articulation or intelligibility. The component syllables of speech have a range of intensity of nearly 30 db. Therefore, the instrument needs a careful design to produce a list of syllables and words for a specific purpose. In some audiometers these are spoken or read in the inbuilt microphone of the instrument, but the usual convention is to record them on tape. The speech signal is presented to the subject through microphones or free-field. The intensity level during recording is read on a volume indicator (eg. VU meter) of known response. To obtain the speech audiogram, a plot of the number of correct words (word score) against intensity is made. This has the same S-shape as the curve for pure tones shown in Fig.3.3.4. Here again, the threshold response is taken as the 50% level.

After brief explanation of different subjective tests, we come to the objective tests. These tests are specially useful in cases where lack of co-operation in other tests is observed. Thus for children and patients who cease to follow the instructions given by the personnel conducting audiological examination, the objective tests offer a useful approach. They are as follows.

3.5.1 Evoked Response Audiometry

Here the response of the patient to an auditory stimulus is detected in the EEG. The most prominent signals are from the vertex of the scalp (known as V-potentials, μV in amplitude), in the form of a complex of waves. These responses are divided into three classes, the categorization depending on the time of appearance of the response after application of the stimulus:

(i) Fast; with a latency of 8-50 milliseconds.
(ii) Slow; with a latency of 50-300 milliseconds.
(iii) Very slow; with a latency of 300 milliseconds to several seconds.

These very low voltage signals are detected by a specialized computer known as Computer of Average Transients (CAT). The CAT operates on the basis of summing many signals and then presenting their average as the final output (response signal). This technique of summation and averaging has a very beneficial advantage of effectively increasing the signal to noise ratio. Noise is a common feature marking the weak EEG signals and being random in nature is erased out since summation of random signals, eventually, cancels them to zero. The signal to noise ratio is improved by a factor $\sqrt{N}$, where N represents the number of total responses added together. The triggering of the averaging system is done by using and applying a signal from the audio-stimulus generator so that CAT starts operation instantaneously performing the averaging in about 500 ms.

3.5.2 Acoustic Impedance Audiometry

This technique of assessing auditory behaviour is very widely used, and is an objective examination, for diagnosing the middle ear diseases, in particular. It is well known that the acoustic impedance of the tympanic membrane determines the transmission characteristics of the middle ear i.e. if the acoustic impedances changes it directly affects the transmission of sound signal through the middle ear. Therefore measurement of this acoustic impedance is performed, in this objective test, by varying the pressure on the ear drum. The variation in pressure is brought about by using a manometer with a coupling tube and then reflecting sound waves of known intensity off the tympanic membrane. The membrane reflecting the sound waves intensifies or attenuates their intensities substantially according to the defects of the ear. The intensity of the reflected wave is detected by a microphone and this observation is used to calculate the impedance offered by the membrane. When the recorded impedance is lower than normal the patient suffers from ossicular discontinuity. If this acoustic impedance is higher than normal, the deficiency is clinical otosclerosis , and for very high value of the impedance above normal the patient is said to suffer from acute inflammatory and chronic diseases of the middle ear.

3.5.3 Eighth Nerve Action Potential

It is another name given to action potential of the cochlear nerve and is a very important physiological variable used in objective audiometry to diagnose diseases of remote inner ear. Measurement of this potential is entirely a cumbersome and careful operation presenting the latest technique used by medical-physicists these days, to detect all types of cochlear disorders and the disorders of nerve pathways between the cochlea and the auditory cortex. First of all a sound stimulus is given to the ear which eventually converts it to a series of action potentials travelling to the brain via the cochlear nerve. These action potentials form the response to the original sound stimulus and are measured by piercing needle electrodes in the auditory nerve or by using electrodes in the medullary region. The recorded response is amplified and sent to the CAT so that the information is computer processed just as in the case of evoked response audiometry. The characteristics of this processed information lead to the detection and diagnose of the many diseases, defects, and losses of audition in the inner ear and the auditory nerve.

Another recently developed technique is that of taking the EMG of the post auricular muscle. The electro-myogram is monitored for response to auditory stimuli and the signal is again extracted from background noise by computer averaging techniques [1,4,15,20,38].

CHAPTER-IV

MODELLING OF HUMAN AUDITORY SYSTEM

CHAPTER IV

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4.1.0 Introduction

As a whole, the entire human system and its functioning is a complex mechanism undergoing every moment some unknown and some known changes. Out of the five sense organs, the human ear is no exception. Numerous methods and theories have been laid down to analyse the undergoing processes in the, yet, partially undiscovered ear mechanisms. Modelling, is the outcome of the many methods adopted and followed that, answers and deciphers the intricate operations of the human ear-thus simplifying its operational-analysis to best anatomical evidences. It is a powerful process to classify and examine the different parts and performances of the ear. In the past few years, the most up-to-date technique of modelling the sense organs, widely used and improved upon gradually, is the technique of 'Electrical Modelling' Besides unrolling the complexities of the ear it is the only technique available that enables a biomedical expert to engineer the formulation of the complete ear as an independent unit and hence analyse to deepest intricacies the remarkable function and performance of different parts of the ear-unraveling thereby, the defects, deficiencies and diseases affecting the ear to valuable diagnostic results. In the present work an attempt has been made to carry out the task with the help of elaborate computer software and graphics. Details are discussed in relevant sections.

For convience purposes, modelling and performances of each part of the ear are considered first separately and then the equivalent model of the complete ear is analysed.

4.2.0 Electrical Modelling of Outer Ear

The most peripheral of the auditory subsystems is the external ear which includes not only the acoustic effects of the external auditory meatus (ear-canal), but also the diffraction and shadowing produced by the head and the auricle. The parts of the external ear before the tympanic membrane can be modelled, for most acoustic purposes, as a lossless structure with rigid walls. In its simplest form, the structure can be compared to a cylindrical pipe or tube. But since different individuals have varying shapes and sizes of the ear canal, it would be proper to illustrate the transmission of sound through the ear canal by giving it different forms or shapes.

In the ideal condition, conventionally assumed, the ear canal transmits all the incident sound energy without loss into the middle ear via the tympanium. Therefore the canal is modelled and compared to its electrical counterpart - the lossless transmission line. At the input of this model, sound pressure is equivalent to electrical voltage that is carried by the transmission system in a manner quite analogous to ear canal transmitting sound waves. In general, a wave represents a collection of disturbances whose occurrence at two different instants of time depends on the time lag factor being proportional to their space-location distance or separation length along the path of travel. Occurrence of these disturbances at successive moments is called motion of the wave and is usually known as propogation of the wave along a direction. Relating all these factors mathematically, we proceed as follows.

Let us assume that the instantaneous value of voltage, at a particular location, along the transmission line is $V(d,t)$, where 'd' represents the distance variable and 't' the time variable. For pure tone inputs, the voltage varies sinusoidally and for any frequency 'w', the input voltage, initially, (i.e. at $d = 0$) can be given as $V(0,t) = V_m \sin wt$. At some variable distance d, the signal is delayed by the term d/u corresponding to time t, and can be written as,

$$\begin{aligned} V(d,t) &= V_m \sin w(t - d/u) \\ &= V_m \sin (wt - wd/u) \\ &= V_m \sin (wt - \beta d) \\ &= V_m \sin (wt - \theta) \end{aligned}$$

where,

V_m = Peak magnitude of input signal

u = Velocity of propogation of waves

$\beta = \frac{w}{u}$ = propogation constant

$\theta = \beta d$ = delay phase angle.

Again,

$$\beta = \frac{w}{u} = \frac{2\pi f}{u}$$

$$\therefore \quad \theta = \frac{2\pi f}{u} d = 2\pi d/\lambda \qquad (1)$$

where λ represents the wavelength along the transmission line.

The delay phase angle 'θ' is a very significant parameter here. We have seen from Eq.(1) that 'θ' depends on wavelength (λ) and any distance 'd' along the transmission line. Since 'θ' varies inversely with λ, we choose the upper limit of audio frequency range, and obtain, 'λ' by the relation,

λ = Velocity of propogation/frequency of sound.

Then from expression (1) above, we can calculate the value of 'θ'. The value for 'd' can be chosen from the set of different lengths, of ear canal, experimentally estimated by various scientists. The magnitude of 'θ' so calculated, gives the maximum delay in phase, which is a negligibly small value.

This small value of maximum delay obtained, allows the modelling of ear-canal as a transmission line with lumped circuit elements. In other words, it allows the assumption of the fact, that at a given instant of time the current flowing at each point of the system has identical magnitudes and that the magnitude of voltage between all pairs of opposite points of the transmission system is identically same at a particular time instant. Hence, the distributed parameters of inductance, capacitance and resistance can be represented as lumped ones. The circuit configuration of lumped T-networks is chosen as the transmission line model of ear canal becausethis is the only arrangement that permits the simple conversion of individual network elements into their equivalent transformed acoustical counter-parts, and, thus renders the closest relationship between anatomy and modelling of ear-canal.

The ear canal in its simplest form is considered to be of uniform cross-sectional area. This oversimplified approximation further leads to non-uniform cross-sectional area considerations modelled as more accurate electrical networks. How exactly we proceed to the realistic configuration, is step-lined in following articles [2,6,14,33].

4.3.0 Review of Uniform Ear Canal Configuration

The elements of the lossless transmission line model are capacitances and inductances, with the inductances appearing in the series branches and the capacitances as shunt branches. These parameters have a significant justification for their placements in the model, which is obtained by equating, the inductance in Henrys to acoustic mass units; and capacitance in Farads to acoustic compliance units. The acoustic mass and the acoustic compliance in turn depend on two very important anatomical measurements, the radius of ear canal (taken to be a tube of uniform cross-section) and its length. The following relationships illustrate this analogy.

The total inductance of the model is given as,

$$L = d\,\rho_0/\pi r^2 \tag{2}$$

and the total capacitance is given by,

$$C = d\pi\, r^2/\rho_0\, e^2 \tag{3}$$

where,

L = inductance in Henrys

C = capacitance in Farads

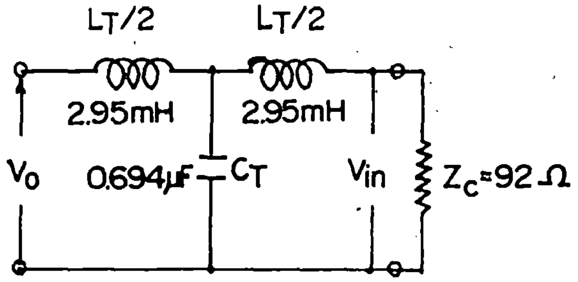
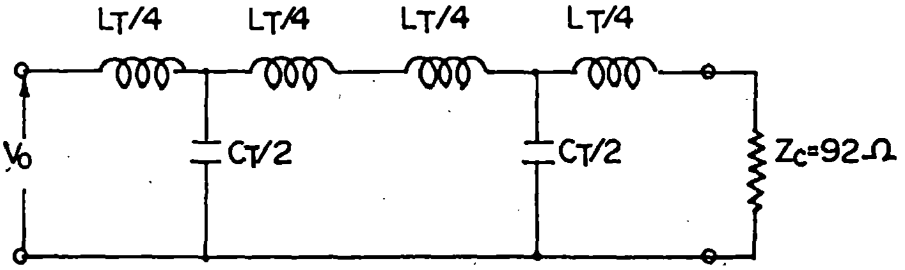
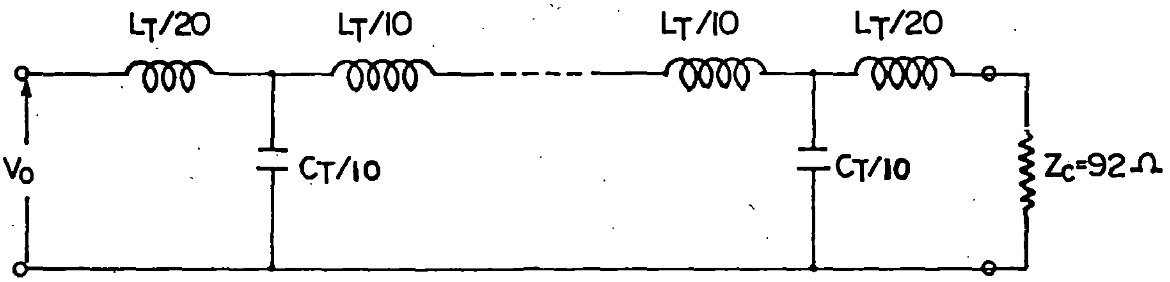


FIG.4.3.0 SINGLE TEE-NETWORK MODEL OF THE EAR CANAL.



LT=5.90 mH, CT=0.694μF



LT=5.90mH , CT=0.694μF

FIG.4.3.1 EAR CANAL REPERSENTED BY 2 & 10 TEE-NETWORKS. IN ALL NETWORKS EAR-CANAL HAS UNIFORM AREA OF CROSS-SECTION.

d = length of ear canal

r = radius of cross section of canal

ρ_0 = density of air

e = velocity of sound.

The analogy holds, and is performed, for the ambient conditions of temperature and pressure. The values of r and d vary from individual to individual. A group,of different values of radius and length of canal, investigated by a few scientists,points to the obvious variation,

Length of Ear Canal (cm)	Radius of Cross-section (cm)
2.2 (Bauer)	0.38
2.7 (Békésy and Rosenblith)	0.35
2.25 (Teranishi and Shaw)	0.35
2.3 (Weiner and Ross)	0.37
2.25 (Zwislocki)	0.374

Therefore, L and C, really cannot be fixed at a particular value. To construct the model, we choose $d = 2.25$ cm and $r = 0.374$ cm, to begin with. Substitution of these values in equations (2) and (3) gives the total inductance L_T as 5.90 mH and the net capacitance magnitude as C_T equal to 0.694 μF. Applying these values in the T-network configuration, the single-T-representation of the ear-canal is depicted in Fig.4.3.0. Although this model represents the external ear to a considerable extent but essential nature of the network representation is actually configured in a multiple T-network arrangement which can be easily simulated as an independent 'electrical-ear-canal' model, for analysis purposes

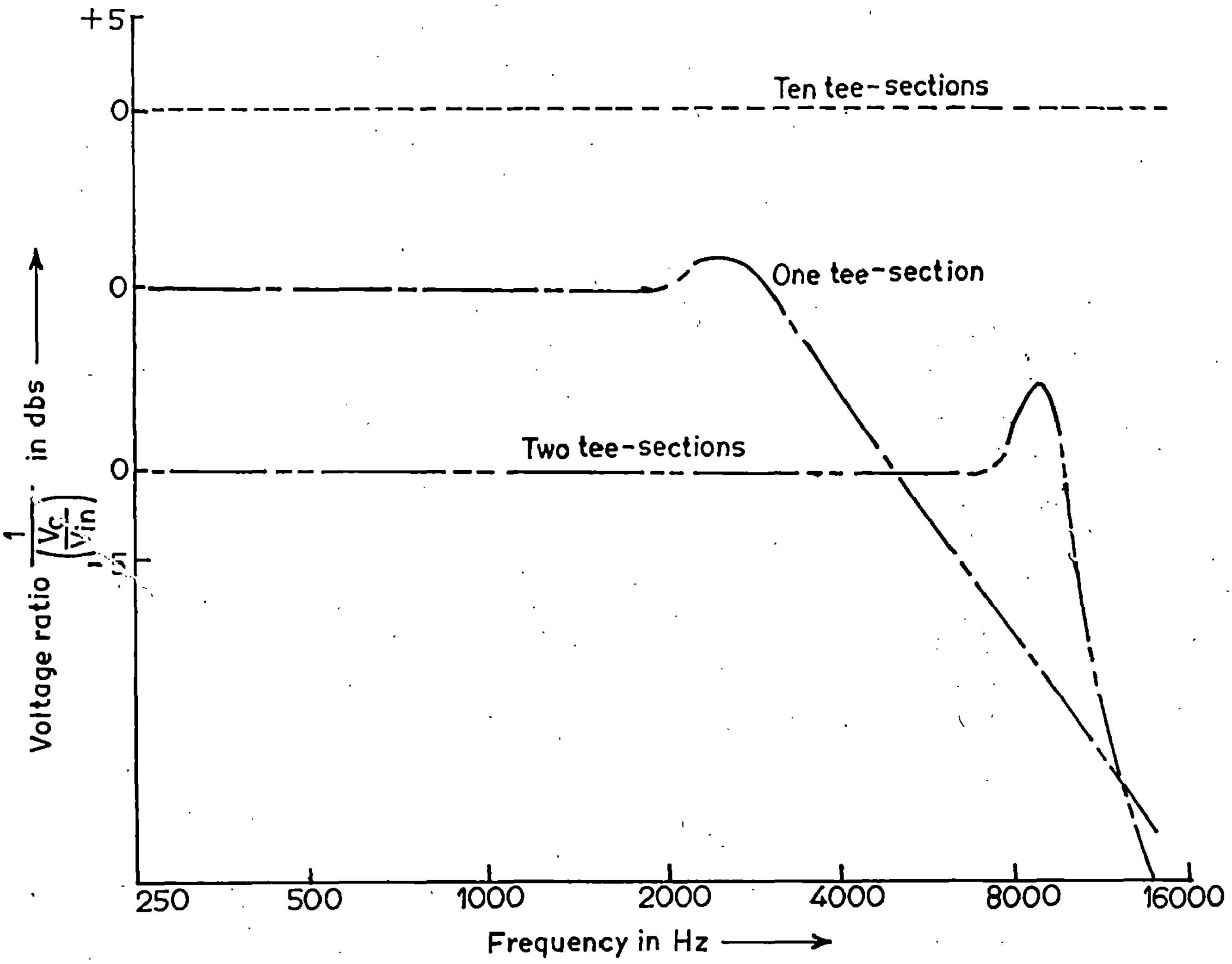


FIG.4.3.2 VOLTAGE TRANSFER CHARACTERISTICS FOR 1,2 & 10 TEE SECTIONS REPRESENTING THE ELECTRICAL NETWORK MODEL OF HUMAN EAR CANAL. (All the network models are terminated by 92-Ω

Now the question arises - what is the criteria of determining the number of T-sections, and what is the optimum value of this number Before entering these details let us consider the most effective parameter of a non-dissipative transmission line - the characteristic impedance Z_c.

The lossless transmission line when terminated by its characteristic impedance, presents a very useful behaviour of its voltage-transfer characteristics, that offer the greatest help in determining the number of T-section. The response plots for single, double and ten section networks, shown in Fig.4.3.1, are drawn in the graphic representation of Fig.4.3.2. Referring to these figures ; the networks terminated by 92 ohms (explained later), show a response that deviates from unity for the section less than ten, meaning thereby, that a minimum of ten tee-section forming the transmission line, model accurately the ear-canal.

The end branch of these network representation's comprises of the terminating resistance which is shown to be 92 ohms. It is specially to be noted here, that this value of terminating resistance is but one of a number of values that have been found in various investigations. Therefore, it is suggested that values of the terminating resistance can be taken from 25 ohms to 10,000 ohms. Fig.4.3.3 depicts the effect of changes in Z_c, for a ten-section network configuration, on the voltage transfer characteristics of the ear-canal and signifies the optimum selection of the resistance termination. A unity response curve/plot signifies the lossless and distortionless transmission of sound signal [2,4,6,9,26,28].

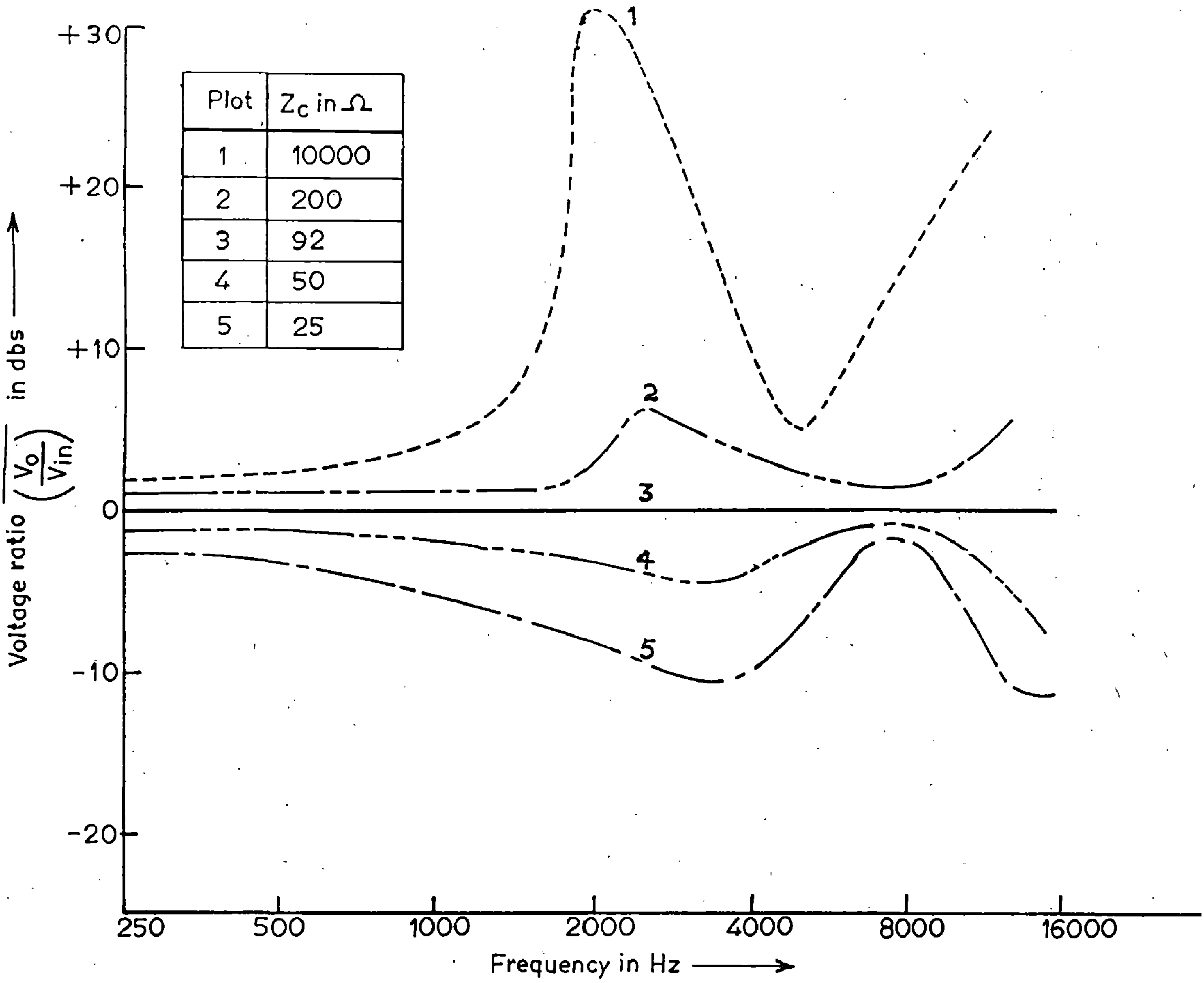


FIG.4.3.3 EFFECT OF THE CHANGE IN Zc (Terminating resistance) ON THE CHARACTERISTICS OF THE 10-TEE SECTION NETWORK MODEL OF EAR CANAL.

4.4.0 Non-Uniform Ear-Canal Representation

When the ear-canal is compared to a tube of uniform cross-section, the purpose of modelling is basically to study, and infer, the effects of transmission line network on the sound signal i.e. to theoretically justify that a transmission line with lumped elements channelizes all the input signals faithfully to the tympanium. Anatomy of the ear dictates that the ear canal is not one with uniform dimensions i.e. the radii of the tube-structure, taken as physical model, differ in magnitude at the entrance and at the end of the canal. In other words, the more practical representation is offered by a tapered canal. Since the volume occupied by a uniform canal and a tapered one is same (approximately), modelling and analysis in both the cases is similar. The details of tapering and the subsequent alterations in the elements and hence in the entire network are enumerated in the paragraphs to follow.

It has been investigated that canal taper depends on the individual. Very rarely, an individual, with normal ears, can have differing ear canal taperings. A few investigators have discovered that, on an average, ear canal at its entrance possesses a radius of 0.332 cm, while at the tympanium end has a radius of 0.415 cm. The dimensions are found in reversed magnitudes in many individuals. This physical model of the human ear canal, quite identical to the frustrum of a right cone, is shown in Fig.4.4.0. From this figure the ratio of 2 radii is 1.25 for one case (shown) and 0.80 for the reversed taper, and is called taper ratio. Due to tapering, considerable changes in the elements of

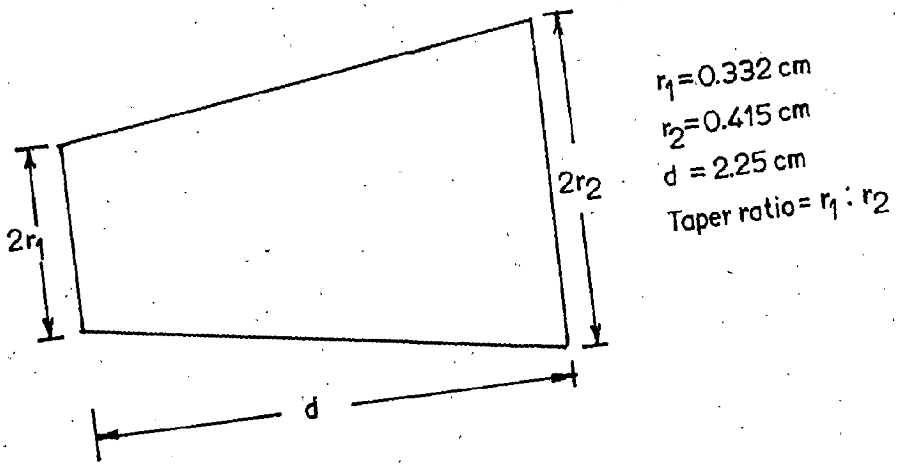


FIG.4.4.0 PHYSICAL MODEL OF THE TAPERED EAR-CANAL.

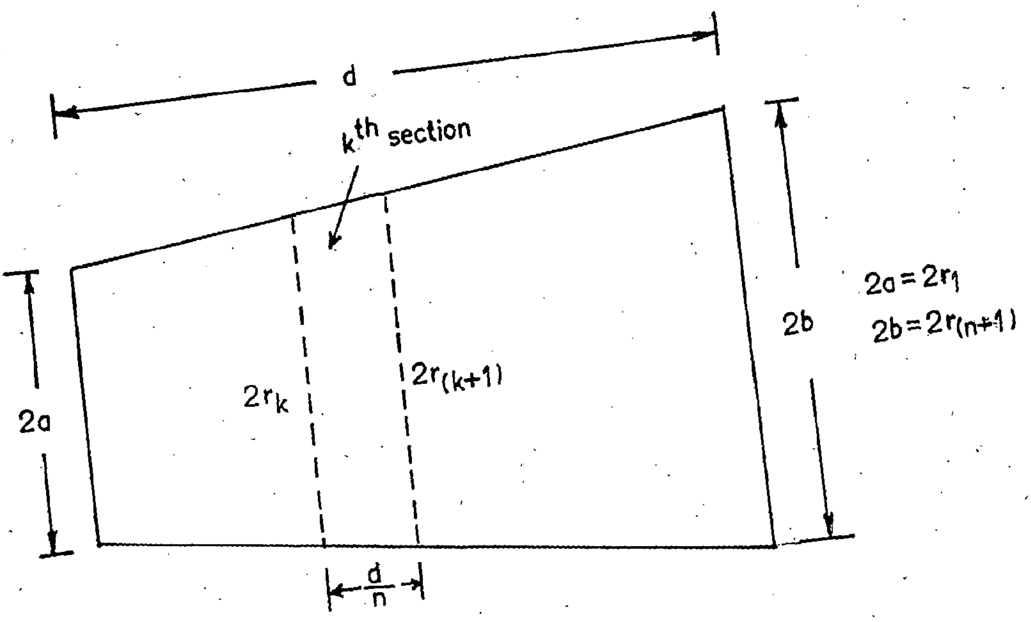


FIG.4.4.1 TAPERED EAR CANAL DIVIDED INTO 'n' EQUAL SECTIONS.

the transmission line model are brought about, effecting the response plot of the network. Modifications in the mathematics of uniform canal configuration help a great deal in knowing the new inductance and capacitance parameters. For the purpose of modelling the tapered ear canal, the complete frustrum shaped figure is divided into a number of equal parts or sections, the individual elements of inductance, capacitance etc. being calculated, by evaluated analogous quantities of acoustic mass and compliance etc. The element inductance of the tapering canal is given by,

$$L = d\ \rho_o/\pi\ r_1 r_2 \quad \text{in Henrys}$$

and the element capacitance is given by,

$$C = \frac{\pi d}{3}\ (r_1^2 + r_1 r_2 + r_2^2)/\rho_o C^2 \quad \text{in farads.}$$

In these expression for total inductance and capacitance occurring in the series and shunt arms respectively of the mathematically modified transmission line model, r_1 and r_2 represent the radii of ear canal at the two ends. Supposing the ear canal to be divided into 'n' equal sections, n being any arbitrary natural number, the individual magnitudes of series inductance and shunt capacitance in general forms for any Kth section (K is a natural number) are given as.

L_K = inductance element for Kth section among n sections

$$= d_k\ \rho_o/\pi\ r_k\ r_{(k+1)} = \frac{d}{n}\ \rho_o/\pi\ r_k\ r_{(k+1)}$$

and,

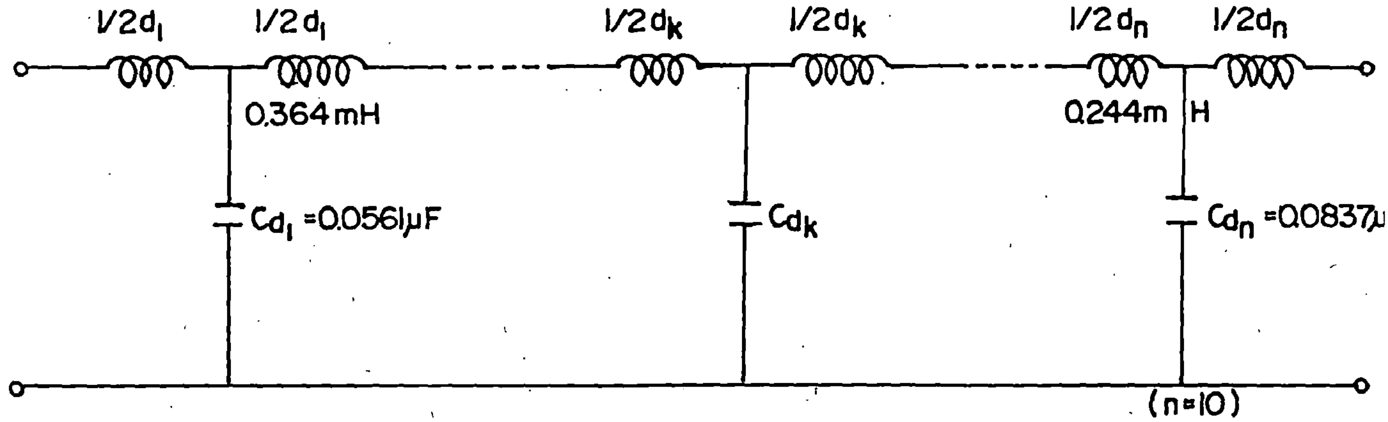


FIG.4.4.2 ELECTRICAL NETWORK MODEL OF TAPERED EAR CANAL REFERRING TO FIG.4.4.1

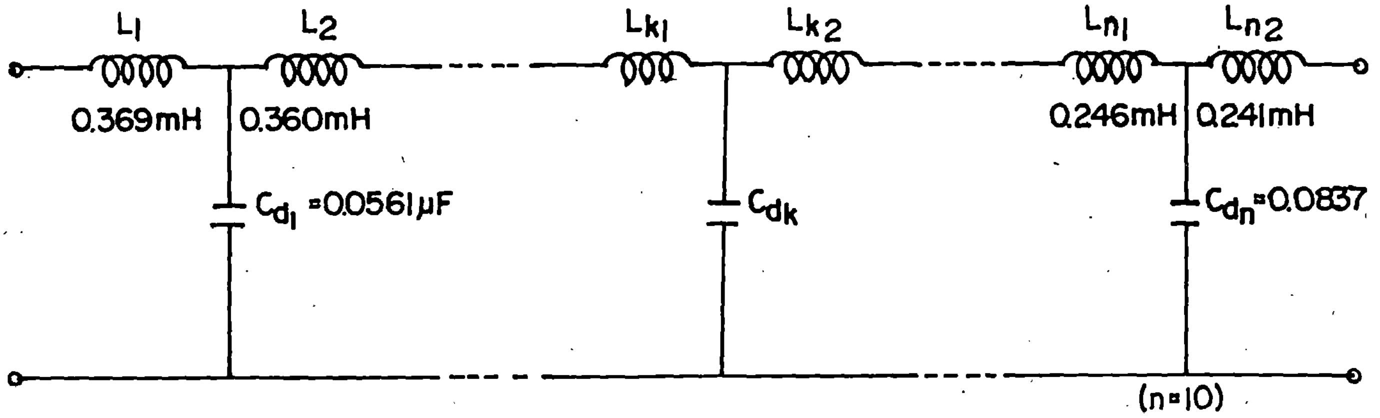


FIG.4.4.3 MODIFIED FORM OF ELECTRICAL MODEL IN FIG.4.4.2 FOR EAR CANAL.

C_k = capacitance element for kth section among n sections

$$= \frac{\pi d_k}{3} (r_k^2 + r_k\, r_{(k+1)} + r_{(k+1)}^2)/\rho_o\, C^2$$

$$= \pi \frac{d}{3n} (r_k^2 + r_k\, r_{(k+1)} + r_{(k+1)}^2)/\rho_o\, C^2$$

where r_k is calculated by,

$$r_k = a + \frac{(K-1)(b-a)}{n}$$

where k denotes the number of section among total 'n' sections; and 'a' and 'b' are the two end radii of the ear canal shown in Fig.4.4.1. For the tapered canal representation in network form we have the electrical analog shown in Fig.4.4.2. The diagram depicts a 10-tee network (with a terminating resistance R). The two inductances of an individual T network cannot be equal since the tapering changes the inductance parameter at each distant location along the ear-canal. Therefore, it is very obvious that the inductance modelling towards the decreasing taper possesses a larger magnitude than that signifying the increased taper section. These two inductances for each T-network are calculated by further sub-dividing each section into two sub-divisions i.e. each kth section into K_1 and K_2 sub-sections and then modifying the individual elemental values to,

$$L_{K_1} = \frac{d}{2n} \times \rho_o/\pi\, r_k\, r_{(k+0.5)}$$

and $$L_{K_2} = \frac{d}{2n} \times \rho_o/\pi r_{(k+0.5)}\, r_{(k+1)}$$

Applying all the above modifications, a typical tapered ear canal electrical analog is obtained and shown in Fig.4.4.3. The figure also shows the divisions performed on the tapered structure of

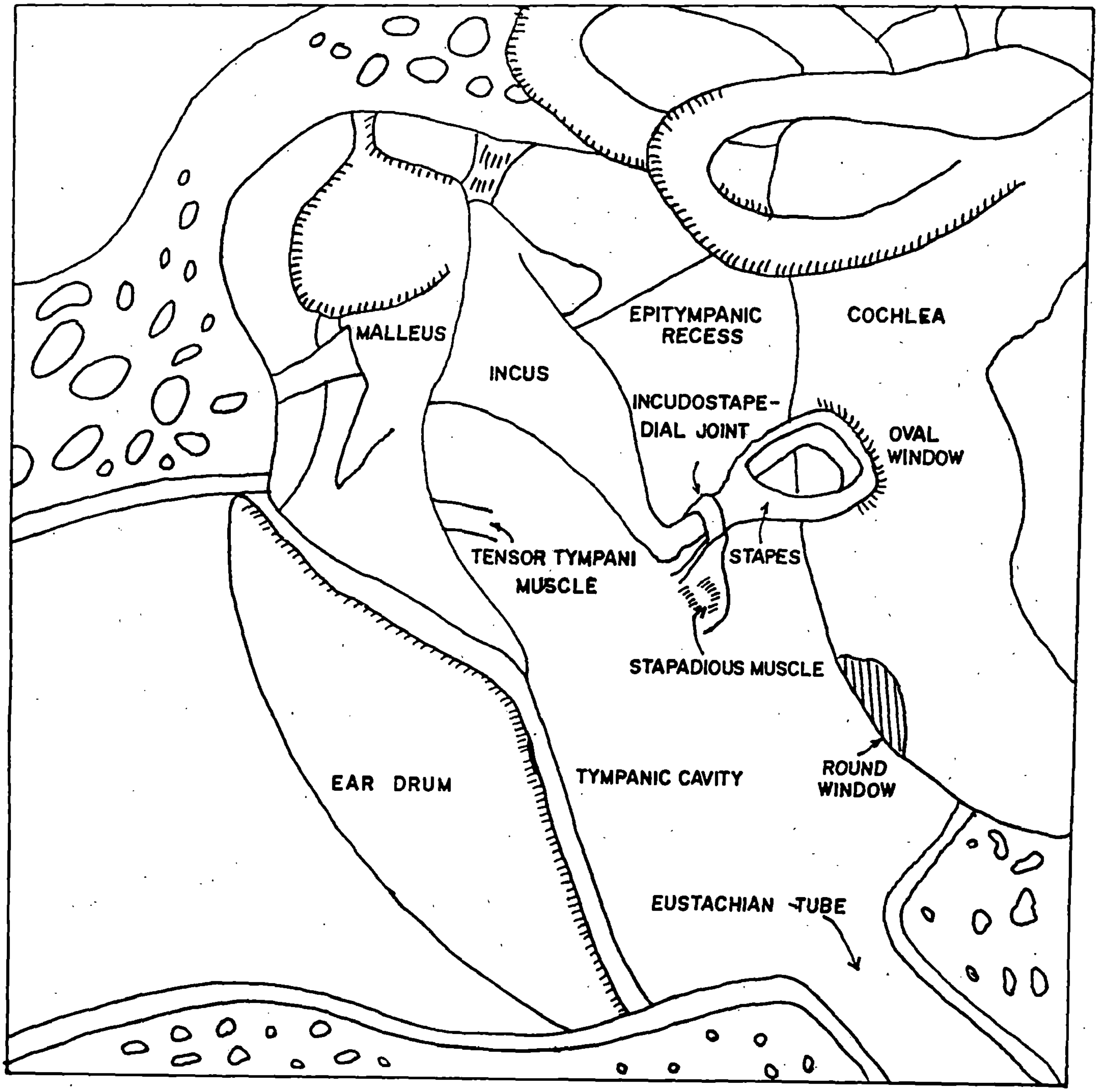


FIG.4.5.0 ANATOMY OF THE HUMAN EAR MODELLED BY AN ELECTRICAL SET-UP OF PARAMETERS EFFECTING THE EAR's AUDIOGRAM.

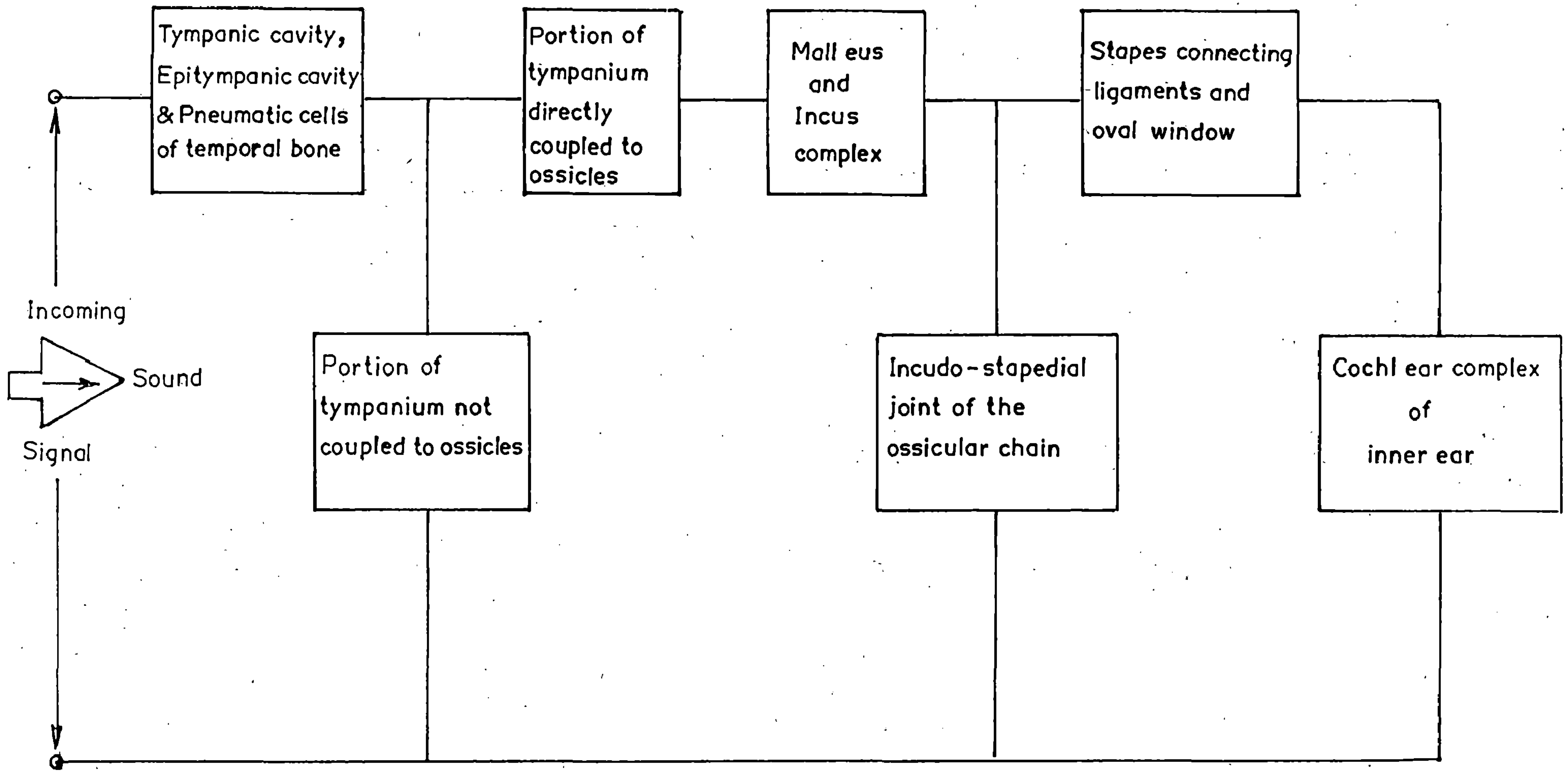


FIG.4.5.1 BLOCK DIAGRAM OF THE ELECTRICAL NETWORK MODEL OF THE HUMAN EAR WITH REFERENCE TO FIG.4.5.0 REPRESENTING THE EFFECTIVE IMPEDANCE TO SOUND.

the ear-canal. The numerical values of individual elements are calculated for n equal to ten. The ideal and most appropriate ear canal network analog is one consisting of an infinite number of sections, and only this electrical analog would represent the communication of complete transmission. Practically, this analog is not attainable, hence a minimum of 10 section are taken for accuracy purposes [4,6,9,29,33,35].

4.5.0 The Complete Model of the Human Ear

The ear-drum separates the outer ear from the middle and inner ear sections. The external ear mainly and necessarily functions to channelize the entire incident sound energy, via its transmission line behaviour, to impinge without any loss on the ear-drum. The ossicular chain of the middle ear amplifies this incident energy according to the conditional reflexes and requirements and converts it into a form that matches the cochlear sound transmission levels. How, this mechanism takes place physically we have already studied earlier. The manner in which the sound is transmitted, via the electrical analog of a real human ear, is discussed in the following paragraphs. A complete normal human ear is represented, first, in the form of an electrically analogous block diagram and then each block is represented by a network based on anatomical - evidences and findings, for prediction of individual elements of every network.

Referring to the construction of the human ear described in Chapter II and Fig. 4.5.0, the block diagram of the functional acoustic units of the ear is drawn in Fig.4.5.1. It contains the essential functional anatomy of the complete ear structure including all the important ear parts right from the ear drum to the cochlea. The diagram depicts five blocks. The block representing the middle ear-cavities placed prior to that depecting the ear-drum has been explained by Zwislocki on the basis of his experimental results performed on pathological and real ears. He concluded on the basis of his findings that, displacements of any part of the ear drum ... cause compressions and rarefactions in the air enclosed in the middle ear cavities. But it is not necessary that these displacements may be faithfully transmitted to the ossicular chain. Hence the blocks are arranged as shown. The second block depicts the ear drum. This block represents only those parts of the tympanium which vibrate in a manner different from that of the middle ear bones.

Some portion of the tympanic membrane does vibrate with the same amplitude and phase as the malleus and incus attached to it, therefore the third block is taken to depict all the three in one unit. We have known earlier that the middle ear reflex muscles acting as damping agents cause transmission of only the appropriate amount of sound energy via the incudo-stapedial joint into the inner ear. The next block i.e. the fourth, accounts for this factor representing the incudo-stapedial joint through which the sound energy is not transmitted in a lossless mode, thereby offering a protective mechanism against very loud and very high frequency sounds. The last and the fifth block represents the end of the middle ear and the beginning of the inner ear, the cochlea. This final block together comprises of the

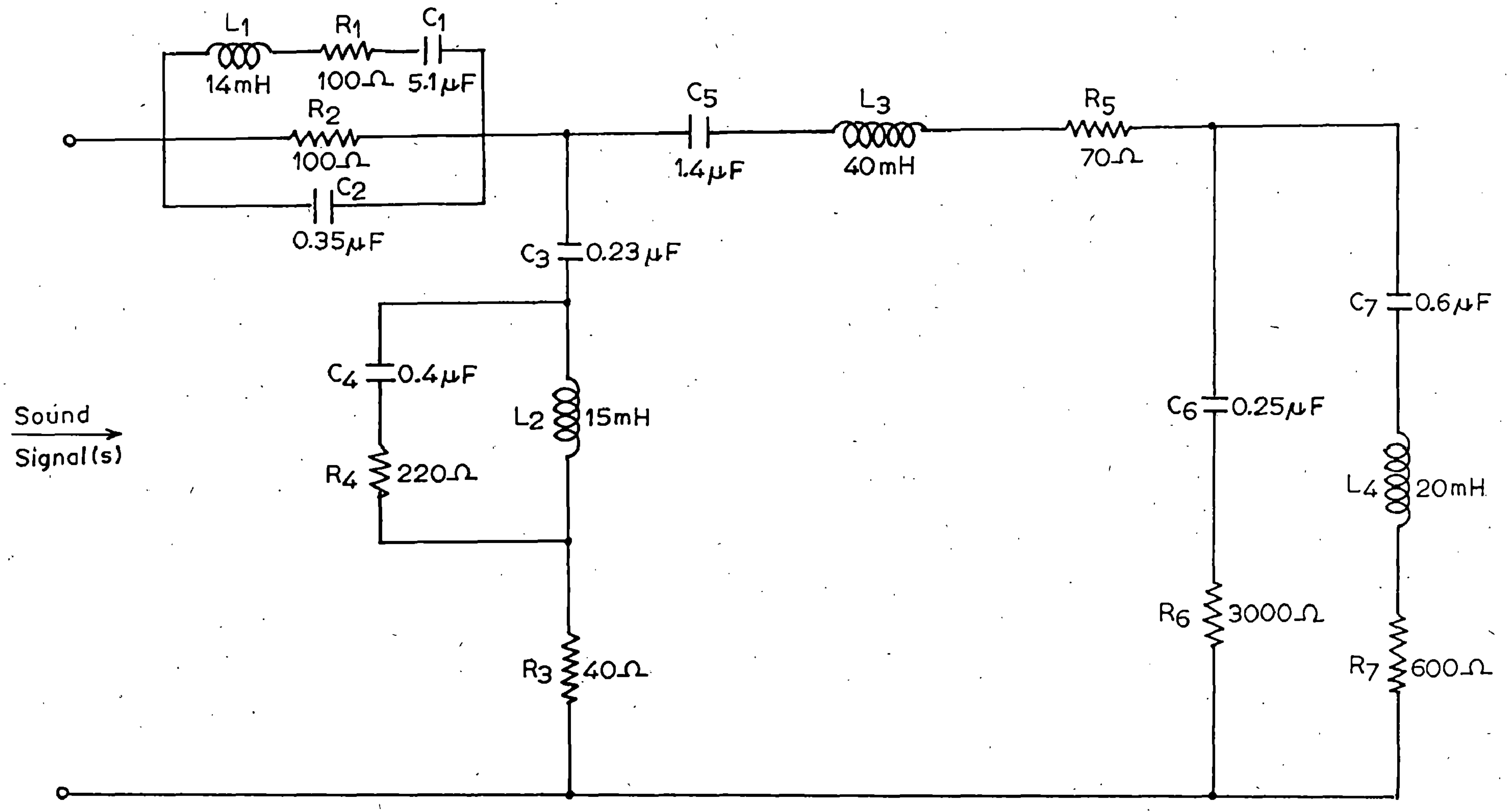


FIG.4.5.2 ELECTRICAL NETWORK ANALOG OF HUMAN EAR COMPRISING OF NET. IMPEDENCE (Z), CHARACTERISING THE STANDARDS & AUDIOGRAM OF A NORMAL EAR.

stapes, cochlea and the round window. In other words, it models those network elements which form the last and final impedance offered to the acoustic energy entering the cochlea. Beyond this point we have the intricate structure and mechanism of the basilar membrane and resting on it, the organ of Corti. As will be discussed a little later, the cochlea's basilar membrane enabling the travelling wave mode of transmission to the sound signals is best and most appropriately modelled as a transmission line.

Referring to the block diagram depiction of the normal ear, the analogous electrical network obtained by investigations and experiments of several scientists is drawn in Fig.4.5.2. The values of the inductances, capacitances and resistances are chosen from a variety of values obtained by researchers like , Onchi, Mollar, Zwislocki and many others who improved upon the anatomical and physiological facts, laid down primarily by Békésy, while employing them to analogous electrical network simulations, which when composed of certain parameters of appropriately defined placements in the network and dictated to possess the anatomically evidence based magnitudes, offered wonderful and desired results predicted, priorly, by former anatomists and medical physicists.

An electrical network that possessed the closest resemblance to the functional mechanism of the human ear is discussed here and as already mentioned, is shown in Fig.4.5.2. All the sound energy transmitted by the ear canal with ideally no losses is actually subjected to an impedance, mathematically quite complex in nature. This is the impedance that is offered by the network of normal ear presented in Fig.4.5.2, which processes the sound energy to be communicated to the inner ear, while attenuating, and sometimes amplifying it from point to point along the network. All that the inner ear receives are sound signals of an acceptable intensity within the audio-range. The actual frequency analysis of the sound signals (or a signal) take place along the entire length of the basilar membrane whose resonance frequency varies from 20 KHz to about 100 Hz, this peculiar frequency selection being the cause of audiogram frequency range starting from 100 Hz and extending maximum upto 8 KHz or 10 KHz (in some cases). The upper limit is fixed at 8 KHz because beyond this frequency plotting of the audiogram is, of a very misleading information. A few recent investigations have led to the conclusion that losses in hearing, occurring around 8 KHz account for other higher frequency losses too, thereby leading to an unreasonable diagnosis. But again this internationally accepted practice, does not answer the question of intermediate-particular frequency losses above 10 KHz or that whether these losses contribute to the still, various undiscovered yet suspected hearing losses.

While evaluating the performance of the electrical network model (Fig.4.5.2) it was found that the net impedance of the network had a strict resemblance with the normal audiogram (A.C.) and with the standards of ISO-1964 (4.5.3). The graphical behaviour of the network, described by its input impedance, which is the impedance offered to any and every sound signal at the ear drum, is shown in Fig.4.5.3. In this graphic representation it

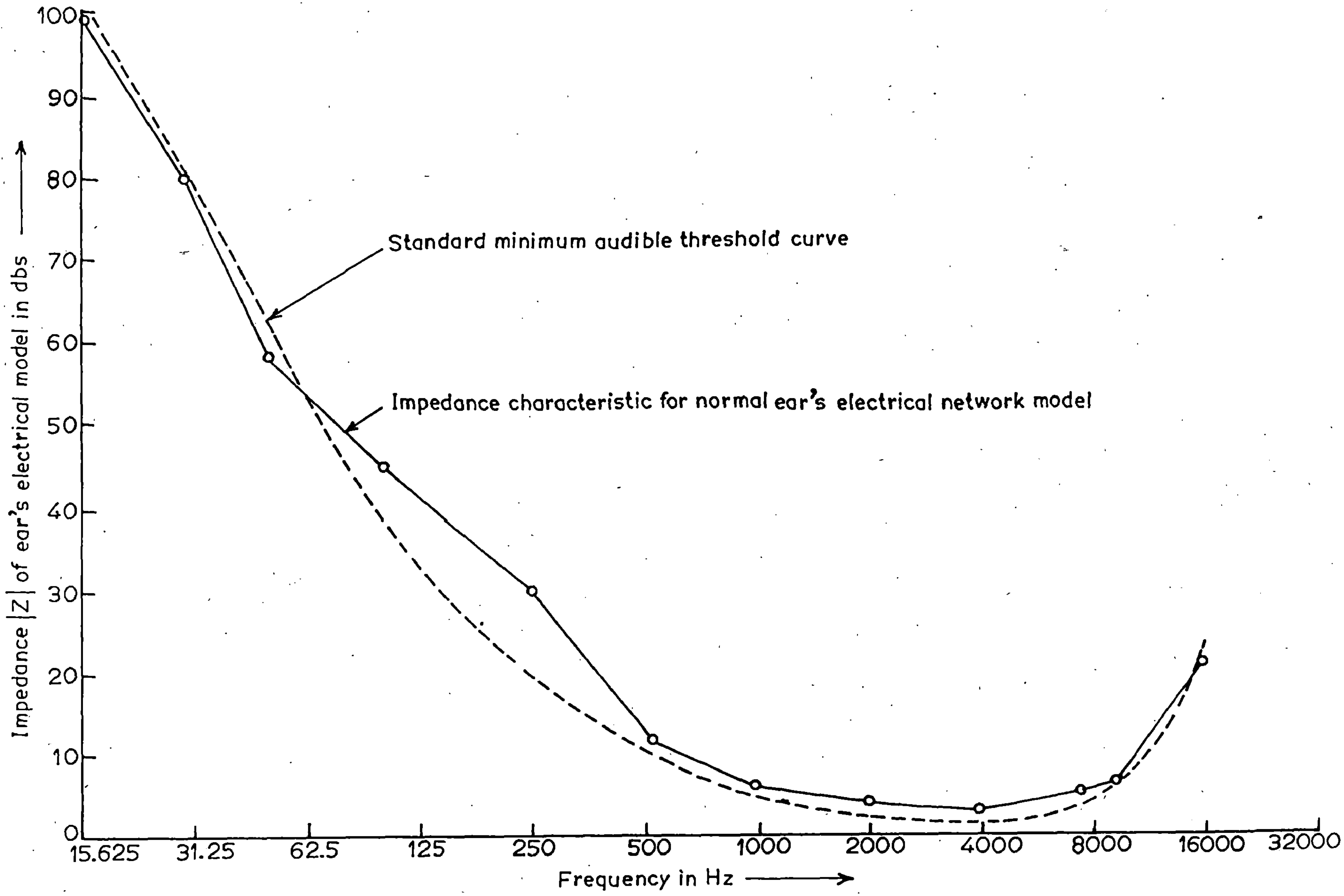


FIG.4.5.3 GRAPHICAL BEHAVIOUR OF THE MODEL CHARACTERISING THE ISO-1964 STANDARDS.

is observed that for low frequencies the impedance is much higher than that for higher frequencies. Again beyond the region of 6.8 KHz the impedance starts increasing. The solid line depicts the required region under study. Another important conclusion arrived is, that the range of maximum sensitivity for a normal human ear is from 1000 Hz to 6800 Hz i.e. the impedance offered is the minimum, thereby implying that the audible threshold is lowest in this frequency range.

Some very important and extremely useful results were obtained regarding the variation of the network elements for diseased care, with the help of the graphical depiction in Fig.4.5.3.

Any audiogram exhibiting a nature different from that of a normal audiogram is referred to as one of hearing impaired individual. The self-explanatory implication follows immediately: a different audiogram must be the response of an individual with the ears modelled by a different impedance function. Meaning thereby, a different set of parameters of the network model other than the one formed by values shown in Fig.4.5.2. Therefore, the technique of parameter estimation was employed using the computer software to evaluate the performance of each audiogram and justifying for the electrical model variations and the disease classification to satisfactory extents.

All these procedures and conclusions are discussed in details in the articles to follow [4,6,19,21,26,34,36].

4.6.0 Transmission Line Model of the Basilar Membrane

The lossless transmission line structure of the ear canal transmits all the sound energy entering it, to impinge on the tympanium. This membrane responding and thus vibrating only for the frequencies within the audio range, offers the first and foremost set of impedance parameters along with the other successive impedances of the middle ear. The sound energy after being processed by the complex impedance behaviour of the ear-parts is ready at the effective resistance of the cochlear complex to be communicated to the brain. It is the mysterious delicacy of the basilar membranc that functions to convert the vibrations of sound or the sound electrically impeded by the complex impedance set (Fig.4.5.2) to be transformed to a form recognised by the brain as sound. Referring to the structure of the basilar membrane in Chapter II, it has been pointed out that every group of hair cells (or a cell) situated all along the organ of Corti send(s) a nerve fiber to the cortex of audition. Also, the basilar membrane is the place in the ear where the frequency analysis of the sound, reaching the cochlea, takes place. Differen hair cells respond to differing frequencies. Hair cells of the cochlea towards the outer portion respond to lower frequencies and the responsive attitude of the hair cells for higher frequencies comes into play as we go deeper towards the end of the cochlea. Therefore we can say that the movement of the stapes is transmitted by the oval window to the labyrinth, which is filled with fluid. The fluid (details already discussed in Chapter II) conducts the sound to the cochlea, where the receptor

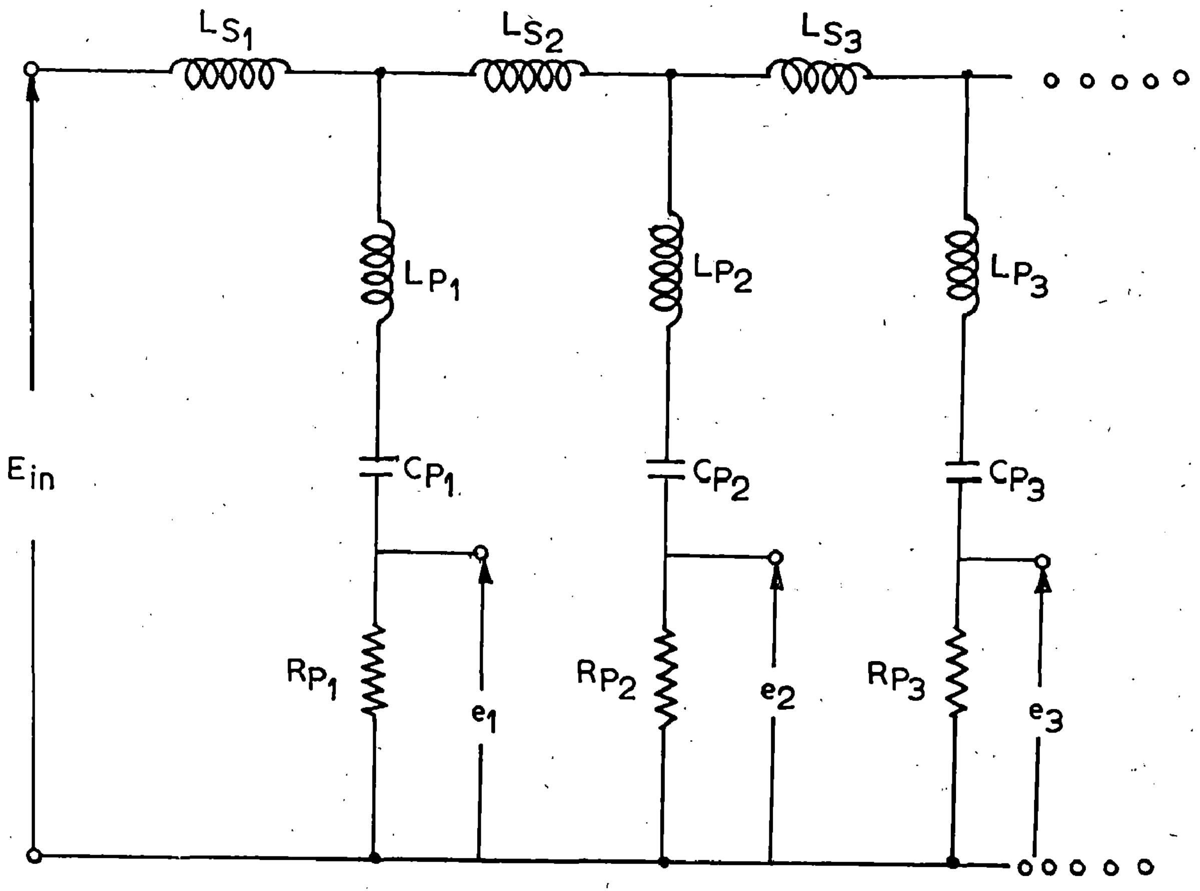


FIG. 4.6.0 ELECTRICAL NETWORK MODEL OF BASILIAR MEMBRANE.

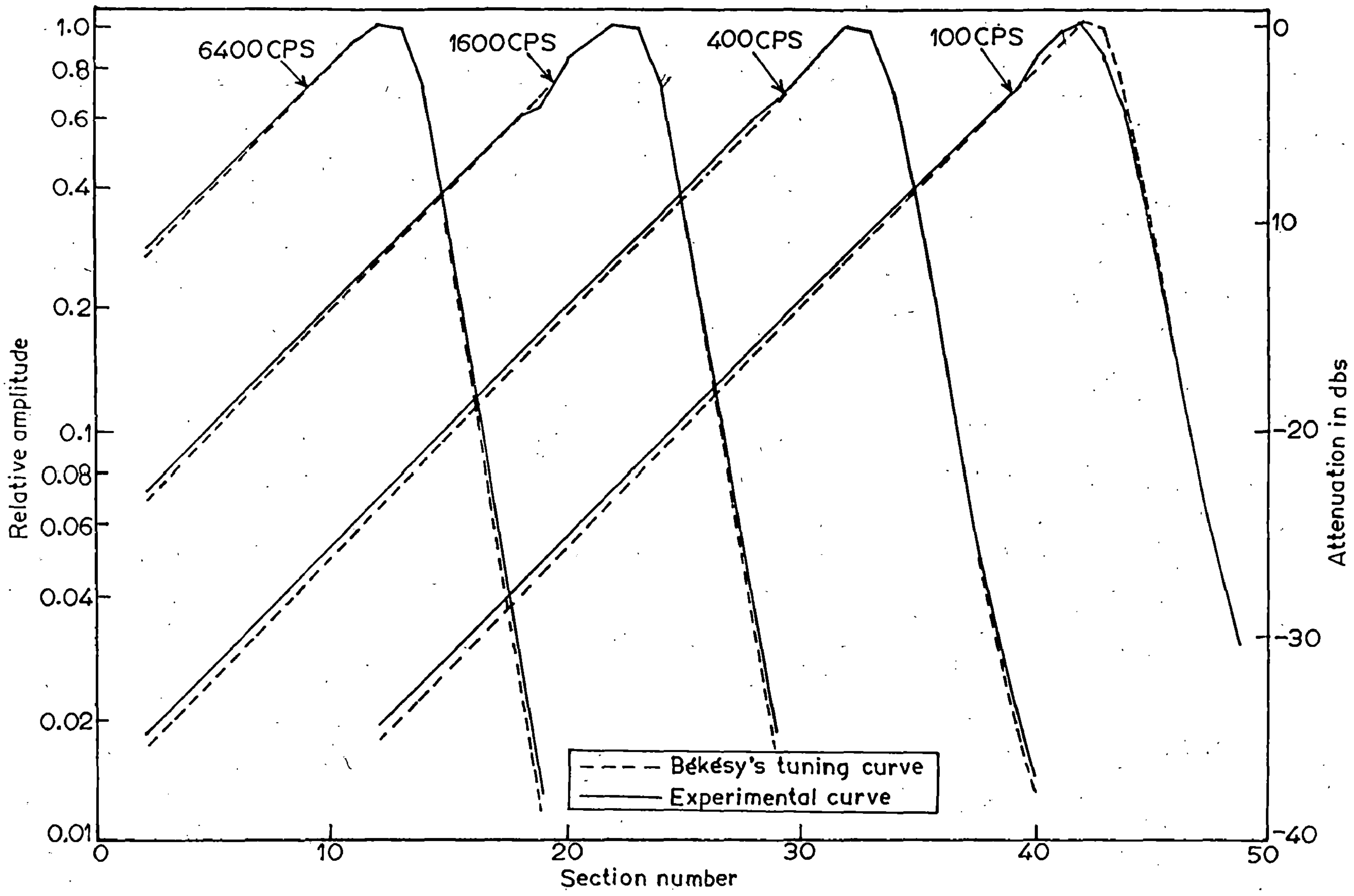


FIG.4.6.1 RESPONSE PLOTS OF NETWORK MODEL OF BASILAR MEMBRANE.

are located which convert the acoustic signal to nerve impulses. Different frequencies cause wave resonances to occur at different locations along the basilar membrane and frequency discrimination occurs by stumulation of receptors in different positions of the membrane. With the underlined as the principle, Dennis H. Klatt and Gordon E. Peterson examined the cochlear selective resonance, postulated by G. Von Békésy, Zwislocki, B. Bogert and H. Fletcher, and combined a group of identical series resonant R-L-C networks each separated by an inductance-to model the typical transmission line behaviour of the cochlear path. The model designed by them is shown in Fig.4.6.0. This electronic circuit was developed to experimentally justify the behaviour of the re-examined transmission line model of the cochlea. The network is a passive ladder network of fifty sections (the ideal number being five hundred for the ideal response of continuous resonance within the audio range). The input (voltage) to this network model is analogous to stapedial displacement and the output is at each parallel branch resistor, which is the voltage corresponding equally to the displacement of a corresponding point along the basilar membrane. Component values were predetermined by a trial and error procedure on a digital computer. The component values were then modified by the experimenters until the voltage transfer functions matched Von Békésy's tuning curve data. The responses to a selected set of input frequencies, for the finally constructed electronic hardware (Fig.4.6.0), are shown in Fig.4.6.1.

Refering to the electrical model of Fig.4.6.0, the inductance L_s is an element determined by the width of the basilar membrane; L_p is determined by the mass per unit length of the membrane; C_p is determined by the stiffness per unit length of the basilar membrane and R_p is determined by the dissipation or loss per unit length of the membrane. The width, mass, stiffness and resistance all are different at the different points of the membrane and therefore the vibrations of the membrane's hair cells and the respective membrane portions are varied for different frequencies. The sound energy dissipated, at each parallel branch resistor (R_p), possesses a single frequency that is carried as a nerve impulse and is perceived as sound at the cortex [4,13,14,20,27].

CHAPTER-V

CLASSIFICATION OF HEARING DEFICIENCES BY AUDIOGRAM

CHAPTER V

CLASSIFICATION OF HEARING DEFICIENCIES BY AUDIOGRAM

5.1.0 Introduction

In addition to the categorizations so far described earlier in Chapter III, several attempts have been made to define the categories of hearing impairment. The most empirical method possessing highest importance and popularity in legal and practical applications classifying and hence identifying hearing impairments, of varying degrees to the most minute diagnostic evidences, is by the audiogram. Bio-medical and bio-engineering experts like I.J. Hirsh, A. Risberg and J. Martony have done outstanding work in describing this major field of classification, while they studied communication for the deaf in the past twenty years, and their contributions are referred to, many times. Until recently, two zero reference standards for audiometry and audiometers were in use. The American Standards Association (ASA) scale applies to much of the data gathered prior to the year 1964, while, the International Organisation for Standardization (ISO) scale has been used with increasing frequency since that date. The ISO scale has been officially adopted by the American National Standards Institute (ANSI, formerly ASA) in the recent years and is now incorporated in the newly manufactured audiometers. To a rough approximation, the ISO threshold sound pressure

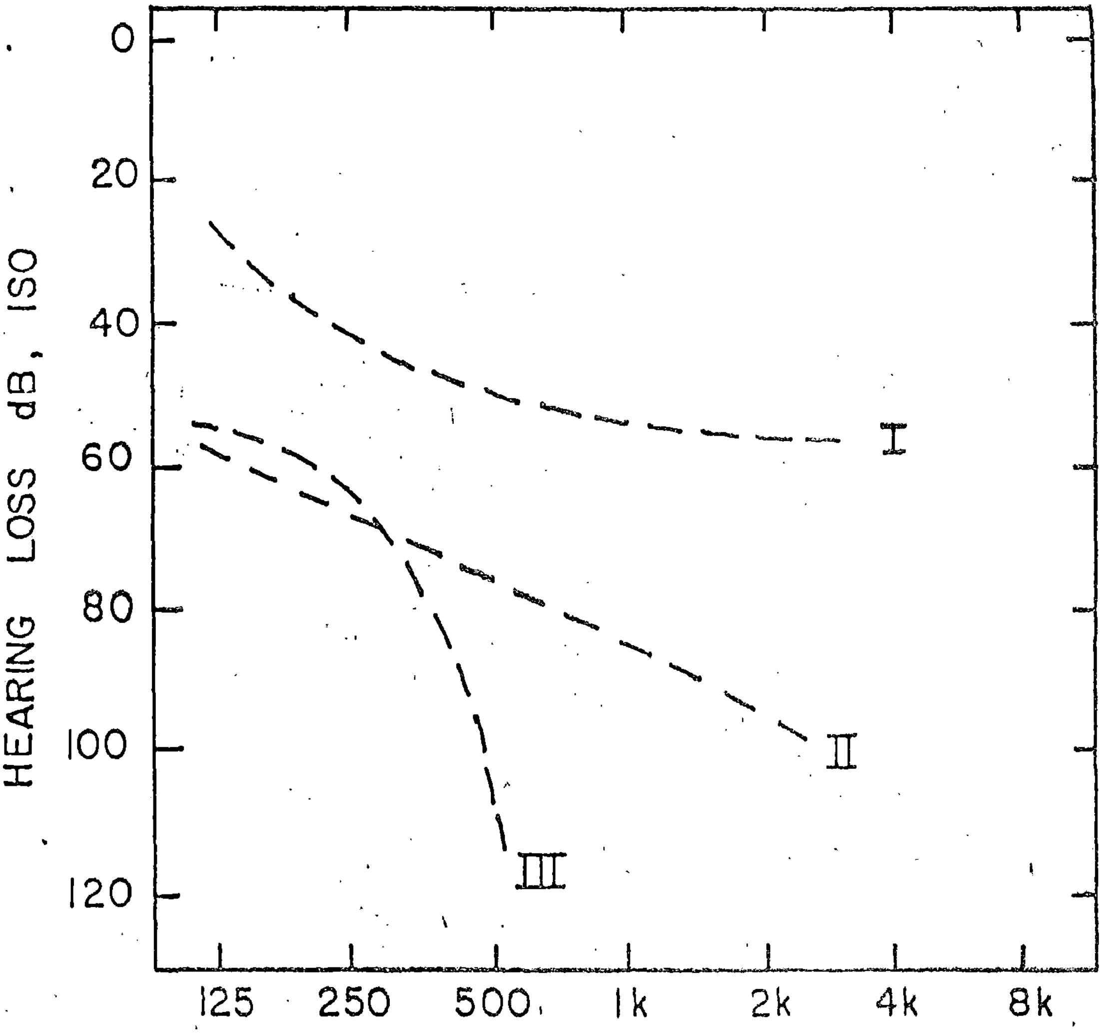


FIG. 5.1.0 SAMPLE DIAGRAMS BY HIRSH FOR THREE GROUPS OF HEARING IMPAIRED CHILDREN.

level is 10 db more sensitive than that on the old ASA scale.

The method of audiogram classification described by Hirsh involves the calculation of the mean hearing level for three pure-tone frequencies, 5000 Hz, 1000 Hz, and 2000 Hz. Three categories are defined. Referring to Fig. 5.1.0, Group I embraces mean hearing levels between 50 db and 60 db (ISO). Group II includes those with mean hearing levels in the range 60 db to 90 db and Group III contains audiograms with mean hearing levels poorer than 90 db. Typical audiograms demonstrating the three classes are shown in the figure. In most practical situations the factor which distinguishes Group II from Group III is the question of whether there is any hearing at all above 1000 Hz. Group III audiograms can sometimes be further subdivided into those that have some high frequency hearing from those that do not.

The method of Risberg and Martony is a modification of the system described by Wedenberg which, takes into consideration the information bearing elements in the acoustic speech signal, the limit between hearing and vibration in the low frequency range, the intensity of the speaker's own voice and finally the threshold of discomfort. Risberg and Martony have examined the relationship between these factors and the audiogram, and have developed the classification boundaries shown in Fig. 5.1.1. The frequency range is divided into two bands, 125 Hz to 1000 Hz and 1500 Hz to 6000 Hz. The low band is divided into five intensity regions and the upper band into six regions. The C region, for

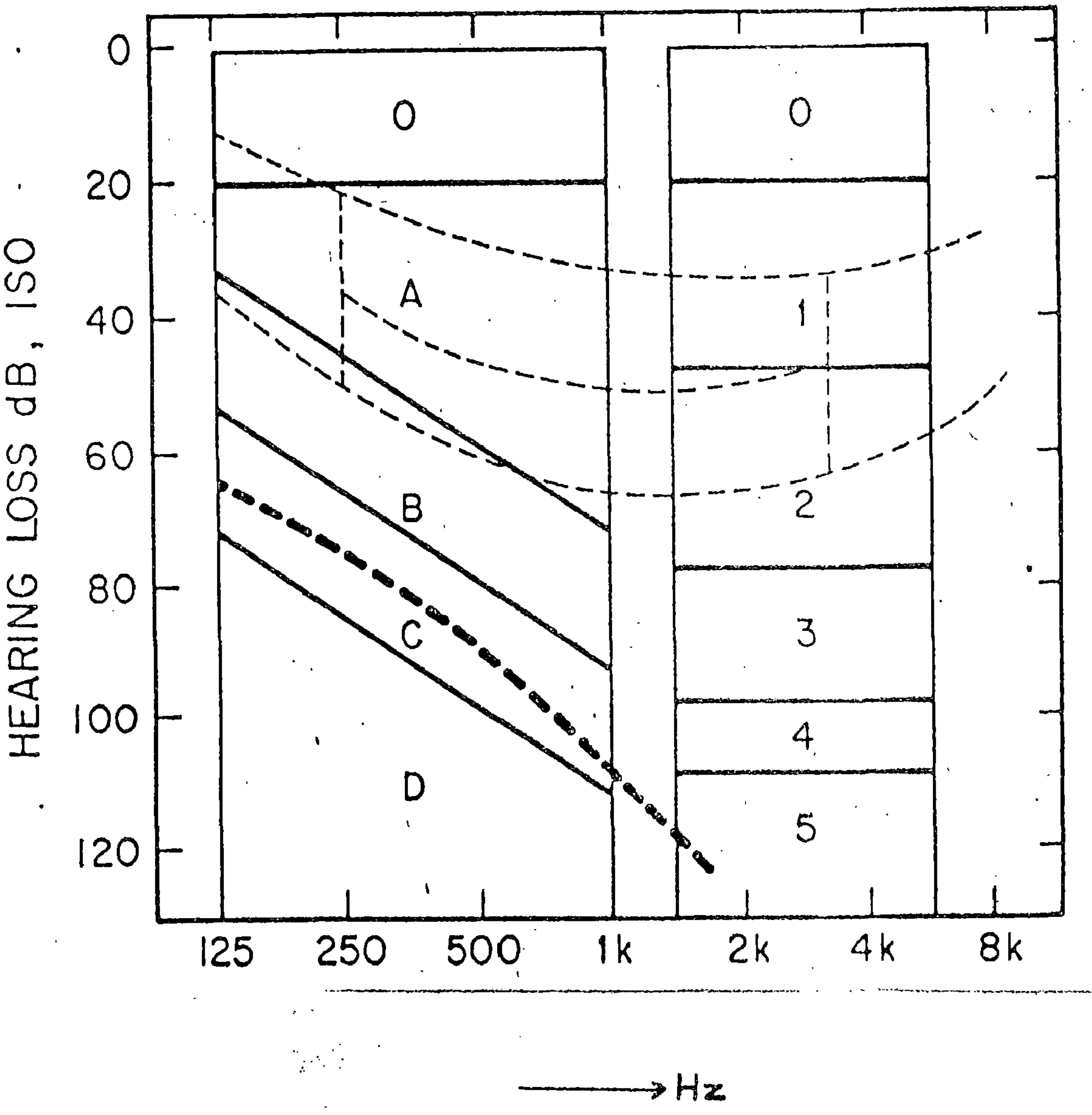


FIG. 5.1.1 An Illustration of the Classifcation System by Risberg & Martony (Heavy dotted line indicates a C5 Audiogram)

example, approaches the limit of hearing. Region B, however, does indicate hearing. A classification B3 indicates that the audiogram is in the region "B" for low frequencies and "3" for high frequencies.

An audiogram helps in evaluation of auditory problems by determination of the type of hearing loss by comparison of airconduction and bone-conduction thresholds. It also, helps in determining the type of rehabilitation needed for an individual suffering from hearing impairment. Hearing test results, particularly those of pure tone audiometry are presented in the form of a graph - the audiogram, thus, defining the graphic representation of hearing as the test results. The term audiogram was first used by Fowler and Wegel (1944). For puretone hearing testing, frequency is expressed in Hertz and intensity in decibel. The American Standards Association recommended in 1974, that frequency be represented by the horizontal line (abscissa) and hearing level by the vertical line (ordinate) of the graph. The digits of the hearing range in the audiogram correspond to the digit ranges given in the intensity dial of the audiometer. The same holds true for frequency also.

Although no standard specifies the frequency and intensity range, an audiogram generally has frequency range of 125 Hz to 8000 Hz at octave intervals and an intensity range of 0 to 100 db which in many cases extends from -10 db to 110 or 120 db, depending upon the audiometer. 0 db on the audiometer dial is not the absolute zero of the sound pressure level, but rather a

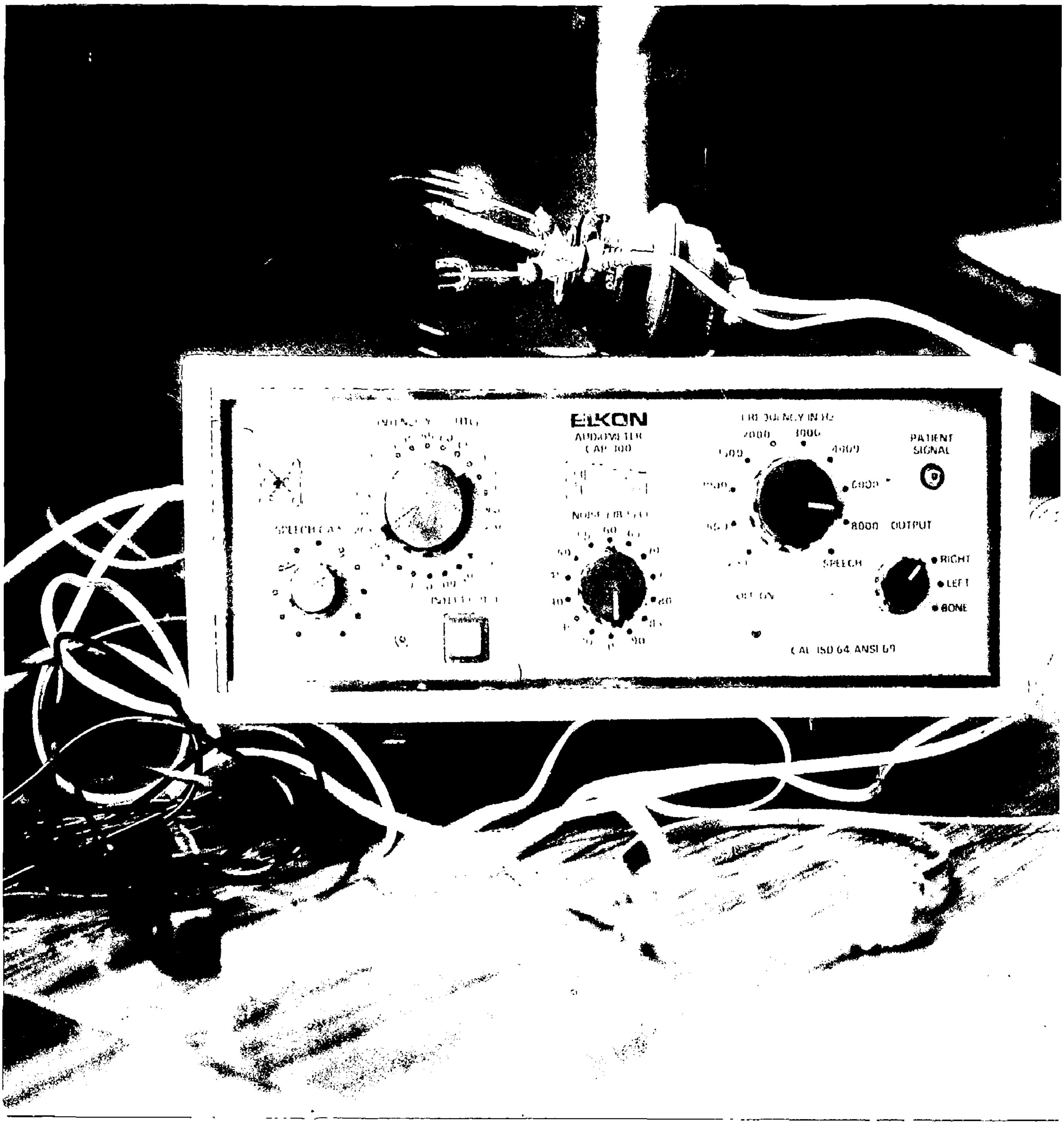

ELKON
AUDIOMETER
CAP 300
FREQUENCY IN Hz
2000
3000
4000
6000
8000
SPEECH
PATIENT
SIGNAL
OUTPUT
RIGHT
LEFT
BONE
OFF ON
CAL ISO 64 ANSI 69

FIG 5.2.0.

reference sound pressure level which represents normal hearing level for normal hearing adults. It is equivalent to 0.0002 degrees/cm^2 for puretones. Thus a line at 0 db HL is some sort of normalizing line which represents normal hearing. The point above this line indicates hearing that is better than the standard norm and point below it indicates hearing. The hearing level of -10 db indicates that the individual who shows threshold of -10 db has the hearing ability which is more sensitive than average [15, 18].

5.2.0 Audiometer Used

In the present work, for experimental and diagnostic purposes, the audiometer that was used, for recording and plotting of audiograms, is a clinical audiometer. It has a provision of turn channel facilities, is intended for pure tone threshold measurements by air and bone conduction, provides the facility of speech audiometry and many complicated tests such as threshold tone decay, shifting voice, Supra Threshold Adaptation Test (STAT), audiometric weber test and etc. etc. Hence, the pure tone audiometer apparently offering the purpose of general diagnosis, actually leads to a comprehensive evaluation of hearing acuity or hearing impairments.

The instrument is designed for use on A.C. supply of 230 volts, 50 Hz. It is not to be connected to DC supply. A safety and slow blow fuse of 500 mA rating is provided on the near panel of the instrument. Referring to Fig. 5.2.0, the power (Mains) ON/OFF switch is located at the right bottom side of the front panel. A red neon glow inside the VU meter is illuminated when the power supply is ON. A warming up period of about a minute is required before the instrument becomes ready to operate. As pointed out in the figure, the frequency control switch is located at the right centre of the front panel and it selects the puretone frequency ranging from 250 Hz to 8 KHz. In its final position it selects speech signal for speech Audiometry. On the left side of the front panel is seen the hearing level alternator. The control knob rotates in clockwise direction to increase the sound intensity. It serves the purpose of measuring the patient's hearing level in decibel referred to ISO zero (0.0002 degrees per cm^2) and is calibrated in increaments of 5 db over the complete range of 0 to 110 db. The readings are common for both Air Conduction (AC) and Bone Conduction (BC) measurements. The maximum intensities available at various frequencies for Air Conduction and Bone Conduction are as follows:

Maximum Intensity for AC and BC

Frequency in Hz	Air Conduction in db	Bone Conduction in db
250	100	25
500	110	60
1000	110	60
1500	110	60
2000	110	60
3000	110	60
4000	110	60
6000	110	
8000	100	

The front panel of the audiometer also contains a Masking Selector Switch below the frequency control. The knob rotates in clockwise direction switching in 10 db steps over the entire masking noise range from 30 db to 90 db SPL. The Masking Selector switches off when masking is not required. When the instrument is used as a speech audiometer the frequency control is shifted to select speech signals. The speech gain control is located at the left corner of the front panel, and is used to adjust the input, of speech, as a live voice through the inbuilt microphone as shown in figure, or as a speech signal from a pre-recorded tape. The VU meter in this case serves as a voice level monitor, and the speech gain is adjusted to deflect the needle to the special mark indicated in the speech level meter.

At the top left end of the panel there is located the interruptor switch marked as INTERRUPTER. This switch has a special significance of locating the pure tone or speech signal momentarily and operates by pushing in for signal present and again pushing in for signal absent. Another significant operator switch is the output switch used as the mode selector. This is the output switch used as the mode selector. This placed at the extreme right end corner of the facing panel. Following are the modes of operation of this selector (in clockwise direction)

(a) Position Right,

Tone/Speech .... To right Ear Phone
Noise .... To left Ear Phone
Bone Conduction .... No signal

(b) Position Left,

Tone/Speech .... To left Ear Phone
Noise .... To right Ear Phone
Bone Conduction ...... No signal

(c) Position Bone,

Tone .... To Bone Conductor Vibrator
Noise .... Left Ear Phone
Right Phone .... No signal

5.2.1 Testing Procedures

While performing different tests with subjects the audiometer is placed in a quiet room, although an 'Audiometer Booth' is preferred. A special apartment is a necessity to provide proper environment conditions for threshold audiometry. An important precaution while using the instrument is that it must be placed so that the subject cannot see the front control panel. Before starting the test the operator explains to the subject about a series of tones that are heard, via the earphones or bone vibrator. From low notes to high notes and that these sounds will be switched on and off, gradually getting quieter. Also, the operation of the press button switch, exclusively provided for the patient, is detailed so that as long as the patient presses the button a small glowing red light display indicates that the patient is hearing the signals. Special attention is given to deaf and dumb children in order to perform the tests giving correct diagnosis.

5.2.2 General Tests

Air Conduction Threshold measurement, Bone Conduction Threshold measurement, Masking Threshold measurement for AC and BC and Speech Threshold measurement are the most common testing procedures performed by ENT specialists all over the world.

5.2.3 Air Conduction Threshold Measurement

The procedure consists of setting the threshold of hearing at the quietest level for different frequencies. The headband fitted by the two earphones at its two ends is adjusted on the patient's head so that the earphones provide a proper seal over the ears and that the ear cushion is correctly positioned to the subject's ear canal. The masking attenuator is set to OFF, the frequency control to 1000 Hz and the hearing level attenuator at an intensity to which the subject is expected to respond (it is usually 60 db). In cases of mild impairment the patient indicates that a tone is heard when the INTERRUPTOR is depressed for one or two seconds. But if there is severe impairment the tone is not heard and the hearing attenuator is switched in 10 db steps until a response is evoked. The hearing level is then reduced in steps of 5 db to recheck the threshold. This entire procedure is repeated for increasing frequency levels upto 8000 Hz and finally the threshold levels for low tones are obtained i.e. at 500 Hz and 250 Hz. Air Conduction Thresholds are recorded for both the left and right ears separately in a graphical form - the audiogram. As a convention dictated by the audiometer literature, the left ear threshold levels are marked by a small 'x' and joined as a complete plot by a solid blue line, and the right ear threshold levels are marked by a 'O' mark all connected by a solid red line. An audiogram is discussed in more details later.

5.2.4 Bone Conduction Threshold Measurement

The bone conductor and headband are placed on the head with the bone conductor resting on the mastoid bone behind the ear to be tested. Before commencing the test of each ear, 250 Hz puretone is applied by pressing the interruptor to lock in position and asking the patient to explore the area behind the ear for the most sensitive point i.e. the position where the pure tone is heard the loudest. A frequency of 250 Hz is chosen because it is easier at low frequencies to judge the correct contact point. For this purpose the hearing loss attenuator control is set to 15 db above the subject's threshold. Once the bone conduction point has been located, the conductor and head band must remain in this position throughout the test on that ear for all frequencies from 250 Hz to 4000 Hz. As a rule, the test is commenced at 1000 Hz and testing performed for higher frequencies in steps first and then the bone conduction thresholds being recorded for 500 Hz and 250 Hz. The audiogram shows the graph in the form of a dashed line. Figures 1 to 20 in Chapter VI, show an audiogramsfor pure tone tests, performed on normal subjects.

5.2.5 Masking Threshold Measurement For AC and BC

In the course of the testing procedures for air conduction threshold recording, described above, if it is found that the difference in air conduction thresholds of the two ears, at any particular frequency exceeds 40 db, or if it is suspected that the response has been evoked from the opposite ear (non-test or N.T. ear), masking is applied to the NT ear and the threshold of the T-ear is rechecked. Masking can be delivered to alternate ears and thus the puretone stimulus is obtained in the ear under test for all positions of the output switch. The same principle of masking the untested ear and keeping the ear under test unoccluded is followed in bone conduction audiometry. For proper masking, the noise intensity is raised by 5 or 10 db, above the threshold of Air Conduction of the T-ear, into the N.T. ear. This is known as the Masking Threshold level and is often used for retesting the B.C. thresholds. Going in the details of B.C. testing, the masking intensity is raised by 10 db above the Masking Threshold Level followed by an increase of 10 db in Bone Conduction Threshold. The noise intensity switch is again rotated for a further 10 db increase and the BC threshold checked again. This procedure is continued until a point is reached at that value of the BC threshold which remains constant with further additional increamental steps of 10 db of masking noise. The value of BC threshold so obtained is its true value.

It is customary to plot the BC threshold on the air conduction audiogram. This points to a very prominent diagnostic feature, required by the Ear Specialist, which is responsible for displaying the actual relationship at the different pure-tone frequencies between BC and AC thresholds, called the air-bone gap. Referring to Figs. 1 to 20, the bone conduction threshold indicates the perceptive hearing loss, and by subtracting the BC Levels from AC levels indicates the loss due to conductive deafness. Hence the tests described so far provide a sufficient data not only for these two types of general and commonly occurring losses but also help to categorize the losses of inner ear and many of the well known ear diseases.

5.2.6 Speech Threshold Measurement (Speech Audiometry)

Speech Audiometry is performed in two stages. One is Speech Audiometry without masking and the other is Speech Audiometry with masking. In the former stage an external microphone is fixed to the audiometer and care is taken that the specialist operator's mouth is 6" to 12" from the microphone. The frequency selector switch is set to speech and the speech gain control adjusted, until the needle of the VU meter fluctuates within the desired-established sector. This is done to set the alternator readings relative to 1000 Hz ISO i.e. 9.0 db above 0.0002 dyne/cm^2. The above procedure is also adopted if a prerecorded signal is used from a tape recorder. For Speech Audiometry without masking, the setting of the output switch is done to the desired position so that the signal is presented to the required ear and the noise signal is turned off. The speech signal is presented from higher level to lower level until the subject's threshold is obtained. In case of live voice audiometry, the operator's voice becomes audible to the subject's normal value when the experiment is conducted in an enclosed, quiet single room. Best results are obtained when an audiometer booth is used, thus separating the operator and the subject acoustically.

Often it becomes necessary to mask the untested (N.T.) ear, by the noise signal, when conducting speech tests. This necessity arises as a result of the fact, that speech is usually conducted across the head about 40 db below the level of the air conducted signal. Therefore, the masking generator is monitored to present the masking noise, to the opposite ear at the required intensities, for speech audiometry.

5.2.7 Special And Rare Features of the Audiometer

Comprehensive evaluation of auditory losses is possible with the help of some rare test procedures conducted by the audiometer, enabling the specialist, operating it, to deduce and detect complicated causes in difficult situations. The principles and procedures of few such examinations, carried out for deaf or/and dumb subjects, are discussed in the paragraphs to follow.

(i) Shifting Voice Test

The principle behind the test is that of transferring the voice from the good ear to the alleged deaf ear in the middle of a question. If the subject answers correctly, the last half of the question delivered to the supposedly deaf ear, must have been heard. It is a simple test for suspected unilateral malingering occurring in a deaf person. The test starts by presenting the speech signal to one of the ears, at a comfortable level, and masking the other alleged deaf ear. The subject is asked split questions, for example, "what is your name and where do you stay?", and switching is done, say at the word "and", from the good ear to the supposedly deaf ear. As the speech is transferred from one ear to the other ear, the masking is reversed. Thus, preventing the subject from hearing the second part of each question by air transmission over the earphone in the admittedly normal ear, which is automatically masked in between the speech signal. If the subject responds to the second half of the question then the first ear is the deaf ear.

(ii) Tone Decay Test

The first clinical test designed to investigate the phenomenon of "relapse" or abnormal auditory adaptation was the Threshold Tone Decay Test developed in 1954 at North Western University and described by Carhart in 1957. He proposed a method of measuring abnormal adaptation, or tone decay, using a standard clinical pure tone audiometer.

Test of tone decay is one of the major tests used to diagnose retrocochlear pathology. The diagnostic significance of this test is mainly at 1 KHz and 2 KHz. There are many modifications or different types of tone decay tests, which differ in stimulus presentation level, instructions given for the test and the criteria for the test to be positive or negative. Three such popularly used tests are discussed in this context.

(a) Threshold Tone Decay Test (TOT)

This test was introduced by Carhart in 1954. As postulated and formulated by him the test starts by instructing the patient to raise his finger as long as he hears the pure tone and drop his finger as soon as he stops hearing the tone. Pure tone at a particular frequency is presented at the subject's conventional threshold level for 60 seconds and immediately the tone intensity is increased in 5 db steps without interruption, keeping a vigilant eye on time. At the end of another 60 seconds the tone is turned off. Next a computation is done to calculate the difference between the initial threshold and the auditary threshold following 60 seconds of stimulation. The computed value gives the amount of threshold shift or, correctly, the amount of tone decay. In this manner, a standard indication of tone decay measurement is obtained in a total testing time of one minute per ear. Interpreting the results Carhart diagnosed, as is diagnosed up to date, that from 0 to 15 db of tone decay for one minute is considered to be normal. Mild to moderate levels of decay, such as 20 to 25 db in 60 seconds, are a frequent observation accounting for the pathology involving the organ of Corti. Positive tone decay is any threshold shift in excess of 30 db during the test period (60 seconds) and it always indicates misfunctioning of cochlear reactions.

(b) Owens Tone Decay Test

In 1964, Owens introduced a further modification of Carhart's Threshold Tone Decay Test by utilizing a rest period between tonal presentations. His test begins 5 db above threshold, if the test tone fades away prior to end of a minute, the subject is given a rest period of 20 seconds followed by presentation, of the tone at the next higher 5 db intensity level. This procedure is continued until the patient hears the tone for a full minute, or until at least four increaments in the intensity have been given. The recovery time of 20 seconds between stimuli was chosen by owens on the basis of Hood's earlier work, charting the recovery from prestimulatory fatigurc in which the most rapid rise occured within 10 seconds and the flattering of the curve began at about 20 seconds. The results of this test are interpreted in the same manner as in Carhart's test.

(c) Supra Threshold Adaptation Test (STAT)

This test was used and given by Jerger in 1975. The procedure of the investigation starts by giving a pure tone of either 1 KHz or 2 KHz at 110 db SPL to the test ear for 60 seconds and masking, simultaneously, the non-test ear by 90 db noise signal. If the subject hears the tone in test ear for 60 seconds, then the test is interpreted as negative, and if he does not hear the tone for 60 seconds the test is positive and suggestive of retrocochbear lesion. This test is the most diagnostically significant of all the tone decay tests. The information obtained by this test indicative of an injury or defect in the cochbea is further utilized in recording of the Eighth Nerve Potential which eventually leads to locating the site of the lesion - a very eminent research work field in recent times, where extensive and intricate investigations are being carried out by scientists and pathologists in many laboratories, hospitals and clinical research workshops to unfold the still underlying mysteries of audition while locating the lesions' sites in the nervesand nuclei which lead from the cochlea up to the brain.

(iii) Audiometric Weber Test

Weber test is a test of lateralization, originally given by Weber in 1834. In his experiments he used tuning forks, but now the test, with the same procedure carried out by him, is performed by using bone conduction vibrator provided with the clinical audiometer. The test is used in diagnosing cases of unilateral hearing loss and is very helpful in differentiating between conductive loss and sensori-neural hearing loss. In this test, the Bone Conduction Vibrator is placed on the midline in the centre of the patient's forehead and pure tone is presented at different frequencies. The patient is instructed to indicate the ear in which he hears, by raising his left hand for left ear and right hand for right ear. The subject is also informed that tone can be heard in the poor ear too.

If the subject responds, at different frequencies, for the poor ear then he or she suffers from the conductive type of hearing loss in that ear. The patient suffers from sensori-neural loss in poor ear, when hearing in the better ear is reported, at variable frequency values [18, 24].

5.3.0 Audiogram Interpretation

An audiogram can be interpreted under the following headings:

Types of hearing loss,
Pattern of hearing loss, and
Degree of hearing loss.

5.3.1 Types of Hearing Loss

The information regarding the types of loss, conductive, mixed or sensorineural type can be obtained from the audiogram by comparing AC and BC thresholds. The gap between AC and BC threshold is termed as air-bone gap which is critical in determining the type of loss.

(a) Conductive Loss

A conductive loss is demonstrated by the presence of hearing loss by AC but normal hearing by BC (Newby, 1972). The existing airbone gap must be atleast 10 db HL. If such a gap exists when both AC and BC thresholds are within normal limits, it is termed as minimal conductive hearing loss. AC loss generally does not exceed 60 db HL (Feldman 1963) because beyond this level, the whole skull vibrates resulting in direct stimulation of the cochlea. Thus if the threshold level exceeds 60 db HL, problem cannot be purely conductive.

(b) Sensori-Neural Hearing Loss

The audiogram shows greater loss for the high frequency with lower frequency being normal or near normal. BC thresholds are approximately same as that of AC thresholds within 10 db airbone gap.

(c) Mixed Hearing Loss

In this type of hearing loss both AC and BC thresholds show poorer hearing than normals. But the loss of BC is not as much as that of AC (O Neil and Oyer, 1970). AC thresholds may be relatively flat or dropping off at high frequencies i.e. with a dropping audiometric configuration.

5.3.2 Pattern of Hearing Loss

There is no standard as such, regarding the pattern of hearing loss. However, various bio-physicists like Carhart (1945), Davis (1978) and Hodgsm (1980) have described different patterns. The following patterns are generally recognized,

(i) High Frequency hearing loss
(ii) Low Frequency hearing loss
(iii) Flat hearing loss
(iv) Through or Soureer shaped hearing loss
(v) Corner Audiogram
(vi) Irregular Audiogram

(i) High Frequency Hearing Loss

High frequency hearing loss is characterized by presence of a slope from low frequency to high frequency with a loss of at least 25 db HL for speech frequency or a total loss of hearing beyond 3000 Hz or both 7Johnson 1966). The slope should be at least 15 db between 500 Hz and 4000 Hz (Anderson). It has been classified into two types, gradual and sharp type.

(a) Gradual Type

In gradual type of high frequency hearing loss, the loss begins at low frequency with a gradual increase in the loss at high frequency. At 500 Hz, a threshold of 25 db HL or greater is recorded and change per octave by 10 db is noted. The difference between the highest and the lowest thresholds is not to be more than 35 db (Stephens and Rintelmann, 1978).

(b) Shapb Type

It is characterized by normal or near normal hearing at low frequency with a threshold of 30 wb HL or better at 500 Hz. Between 500 Hz and 1000 Hz or between 1000 Hz and 2000 Hz, there is a drop in the threshold of at least 20 db. The difference between the lowest and highest thresholds is greater than 40 db (Stephen and Rintelmann, 1978). This pattern is associated with sensori-neural hearing loss, and is known as conductive high tone hearing loss when the problem is purely conductive in nature. Here AC threshold shows high frequency loss, the BC threshold remaining unaffected.

(ii) Low Frequency Hearing Loss

This audiometric pattern shows significant loss at low and mid test frequencies, with relatively normal or near normal hearing in the high frequency region (Ross and Matkur, 1967, Davis Johnson, 1966).

Johnson (1966), defined it as reduced threshold in the low frequency with a rising curve through the speech frequency range into the higher frequency range. Davis (1978) termed the deficiency as rising low frequency hearing loss. The defect is often observed in conductive hearing loss cases and is also sometimes noted in some sensari-neural loss conditions like Meniere's syndrome at its early stage.

(iii) Flat Hearing Loss

In this pattern, there is approximately equal degree of hearing at all test frequencies. The magnitude of the difference does not exceed 5-10 db (Johnson, 1966, Davis 1978). It is frequently associated with conductive hearing loss, such as serious Otitis Media. The pattern is also a diagnostic symptom of collapsed ear canal and moderately advanced condition of Meniere's disease.

(iv) Trough or Saucer Shaped Loss

This pattern is demonstrated by better hearing at low and high frequencies and poorer hearing in mid or speech frequency range. Johnson (1966) has postulated, that when the threshold difference between poorest and best thresholds are large, the andiogram appears as V-shape, and when the difference is small, a saucer shaped audiogram is obtained.

(v) Corner Audiogram

The pattern unmistakeably denotes profound deafness. Corner audiogram is characterized by presence of response to only low frequencies such as 250 Hz or 500 Hz and that too when a very high intensity sound level (usually the maximum) is presented by the audiometer. A testee possessing a corner audiogram does not respond to mid or high frequency sound, even of the highest level. The audiogram symbolises, congenital hearing loss, viral disease and drug induced hearing loss (Davis, 1978, Hodgson, 1980).

(vi) Irregular Loss

When the audiogram does not fit into any of the above categories, the pattern is often termed as irregular loss (Hodgson, 1980). This audiometric pattern yields valuable information when correlated with a certain type of hearing loss. Consideration of only the pattern as an independent factor in diagnosis is usually misleading since exceptional conditions are always present in the intricate methods and diagnostic results of audiological examination (Hodgson, 1980). Hence, the information is, as a rule used as, a supplement to the other diagnostic patterns.

5.3.3 Degree of Hearing Loss

Another useful conclusion dictated by the audiogram is the degree of hearing loss indicating to an extent the difficulty experienced by the individual in communication with the world and people around. The degree of hearing loss is obtained by comparing AC threshold values with the standards established. In the event of the audiometric tests being conducted in a sound treated room, so that the specified maximum ambient noise level declared permissible, by ASA (1951) or ANSI (1977) or ISO, for audiometric testing is met - audiometric zero level is considered, then, as the normal average response of young adults. Although this normal reference has been established, yet individual variations in normal hearing range are permitted by ANSI (1969). Those individuals whose thresholds fall between -10 db to 20 db HL are usually considered to have normal hearing. Therefore hearing level greater than 26 db HL represents hearing loss and its severity is graded depending upon the degree of hearing level threshold. The utility of the audiogram in helping the diagnosis, of the degree, of an impairment is based upon the scale of hearing impairment, which relates hearing threshold level (HTL) with the degree of impairment and also relates HTL in terms of probable handicap and needs of the individual. This scale of reference was prepared by Goodman in 1965 and is used by ISO and ANSI. It is as follows

SCALE OF HEARING IMPAIRMENT

HTL in db	Descriptive Term	Probable Handicap and Needs
10 to 26	Normal limits	--
27 to 40	Mild Hearing Loss	Handicap: Difficulty in hearing faint speech. Needs: Favourable seating arrangement, lip reading and hearing aid.
40 to 55	Moderate Hearing Loss	Handicap: Hearing of conversational speech at a distance of less than 3-5 feet. Needs: Hearing aid, auditory training, lip reading and favourable seating.
55 to 70	Moderately Severe Hearing Loss	Handicap: Understanding speech at normal conversational level specially in group discussion, is difficult. Needs: All those in previous case plus language therapy.
70 to 90	Severe Hearing Loss	Handicap: Lound voices can only be identified within 1 foot: Environmental sounds are heard but distinguishing consonant sounds is difficult.

HTL in db	Descriptive Term	Probable Handicap and Needs
		Need: Special education for deaf, but may enter regular classes later.
90	Profound Hearing Loss	Handicap: Loud sounds may be heard but the suffering individual cannot rely on hearing for communication.

In the above table all the above HTL values are an average of those at 500 Hz, 1000 Hz and 2000 Hz.

The above guideline chart is widely used but it suffers from a serious and noteworthy limitation. It neglects the type of hearing loss which is very crucial in determining rehabilitational needs. Also, these guidelines set up overlooks cases like, an individual may show only mild hearing loss by puretone thresholds but may suffer from complete loss of ability to understand speech of an intensity level: for example in case of presence of a tumour in the cortex in a moderately advanced stage (Davis and Green, 1979). However, an estimate of speech handicap, in cases of this type, is made by considering speech frequencies and their thresholds; although detailed examination using speech audiometry does only present accurate diagnosis.

Degree of hearing loss is often used to categorize the person into deaf or hard of hearing. Those individuals, whose hearing loss is less than 85 db HL, are labelled as hard of hearing; and for those it exceeds 85 db HL are categorized as deaf (Davis, 1978). The patient's need for hearing aid and the requisite power use is determined by considering hearing threshold levels and the pattern of hearing loss. Hearing loss upto a degree of 80 db HL is benefitted by hearing aids. For those with profound hearing loss speech perception may be limited but the hearing aid may help to increase awareness of environmental sounds. Individuals showing flat type of audiometric pattern are better benefitted from amplification of sound signals. Different audiometric patterns, recorded and plotted for a variety of group of individuals with normal hearing or disease and hearing deficiency classification, are shown in Figures 1 to 20 and Figures 39 to 79 in Chap. VI.

The absolute threshold of hearing for a particular sound is the weakest pressure amplitude for which that sound can be reliably detected in a quiet background. If loudspeakers are employed in the tests, the threshold pressure is usually taken as the free-field pressure, that would be measured at the position of the centre of the head in the absence of the listener, this is called the minimum audible field (MAF). If the ear phones are used, the threshold pressure is taken as that at the tympanic membrane (ear drum); and is called the minimum audible pressure (MAP). Pressure at the eardrum is rarely measured directly, but, is inferred from calibration tests of the earphone using a standard coupler to represent the whose hearing loss is less than 85 db HL, are labelled as hard of hearing; and for those it exceeds 85 db HL are categorized as deaf (Davis, 1978). The patient's need for hearing aid and the requisite power use is determined by considering hearing threshold levels and the pattern of hearing loss. Hearing loss upto a degree of 80 db HL is benefitted by hearing aids. For those with profound hearing loss speech perception may be limited but the hearing aid may help to increase awareness of environmental sounds. Individuals showing flat type of audiometric pattern are better benefitted from amplification of sound signals. Different audiometric patterns, recorded and plotted for a variety of group of individuals with normal hearing or disease and hearing deficiency classification, are shown in Figures 1 to 20 and Figures 39 to 79 in Chap. VI.

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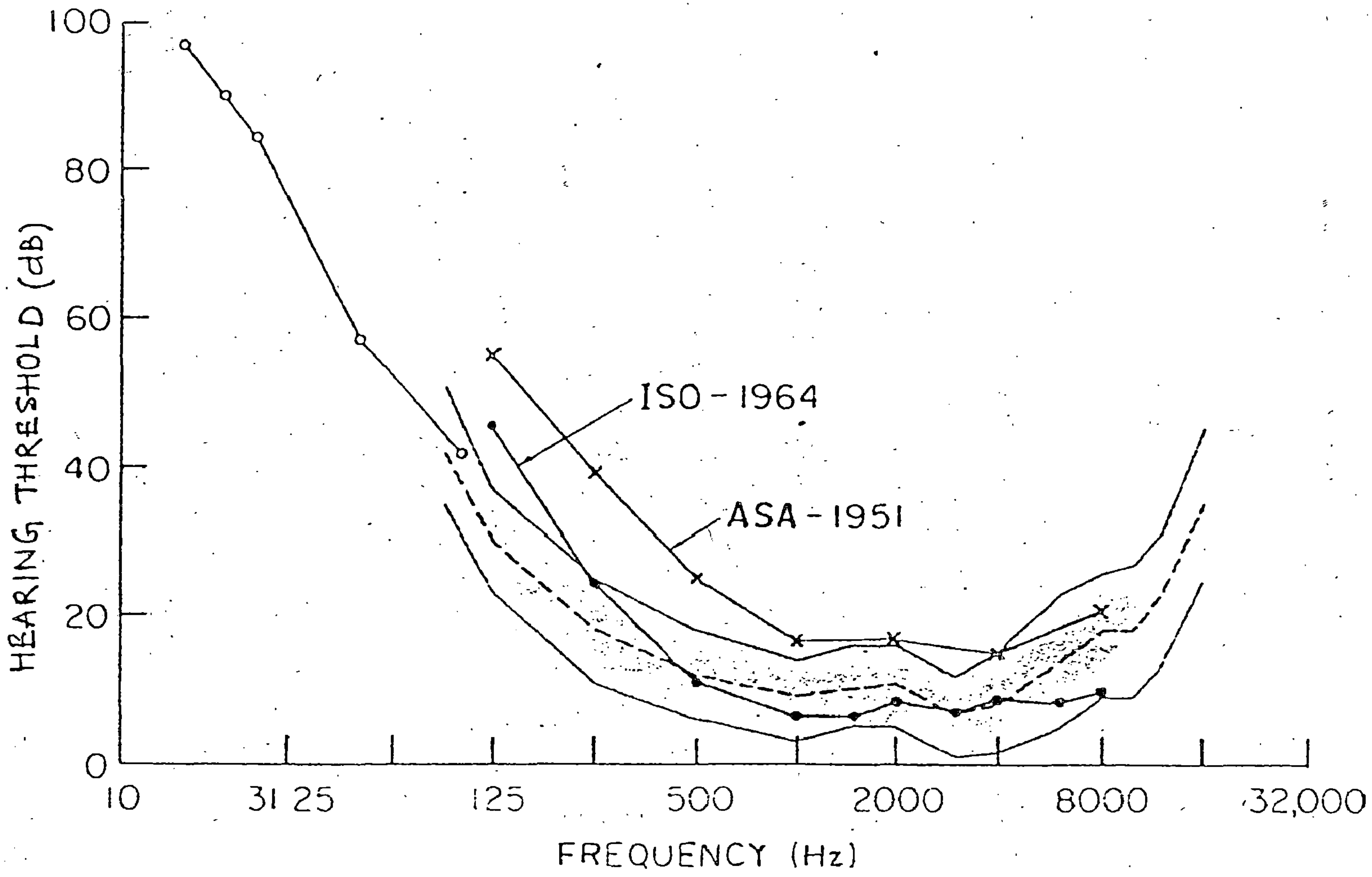

FIG. 5.3.3 Threshold of Hearing (MAP) versus Frequency for Pure Tones. Dashed Curve & Shaded Area show a Typical Series of measurements by Dadson & King.

effects of the ear canal and middle ear. In theory, the threshold pressure at the tympanic membrane should be independent of the sound source. In practice, threshold pressures measured with earphones, seem to be, and are in fact, 6-10 db higher than those measured with an open ear canal. This phenomenal increase in HTL is still partially unexplained. Fig. 5.3.3 shows the International Standard audiometric-zero , adopted in 1964 as the best summary of a number of studies, of the average monaural hearing threshold (MAP), for young listeners and pure sinusoidal tones of long duration. As referred to in the figure and held, otherwise, as a practised convention, the intersubject variability for normal listeners is approximately 10 db. Also, in casual clinical practice lack of listener training, noisy backgrounds, and other factors lead the average normal thresholds to go higher up by 10 db above the ISO - 1964 Standard (as indicated by the ASA - 1951 audiometric zero in the figure). Hearing loss categorization and hence the associated disease classification is reported as the deviation between the measured thresholds (plotted in the patient's audiogram) and the normal standards like depicted in Fig.53.3. Besides this standard as the basis of hearing evaluation, together with the guidelines discussed earlier, the present work follows yet another well known approximation throughout its course. Given sufficient intensity, pure tones can be detected, by the human ear, at extremely low and high frequencies. For example at the extreme frequencies of less than 5 Hz and greater than 100 KHz pure tones are heard by bone conduction. But at these extremes it is quite debatable that whether the sensation can be called hearing and this has been experimentally proved too, though controversial yet encouraging conclusions have been drawn about very low sonic and very high ultrasonic hearing. The nominal range, 20 - 20,000 Hz, has been accepted here, which includes all those frequencies that can be heard at intensities less than approximately 80 db SPL. Also, this is the usually accepted audio-range, since these frequencies are also those that evoke the subjective experience of pitch in normal listeners.

With all the above considerations and clinical-diagnostic regulations as standards, an attempt is being made to evaluate the human hearing ability and predict the electrical modelling parameters, describing the human ear as an electric network system, for different individuals [3, 4, 5, 10, 15, 21, 38].

CHAPTER-VI

EVALUATION OF IMPEDANCE FUNCTION OF HUMAN EAR MODEL AND CLASSIFICATION OF DISEASES

CHAPTER VI

EVALUATION OF IMPEDANCE FUNCTION OF HUMAN EAR MODEL AND CLASSIFICATION OF DISEASES

6.1.0 Introduction

The human body and its operative systems are a very difficult task to analyse and represent as definite physical, mathematical, mechanical and electrical or electronic models. However, since the past few centuries a great many people have pooled their sincere efforts amongst which a few dedicated their entire life span pouring the essence of deep knowledge into the challenging and unraveling mysteries of human mechanisms. Yet, a perfect model or replica of human systems has not been developed or obtained either on paper or in practice. Innumerable techniques have been used to model the exactness of human auditory system, as well, but no model explains the complete behaviour of the ear. Although every model gives us some well-defined and satisfactory conclusions but explaination of all the anatomical facts at the same time is a limitation of every model formulation. If all the models of the human ear are analysed, each arrives at a different solution and the theories forming their bases are, ironically, all tested and proved to sufficient levels of different categories of accuracy. Separate models have been proposed and developed for external, middle and inner ears. Further, each of these models has been again sub-classified for different operative and pre-assumed conditions. The only model that; quite ideally represented the behaviour of its elements, whose combined effect, matching the characteristics of a normal audiogram: could offer a strong resemblance to the standards dictated by ISO - 1964, is the one discussed at present.

To be precise, the response function or in general the describing function of any electrical (or non-electrical) system is a property of the system elements only i.e. the R, L, C elements comprising the electrical analog of Fig. 4.5.2 are the sole factors effecting the network's characteristics. The presentation of the input sound signal at the output of the model is truely dependent on the magnitudes or values of the R, L, C elements. Any change, in any of these units (referring to Fig. 4.5.2) would mean a differing presentation at the output and would thus decide the deviation of the abnormal audiogram from the normal one. Keeping in view the fact that the acoustic impedance offered to sound waves at the ear would be a direct analog of the electrical impedance at the input of the network, the net impedance of the electrical analog is deduced. A slight change in any of R, L, C parameters would directly effect the magnitude of the impedance offered to the input and would immediately affect the response-record i.e. the audiogram.

6.2.0 Evaluation of Input Impedance of the Human Ear Model

The expression for the input impedance of the electrical network (Fig. 4.5.2) of the human ear is deduced as follows:

Let,

$$z_2 = \frac{(1/C_7 s + L_4 s + R_7)\ (1/C_6 s + R_6)}{1/C_6 s + R_6 + 1/C_7 s + L_4 s + R_7} + 1/C_5 s + L_3 s + R_5$$

and,

$$z_1 = 1/C_3 s + \frac{(1/C_4 s + R_4)L_2 s}{1/C_4 s + R_4 + L_2 s} + R_3$$

the combination of z_1, and z_2 being z_3 i.e.,

$$z_3 = z_1 \ || \ z_2 = z_1 z_2/z_1 + z_2$$

$$= \frac{1/C_3 s + \dfrac{(1/C_4 s+R_4)L_2 s}{1/C_4 s+R_4+L_2 s} + R_3 \ \dfrac{(1/C_7 s+L_4 s+R_7)(1/C_6 s+R_6)}{1/C_6 s+R_6+1/C_7 s+L_4 s+R_7+1/C_5 s+L_3 s+R_5}}{1/C_3 s + \dfrac{(1/C_4 s+R_4)L_2 s}{1/C_4 s+R_4+L_2 s} + R_3 + \dfrac{(1/C_7 s+L_4 s+R_7)(1/C_6 s+R_6)}{1/C_6 s+R_6+1/C_7 s+L_4 s+R_7} + 1/C_5 s+L_3 s+R_5}$$

Another combination impedance,

$$z_4 = \frac{(L_1 s + R_1 + 1/C_1 s)R_2\ (1/C_2 s)}{(R_1+L_1 s+1/C_1 s)R_2 + R_2/C_2 s + (L_1 s + R_1 + 1/C_1 s)(1/C_2 s)}$$

The net input impedance offered to sound signal is the combination of z_3 and z_4 :

i.e. $Z = z_3 + z_4$ is the total impedance or the final value of the describing function affecting the response of ear.

Putting $s = j\omega$, where $\omega = 2\pi f$, the simplified expression for z_1 is,

$$z_1 = \frac{1+R_4C_4j\omega-L_2C_4\omega^2-(1+R_4C_4j\omega)L_2C_3\omega^2+R_zj\omega C_3[1+R_4C_4j\omega+L_2C_4(j\omega)^2]}{j\omega C_3[1+R_4C_4j\omega-L_2C_4\omega^2]}$$

After substitution of values of R, L, C components, and simplifying the expression

$$z_1 = \frac{1-\omega^2(1.75 \times 10^{-9}) + j(9.72\omega - 3091.2 \times 10^{-15}\omega^3)}{-\omega^2\, 20.24 \times 10^{-12} + j(0.23 \times 10^{-6}\omega - 1.38 \times 10^{-15}\omega^3}$$

Similarly,

the final values of z_2 and z_4 are:

$$z_2 = \frac{\omega^3 9\times10^{-15}-\omega^2 27\times10^{-8}+j(1.11\times10^{-3}\omega)}{-\omega^2 0.54\times10^{-9}+j[0.25\times10^{-6}\omega-\omega^3 3\times10^{-15}]} + \frac{1-\omega^2 56\times10^{-9}+j0098\times10^{-6}}{j(1.4)\times10^{-6}\omega}$$

and,

$$z_4 = \frac{(100 - 7140 \times 10^{-9}\ \omega^2) + j\ 5.1 \times 10^{-2}\ \omega}{(1-89.4 \times 10^{-9}\ \omega^2) + j\ 10.55 \times 10^{-4}\ \omega}$$

The total impedance Z has been evaluated for different values of frequency with the aid of computer software. The impedance hence obtained, is plotted as a function of frequency in Fig. 4.5.3 . The values of this impedance have been directly calibrated in decibles after point to point comparison with the most precisely recorded normal audiograms and the ISO - 1964 standard audio-threshold plot. For calibration purposes and for the parameter estimation method (used first to evaluate the R, L, C components of the ear-electronic model) the AC audiograms taken, under consideration, differed. Those AC audiometric configurations that were well within the absolute standards of normality, were the sole basis of interchange between the impedance in ohms and the audible/hearing threshold in decibels.

6.3.0 Estimation of the Network Model Parameters for Normal and Defective Ears

In order to estimate the ranges of R's, L's and C's of the model, the slightly deviating audiograms were also counted. Twenty such audiograms of individuals with normal and healthy ear-pairs are shown in Fig. 1 to 20. The minimum audible threshold vs frequency plots or the minimum impedance vs frequency plot now being comparably identical offered the next step and that was of estimating the components of a network if the describing function of that network is known. The describing functions of the electrical-network model of the human ear, the audiograms, were analysed-each in succession by computer program based on Least Square Estimation method, to predict the

R_1 = 100, 110, 310, 170, 106, 205, 170, 142, 150, 150, 185, 180, 205, 211, 211, 242, 250, 249, 257, 230

R_2 = 100, 165, 104, 85, 100, 73, 140, 172, 160, 149, 120, 118, 106, 99, 114, 117, 121, 133, 124, 135

R_3 = 40, 43, 65, 58, 63, 33.3, 85.1, 51.0, 56.0, 61.0, 66.0, 35.8, 53.0, 82.0, 36.0, 41.0, 48.0, 84.0, 72.0, 78.0

R_4 = 209, 220, 323, 248, 235, 485, 256, 190, 327, 202, 310, 328, 356, 259, 231, 226, 288, 291, 273, 280

R_5 = 63, 93, 62, 59, 70, 100, 173, 90, 74, 75, 83, 145, 121, 66, 98, 87, 109, 113, 105, 119

R_6 = 3900, 2454, 2700, 3700, 3000, 2037, 3850, 2656, 2500, 2496, 3300, 3616, 3099, 3151, 2887, 3777, 3790, 2799, 3100, 2557

R_7 = 600, 619, 573, 560, 690, 513, 544, 510, 566, 580, 589, 612, 622, 634, 650, 539, 546, 522, 633, 585

C_1 = 5.1, 4.0, 10.5, 15.5, 7.1, 9.25, 8.24, 5.65, 7.45, 5.44, 13.3, 10.9, 8.88, 11.6, 6.4, 4.67, 9.7, 9.7, 4.0, 4.4

C_2 = 0.58, 0.85, 0.35, 0.55, 0.54, 0.29, 0.70, 0.48, 0.67, 0.50, 0.40, 0.70, 0.39, 0.78, 0.30, 0.85, 0.60, 0.32, 0.46, 0.75

C_3 = 0.23, 0.34, 0.16, 0.18, 0.36, 0.83, 0.50, 0.71, 0.19, 0.77, 0.55, 0.62, 0.17, 0.29, 0.16, 0.25, 0.40, 0.47, 0.58, 0.79

C_4 = 0.40, 0.53, 0.44, 0.13, 1.80, 0.33, 0.25, 1.50, 0.18, 0.22, 0.25, 0.76, 0.80, 0.84, 1.00, 0.87, 0.94, 0.38, 0.60, 1.40

C_5 = 1.40, 0.06, 0.91, 0.09, 0.10, 1.95, 1.00, 2.00, 0.14, 0.66, 0.88, 0.94, 0.99, 1.33, 1.50, 1.71, 1.15, 1.78, 0.68, 0.78

C_6 = 0.23, 0.47, 0.25, 0.18, 0.40, 0.51, 0.08, 0.42, 0.33, 0.28, 0.19, 0.12, 0.10, 0.09, 0.15, 0.37, 0.42, 0.50, 0.06, 0.44

C_7 = 0.60, 0.30, 1.15, 1.60, 2.10, 0.47, 0.13, 0.09, 0.12, 0.89, 0.25, 0.49, 0.35, 0.55, 1.20, 1.35, 1.40, 1.47, 0.66, 0.84

L_1 = 19.5, 17.2, 13.7, 15.9, 64.2, 14.0, 38.2, 41.0, 44.5, 53.0, 14.7, 16.7, 21.0, 27.0, 33.0, 30,0, 18.5, 15.0, 60.0, 58.5

L_2 = 14.0, 15.0, 18.7, 8.80, 18.0, 21.0, 24.0, 13.5, 9.40, 12.8, 9.90, 13.5, 19.3, 14.6, 19.0, 21.8, 23.4, 9.00, 16.6, 17.7

L_3 = 15.0, 52.0, 40.0, 12.0, 29.9, 50.0, 55,0, 34.4, 14.5, 17.2, 18.0, 24.4, 47.0, 44.3, 36.0, 39.2, 49.7, 53.3, 55.0, 50.0

L_4 = 20.0, 11.6, 9.20, 14.0, 12.5, 18.9, 13.3, 10.3, 13.7, 14.5, 14.9, 15.5, 16.0, 19.0, 20,0, 16.4, 11.9, 12.7, 19.7, 17.3

ogram
er : 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Fig. 6.3.0 Table I: Estimated Values of Resistances in ohms, Capacitances in µF, Inductances in mH for 20 Normal Ears.

The Gaussian Density Function of Probability, say, p(x) is,

$$p(x) = \frac{1}{\sqrt{2\pi}} e^{-(x - \bar{x})^2/2\ \ ^2}$$

where, x = variable data, $\bar{x}$ = mean value of data, = standard deviation = $[(\bar{x^2}) - (\dot{x})^2]^{1/2}$

Parameter from Table I	Mean Value ($\bar{x}$)	$(\bar{x})^2$	$(\bar{x^2})$	Variance(^{2})	Standard Deviation ( )	Range of Parameter from p(x) curves
R_1	191.65	36729.722	40714.749	3985.0	63.0	128 - 255 ohm
R_2	121.75	14823.0	15477.85	654.85	25.59	96 - 148 ohm
R_3	57.56	33.13.5	3579.9	266.43	16.23	41 - 47 ohm
R_4	276.8	76631.8	80996.1	4364.3	66.0	210 - 342 ohm
R_5	95.25	9072.56	9894.65	822.09	28.0	67 - 123 ohm
R_6	3068.0	9415385.0	9708182.1	292797.15	541.11	2530-3600 ohm
R_7	584.0	341465.0	343699.55	2234.55	47.3	536.5-631 ohm
C_1	0.553	0.3056431	0.3367764	0.0311333	0.1764	4.9 -11.25 /uF
C_2	8.0875	65.4076	75.405285	9.997	3.1619	0.37-0.73 /uF
C_3	0.4277	0.1829272	0.2329373	0.05	0.22363	0.20-0.65 /uF
C_4	0.681	0.463761	0.67421	0.210499	0.4587	0.22-1.13 /uF
C_5	0.9495	0.9015502	1.294795	0.3932	0.627	0.32-1.57 /uF
C_6	0.2795	0.0781202	0.100525	0.0224048	0.14968	0.13-0.43 /uF
C_7	0.80075	0.6412005	0.9407962	0.2995957	0.54735	0.25-1.35 /uF
L_1	30.779	947.347	1230.3224	282.97543	16.822	14.0-48.0 mH
L_2	16.009	256.28	277.5113	21.2313	4.6077	11.4-20.6 mH
L_3	36.85	1358.1068	1577.43	219.3226	14.809	22.0-51.6 mH
L_4	15.0715	227.15011	237.35208	10.201965	3.19405	11.85-18.25 mH

Fig. 6.3.1 Table II : Evaluation of the Ranges of Network Model Parameters by Theory of Probability Density Function.

magnitude of R's, L's and C's of the model. The table showing the estimated values of the eighteen components of the model, for the twenty normal audiograms (mentioned earlier) is given in Fig. 6.3.0. This table comprises of those values of resistances, capacitances and inductances that constitute the respective audiometric configurations listed at the lower part of the table.

Now the question arises, as, how would the ranges of these parameters be fixed. Only after a definite range was awarded to each element of the model could the normal deviation, allowable, be defined. Therefore, the theory of Gaussian Density Function of Probability was applied (Appendix I). Gaussian density functions were plotted for each set of data (Table I, Fig. 6.3.0) and from these curves (of probability), shown in Fig. 21 to 38, the deviation of each parameter within the specific range was determined. The mean values, standard deviations, variances and the final ranges obtained are listed in table II, Fig. 6.3.1. Any value falling outside the range of the respective parameter was thus rendered as the abnormal value.

At this stage, the scale of normal parameter was now available so that the parameters estimated for audiograms of hearing impaired individuals could be singled out.

Audiograms for forty hearing impaired individuals (composed of children and grown-ups, girls and boys) recorded

Parameter of Network Model	TYPES OF HEARING IMPAIRMENTS														
	Hard of Hearing			Ossicular Discontinuity, Mild Conduction Loss			Severe Conduction Deafness/Loss						Menier's Disease + Mixed Loss		
R_1	286	303	315.8	392.0	314.99	300.19	365.5	697.70	722.0	650.0	655.0	700.0	630.0	726.5	500
R_2	199.9	254	210.0	233.0	310.10	299.0	314.0	500.0	486.0	472.0	472.0	530.5	490.0	550.0	299.0
R_3	33.74	39.0	35.34	38.8	23.33	21.4	30.56	66.06	75.0	88.0	87.0	80.0	71.25	92.56	46.8
R_4	242	172	195.0	205.5	165.0	170.0	156.0	195.69	386.07	400.0	404.0	310.0	200.0	446.0	200.11
R_5	96.69	117.5	83.5	132.0	125.0	129.0	129.09	656.86	699.4	701.0	700.0	723.0	606.0	786.0	176.0
R_6	2600	2956	3056.6	2550	2538	2546.36	2532.5	3803.34	3820.0	3700	3923.0	3605	3608	3600.0	3100.0
R_7	540.8	622	599.0	546.46	560.0	600.0	621.0	550.0	566.0	550.0	560.0	540.0	540.0	600.0	512.3
C_1	18.0	11.85	19.70	12.05	33.33	17.25	29.05	14.24	16.40	15.5	16.0	14.70	16.0	17.33	10.00
C_2	1.7	0.87	1.00	0.88	2.00	1.22	1.0	3.09	2.89	3.0	3.10	2.00	3.0	3.558	0.5
C_3	0.2	0.41	0.33	1.05	0.19	0.19	0.29	0.32	0.45	0.70	0.70	0.57	0.57	0.70	0.19
C_4	0.11	0.20	0.185	1.89	1.5	0.4	0.56	0.22	1.25	0.89	0.88	1.85	1.80	1.75	1.00
C_5	0.38	1.00	1.00	1.69	1.584	1.715	1.738	2.22	3.18	2.70	2.82	2.00	3.00	5.765	0.33
C_6	0.22	0.38	0.34	0.18	0.15	0.159	0.1755	0.06	0.75	0.48	0.48	0.15	0.23	0.09	0.15
C_7	0.26	0.39	0.92	0.36	0.817	0.722	0.50	0.217	0.195	0.210	0.210	0.186	0.20	0.90	0.35
L_1	49.66	51.0	58.08	83.11	86.00	73.0	75.42	89.00	73.0	66.65	66.0	83.62	91.0	95.0	30.0
L_2	21.24	29.78	21.165	23.0	32.15	39.09	25.4	20.65	28.09	26.4	36.0	31.29	50.4	62.45	20.55
L_3	45.0	51.0	51.5	61.11	57.00	55.00	59.11	200.0	178.0	150.0	155.0	105.0	240.0	277.32	50.0
L_4	12.0	12.20	13.07	14.14	14.25	15.00	15.86	17.5	16.0	18.0	18.27	17.65	18.0	5.26	15.06
AUDIOGRAM NUMBER	50	61	67	56	59	62	41	63	64	65	66	68	55	48	49

Fig. 6.3.1 (i) Estimated Values of Resistances in ohm, Capacitances in μF, Inductances in mH for Hearing Impaired.

Parameter of Network Model	TYPES OF HEARING IMPAIRMENTS										
	Mixed Hearing Loss			Neural Loss of Hearing							Advanced Stage of Meniere's Disease
R_1	746.0	754.5	344.60	952.17	870.0	900.0	941.02	841.0	1050.60	952.17	892.0
R_2	572.46	572.0	317.25	697.07	612.39	630.55	632.85	632.85	756.00	697.07	623.44
R_3	86.07	89.00	20.10	109.0	115.00	117.39	112.04	112.5	133.33	1109.0	110.00
R_4	428.77	429.0	200.0	469.10	430.90	450.62	460.03	460.00	486.90	169.10	424.9
R_5	795.55	800.0	615.0	912.97	920.60	923.0	912.22	912.22	989.70	912.97	918.21
R_6	3200.0	3100.85	300.0	4566.07	4500.0	4588.6	4566.07	4544.4	4022.10	4566.07	4489.60
R_7	587.5	570.0	590.0	542.26	722.22	750.20	748.58	742.40	815.04	742.26	716.24
C_1	19.98	19.99	10.27	25.30	25.00	23.05	25.00	25.67	86.78	25.29	26.06
C_2	4.55	5.0	2.80	71.05	70.0	68.08	71.00	71.55	103.40	71.00	66.18
C_3	0.50	0.50	0.195	0.795	0.700	0.700	0.805	0.800	0.668	0.795	0.68
C_4	1.25	1.20	0.55	2.09	2.13	2.00	2.05	2.00	1.86	2.08	1.98
C_5	5.998	6.05	4.88	8.95	8.60	8.50	8.87	8.70	15.25	8.95	8.24
C_6	0.11	0.12	0.66	1.55	1.00	1.50	1.50	1.09	1.00	1.53	1.00
C_7	0.20	0.25	1.55	1.972	1.56	1.86	1.903	1.85	2.76	1.97	1.58
L_1	100.0	100.0	86.0	209.0	200.0	200.0	200.0	202.00	293.0	209.0	236.66
L_2	35.0	30.50	30.0	105.26	88.88	92.00	100.0	102.69	90.02	105.26	85.80
L_3	277.0	275.0	205.5	350.19	301.00	336.9	346.27	344.0	479.10	350.2	300.00
L_4	12.20	12.00	18.22	18.75	17.90	18.59	18.59	18.236	17.90	18.75	0.30
AUDIOGRAM NUMBER	47	57	42	39	40	43	44	45	52	53	54

Fig. 6.3.1 (ii) Estimated Values of Resistances in ohm, Capacitances in μF, Inductances in mH for Hearing Impaired.

Parameter of Network Model	TYPES OF HEARING IMPAIRMENTS													
	Complete Nerve Deafness / Total Loss of Hearing												Profound Mixed Hearing Loss	
R_1	1110.0	1110.0	1108.0	1110.0	1110.0	1110.0	1110.0	1110.0	1110.0	1110.0	1110.0	1110.0	760.09	760.09
R_2	819.20	819.20	834.85	819.20	819.20	819.20	819.20	819.20	819.20	819.20	819.20	819.20	550.0	800.0
R_3	129.99	129.99	143.20	129.99	129.99	129.99	129.99	129.99	129.99	129.99	129.99	129.99	91.00	108.00
R_4	579.50	579.50	526.60	579.50	579.50	579.50	579.50	579.50	579.50	579.50	579.50	579.50	400.20	511.00
R_5	1775.35	1775.35	1030.0	1775.35	1775.35	1775.35	1775.35	1775.35	1775.35	1775.35	1775.35	1775.35	190.27	1000.0
R_6	4000.00	4000.00	4200.15	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	3996.0	4186.0
R_7	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	1988.50	639.75	740.0
C_1	168.30	168.30	103.236	168.30	168.30	168.30	168.30	168.30	168.30	168.30	168.3	168.3	23.44	5.50
C_2	209.0	209.0	144.40	209.0	209.0	209.0	209.0	209.0	209.0	209.0	209.0	209.0	8.99	76.69
C_3	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.99	0.99	0.99	0.99	0.99	0.725	0.35
C_4	3.55	3.55	2.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	1.90	1.67
C_5	16.55	16.55	18.00	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	10.00	12.25
C_6	1.33	1.33	1.20	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	0.199	1.00
C_7	5.05	5.05	4.57	5.05	5.05	5.05	5.05	5.05	5.05	5.05	5.05	5.05	0.45	2.55
L_1	324.62	324.62	324.62	324.62	400.66	400.66	400.66	400.66	400.66	400.66	400.66	400.66	121.36	166.80
L_2	90.00	90.00	90.00	90.00	113.47	113.47	113.47	113.47	113.47	113.47	113.47	113.47	39.65	79.08
L_3	582.40	582.40	502.20	502.20	582.40	582.40	582.40	582.40	582.40	582.40	582.40	582.40	296.0	419.0
L_4	128.37	128.37	17.99	17.99	128.37	128.37	128.37	128.37	128.37	128.37	128.37	128.37	12.86	18.00
AUDIOGRAM NUMBER	69	70	46	71	72	51	73	74	75	76	77	78/79	58	60

Fig. 6.3.1 (iii) Estimated Values of Resistances in ohm, Capacitances in μF, Inductances in mH for Hearing Impaired.

by the clinical audiometer MODEL CAP-300, were the next to be analysed by the parameter estimation technique of computer software. The relevant theory on which the employed computer program is formulated is given in Appendix II. Magnitudes of resistances, inductances and capacitances thus obtained, are given in the form of a tabular-chart in Fig. 6.3.2. The respective audiogram numbers are also listed in the chart. The underlined parameter values are those that fall out of the respective normal parameter's range (Fig. 6.3.1). This chart also groups the elements responsible for the same deficiency in hearing ability. The audiograms of the hearing impaired are shown in figures 39 to 79, with, the clinical diagnosis of each individual prescribed on the respective audiogram [12, 28].

6.4.0 Hearing Deficiency Classification by Electrical Modelling of the Human Ear

Prior to the classification of hearing deficiencies and their justification on the basis of, respectively, effected electrical parametersω it appears necessary that the design of the electrical network depicting the human ear, be described on the basis of the anatomy and physiology of the ear. Each element/parameter of the network be it a resistance, capacitance or an inductance, posseses a specific reason and relevance regarding its placement - referred to the performance of the ear. All the eighteen elements constituting the net impedance of the ear, offered to the sound signals, are explained therefore one by one - with direct reference to **Figs.** 4.5.1 and 4.5.2.

All the resistances signify the equivalent acoustic resistance, the capacitances depict the acoustic compliance and the inductances account for the acoustic inertance. The inductance L_1, resistances R_1 and R_2 and capacitances C_1 and C_2 constitute the parameters analogous to the three middle ear cavities. The thin passage or gap, through which sound signals travel, between the tympanic cavity and the other two cavities (the epitympanium above the tympanic cavity and the temporal bone cavity composed of pneumatic cells) offers a certain amount of acoustic inertance to the signal of sound, and is therefore represented by L_1 in the model. This narrow path is also dictated to posses acoustic resistance and in the model the resistance is symbolized by R_1, in series with L_1. The pneumatic cells of the temporal bone hold a specific amount of air creating an acoustic compliance, denoted by C_1 in the network. In parallel with the series combination of L_1, R_1 and C_1 we have R_2 and C_2. The resistance R_2 depicts the dissipation of sound signal along the cavities and the Eustachian tube; and the capacitance C_2 stands for the total volume of air in the middle ear portion around the region of ossicles, which causes the related acoustic compliance. Next to the block of middle ear cavities is the block of losses due to the ear drum (Fig. 4.5.1) . The portion of the tympanium not in direct contact with the ossicular chain causes an effective and noticeable impedance to restrict a certain amount of sound energy impinging on its walls. This is the impedance constituted by C_4, R_4, L_2, C_3 and R_3 of the electrical model, where C_4, R_4 and L_2 form one parallel resonant circuit in series with C_3 and R_3 on its two opposite ends. The impedance offered by this configuration of parameters accounts for the three main factors. Firstly at low frequencies resistance and capacitance are operative i.e. R_4 and C_4, secondly at high frequencies since the mass of the tympanium comes into play, the acoustic inertance is accounted by L_2, and thirdly at much above range of audio frequency the eardrum does not vibrate as a whole but moves in sections - therefore the inclusion of C_3 and R_3. These facts were tested and proved by scientists like Zwislocki, Moller and Onchi by performing experiments on real ears - while correlating the anatomical facts with the analogous electrical network formulations.

The block that appears third, is the one comprising of a fraction of ear drum coupled directly to the ossicular chain constituted by malleus, incus and stapes. Since the part of tympanium under study here moves exactly with the same amplitude and phase as malleus and incus i.e. transferring its vibrations without loss and any delay to the malleal-incus complex, the next group of parameters C_5, L_3 and R_5 is responsible for the tympanium and these malleal structures only. This block excludes the incus and stapes joint and therefore obviously the stapes because, where on one hand the coupling of the tympanium (only a portion of it), malleus and incus is very rigid and results in no substantial loss of sound energy; there on the other hand the incudostapedial coupling is not that rigid. This flexibility or looseness in coupling between incus and stapes is the major cause of energy loss in the transmission of sound via the ossicular chain and hence this lossy joint is given a separate block representation in the model. The incudo-stapedial joint has a very small area of cross-section. The bone of which the ossicles are made is known to have a composition, differing from that of the ordinary bones of the skeleton, which renders a specific elasticity to the ossicles, so that a relevant acoustic performance is maintained. During the transmission of sound energy through the ossicular chain, the tiny cross-sectional area of the incudo-stapedial joint undergoes a significant amount of applied forceful stress that causes deformation in this joint of high degree of elasticity. Results of deformation and flexibility enabled Zwislocki to represent this joint, governed by elastic and frictional forces, by a capacitance C_6 and resistance R_6 in the electrical model. The third ossicular bone structure is the stapes that vibrates in and out at the oval window to faithfully transmit all the sound energy it has received to the inner ear's cochlea. Therefore in the block diagram representation the stapes and cochlea are shown directly coupled. The element C_7 represents the compliance of the stapes and cochlea, resistance R_7 represents the resistance due to stapes and cochlea and the inductance L_4 is the inertance of stapes and cochlea. This series resonant circuit offering the cochlear impedance mainly, is the final addition in the net input impedance of the ear, arrived at so far.

All the eighteen parameters building the electrical model of the human ear were given the magnitudes, as shown in Figure 4.5.2, by experiments and detailed research regarding the anatomy, functioning, study of input impedance of the human ear and acoustic electrical correlation between physical and electrical modelling. The network model under discussion is the result of such persistant efforts by A.R. Mollar, J.Y. Morton, Y. Onchi and J.J. Zwislocki.

In the present work, the network is further examined and proved to be one, representing a normal human ear. With the aid of this model a strict analogy was found between the behaviour of its input impedance and the standards of a normal ear's audiogram.

As already mentioned in preceding sections, any set of R, L, C parameters, different from, the ones falling in the normal ranges (table I) would represent an altogether different individual's ear - model, with some hearing impairement(s). Referring this conclusion to the chart in Fig. 6.3.1 it is observed that a particular hearing disability is associated with changes in values of a certain group of circuit parameters. What has been clinically diagnosed by studying the audiogram has been, to quite an extent, proved by the parameters' estimation of the electrical model.

In the tabular classification (Fig. 6.3.1) it can be observed that audiograms classified under hardness of hearing show, deviation (in excess) of the R, L, C parameters comprising mainly the tympanium and middle ear cavities. The parameters representing the other parts of the ear, i.e. the ossicles and cochlea, fall within the respective standard deviations. Therefore, hardness in hearing is due to mainly tympanic membrane losses which may be due to rupture or some sort of damage in the ear-drum. Puncturing of the ear drum results usually in blood flow in and out of the ear or sometimes delay in diagnosis may cause pus-formation -- thereby blocking the ear cavities to some extents. The result is, abnormality also in the parameters of block one (Fig. 4.5.1).

The audiograms numbered 56, 59, 62 and 41 show ossicular discontinuity and streaks of conductive loss. Meaning thereby, there is certainly defective transmission of sound via the ear drum, middle ear cavities and the ossicular chain. Referring to the diseases of outer and middle ear in Chapter III, it is concluded that either a few or one of them is the cause of these deficiencies. The parameters of the model that cross out the respective scales of normalcy are: L_1, R_1, C_1, R_2, C_2, C_3, L_2, R_3, C_4, R_4, C_5, L_3 and R_5, as is underlined in the chart of fig. 6.3.1. It is also clear from the values of R_6, C_6 parameters that their magnitudes just graze the inside limit, whereas the magnitudes of C_5, L_3 and R_5 are just falling outside their normal limits. This is perhaps an indication of the fact that ossicular discontinuity is not a major defect but certainly accompanies conductive problems. Many persons with this type of mild loss, apparently appear suffering from only hardness in hearing when the acoustic environment is favourable.

Severe conductive deafness is completely manageable with the aid of all modern methods and appliances now-a-days except in cases of very severe chronic or hereditary diseases. This loss is also associated with the outer and middle ear parts but the evaluated parameters' table shows a slight discrepancy - bringing into limelight the values of C_7, L_4 and R_7. The magnitude of C_7 in all cases falls out near the limits and the values of L_4 and R_7 appear, just at the threshold. Magnitudes of parameters of middle ear cavities, malleus and incus fall at a fairly large deviation from the thresholds and also those of the elements representing the ear drum and incudo-stapedial joint have a noticeable deviation as observed in the parameters' table, fig. 6.3.1.

The impairment of mixed hearing loss differs from that of severe conduction loss, by the fact that in case of the former, the B.C. audiogram is quite equally defective like the AC audiogram, and in case of the latter, the AC audiogram thresholds are much more in magnitude than the BC counterparts. Although the AC audiogram is poorer in both the cases, the diagnosis in some cases becomes difficult to arrive at. Audiograms numbered 47, 57, and 42 show the deficiency of mixed hearing loss and looking at the parameters--distortions are observed everywhere except in those depicting the incudo stapedial joint and the cochlear complex. The values of R_6 and R_7 remain totally within the normal range, whereas those of C_6 just fall out near the thresholds. The values of C_7 for audiogram 47 and 42 just appear at the limits of C_7 but those of L_4 are absolutely within. C_1, C_3, C_4 at one instant have a normal value and at the other, a fairly deviated one beyond the normal. L_2 and L_3 appear as normal and abnormal parameters respectively. The profound mixed hearing loss is a very poor stage of mixed hearing loss. From the chart classification it shows that the cochlear impedance - R_7 is noticeably effected. L_4 remains normal and the elements C_3, C_6 and C_7 have controversial magnitudes. Justification of the values of these three capacitances cannot be done properly as to whether they should be near normal, normal or within 3σ because only two audiograms appear insufficient for such debatable issues. But one factor is certain that cochlear impedances are effected in cases of profound mixed hearing loss. Also, the elements R_1, R_2, R_3, R_4, R_5 and R_6, C_1, C_2, C_4, C_5, L_1, L_2, L_3, all possess values nearly three times (or slightly or much more) their standard deviations limits. The diseases causing the mixed hearing impairment have been already discussed in Chapter III.

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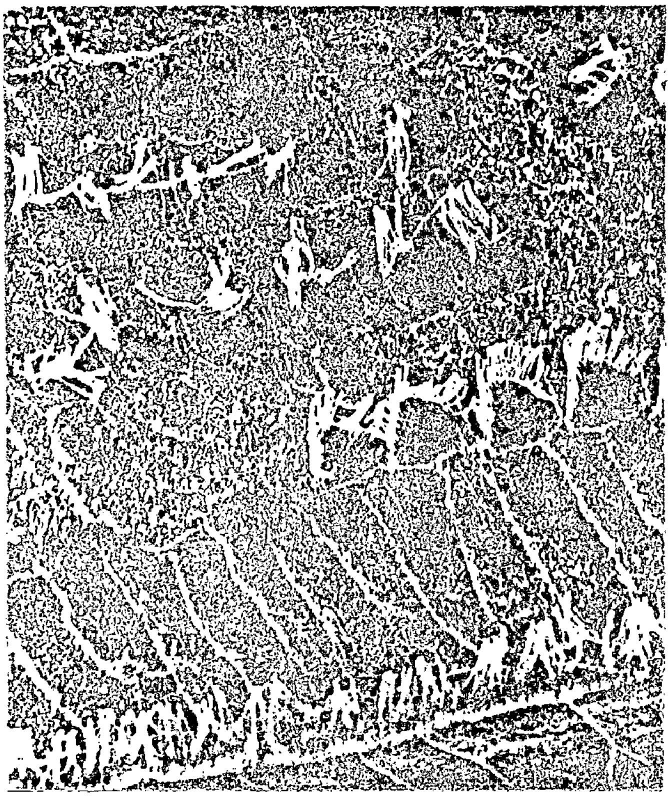
A. Normal Organ of Corti of Guinea pig showing the three rows of outer hair cells and one row of inner hair cells.



B. Injured Organ of Corti after 24 hour exposure to Noise levels typical of very loud Rock music (2 KHz, 120 dB). Several outer hair cells are missing, and the Cilia of others no longer form the orderly "W" pattern.

FIG. 6.4.0 SCANNING ELECTRON MICROGRAPH BY ROBERT E. PETERSON (Courtesy Joseph E. Hawkins, Kresge Hearing Instt. USA)

Another classification is that of neural loss/deafness. The audiograms of persons suffering from neural loss show a nearly complete distortion of BC and AC audiograms but total neural deafness is depicted by typical corner audiograms where only at low frequency very faint sound may (or may not) be audible but usually total deafness results. Only lip-reading and certain hand gestures and postures help during communication with such individuals. Recent surgical techniques for the deaf have been developed by a few American doctors, who claim to conquer nerve loss by operating upon the intricate structure of the cochlea but nerve deafness is absolutely incurable and the solution is yet to be discovered. Nerve deafness due to cancer or brain tumour can be cured to satisfactory results if the cancerous cells are killed in their early stages. A most common injury to the inner ear is due to intense noise. The hair cells are severely damaged by exposure to high intensity noise such as the typical live amplified rock music concerts, engines of jet planes, and revved-up motor cycles. The damaged sensory hairs form giant, abnormal hair structures or are lost altogether, and in cases of long exposure to loud sounds, they and their supporting cells completely degenerate. Much lesser noise levels also cause damage if exposure is chronic (Fig. 6.4.0). All these atrocities causing nerve impairment of hearing with the others discussed earlier in Chapter III, account for the tremendous deviation of cochlea's representative impedances. Although the set of parameters determined for cases of nerve loss and deafness cannot directly predict the cause or that which portion of the inner ear is deficient but certainly this set of parameters exhibits a very large deviation from their normal limits. This singles them out, straight away as a typical set of abnormal data. Looking at the tabular hearing deficiency classification, it is clear that every single parameter has undergone a large deviation. Another significant observation is that all the parameters have increased much beyond the upper limits. The thirteen audiograms showing total nerve loss depict the representative model elements with values still higher in magnitude than those for cases, of only nerve loss of hearing.

Finally a note on Meniere's Syndrome. Audiograms 48,49 and 54 fall under this category. Looking at audiogram 49 it depicts early stage of the disease. The model parameters estimated for this case are a typical set. Only the resistances R_1, R_2, R_4, R_5 and R_7 are seen to exhibit some abnormality that is quite noticeable, but the capacitance C_3 is the only capacitive element out of the normal range. All the inductances remain uneffected. This implies that loss of sound energy due to resistance is the vital cause of deviated hearing thresholds. Most of the energy dissipation is in the middle ear cavities and the malleus incus structure. Decrease in the value of R_7 (cochlea) and the normal values of C_7 and L_4 cause a total decrease of cochlear impedance allowing a distorted noisy version of the signal to reach the brain auditory receptors.

The audiogram shows a low frequency loss that is justified as the effect on the audibility record, due to resistive elements only. Change in R_5 can be accounted by the discontinuity in the ossicular chain. Audiogram 48 shows a record of a moderately advanced case. The associated underlined parameters are all except those representing the cochlear impedance, symbolising that some kind of middle ear infection spreading onto the outer ear is the cause of the distorted signal received. The decreased value of L_4 may be the reason of the signals (already distorted) reaching the auditory nerve at a quicker rate than necessary - rendering the overlapping of signals, the effect of intense noise and vertigo. The cause of this syndrome is yet to be studied and established. Advanced stage of this disease is very similar to nerve loss of hearing except that the element L_4 shows an exceptionally small value. Ironically, the advanced stage of Meniere's disease is incurable and accompanied by severe attacks of vertigo and painful hearing [4, 6, 15, 30].

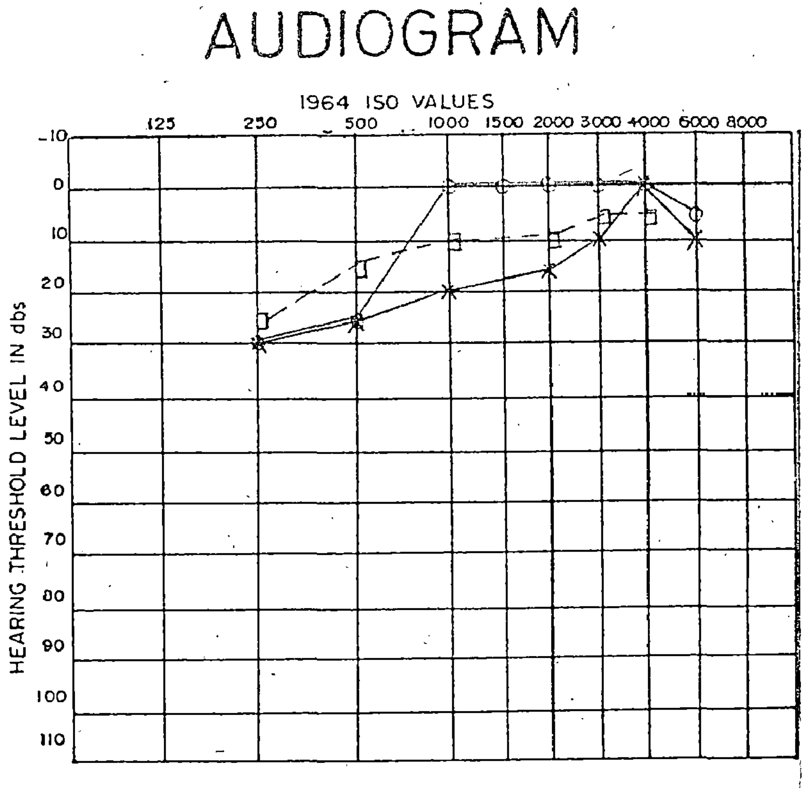


FIG.I

NORMAL EAR PAIR

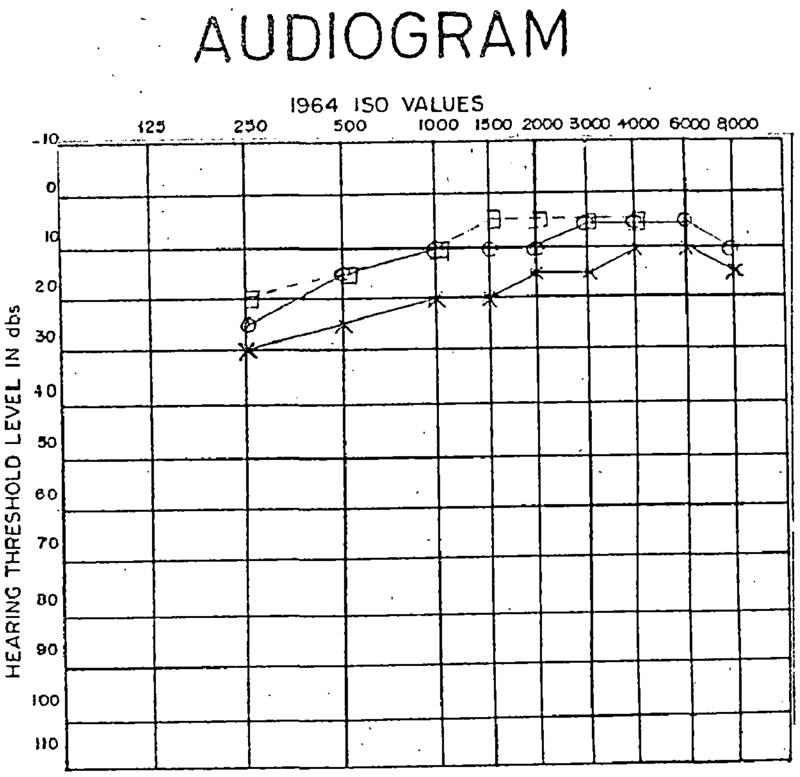


FIG.2

NORMAL EAR PAIR

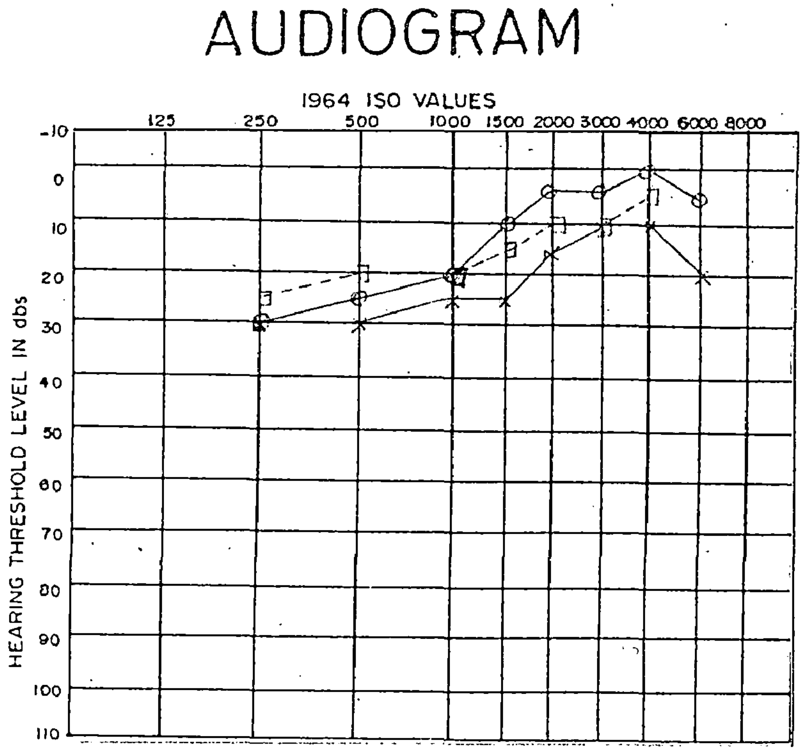


FIG.3

NORMAL EAR PAIR

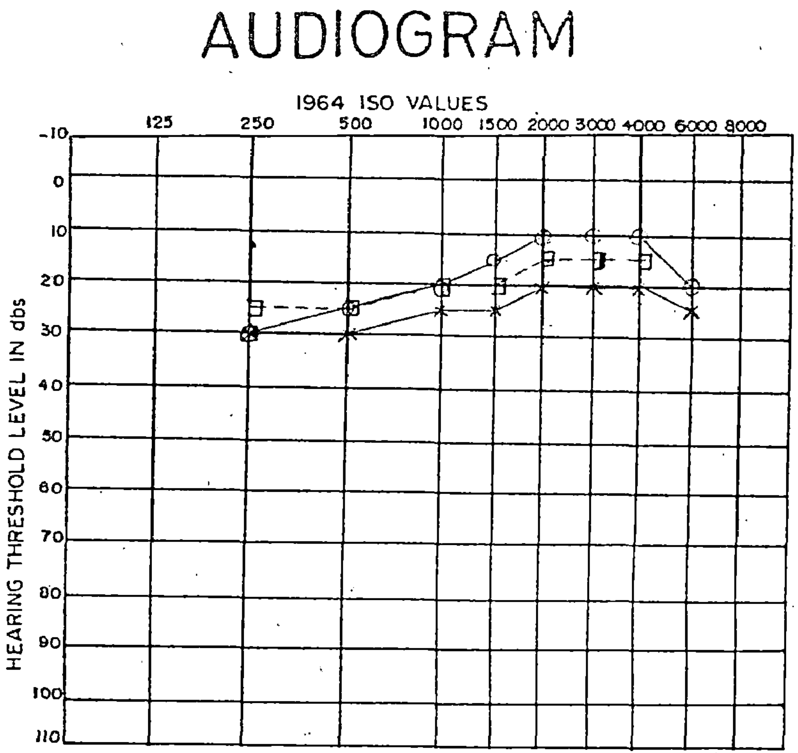


FIG.4

NORMAL EAR PAIR

AUDIOGRAM

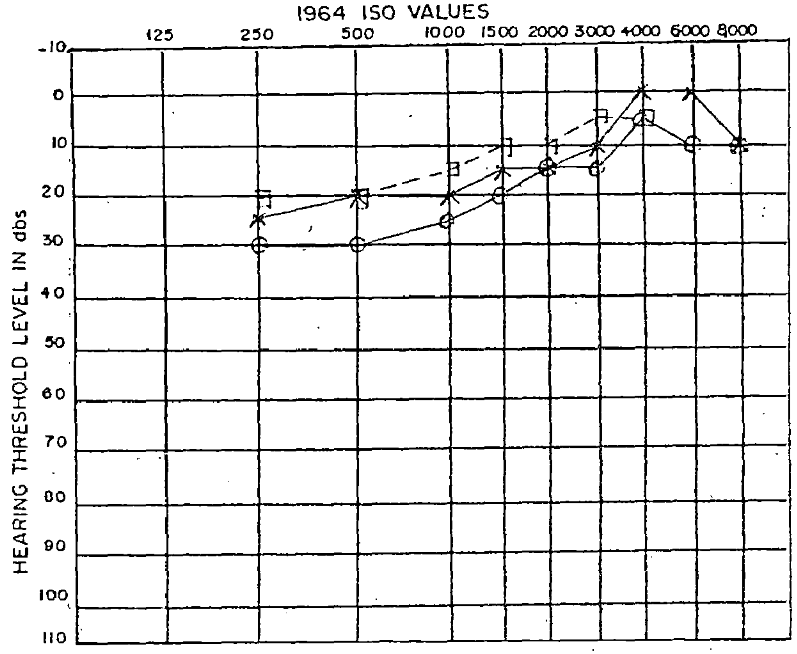


FIG.5

NORMAL EAR PAIR

AUDIOGRAM

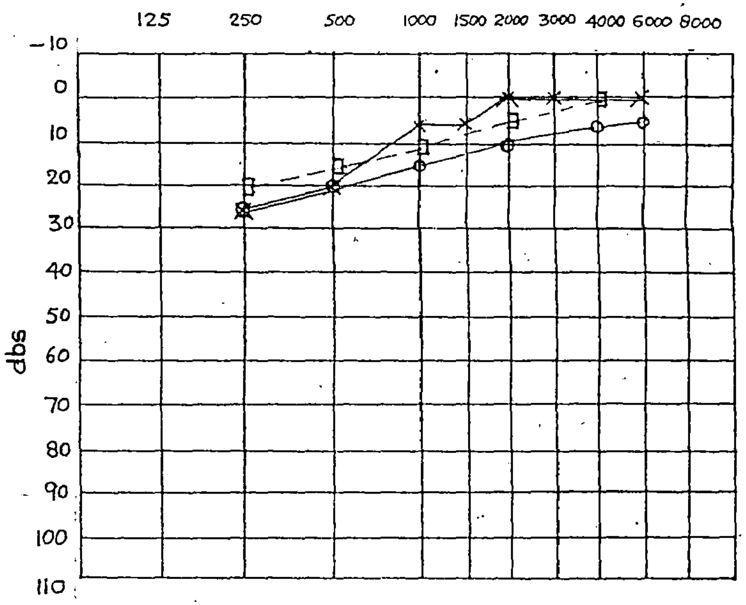


FIG.6

NORMAL EAR PAIR

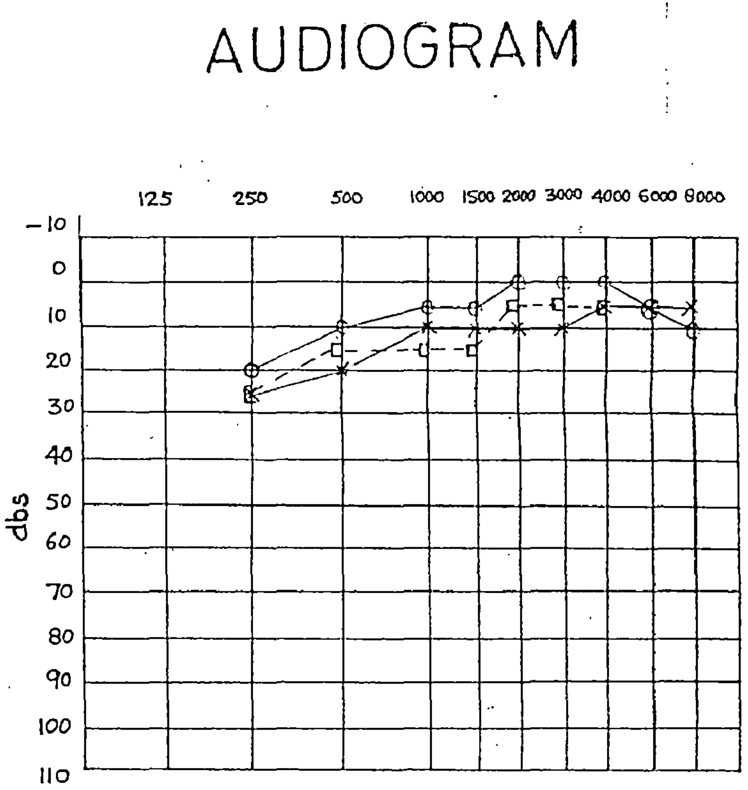


FIG.7

NORMAL EAR PAIR

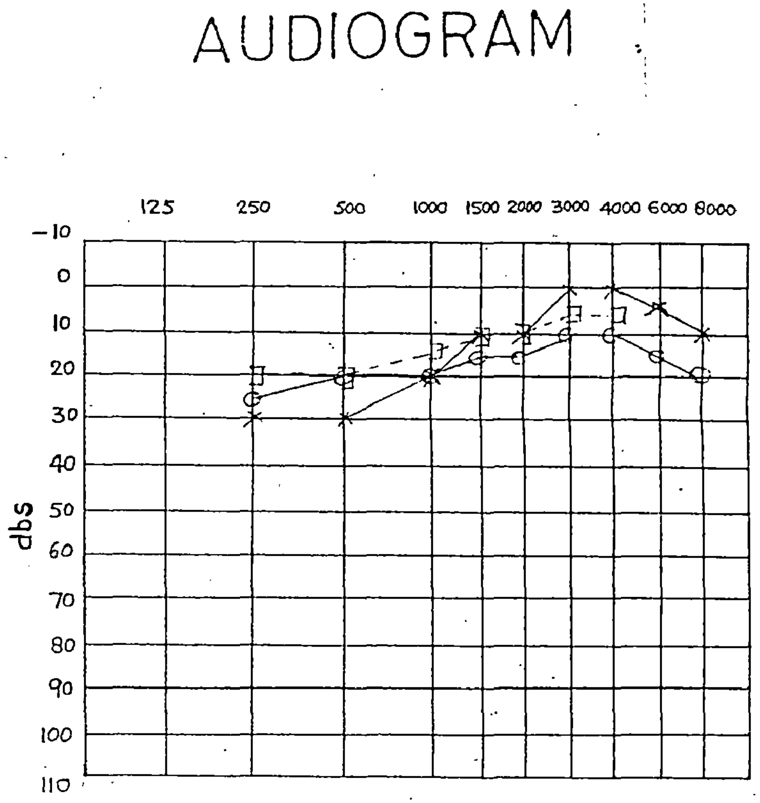


FIG.8
NORMAL EAR PAIR

AUDIOGRAM

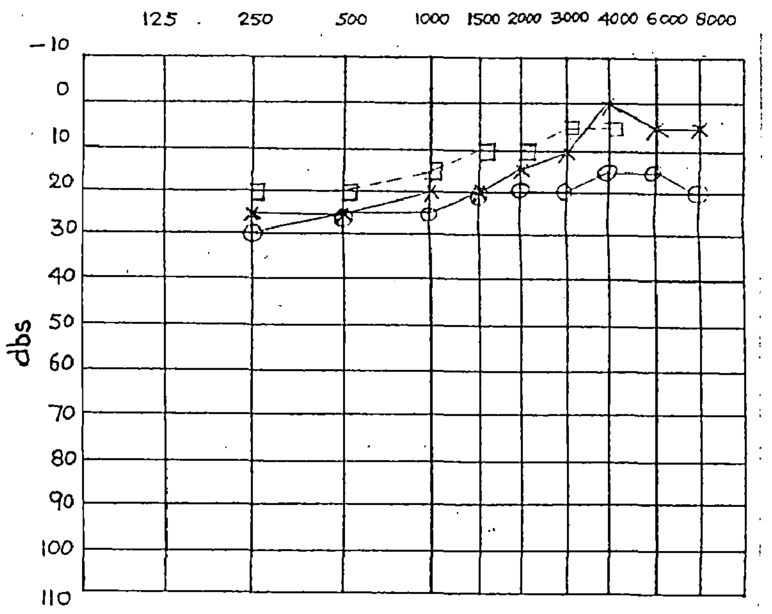


FIG.9

NORMAL EAR PAIR

AUDIOGRAM

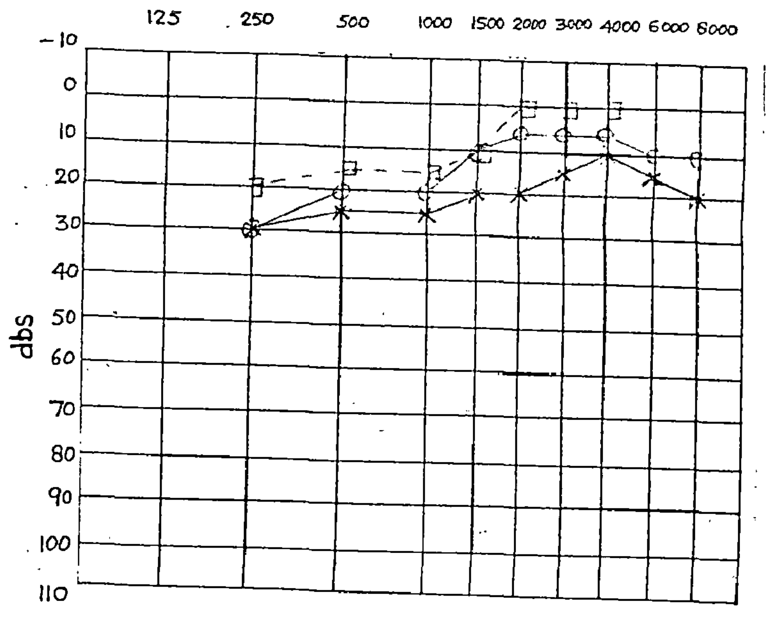


FIG.10

NORMAL EAR PAIR

AUDIOGRAM

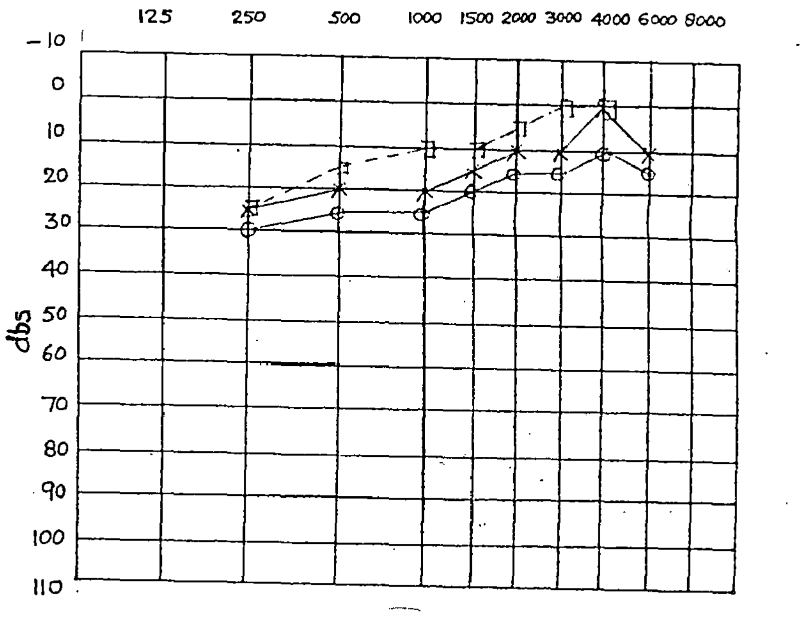


FIG.11
NORMAL EAR PAIR

AUDIOGRAM

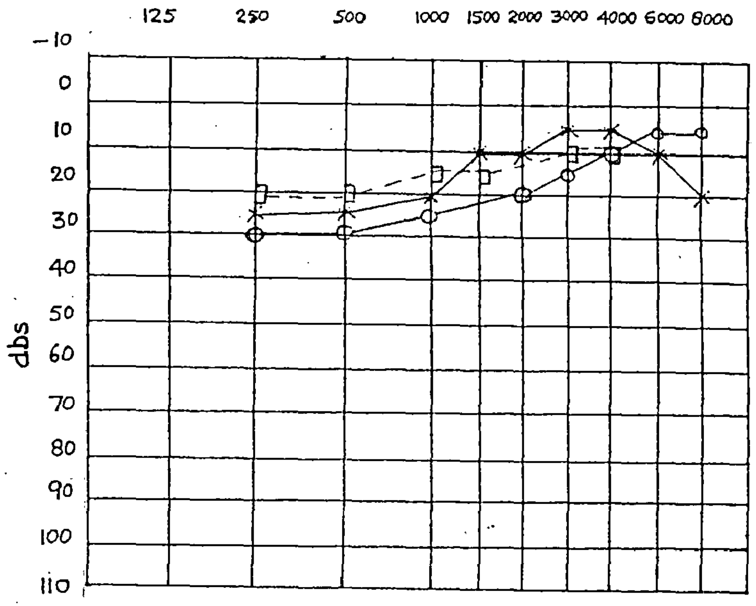


FIG.12

NORMAL EAR PAIR

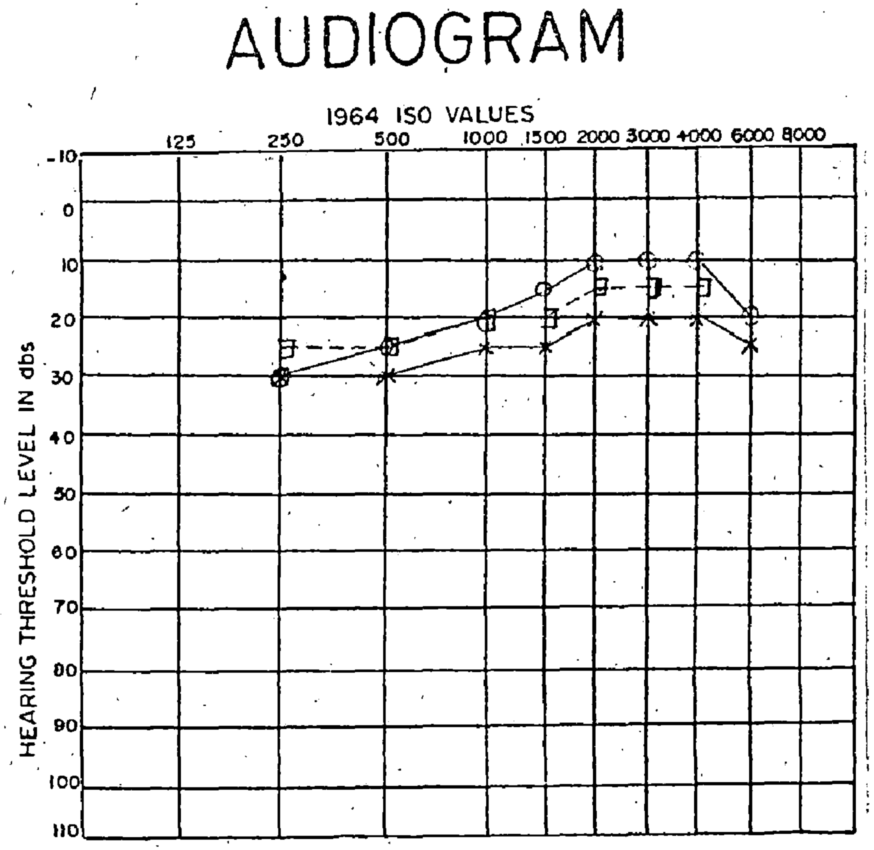


FIG. 13

NORMAL EAR PAIR

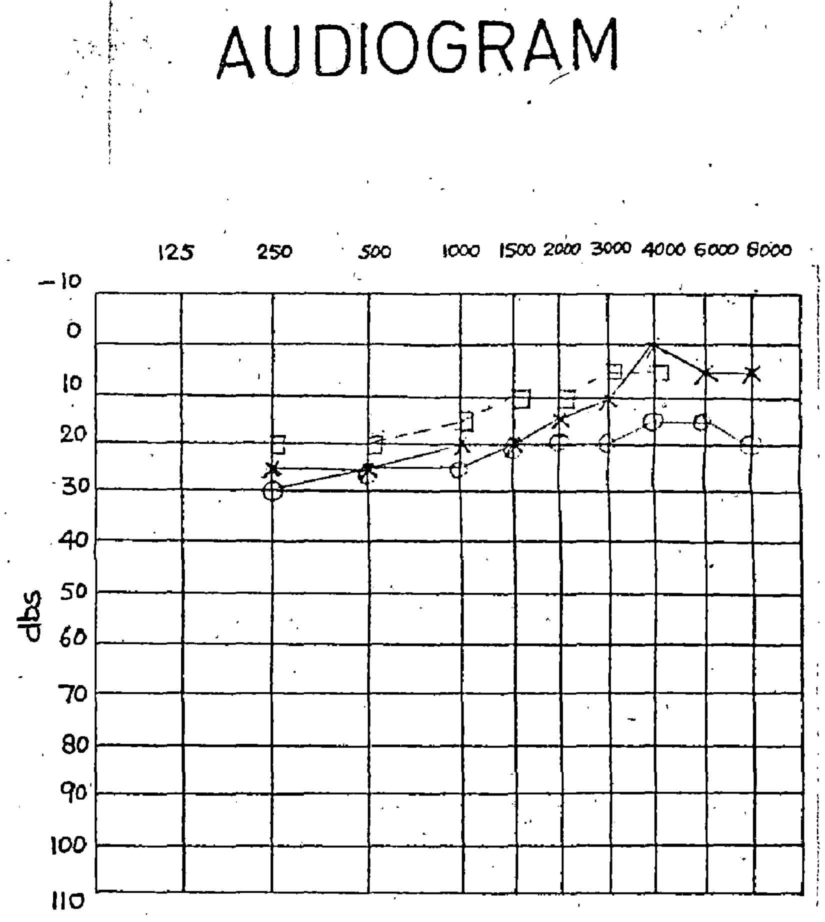


FIG. 14

NORMAL EAR PAIR

AUDIOGRAM

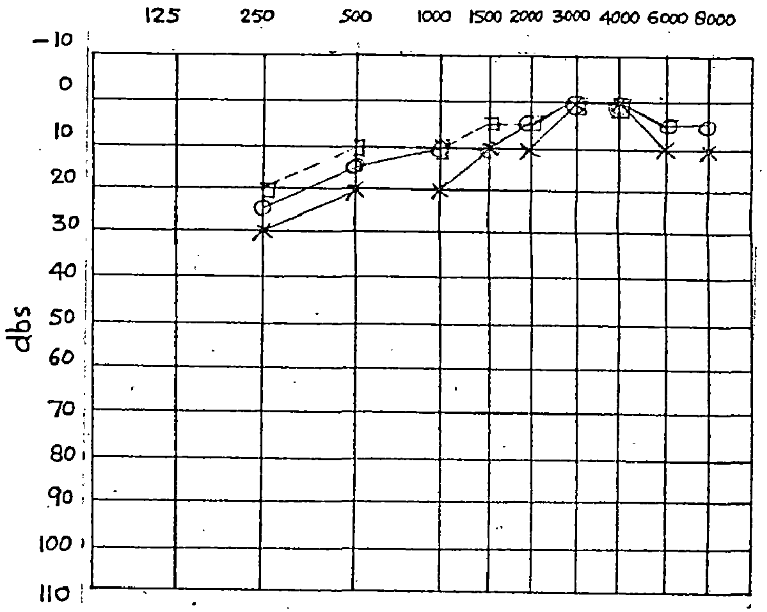


FIG.15

NORMAL EAR PAIR

AUDIOGRAM

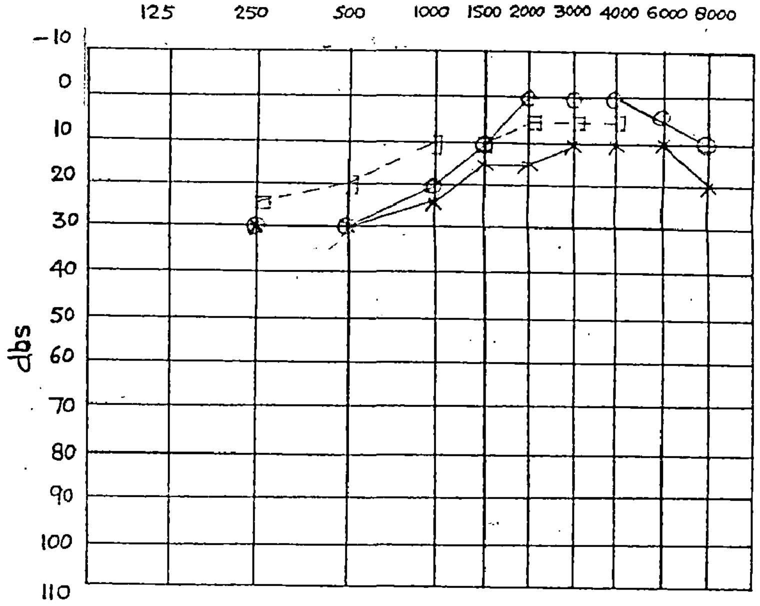


FIG.16

NORMAL EAR PAIR

AUDIOGRAM

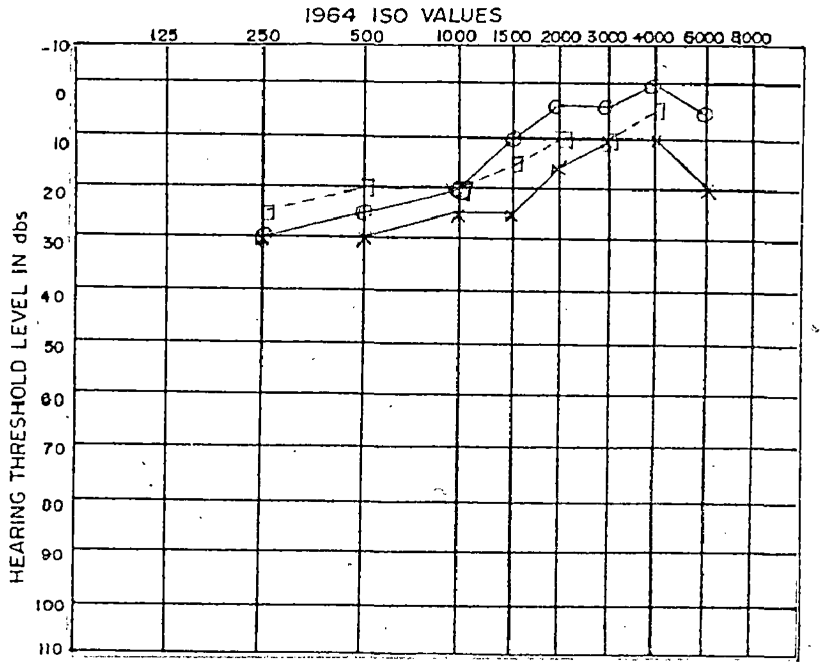


FIG. 17

NORMAL EAR PAIR

AUDIOGRAM

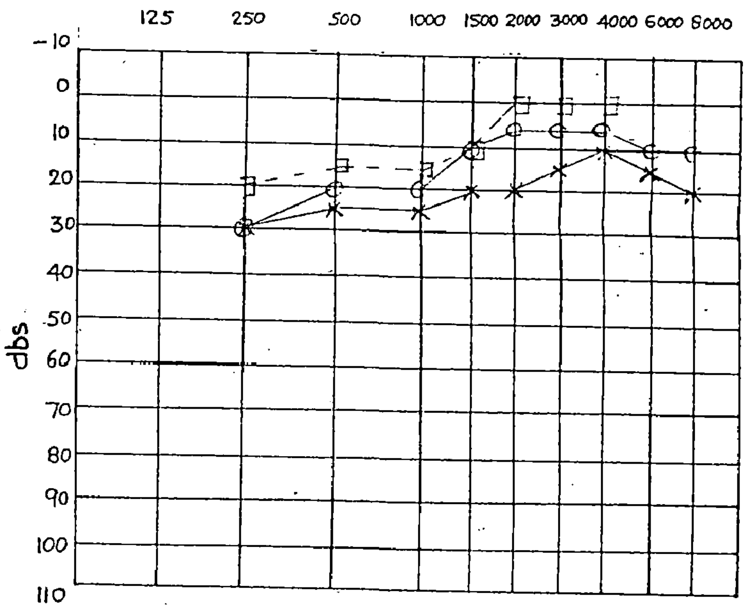


FIG.18

NORMAL EAR PAIR

AUDIOGRAM

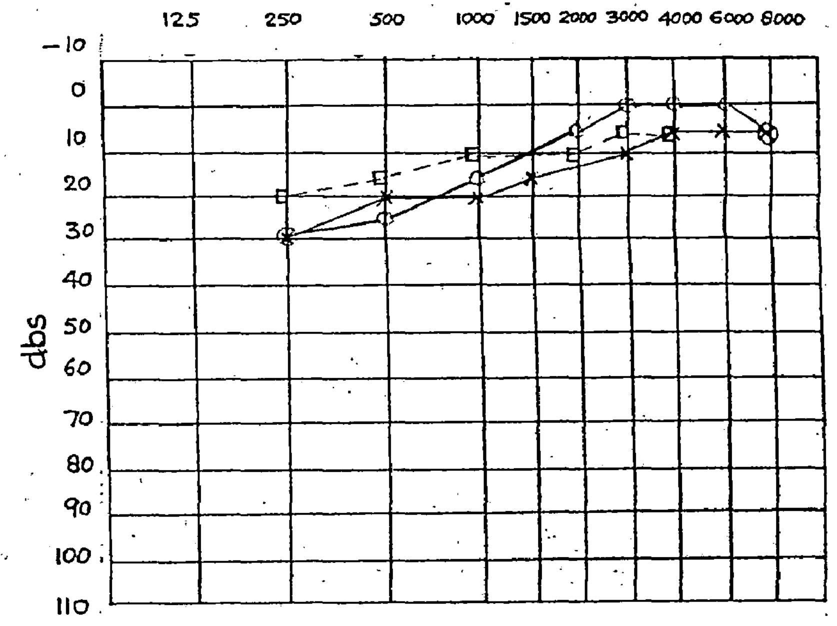


FIG.19

NORMAL EAR PAIR

AUDIOGRAM

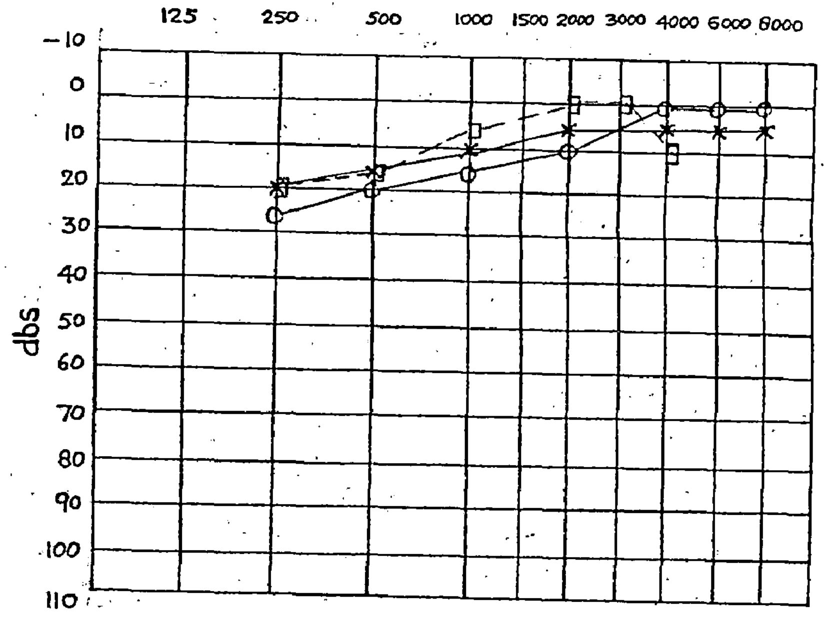


FIG.20

NORMAL EAR PAIR

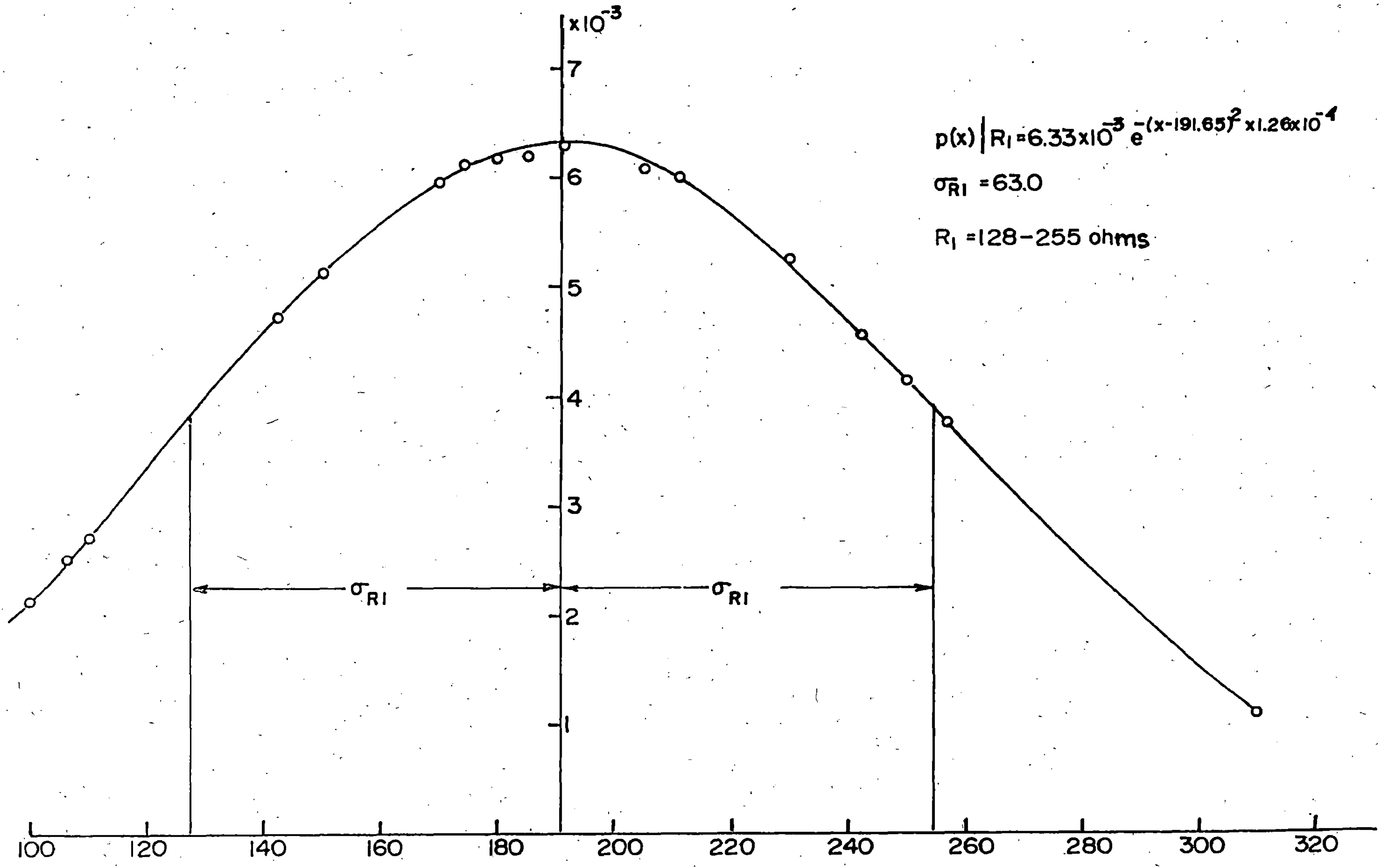


FIG. 21 PROBABLE RANGE OF R_1.

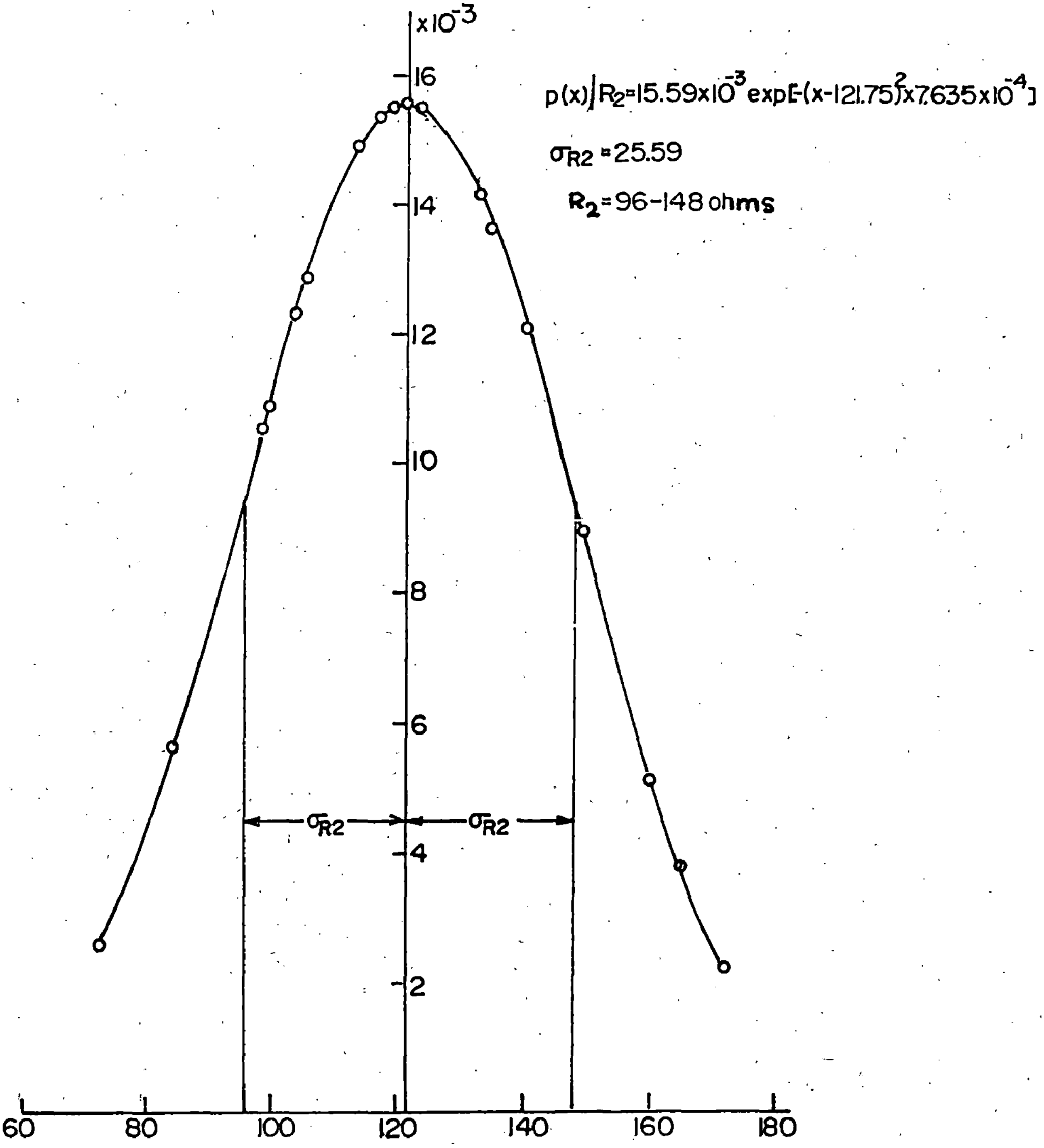


FIG.22 PROBABLE RANGE OF R2.

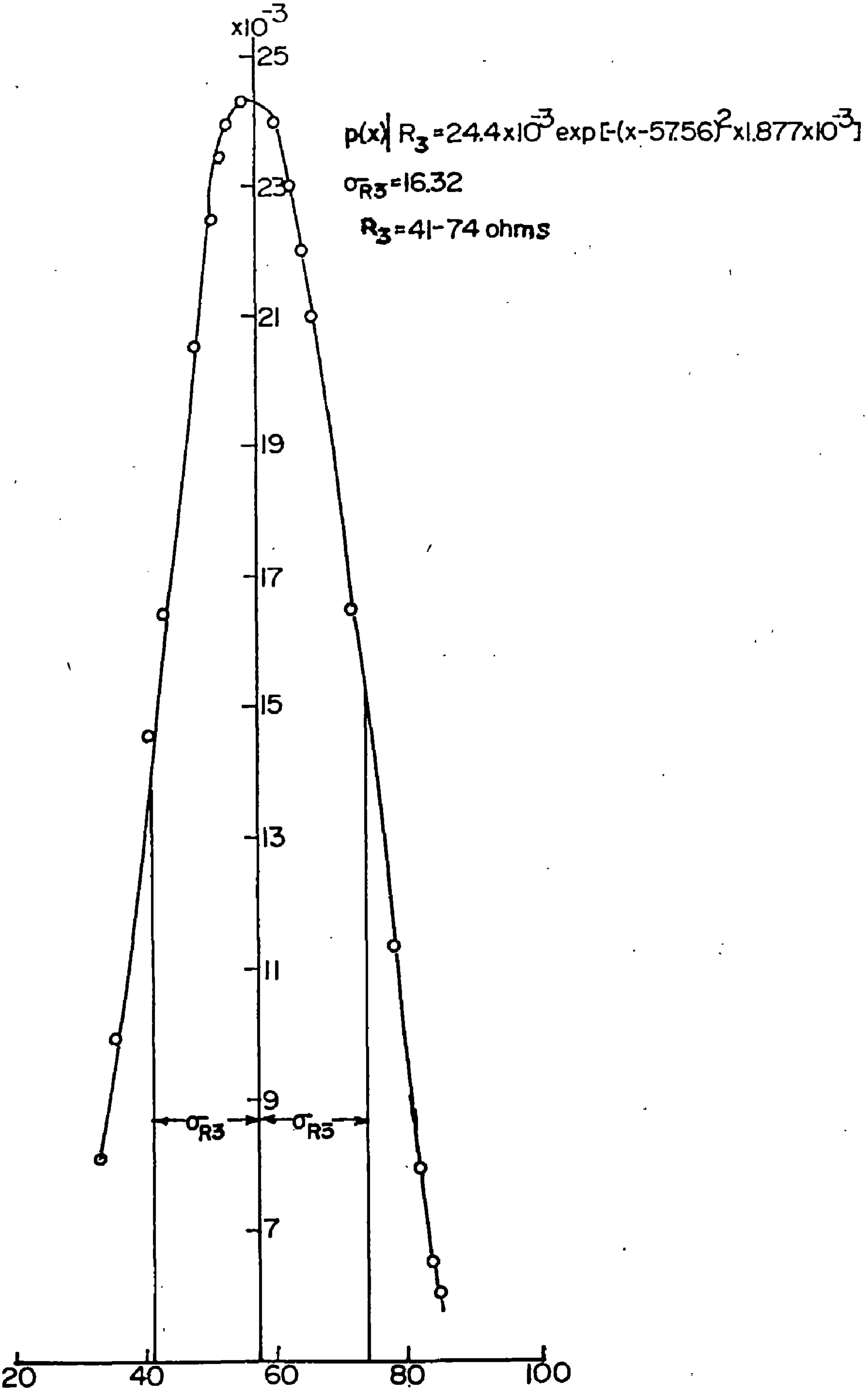


FIG.23 PROBABLE RANGE OF R_3.

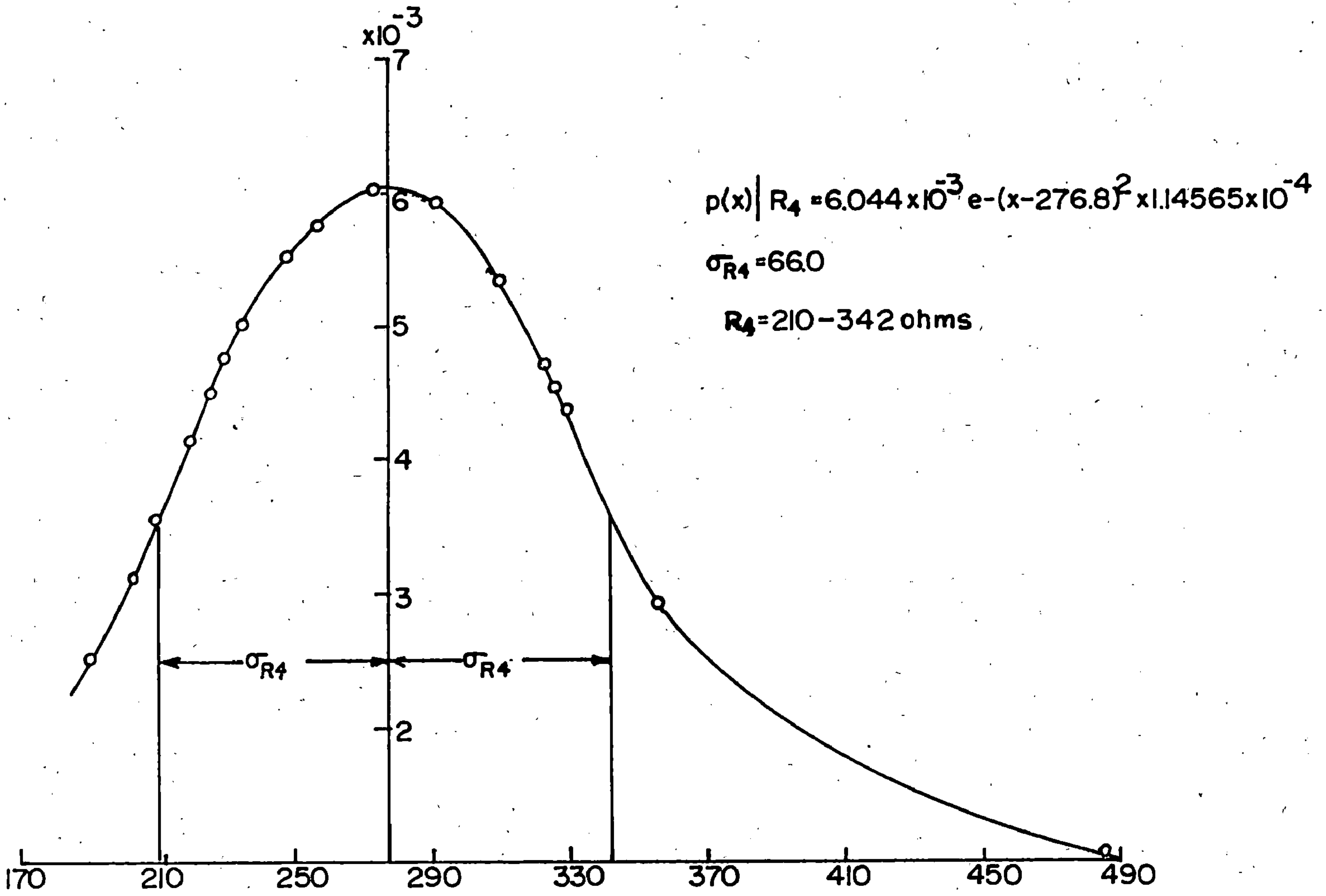


FIG.24 PROBABLE RANGE OF R_4.

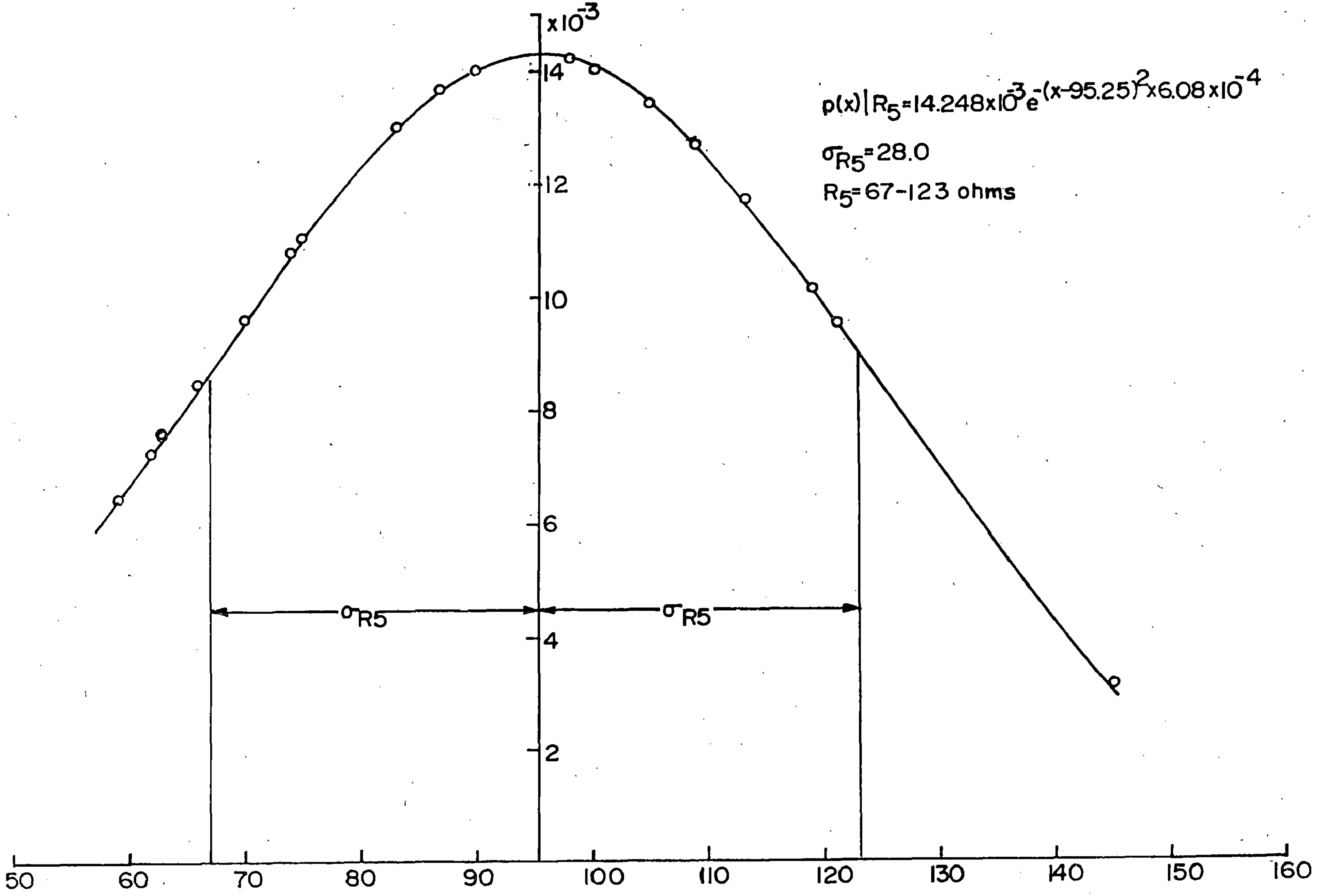


FIG.25 PROBABLE RANGE OF R_5.

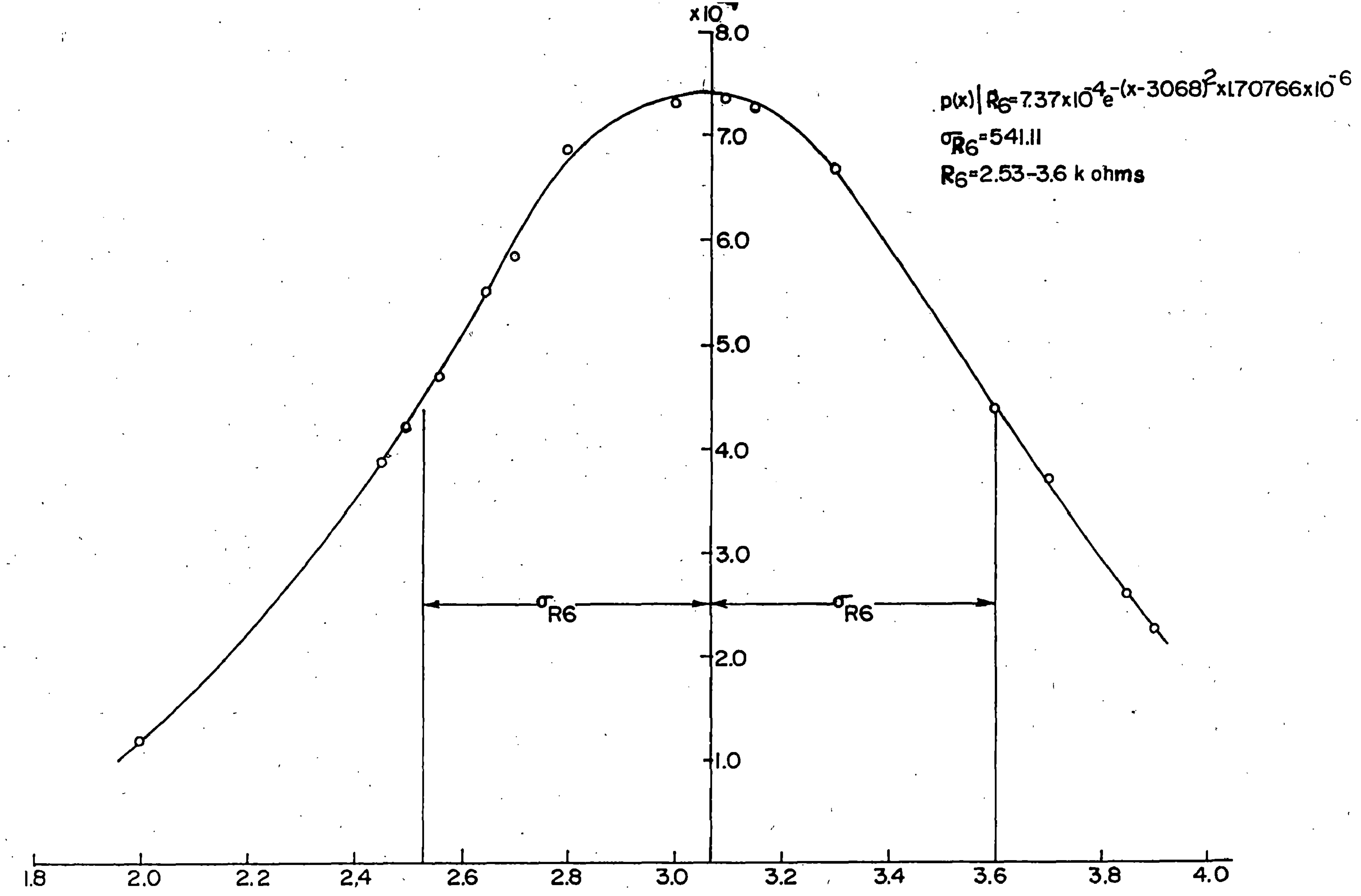


FIG.26 PROBABLE RANGE OF R_6.

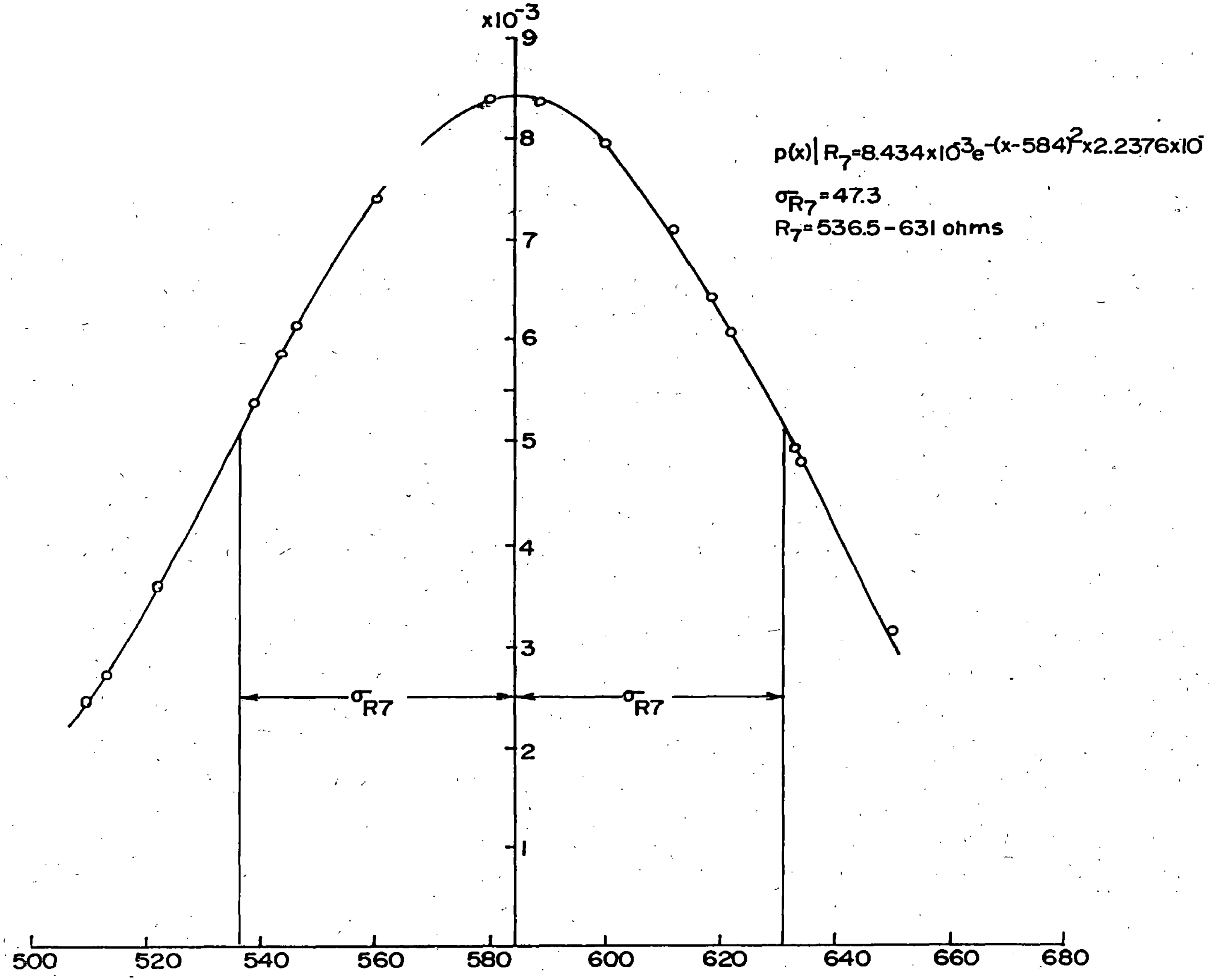


FIG.27 PROBABLE RANGE OF R_7.

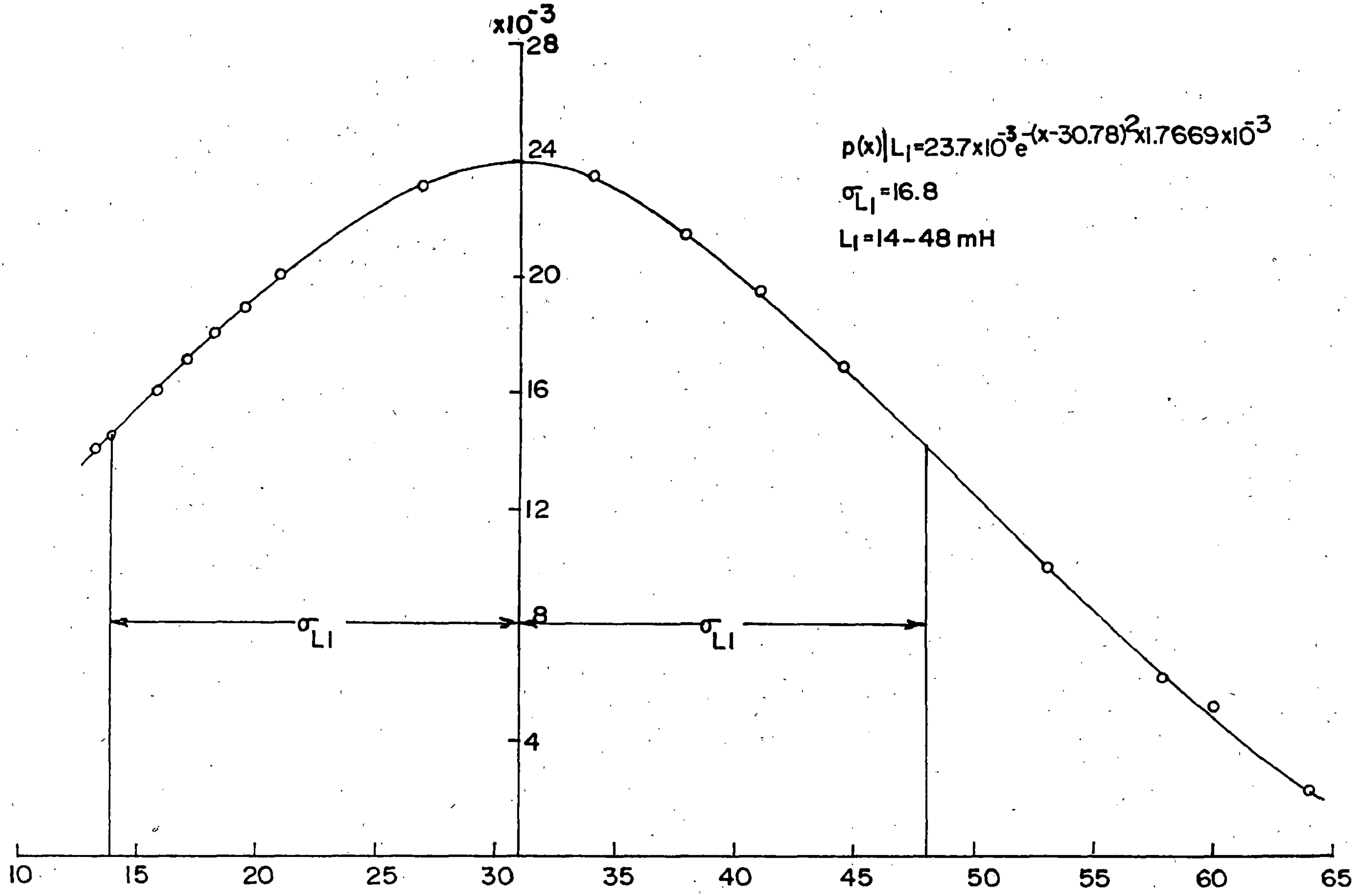
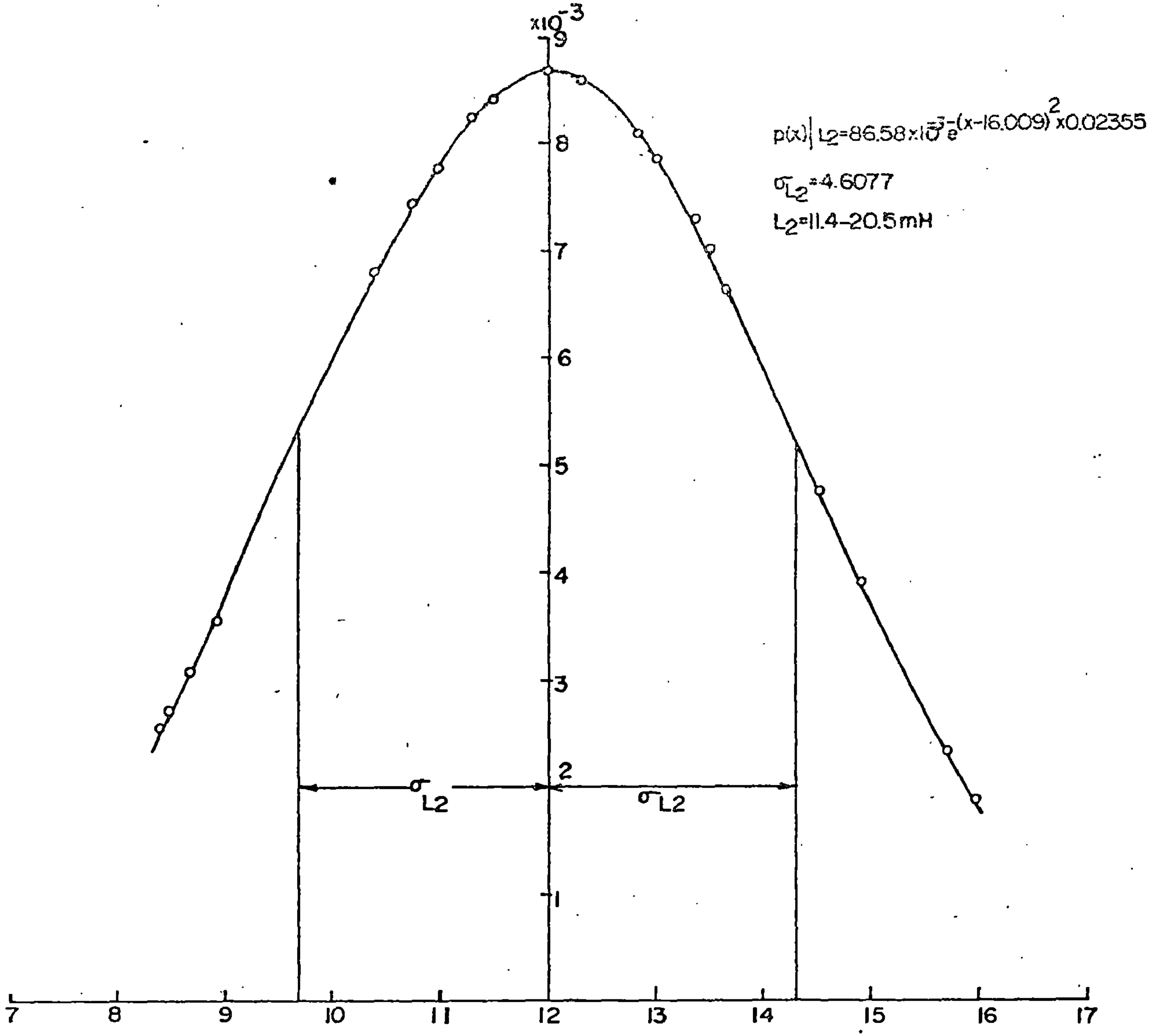


FIG. 28 PROBABLE RANGE OF L_1.



$p(x)\big|_{L_2} = 86.58 \times 10^{-3} e^{-(x-16.009)^2 \times 0.02355}$

$\sigma_{L_2} = 4.6077$

$L_2 = 11.4\text{–}20.5\,\text{mH}$

FIG.29 PROBABLE RANGE OF L_2 .

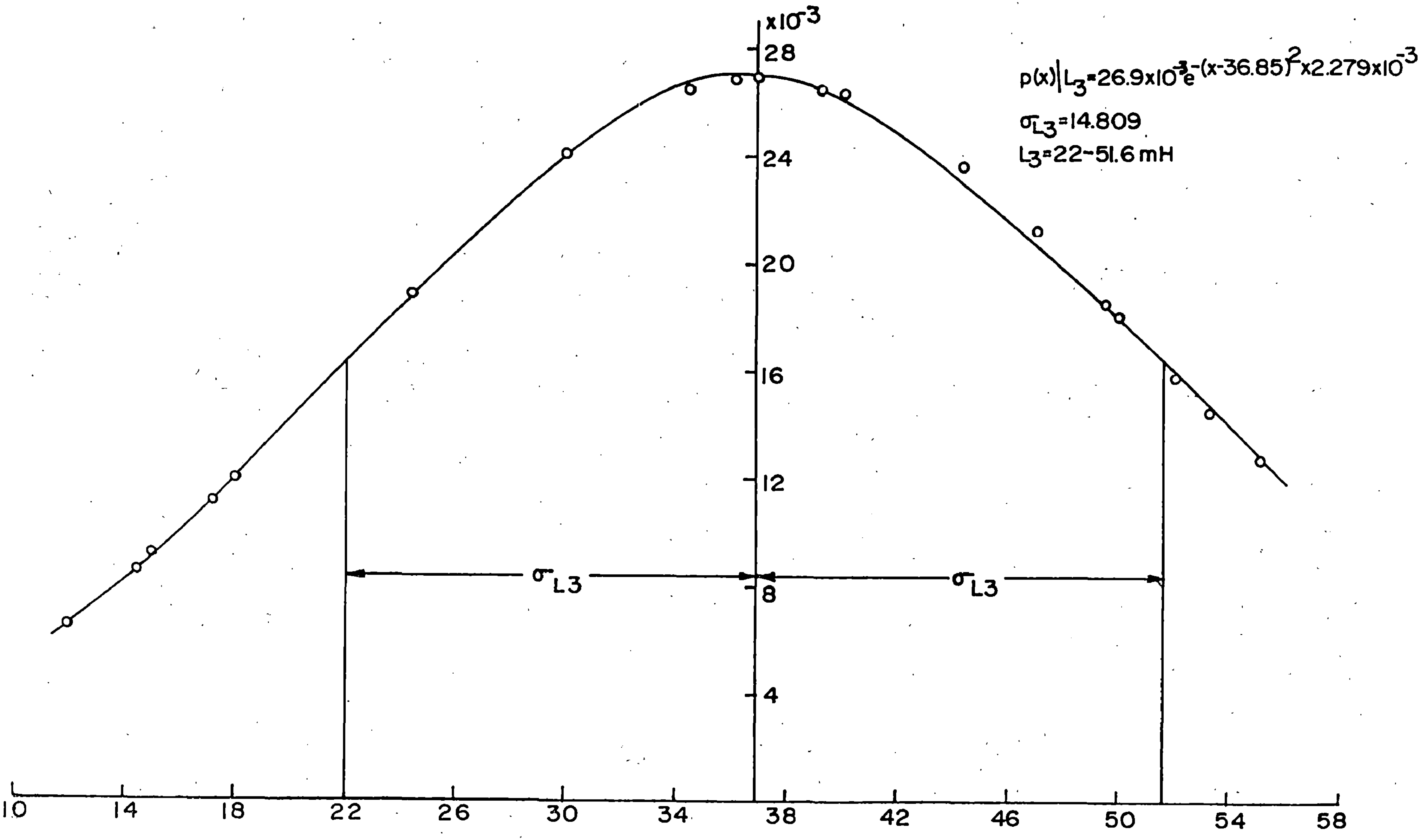


FIG.30 PROBABLE RANGE OF L_3.

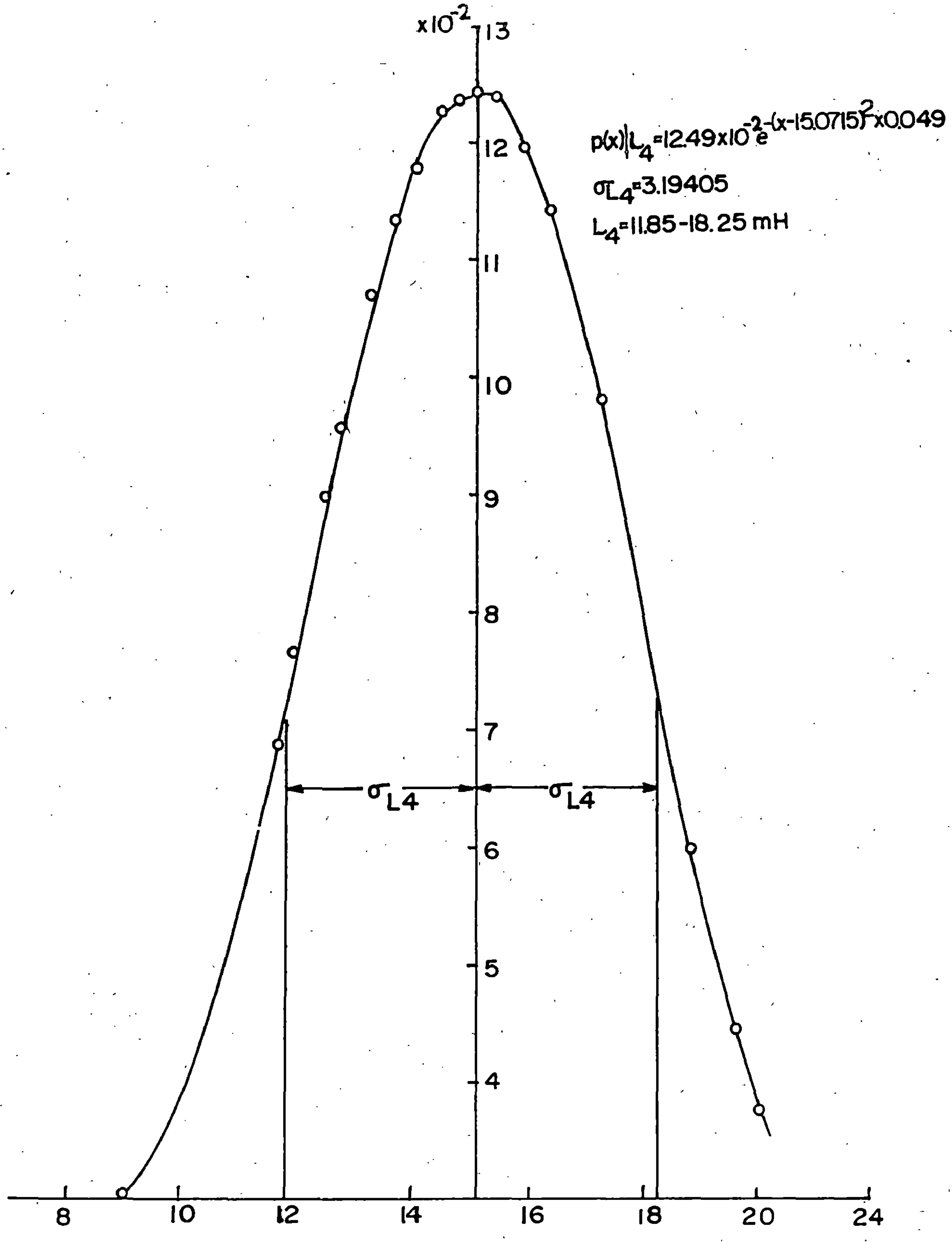


FIG.31 PROBABLE RANGE OF L_4.

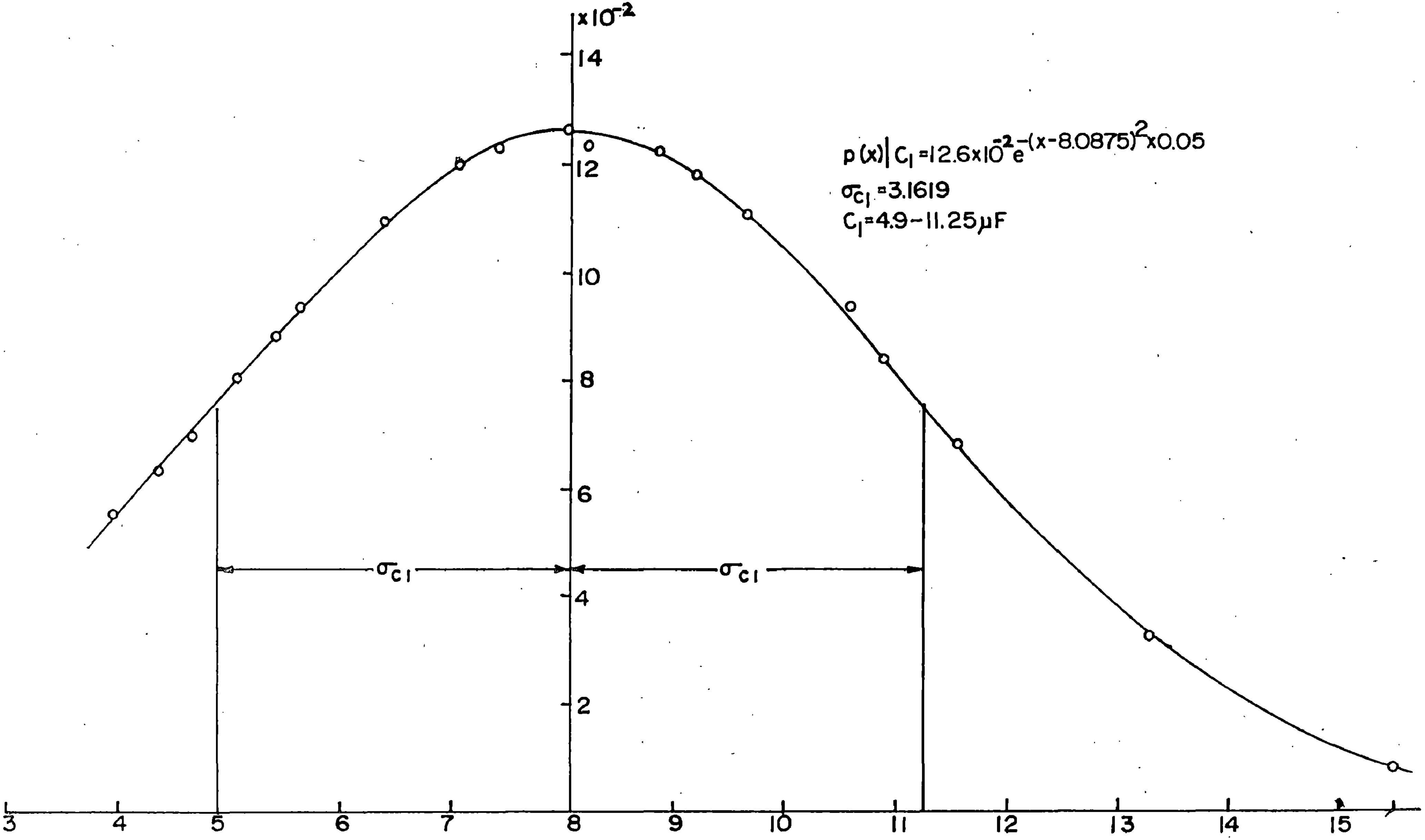


FIG.32 PROBABLE RANGE OF C_1.

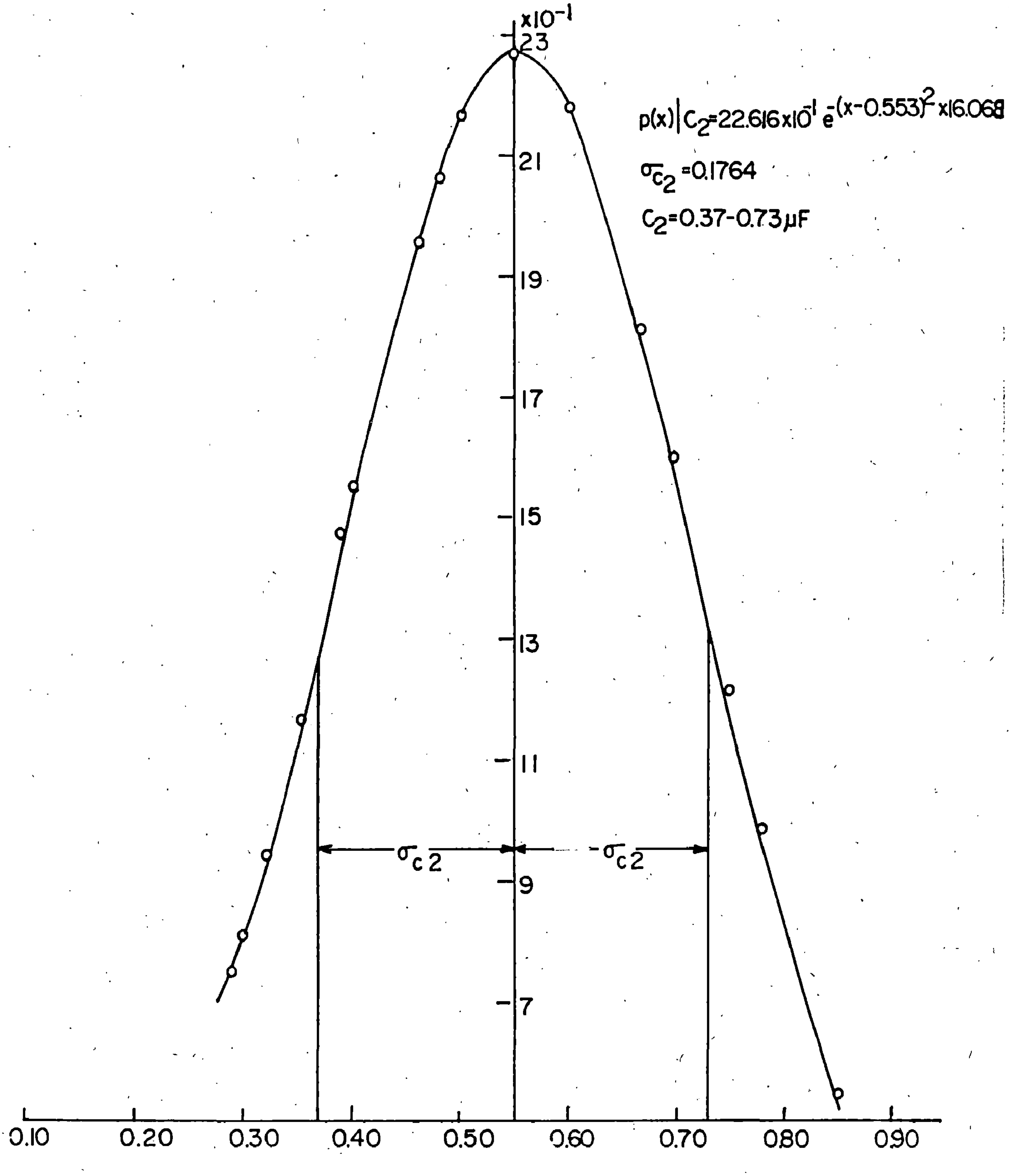


FIG.33 PROBABLE RANGE OF C_2.

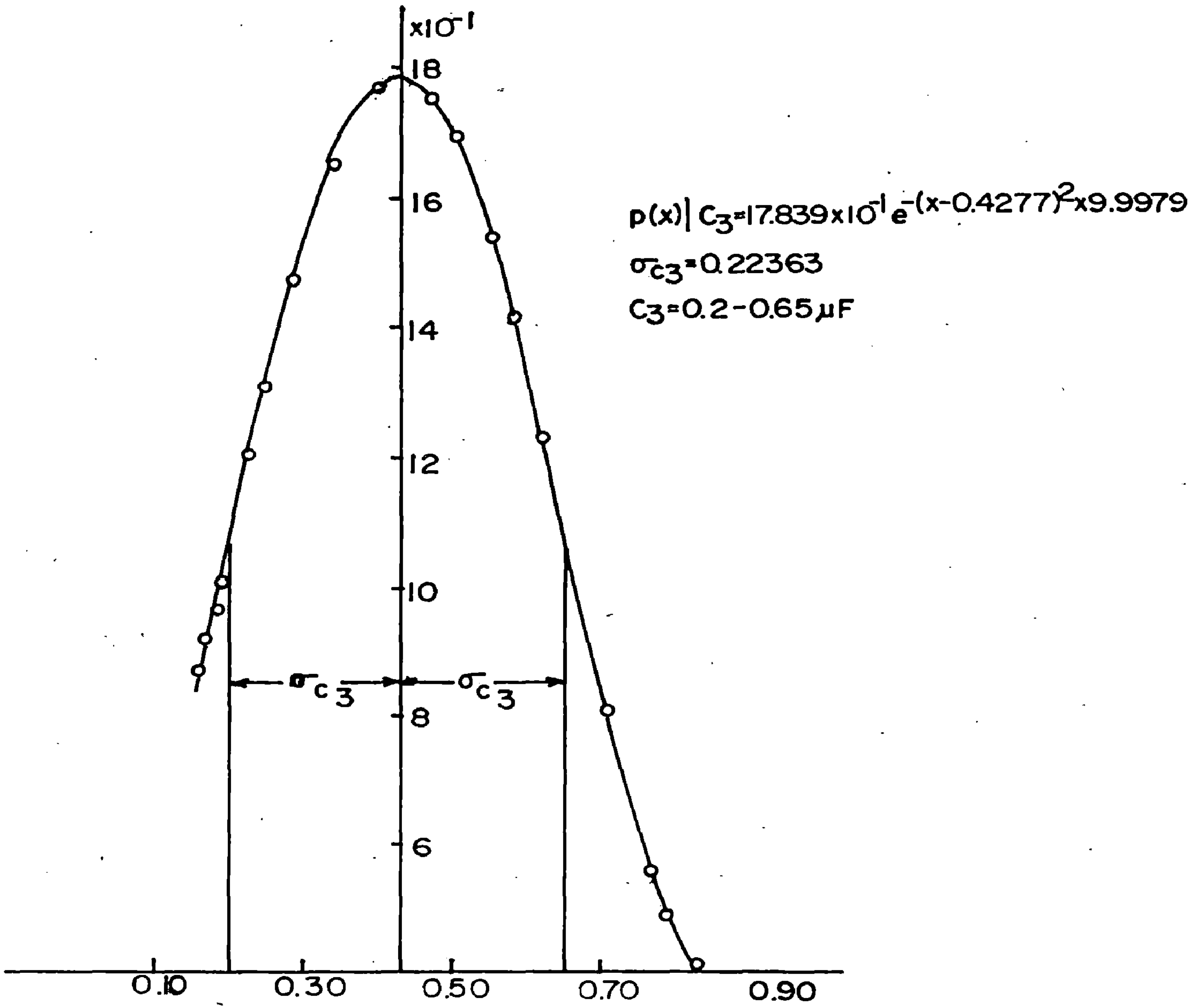


FIG.34 PROBABLE RANGE OF C_3 .

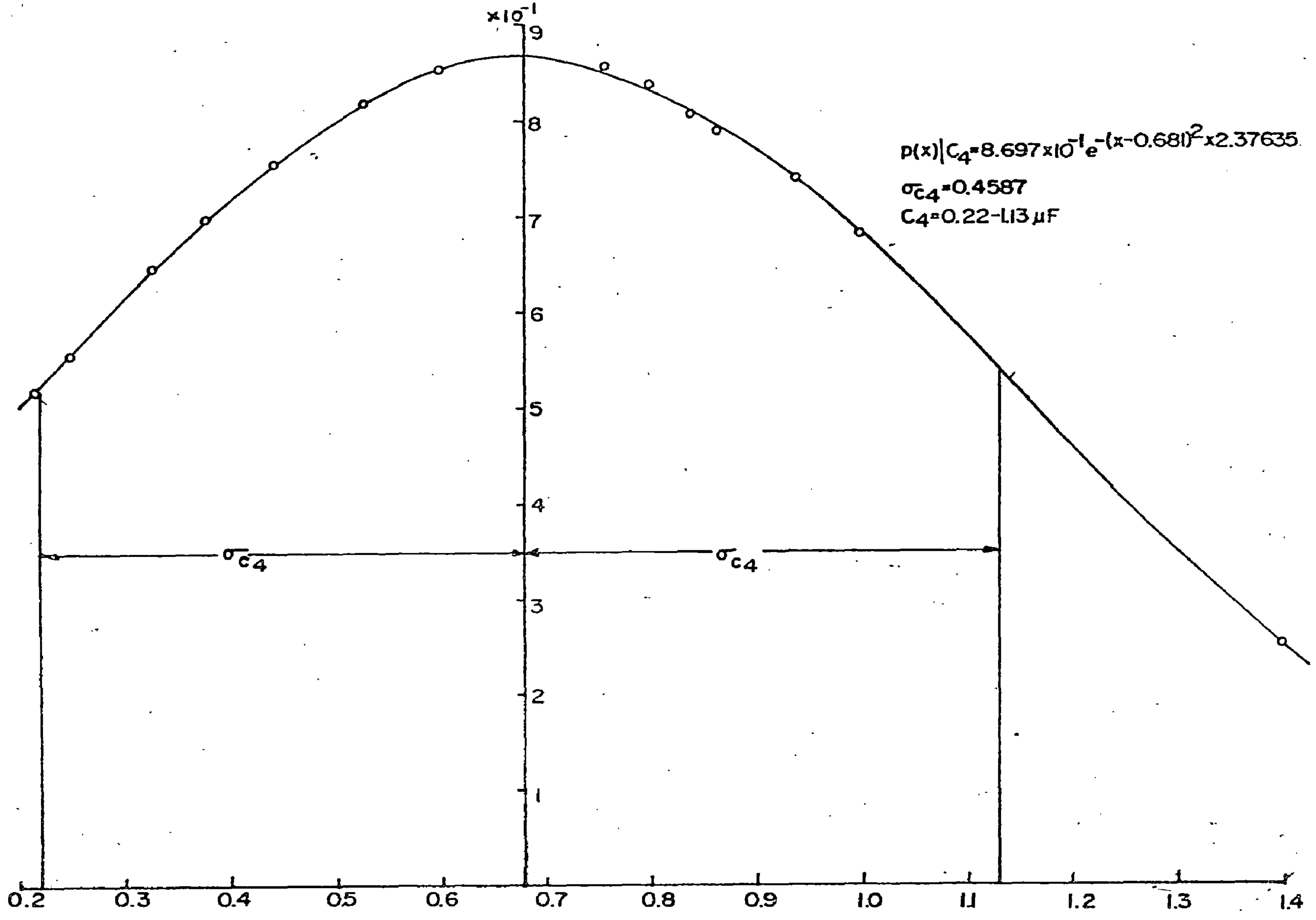


FIG.35 PROBABLE RANGE OF C_4 .

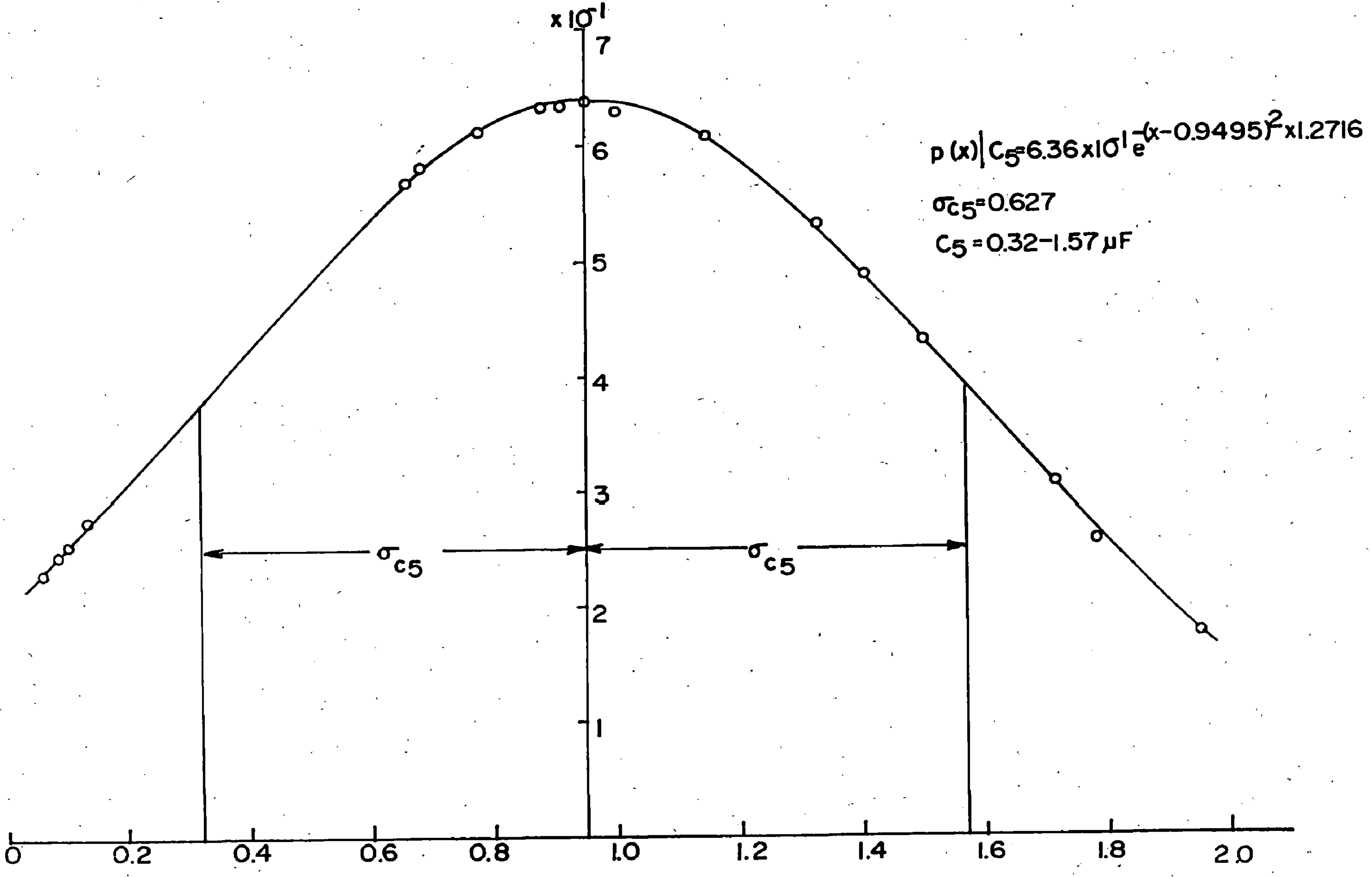


FIG.36 PROBABLE RANGE OF C_5 .

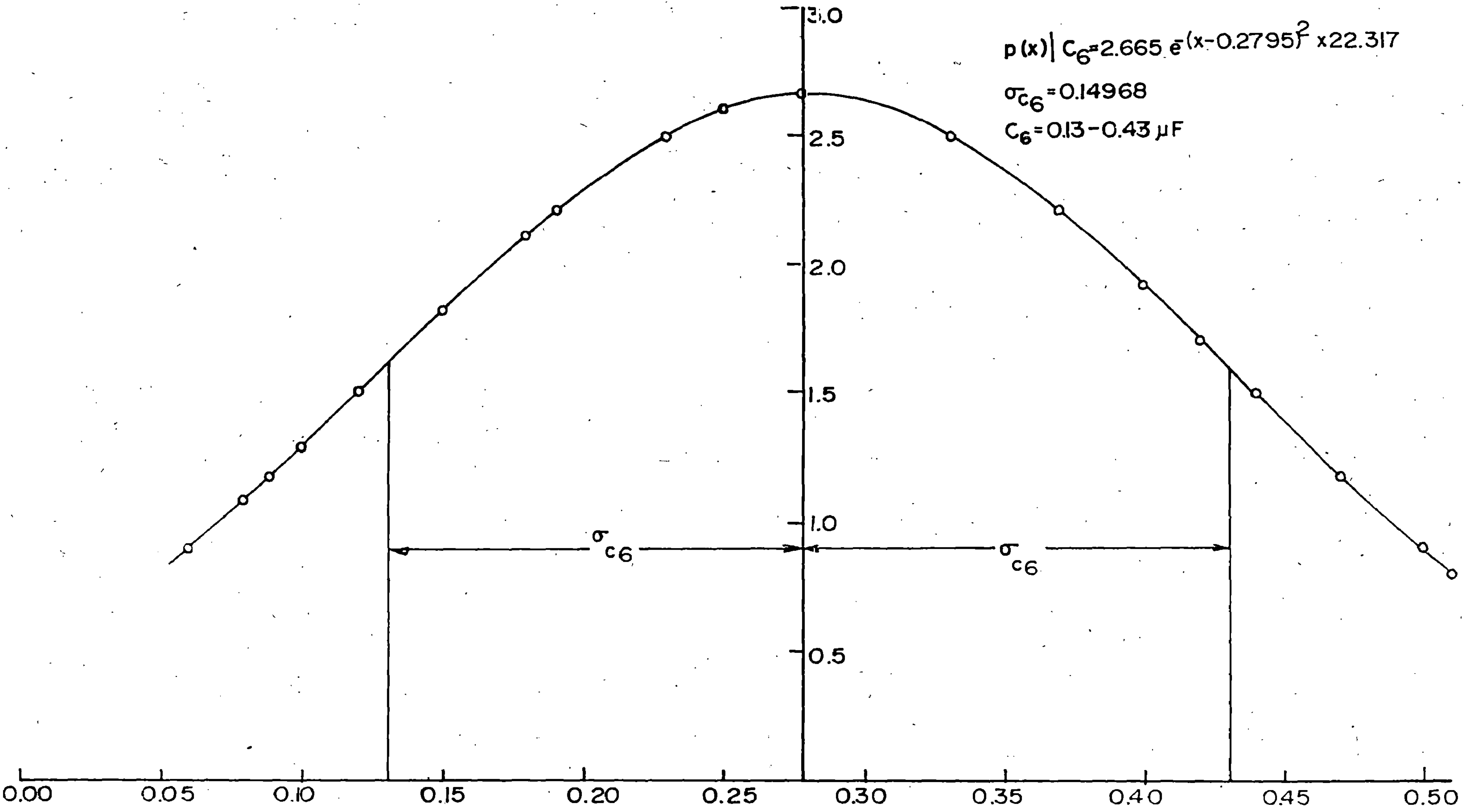


FIG.37 PROBABLE RANGE OF C_6.

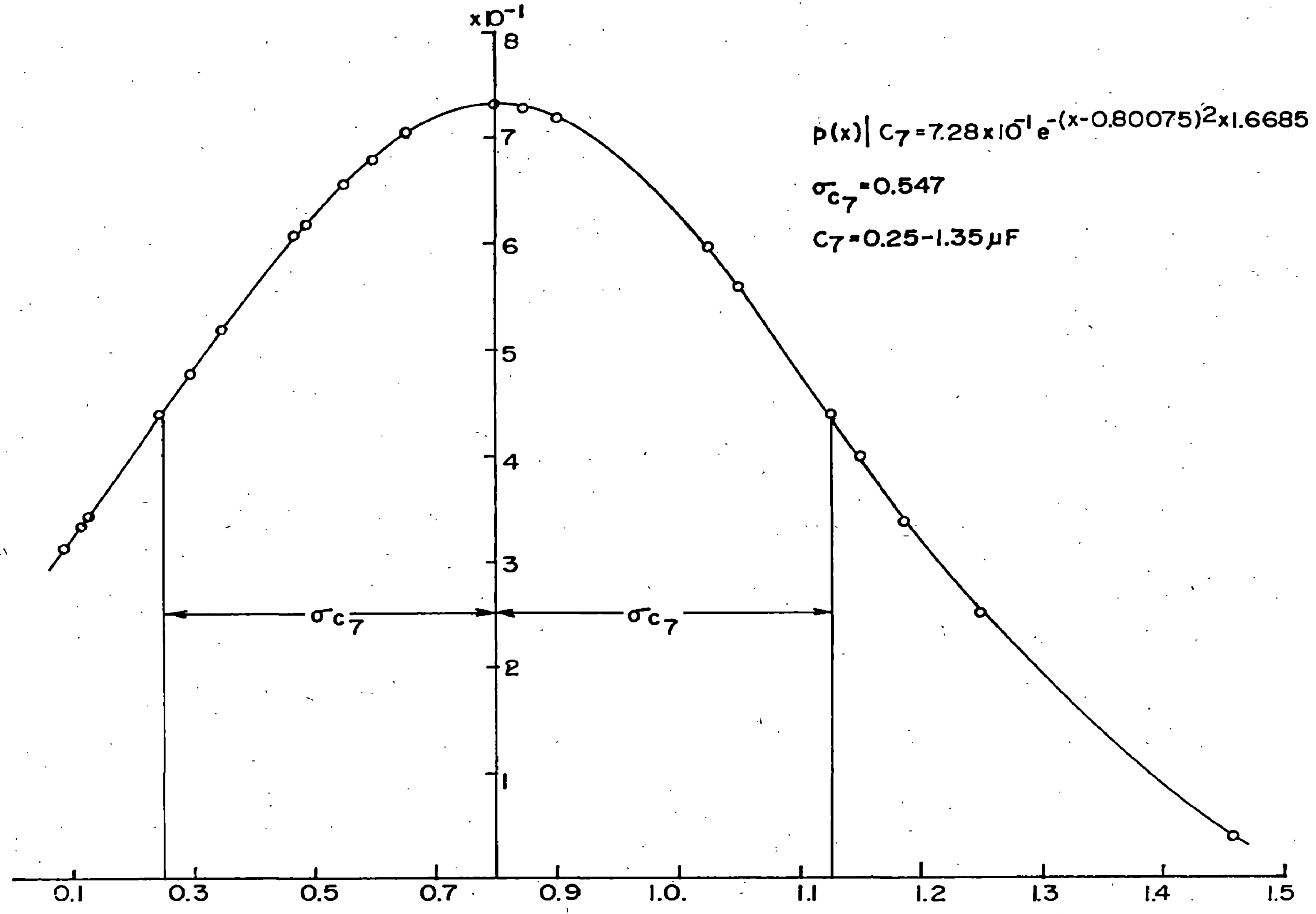


FIG.38 PROBABLE RANGE OF C_7.

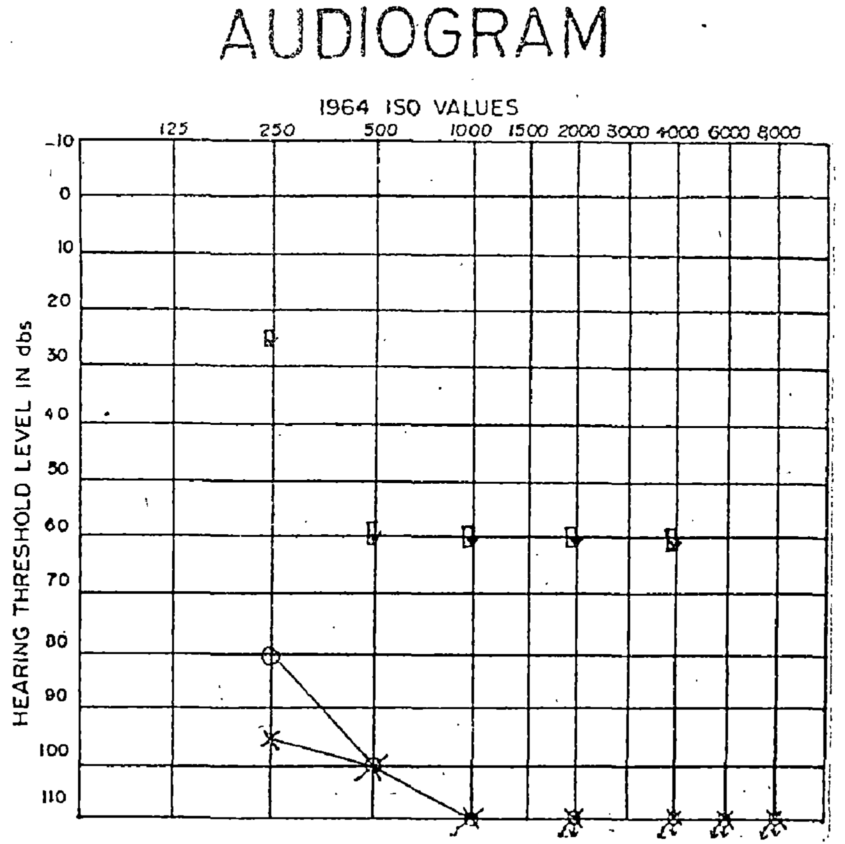


FIG.39

1) CONGENITAL HEARING LOSS
2) VIRAL DISEASE OR DRUG INDUCED.
3) CORNER AUDIOGRAM
4) BILATERAL PROFOUND SENSORI-NEURAL HEARING LOSS.

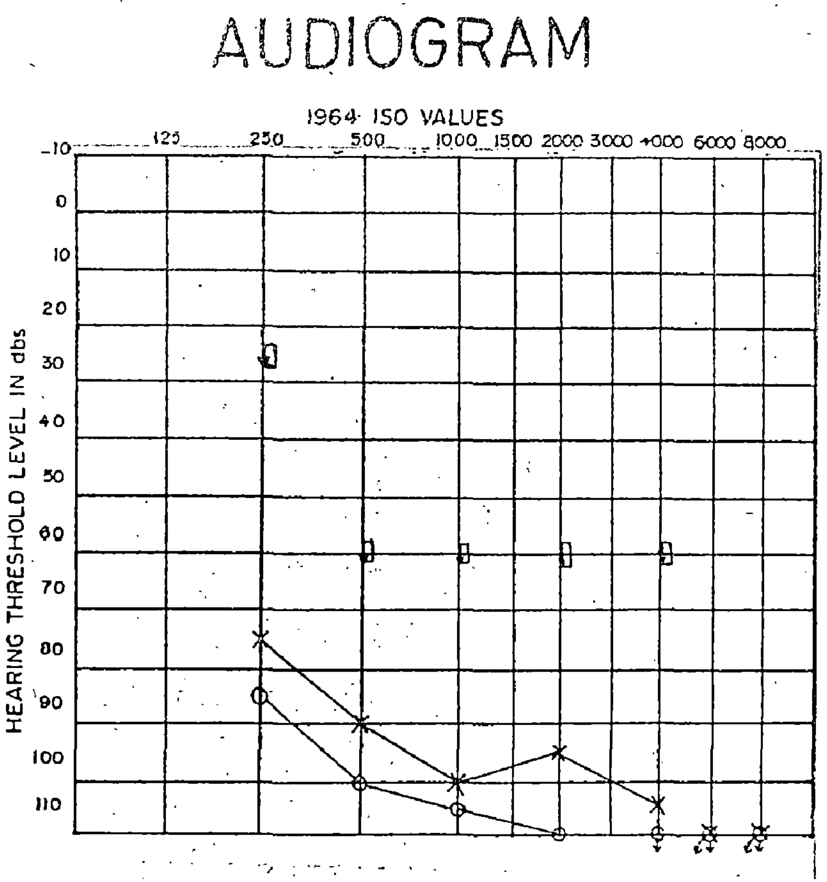


FIG.40

1) BILATERAL SEVERE SENSORI-NEURL DEAFNESS
2) POOR SPEECH DISCRIMINATION AND PRESENCE OF RECRUITMENT.
3) GRADUAL HIGH FREQUENCY DEAFNESS CHANGING INTO PROFOUND NERVE LOSS AT HIGH FREQUENCIES.
4) DRUG INDUCED OR CONGENITAL

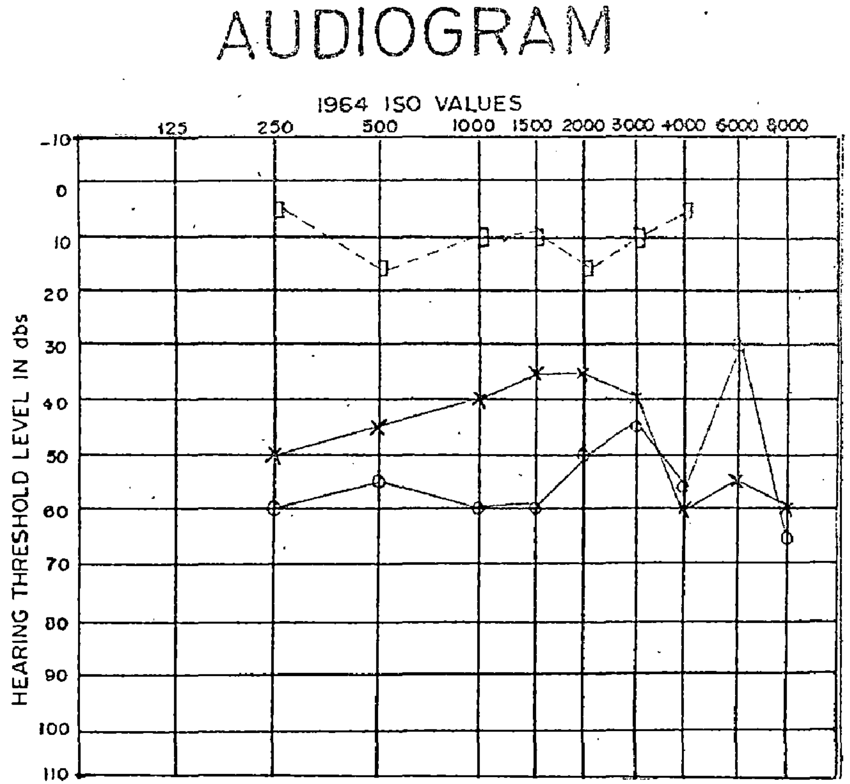


FIG.41

1)OTOSCLEROSIS
2)LOW CONSERVATIONAL SPEECH AT A DISTANCE OF MORE THAN 5 FEET CANNOT BE HEARD
3)MODERATE HEARING LOSS,BILATERAL
4)OSSICULAR DISCONTINUITY
5)INCOMPLETE STPES FIXATION,FREE FROM SN HEARING LOSS
6)HISTORY OF TINNITUS

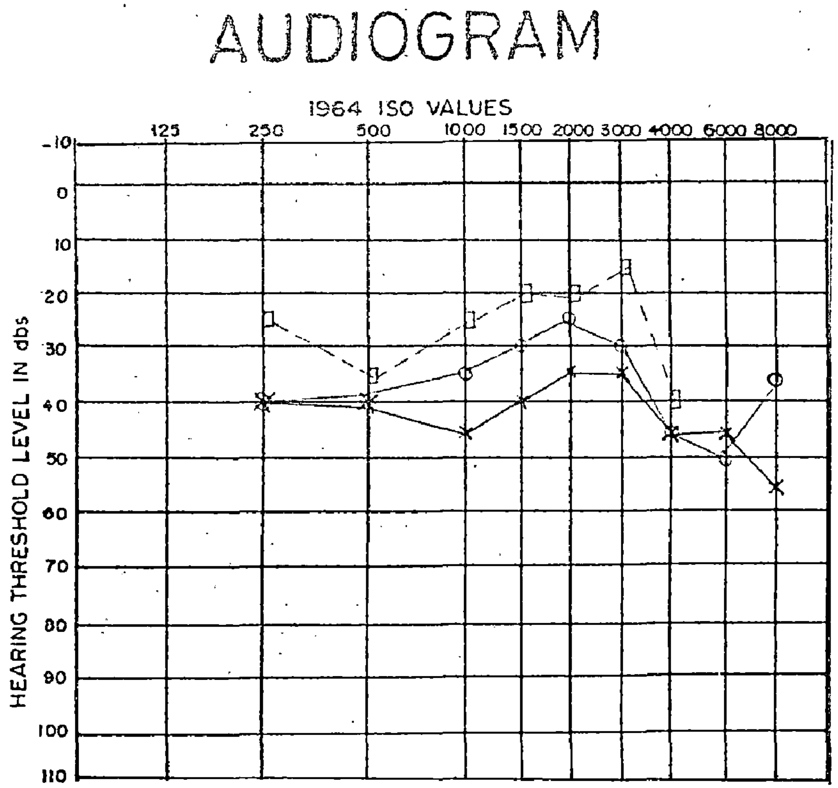


FIG 42.

1)DIP AT 4KHz FOR BOTH AC AND BC
2)NOISE INDUCED MILD HEARING LOSSS,BILATERAL
3)OTOSCLEROSIS WITH COCHLEAR INVOLVEMENT
4)TYPICAL MECHANICAL DISTORTION OF THE BC AUDIOGRAM.
5)HISTORY OF TINNITUS AND EXPOSURE TO HIGH INTENSITY NOISE.

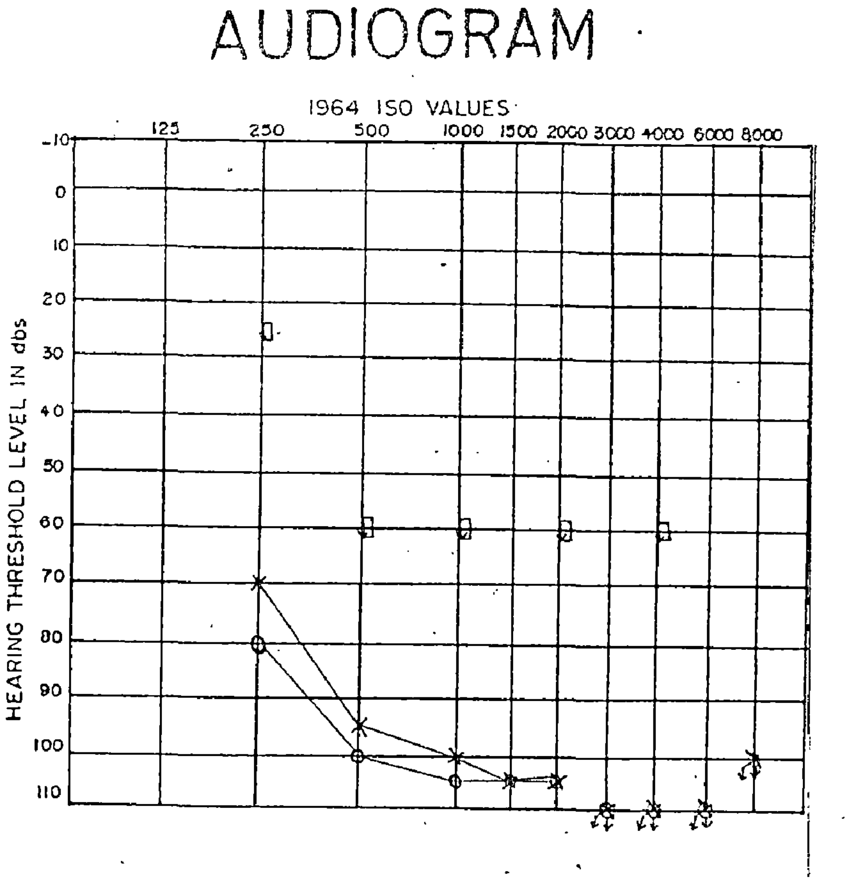


FIG.43.

1)BILATERAL,SEVERE NERVE-LOSS OFHEARING.
2) PRESENCE OF RECRUITMENT
3)MAY HEAR LOUD SOUND BUT CANNOT RELY ON HEARING FOR COMMUNICATION
4)VIRAL DISEASE OR DRUG INDUCED,AT BIRTH

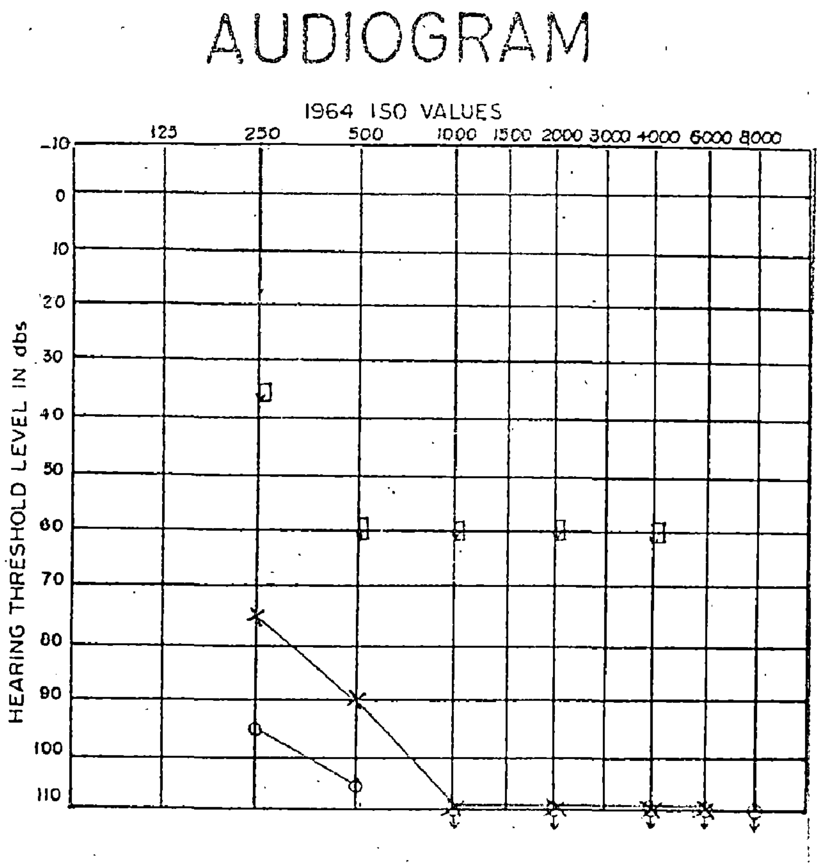


FIG.44

1)UNILATERAL PROFOUND SENSORI-NEURAL LOSS
2)FLAT FREQUENCY HEARING LOSS SENSORY TYPE
3)PRESENCE OF RECRUITMENT
4)HISTORY OFVERTIGO
5)CONGENITAL NERVE DEAFNESS

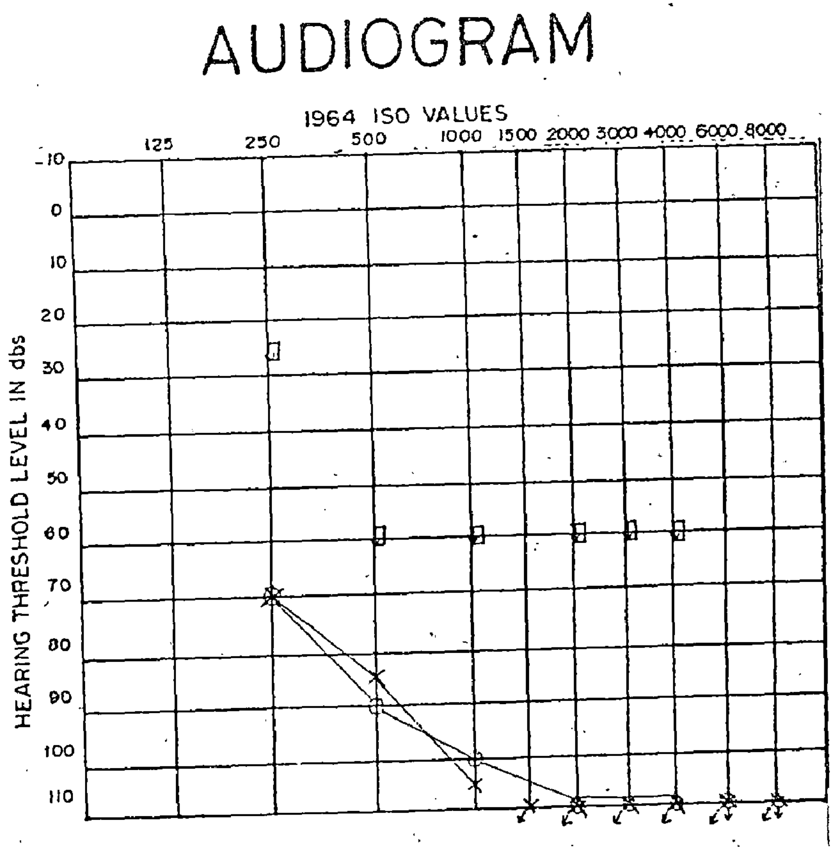


FIG.45

1)VERY POOR SPEECH DISCRIMINATION AND RECRUITMENT
2)SEVERE UNILATERAL NERVE DEAFNESS
3)HEARING LOSS SINCE BIRTH,VIRAL DISEASE
4)HISTORY OF MARKED VESTIBULAR HYPOACTIVITY

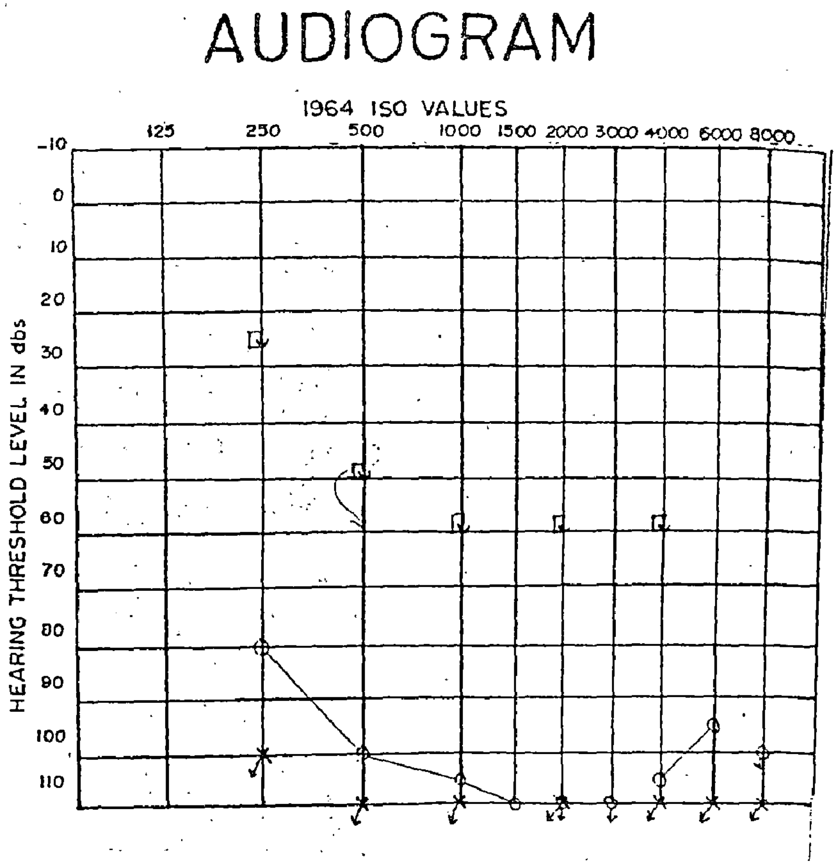


FIG.46

1)UNILATERAL PROFOUND SN HEARING LOSS
2)DISTORTED HAIR CELLS IN THE RIGHT EAR COCHLEA DUE TO
SEVERE PERSISTING ACOUSTIC TRAUMA OR DRUG EXCESS
3)HISTORY OF VERTIGO AND VOMITTING
4)LEFT EAR COCHLEAR COMPLETE DISTORTION.
5)MATERNAL RUBELLA OR MALINGERER

AUDIOGRAM

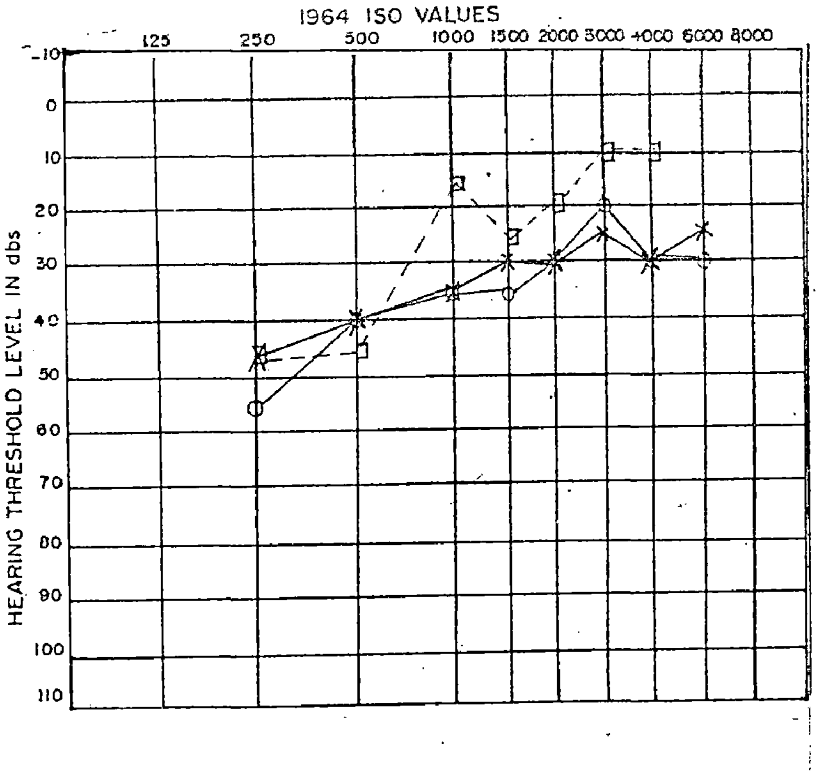


FIG.49

1)LOW FREQUENCY CONDUCTIVE HEARING LOSS,MILD
2)EARLY STAGE OF MENIERE"S DISEASE SUSPECTED.
3)OSSICULAR DISCONTINUITY
4)HARD OF HEARING CONVERSATION
5)HISTORY OF HYPERTENSION AND TINNITUS WITH VERTIGO
6)FUNCTIONS AS A USUALLY NORMAL EAR

AUDIOGRAM

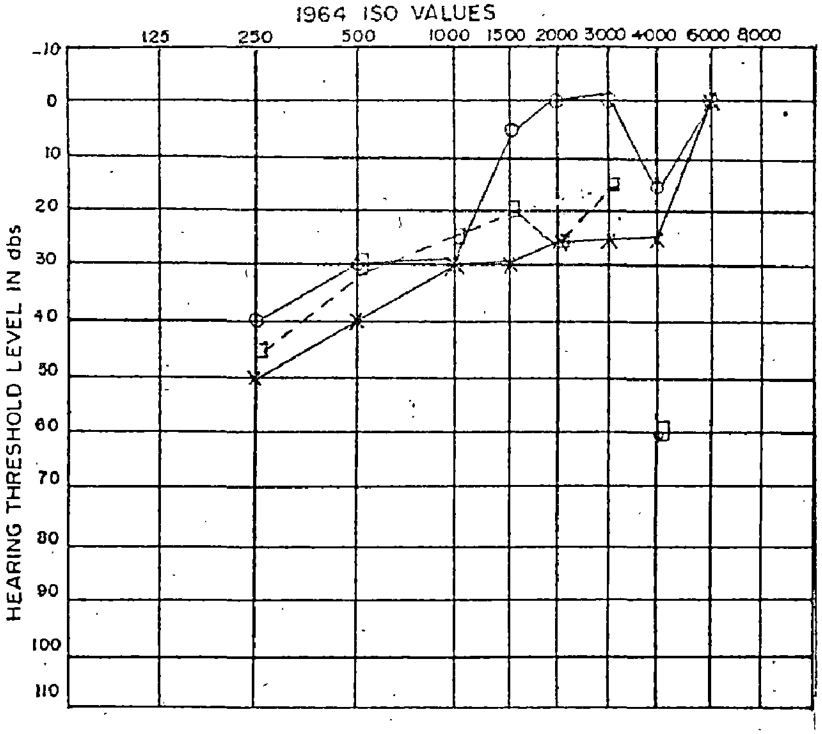


FIG.50

1)BILATERAL,LOW TONE CONDUCTIVE HEARING LOSS,MILD
2)SUFFERING FROM NOISE INDUCED HARDNESS IN HEARING
3)PARTIAL OTOSCLEROSIS.
4)A NEAR NORMAL EAR.

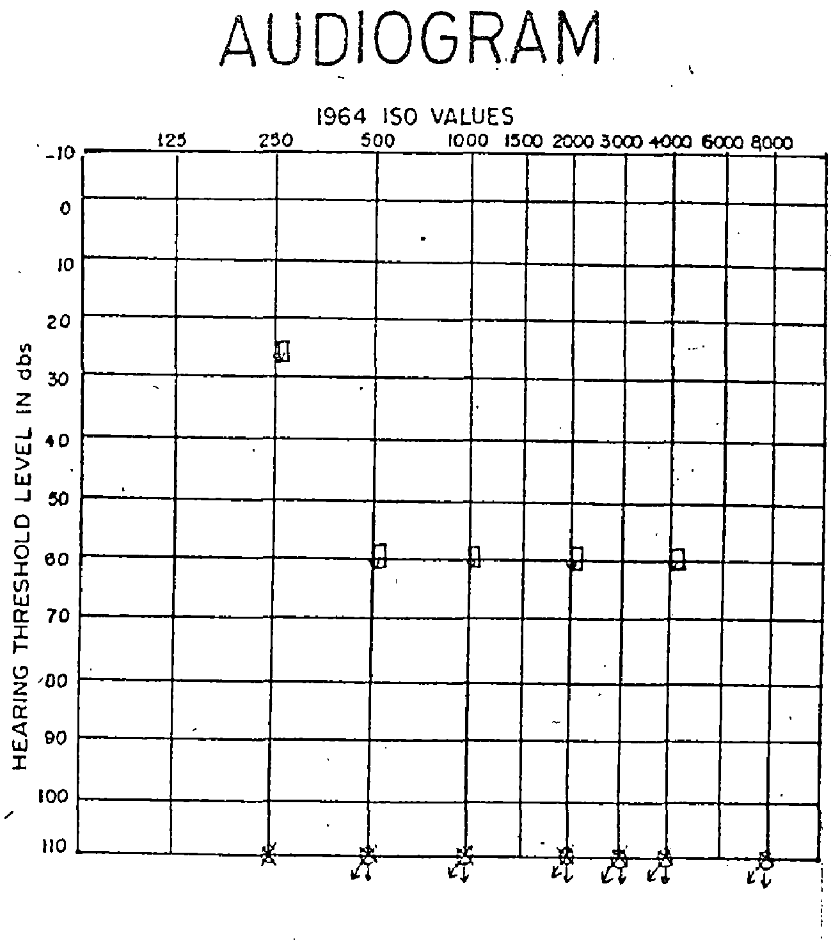


FIG.51

1)TOTAL NEURAL DEAFNESS,CONGENITAL,BILATERAL

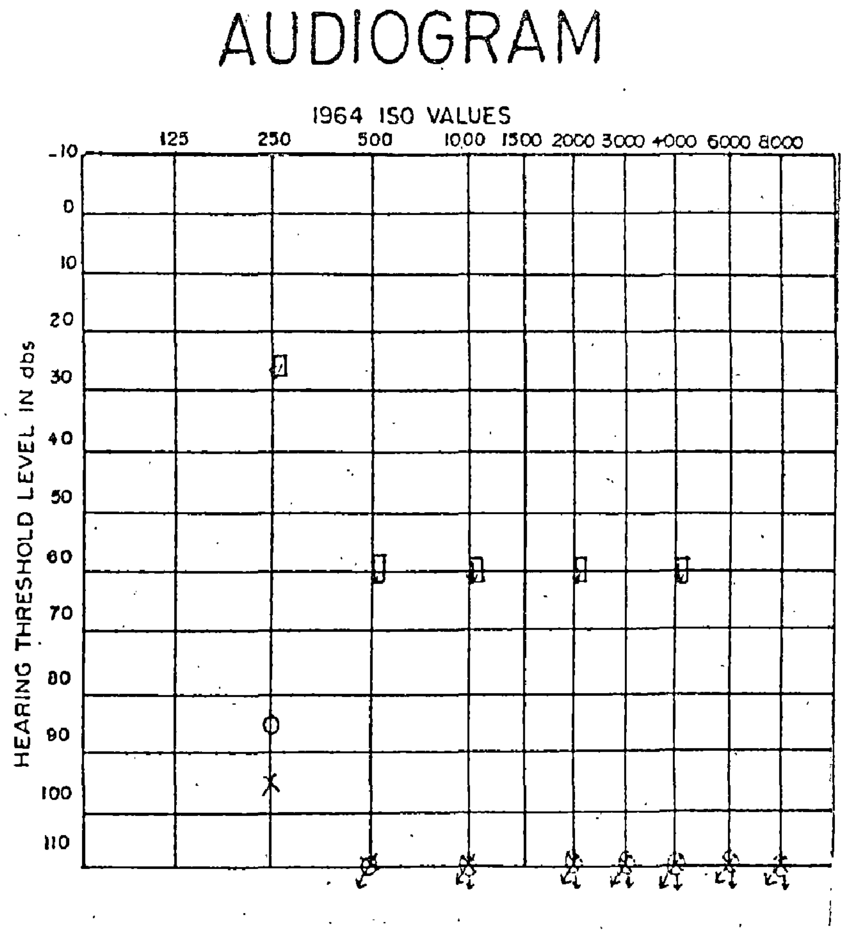


FIG.52

1)BILATERAL PROFOUND SENSORI-NEURAL LOSS

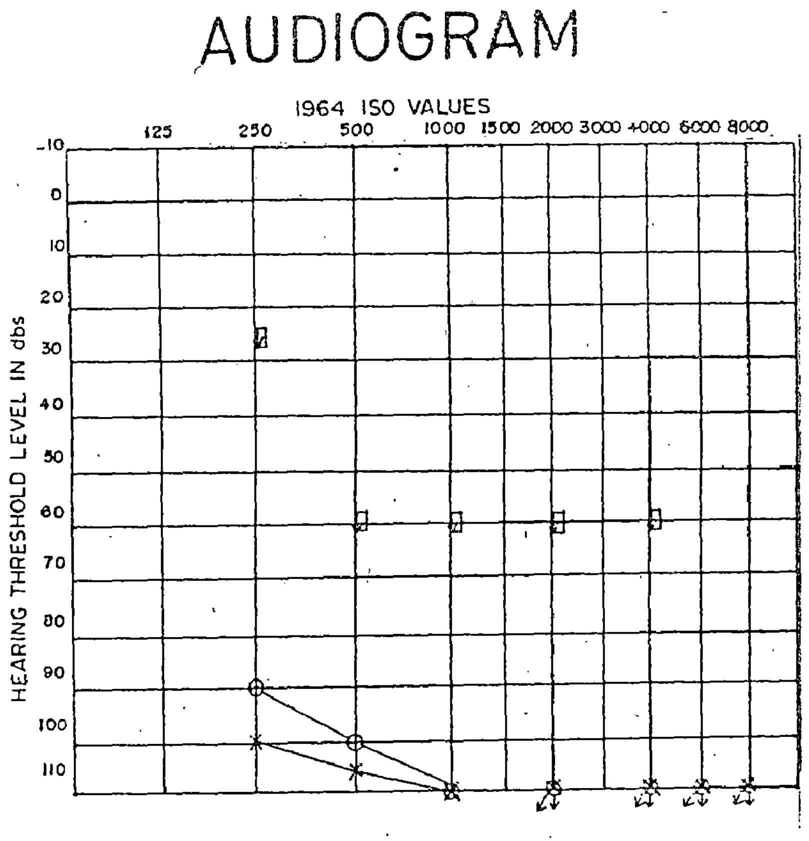


FIG.53

1)TOTAL LOSS AT HIGH FREQUENCIES

2)NERVE DEAFNESS

3)VERY POOR SPEECH DISCRIMINATION AT ULTRA-INTENSE SOUND JUST NEAR THE EARS

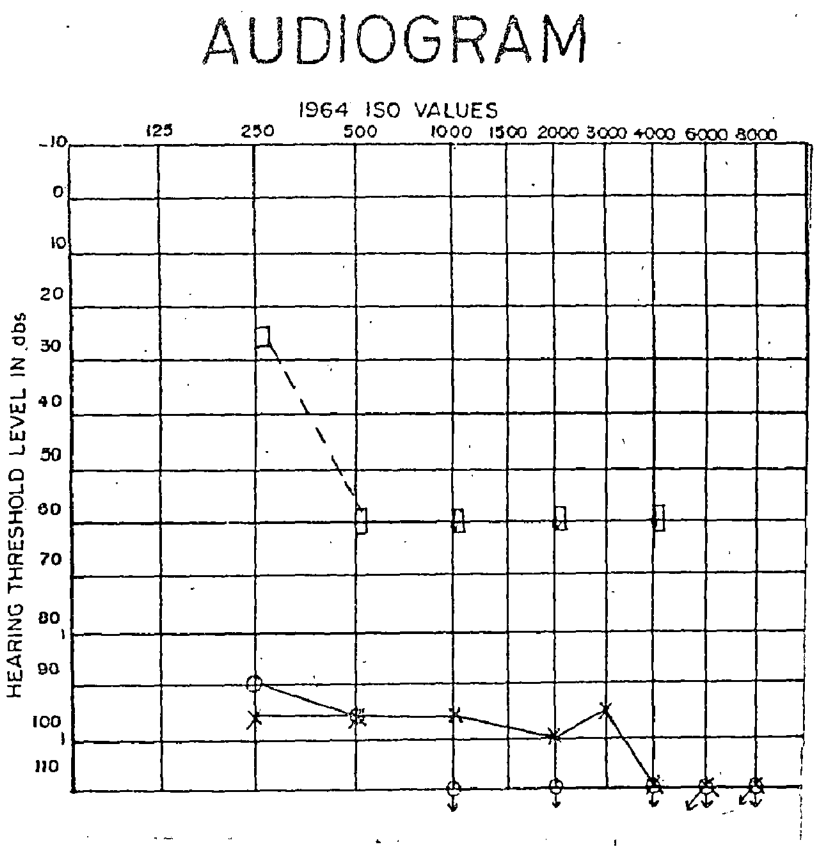


FIG.54

1)ADVANCED STAGE OF MENIERE"S SYNDROME SUSPECTED.

2)SEVERE HEARING LOSS,NEURAL

3)ACCOMPANIED BY VESTIBULAR MISFUNCTIONING AND PRESENCE OF RECRUITMENT

4)HISTORY OF SEVERE VERTIGO

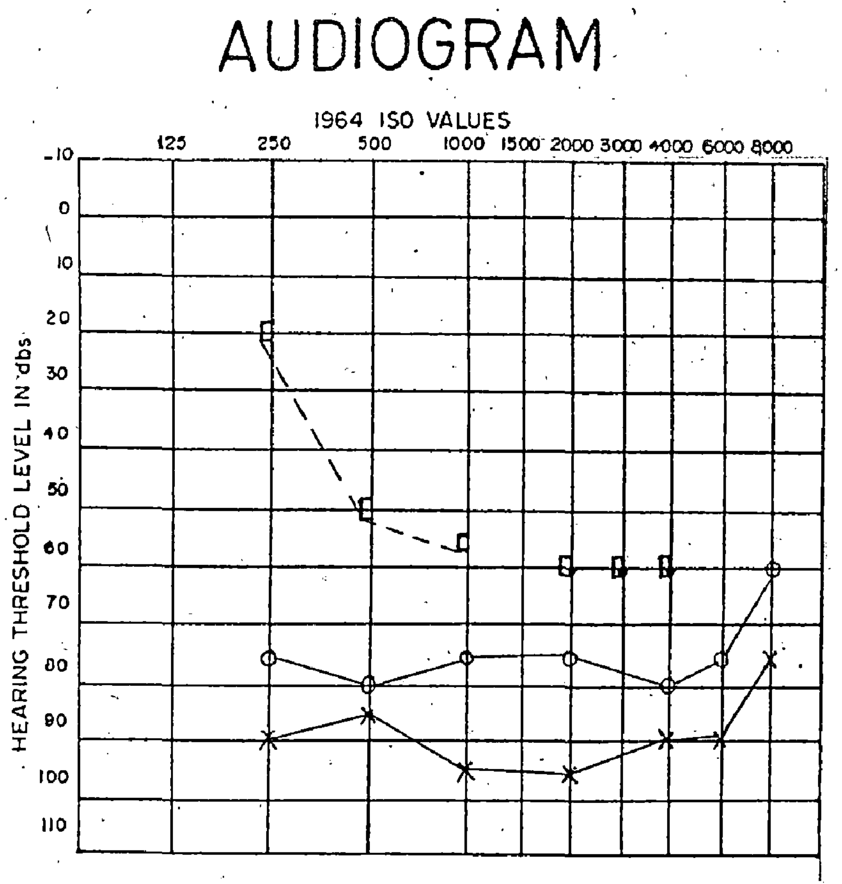


FIG.55

1)MARKED LOSS OF BILATERAL AC HEARING
2)SEVERE OTOSCLEROSIS,COMPLETE STAPES FIXATION
3)FREE FROM SN HEARING LOSS
4)SAUCER SHAPED AUDIOGRAM
5)MATERNAL RUBELLA INDUCED LOSS.

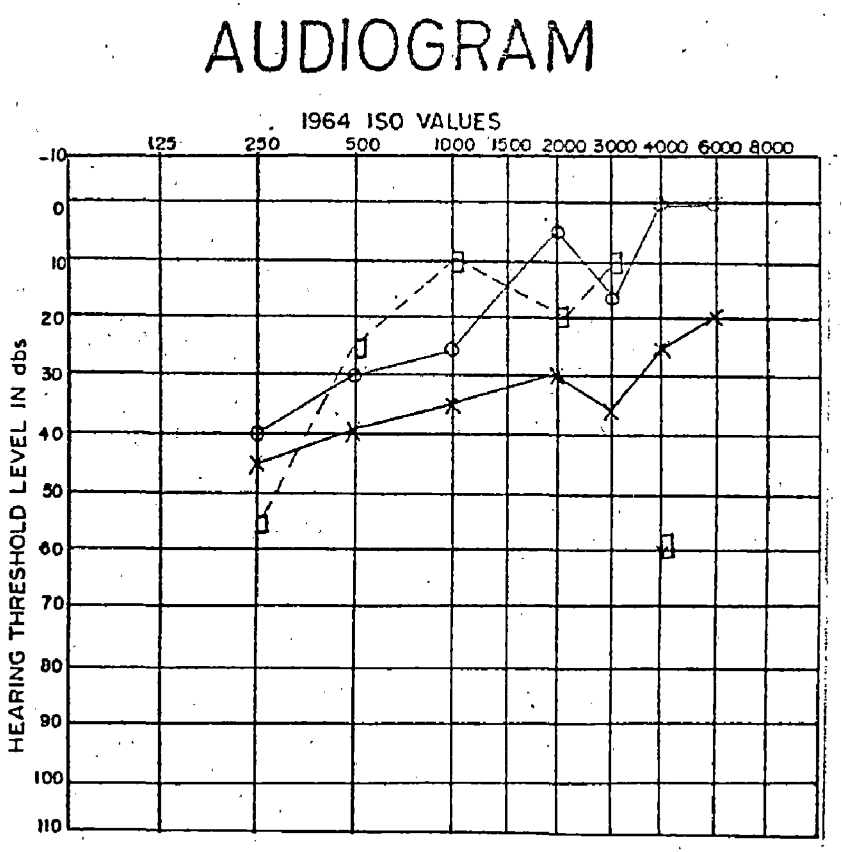


FIG.56

1)DISTORTION IN OSSICULAR CHAIN
2)MILD LOW TONE AC LOSS
3)EARLY STAPES FIXATION FOR LOW TONES
4)DIFFICULTY IN DISCRIMINATING FAINT SPEECH
5)USUALLY NORMAL HEARING WITH SLIGHTLY NOTICEABLE HEARING HARDNESS

AUDIOGRAM

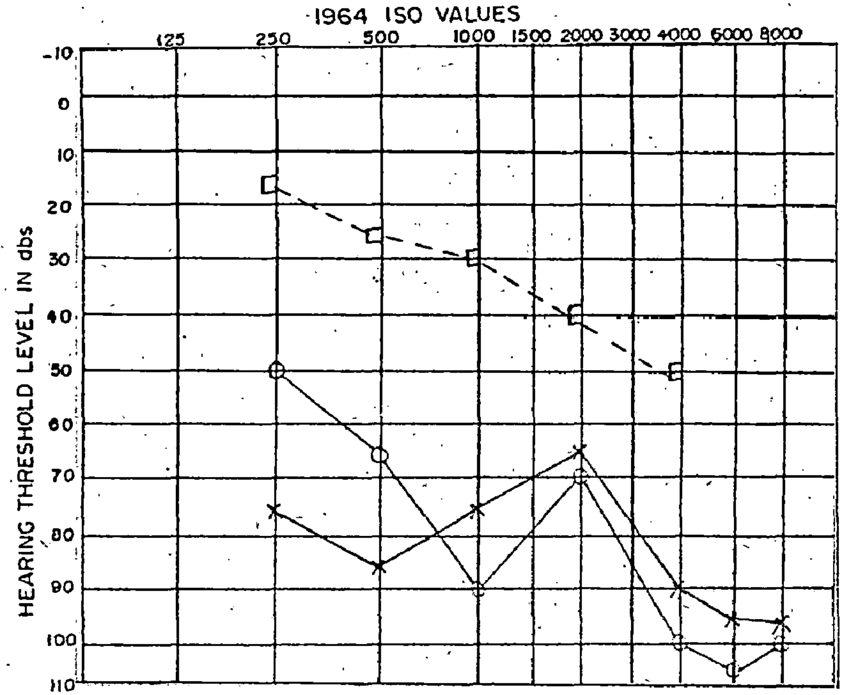


FIG.57

1)SEVERE AC LOSS FOR HIGH TONES
2)OTOSCLEROSIS WITH COCHLEAR IMPAIREMENT INVOLVED
3)MODERATE MIXED HEARING LOSS
4)DIFFICULTY IN HEARING CONVERSATIONAL SOUNDS
5)NEURAL PRESBYCUSIS SUSPECTED.

AUDIOGRAM

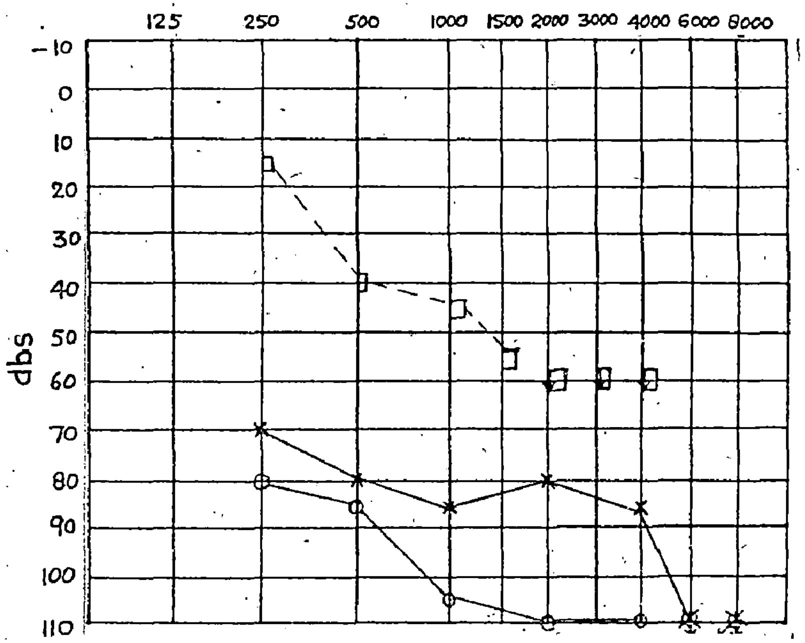


FIG.58

1)BILATERAL MIXED PROFOUND HEARING LOSS
2)SEVERE OSSICULAR DISTORTION WITH COCHLEAR INVOLVEMENT
3)SEVERE LOSS OF AC HEARING
4)TOTAL DEAFNESS BEYOND 4KHz
5)HEARING LOSS SINCE BIRTH

AUDIOGRAM

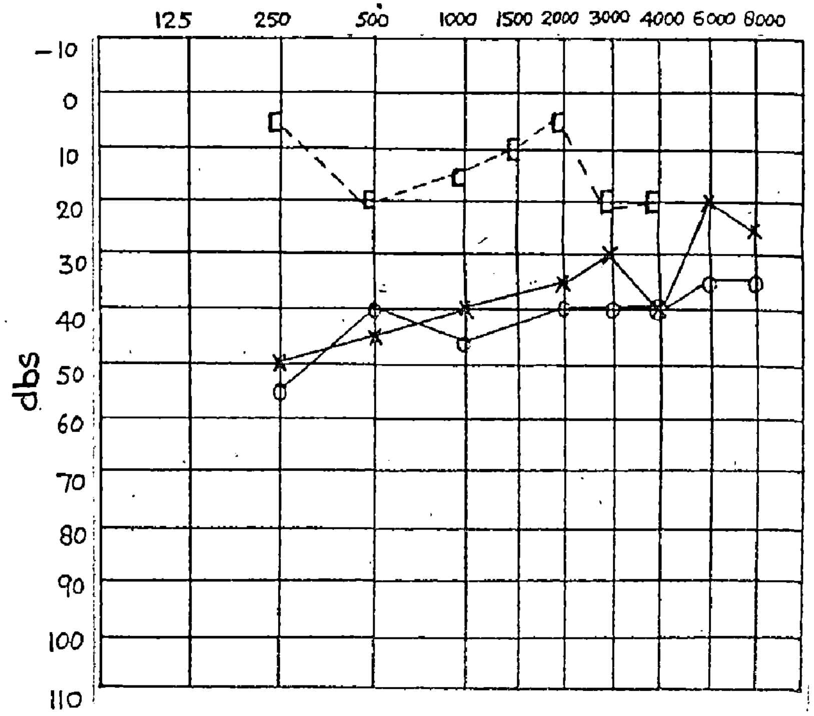


FIG.59

1)DISCONTINUITY IN OSSICULAR CHAIN

2)BILATERAL,MILDLY MARKED AC LOSS FOR LOW TONES

3)FREE FROM SN LOSS

4)MILD CONDUCTIVE DEAFNESS

5)HARD OF HEARING CONVERSATIONAL SPEECH.

AUDIOGRAM

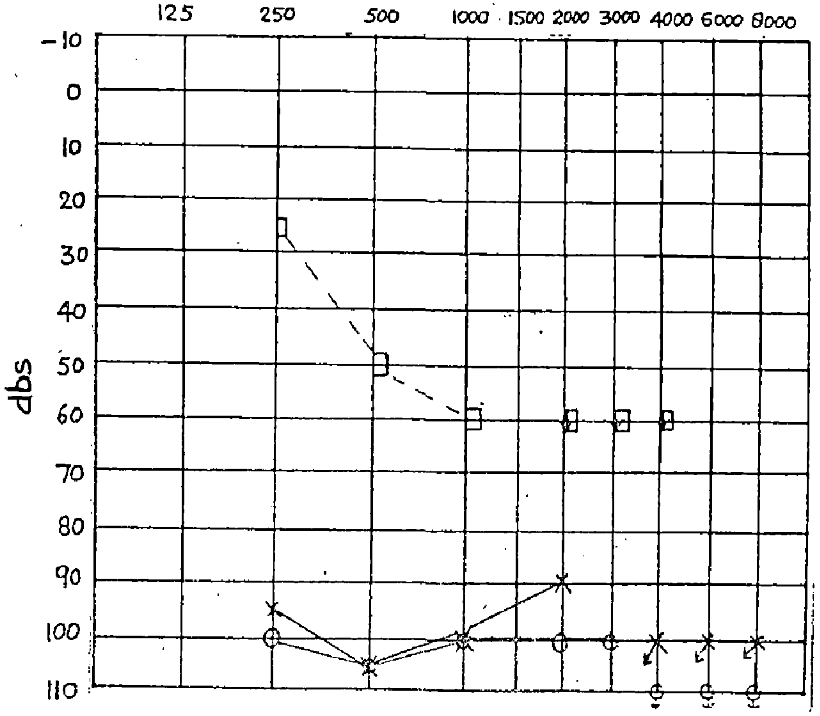


FIG.60

1)BILATERAL MIXED PROFOUND HEARING LOSS

2)TOTAL DEAFNESS BEYOND 3KHz

3)SEVERE OTOSCLEROSIS,COMPLETE STAPES FIXATION

4)POOR SPEECH DISCRIMINATION AT VERY LOUD SOUND.

5)HISTORY OF RE-OCCURING SEVERE VERTIGO.

AUDIOGRAM

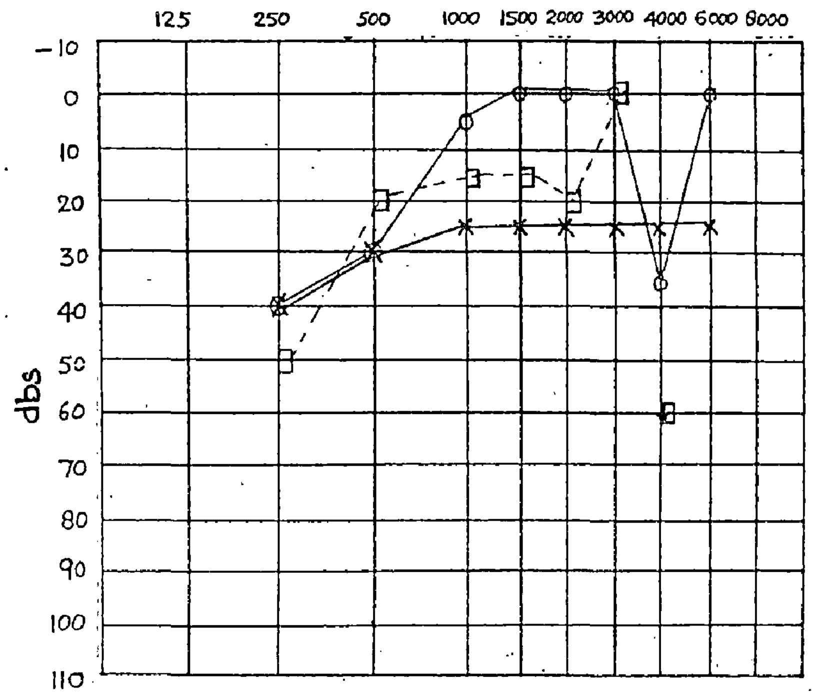


FIG.61

1)DIP AT 4KHz FOR BC AND RIGHT EAR AUDIOGRAM
2)MILD CONDUCTIVE HEARING LOSS FOR LOW FREQUENCIES.
3)RIGHT EAR BETTER THAN LEFT EAR EXCEPT FOR THE DISCREPANCY AT 4KHz.
4)NOISE INDUCED HARDNESS IN HEARING.

AUDIOGRAM

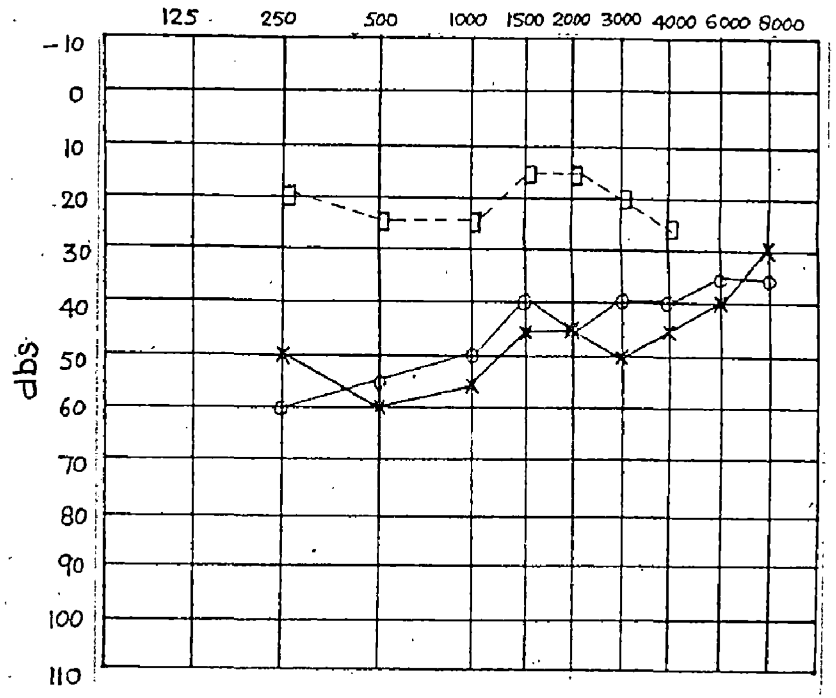


FIG.62

1)MECHANICAL DISTORTION OF THE BC AUDIOGRAM
2)MODERATE CONDUCTIVE DEAFNESS,BILATERAL
3)CAPACITY OF HEARING CONVERSATION NEAR TO THE EARS
4)FREE FROM NERVE LOSS

AUDIOGRAM

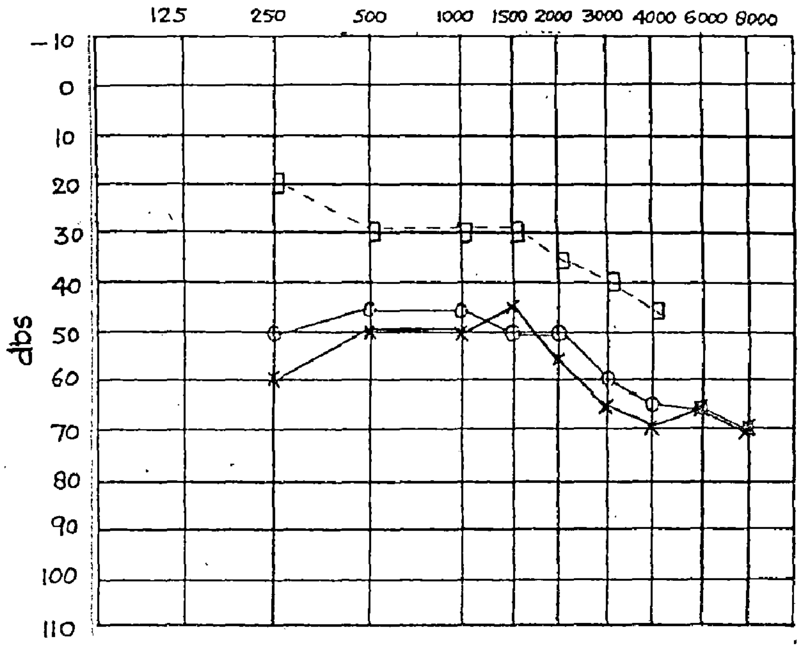


FIG.64

1)HISTORY OF TINNITUS

2)PARTIAL HIGH FREQUENCY LOSS IN BC HEARING

3)MODERATELY SEVERE CONDUCTIVE LOSS, BILATERAL

4)SEVERE HIGH TONE LOSS IN AC HEARING.

AUDIOGRAM

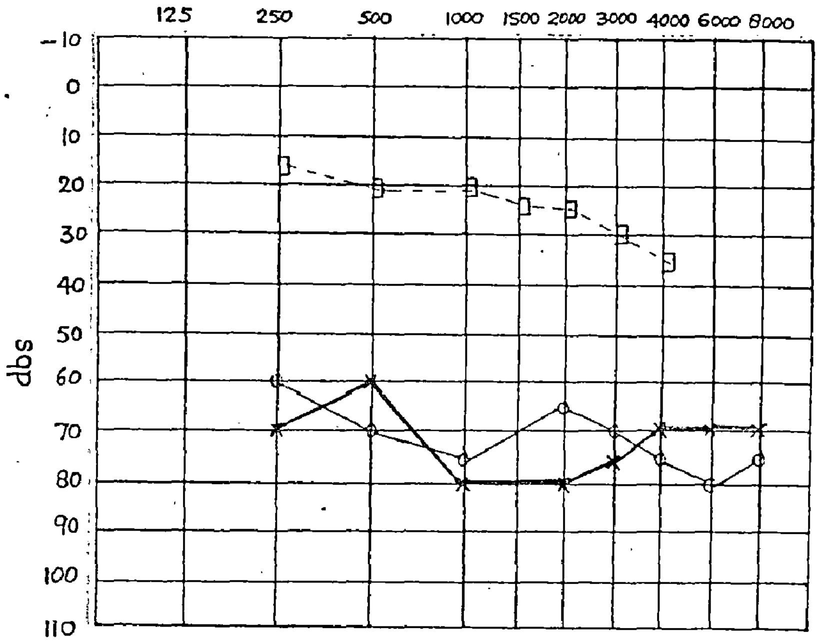


FIG.63

1)MILD :HIGH FREQUENCY LOSS IN BC AUDIOGRAM

2)BILATERAL,SEVERE CONDUCTIVE HEARING LOSS

3)FREE FROM NERVE DEAFNESS

4)SEVERE LOSS BOTH AT HIGH AND LOW FREQUENCIES IN AC AUDIOGRAM

AUDIOGRAM

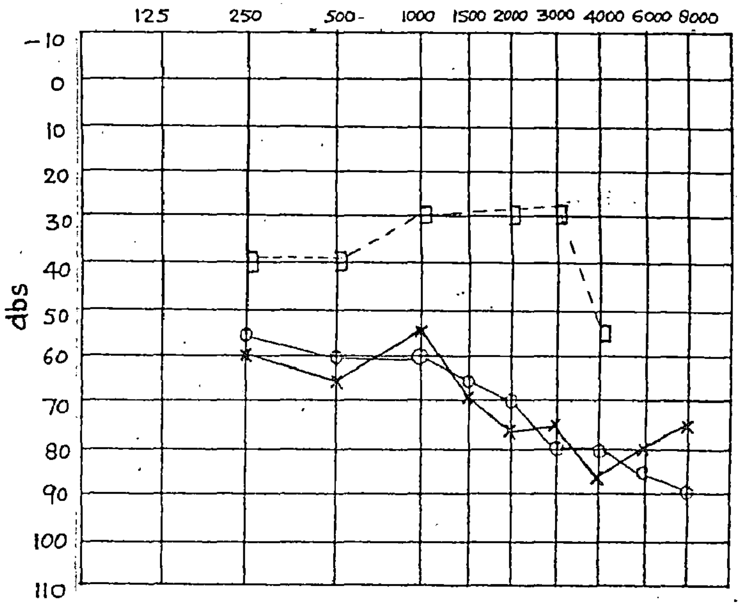


FIG.65

1)OTOSCLEROSIS,WITH DIP AT 4KHz IN THE BC AUDIOGRAM
2)HIGH TONE LOSS FOR BOTH EARS
3)SEVERE LOSS IN AC HEARING
4)MILD LOSS IN BC HEARING FOR LOW TONES
5)POOR SPEECH DISCRIMINATION SINCE CHILDHOOD

AUDIOGRAM

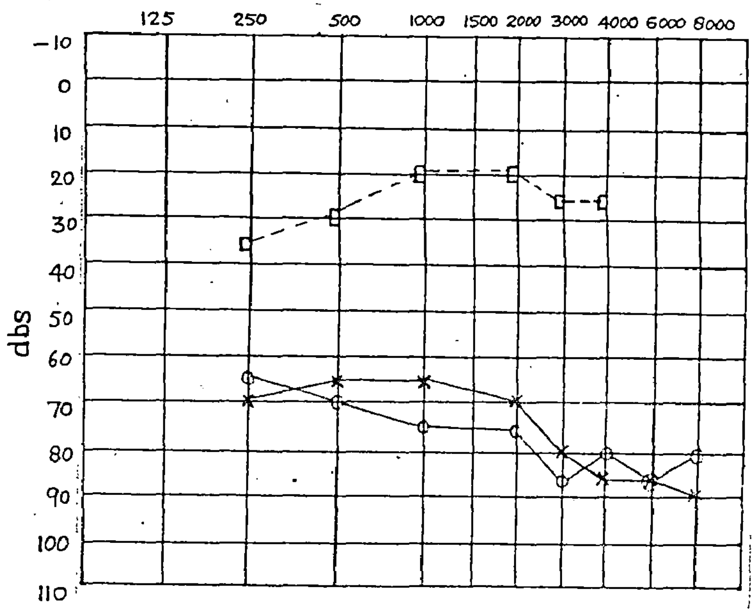


FIG.66

1)BILATERAL,SEVERE CONDUCTIVE LOSS
2)MILD OTOSCLEROSIS
3)FREE FROM SN LOSS
4)HISTORY OF VERTIGO

AUDIOGRAM

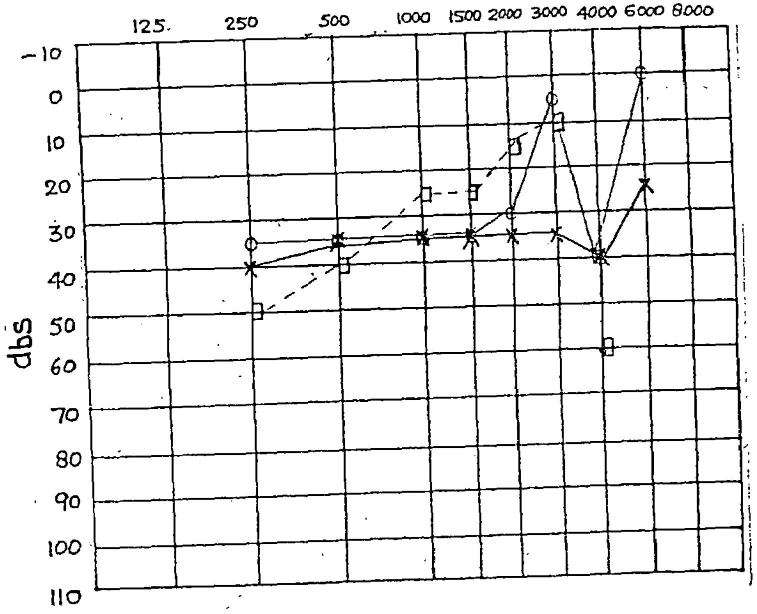


FIG.67.

1)BILATERAL LOW TONE,MILD,CONDUCTIVE HEARING LOSS

2)PARTIAL OTOSCLEROSIS WITH COCHLEAR INVOLVEMENT

3)DIP AT 4KHz FOR BOTH AC AND BC

4) HISTORY OF HARDNESS IN HEARING SINCE CHILDHOOD.

AUDIOGRAM

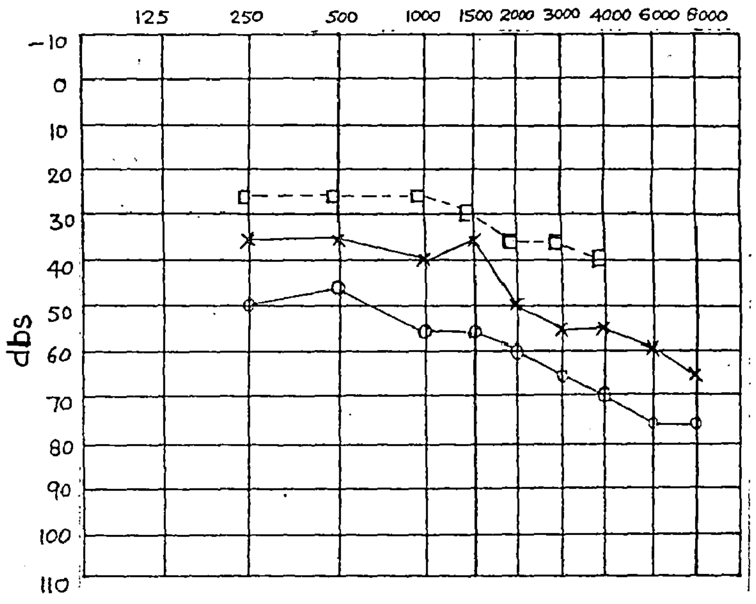


FIG.68

1)MODERATELY SEVERE,BILATERAL CONDUCTIVE HEARING LOSS

2)HIGH FREQUENCY LOSS IN BOTH THE EARS,SEVERE

3)MILD HIGH FREQUENCY LOSS IN BC HEARING

4)HISTORY OF EARACHE

AUDIOGRAM

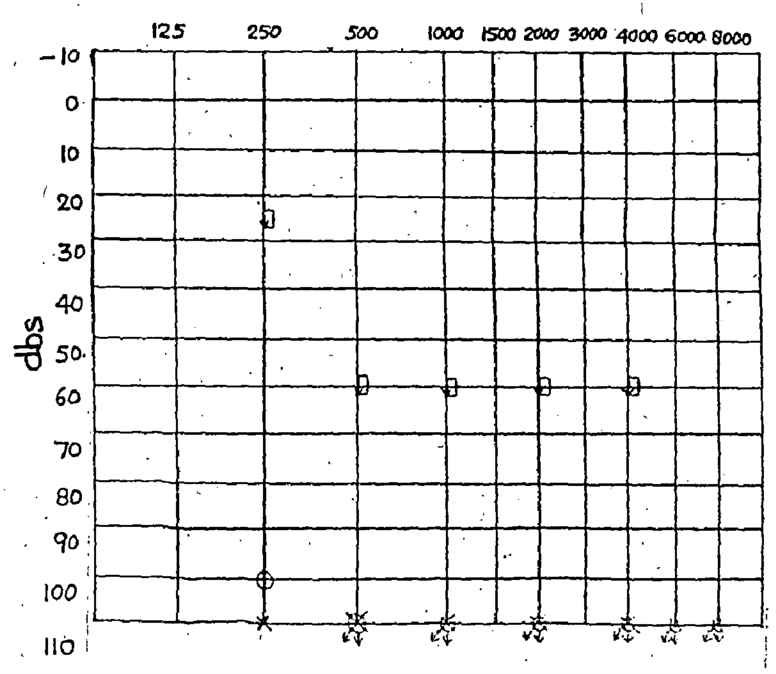


FIG.69

TOTAL NERVE DEAFNESS

AUDIOGRAM

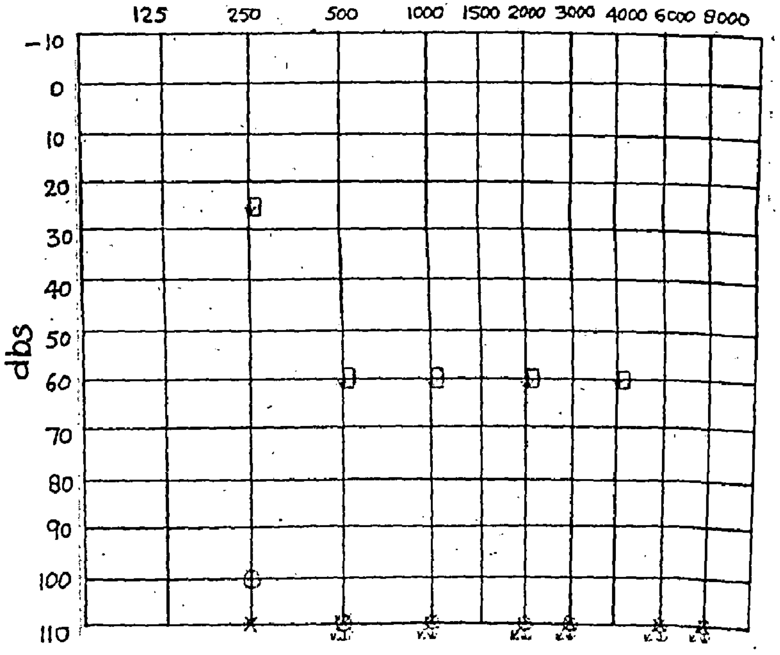


FIG.70

COMPLETE NERVE DEAFNESS

AUDIOGRAM

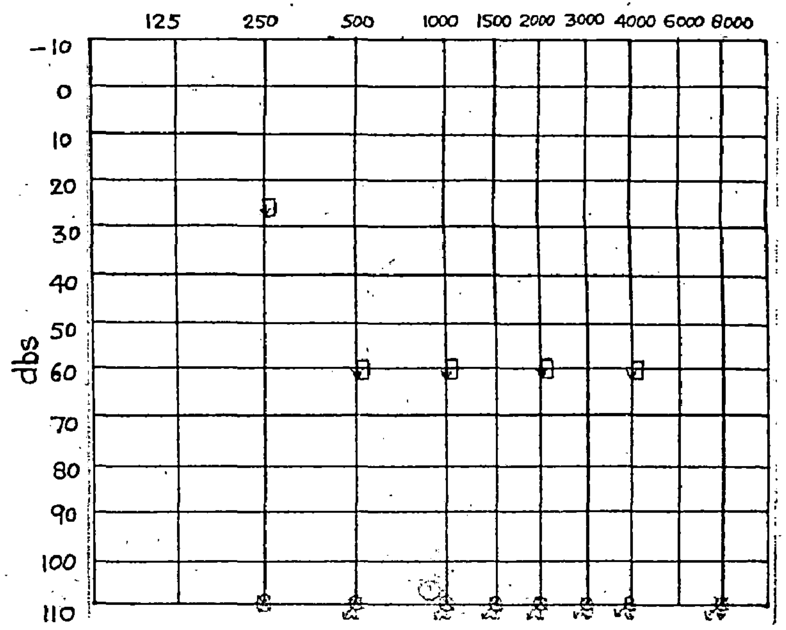


FIG.72

PROFOUND SENSORI NEURAL LOSS

AUDIOGRAM

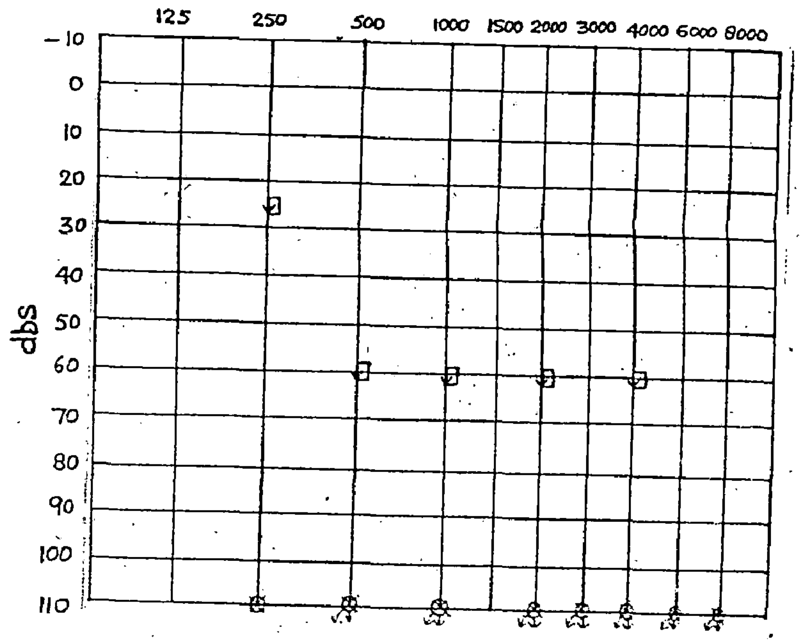


FIG.71

COMPLETE LOSS OF HEARING ABILITY

AUDIOGRAM

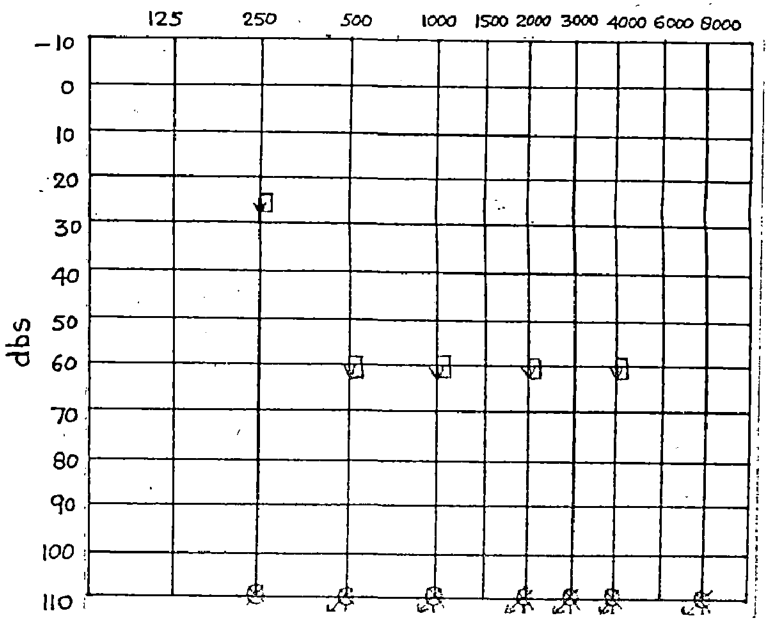


FIG.73

1)COMPLETE LOSS OF HEARING ABILITY

AUDIOGRAM

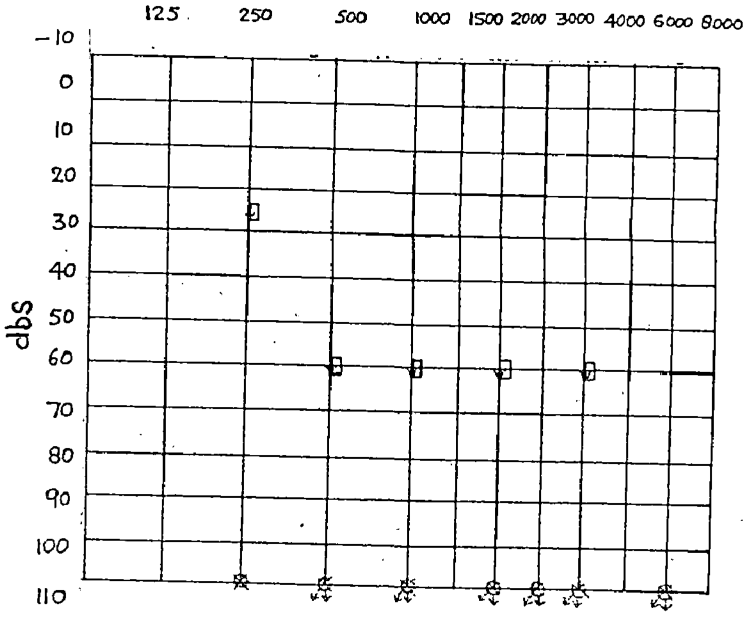


FIG.74

1)TOTAL NEURAL DEAFNESS

AUDIOGRAM

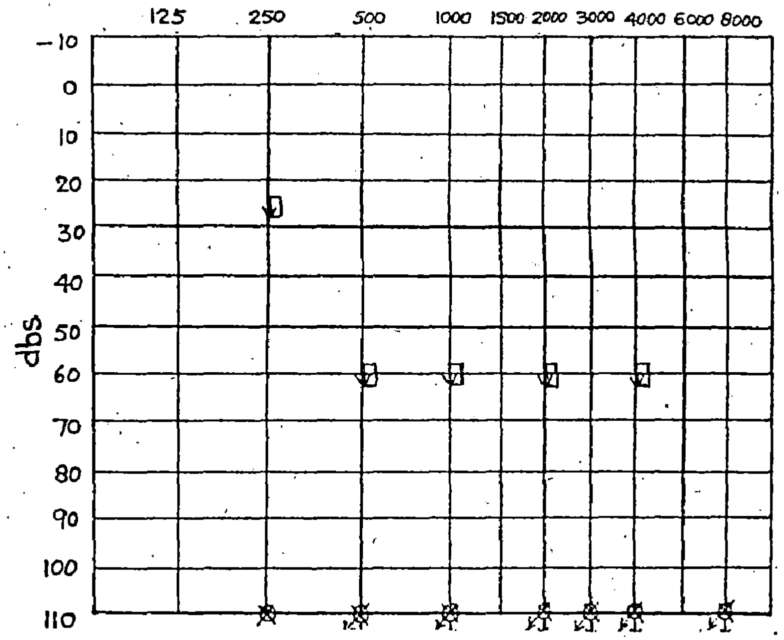


FIG.75

PROFOUND SENSORI NEURAL LOSS

AUDIOGRAM

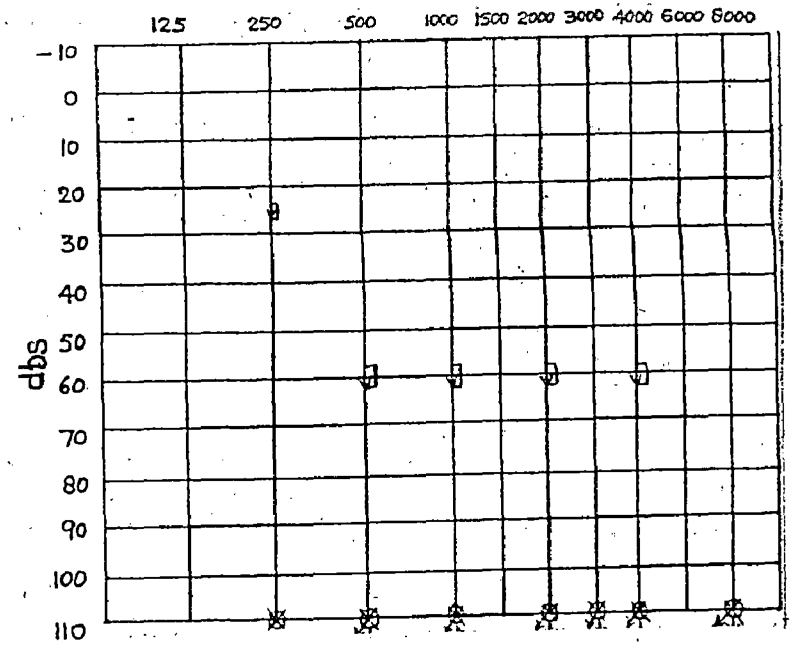


FIG.76

1) PROFOUND SENSORI NEURAL LOSS

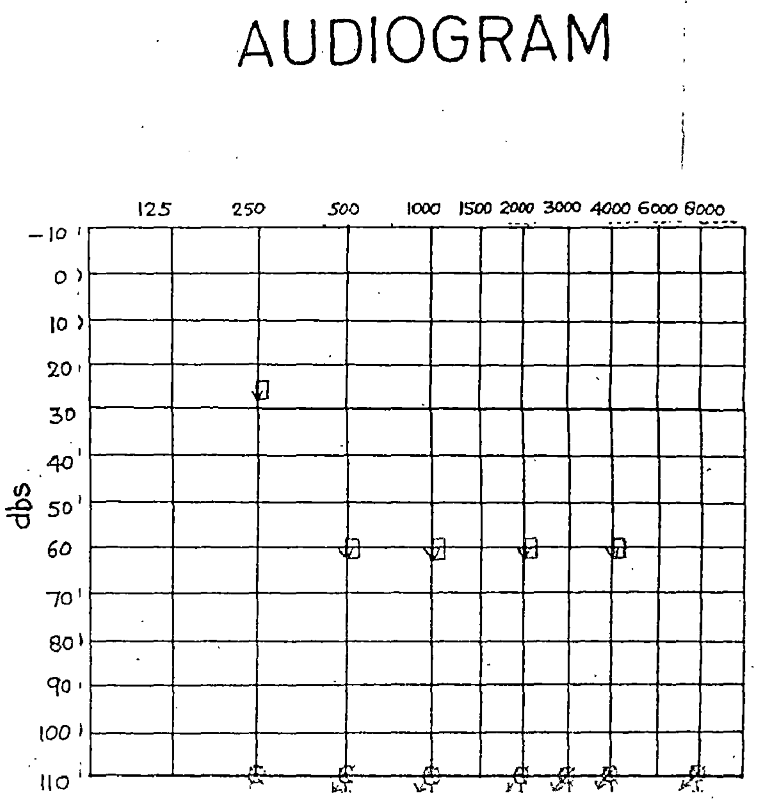


FIG.77

COMPLETE LOSS OF HEARING

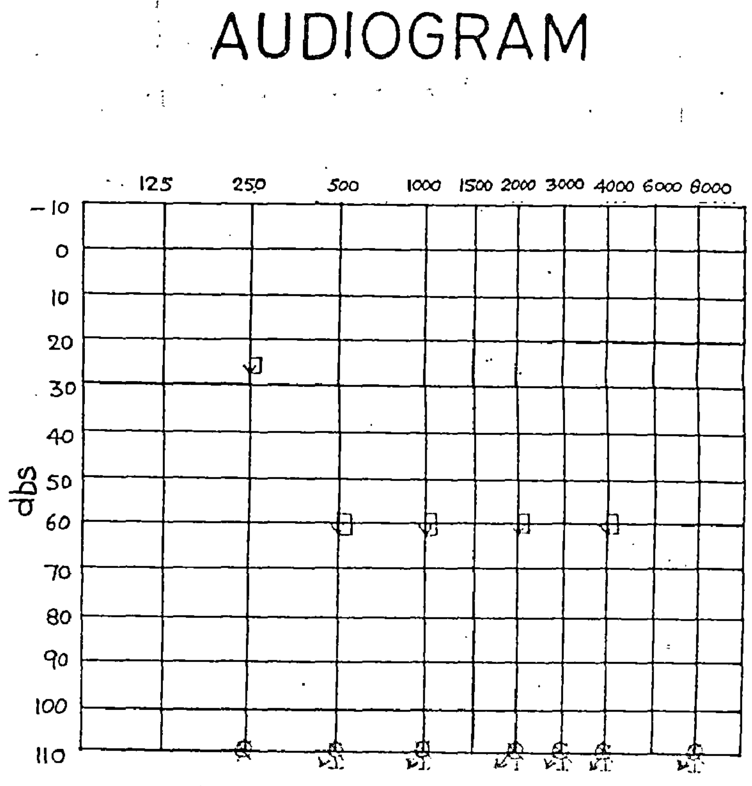


FIG.78

TOTAL NEURAL LOSS

AUDIOGRAM

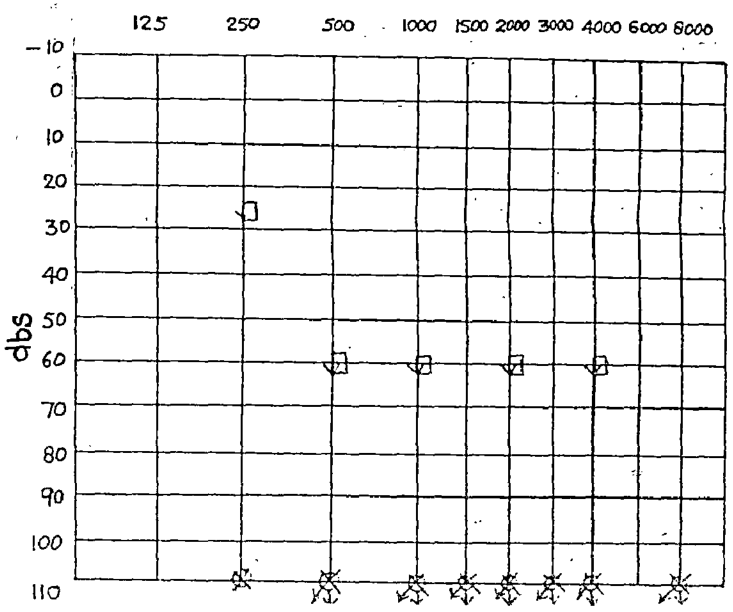


FIG.79

COMPLETE SENSORI-NEURAL LOSS

CHAPTER-VII

CONCLUSION AND SCOPE OF FURTHER DEVELOPMENT

Appendix I

Gaussian Statistics

The Gaussian or normal probability density is one of the most important in analysis of errors and to judge the validity of measured data. Also, a Gaussian representation is often more convenient to manipulate mathematically. The Gaussian density function has a bell-shaped appearance and is defined by,

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(x - \bar{x})^2}{2\sigma^2}\right] \qquad \text{....(i)}$$

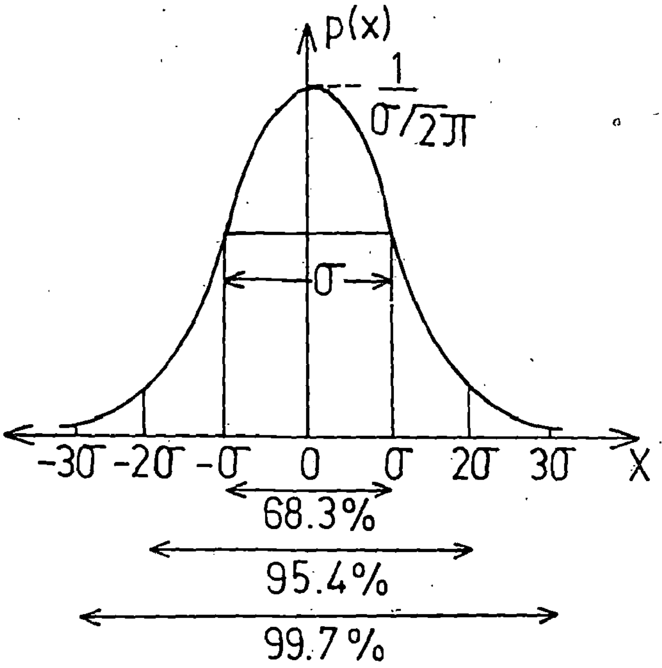
where exp [ ] is the exponential function, and the parameters have been adjusted to satisfy the normalizing condition of equation (ii) below,

$$\int_{-\infty}^{\infty} p(x)\, dx = 1 \qquad \text{....(ii)}$$

If we have N observations x_1 to x_N, x may have a continuous range of values and it is convenient and also necessary to quantize these N results into regions of width Δx. The frequency (f) of occurrence that the result or data x_n (where n = 1, 2, ——— N) lies within a given region is simply the number of times that x_n falls within that region.

The probability density function p(x) is then defined as

$$p(x) = \lim_{\substack{\Delta x \to 0 \\ N \to \infty}} \frac{(\text{number of values in range } \Delta x \text{ at } x)/\Delta x}{\text{total number of values} = N}$$



GAUSSION DENSITY DISTRIBUTION

The probability that a particular measured value lies within the infinitesimal width dx centered at x is simply p(x)dx. By definition the p.d.f. is positive. Since every measurement must yield some value, the integral of the probability density over all values of x must be equal to unity i.e. equation (ii).

The p.d. of the sum of a large number of independently distributed quantities approaches the Gaussian probability density function no matter what the individual distributions may be, provided that the contribution of any one quantity is not comparable with the resultant of all others. This is the central limit theorem. Another property of the Gaussian distribution is that no matter how large a value of x we may choose, there is always a finite propability of finding a greater value. However, the probability diminishes rapidly with increasing x, and for all practical purposes the probability of obtaining an exceedingly high value of x is negligibly small.

A Gaussian distribution plot in general is shown in Fig. Referring to equation (i) we have:

(1) x = data points

(2) $\bar{x}$ = arithmatic mean of N observations

$$= \frac{1}{N} \sum_{n=1}^{N} x_n$$

= the best estimate or the most probable value.

(3) σ = Standard Deviation = $(\text{variance})^{1/2}$

therefore,

$$\sigma^2 = \frac{1}{N}\sum_{n=1}^{N}(x_n - \bar{x})^2 = (\overline{x^2}) - (\bar{x})^2$$

= variance

(4) $$p(x)\big|_{max} = \frac{1}{\sigma\sqrt{2\pi}} \text{ at } x = \bar{x}$$

when a Gaussian distribution applies, there is a 68.3 percent probability that a given observation deviation will lie less than ± σ from $\bar{x}$, a 95.4 percent probability that the deviation will be less than ± 2σ from $\bar{x}$, and a 99.7 percent probability that the deviation will be less than ± 3σ from $\bar{x}$. These percentage values are the areas included between the respective σ values for the Gaussian curve shown in the figure.

Appendix II

The Parameter Estimation Technique Theory

In the present work the computer software used is based on the theory of parameter estimation by the method, for system identification, the unknown parameters are to be estimated from a set of data points obtained by measurement in some experimental work. Referring to the work done, the unknown parameters are the eighteen electrical network components of the circuit in Fig. (10) Chapter , and the set of data points are the various points along the sixty audiogram curves.

Considering a multi-input single output static system where $x_1 \ldots\ldots x_k$ are inputs to the system and $a_1, a_2, \ldots\ldots a_m$ are the unknown parameters. Then the output Y of the system can be expressed by the mathematical model as,

$$Y = F(x_1, x_2, \ldots\ldots\ldots x_k, a_1, a_2, \ldots\ldots a_m) \quad \ldots.(i)$$

To estimate the unknown parameters $a_1, a_2, \ldots. a_m$, N sets of inputs $x_k[k = 1 \ldots\ldots k]$ are given to the system and the corresponding outputs $y_i[i = 1 \ldots\ldots N]$ are measured. Expansion of equation (i) by Taylor Series about the initial estimate of unknown coefficients gives:

$$y_1^o = \bar{y}_i + \left[\frac{\partial y_i}{\partial a_1}\right]\Delta a_1 + \left[\frac{\partial y_i}{\Delta a_2}\right]\Delta a_2 + \ldots\ldots\ldots\ldots\ldots\ldots$$

$$+\left[\frac{\partial \bar{y}_i}{\partial a_m}\right]\Delta a_m \qquad \ldots.(ii)$$

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$$\sigma^2 = \frac{1}{N}\sum_{n=1}^{N}(x_n - \bar{x})^2 = (\overline{x^2}) - (\bar{x})^2$$

$= \text{variance}$

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CHAPTER VII

CONCLUSION AND FURTHER SCOPE OF DEVELOPMENT

7.1.0 Conclusion

Electrical modelling in fusion with human physiology has been the basis of present work. The various electrical models were reviewed and only those that would provide and hence promote sufficient information regarding the hearing deficiency classification have been studied. Twenty normal audiograms and forty audiograms, for hearing impaired individuals suffering from varying degrees of hearing inabilities have been recorded. The major defects of the ear were also studied.

A direct comparison and a close resemblance between the impedance characteristics of the network model and the standards of normal hearing threshold was obtained and this analogy was employed to estimate the electrical-network parameters for audiogram-records of normal ears by the method of Least Square Estimation. A definite range of deviation was determined for each of the eighteen network elements with the help of Gaussian Statistical curves. The impedance and hearing threshold analogy was further utilized to identify the electrical network elements for the forty audiograms of diseased individuals. The parameter values that had fallen within the ranges determined by the Gaussian plots were treated as uneffected or normal and those that exceeded the prescribed range were declared representatives of some hearing deficiency.

Finally, the hearing deficiency classification was done on the basis of these seven hundred and twenty estimated electrical network parameters; and some justification was provided as to which parameter deviated in excess for what defect.

7.2.0 Further Scope of Development

Inspite of many persistent efforts and noteworthy achievements, obtaining a perfect replica of the human organs or organisms always ends in endless assumptions and theoretical hypotheses. However fruitful a research may be, anamolies and discrepancies are always a close encounter. Eradication of these creates new ones and hence there is no end to know about human mechanisms.

Likewise, many facts have been ignored or taken for granted in the present work. Perhaps a better network model would be a more reliable one and a few more added 'complex impedances' would enhance further the detailed representation of different parts of the ear. This would enable a clear-cut diagnosis on the basis of parameter estimation, selecting a particular defect by immediately identifying the corresponding particular parameter. A detailed anatomical survey and a series of persistant and consistant efforts for formulating and designing an ideal electrical network model of the human ear, would be the answer.

Also, the hearing deficiency classification done on the basis of presently chosen ear model is very general. It mainly suggests : what is the magnitude range and which are the parameters that are effected for the hearing impaired under certain

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Also, the hearing deficiency classification done on the basis of presently chosen ear model is very general. It mainly suggests : what is the magnitude range and which are the parameters that are effected for the hearing impaired under certain cases. A more critical classification would be on the basis of revised statistics, that means at least a group of five hundred or a thousand individuals need to be surveyed and their audiograms taken. The next step would be to assign definite ranges to these electrical network parameters and hence form a 'set' or 'block' of specific parameters corresponding to a particular disease. An elaborate computer software could then be prepared that would scan the evaluated parameters and detect a certain parameter immediately placing it in the relevant 'block' representing the specified disability.

This technique of disease classification would be totally computerized and would offer a tremendous save of energy and time. To summarize, an on line evaluation of any audiogram would be done, its parameters evaluated and immediately classified under normal or abnormal blocks - thus identifying evidently the accompanying hearing disability.

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$$+\left[\frac{\partial \bar{y}_i}{\partial a_m}\right]\Delta a_m \qquad \ldots.(ii)$$

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