Chapter 9

Otoacoustic Emissions

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Additional information is available at the end of the chapter

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1. Introduction

In this chapter, we present a very special kind of acoustic emissions, coming from inside the cochlea and generated along the basilar membrane by the electro-motile (active) vibrations of outer hair cells of the organ of Corti. They are called OtoAcoustic Emissions (OAE) and are detected in the ear canal by means of microphones which are usually assembled as part of earphone-like probes. Since their discovery by Kemp [1], the study of otoacoustic emissions has become an hot topic both in basic and clinical research, due to OAE unique feature to inform directly about the normal and pathological functions of the cochlear receptors mechanisms, thus like the efficiency of the middle ear transmission chain.

From the signal point of view, the most interesting characteristics of OAE is their broad band frequency spectrum so rousing also a new interest for broad band ear immittance measurements and interpretation [2]. In this respect, this chapter will focus the reader's attention on two very innovative topics to improve objective and non-invasive audiological tests: the potentiality of Transient-Evoked otoacoustic emissions (TEOAE) to detect hearing impairment and the availability of a new microprobe able to capture directly both the pressure and velocity acoustic signals in the ear canal so allowing the direct measurement of ear immittance.

2. Inside cochlea

The cochlea is located in the inner ear, consisting of the front labyrinth and rear labyrinth, the latter having peripheral vestibular formations. The cochlea has quite a complex structure, just as complex as the Organ of Corti, contained inside the cochlea that with its neuro-epitherial hair cells makes up the first mechanical-electrical transformation stage of the sound impulse;

it permits the stimulation of the afferent neural structures and the transmission of the information contained in the sound input through the acoustic canals right up to the cerebral cortex.

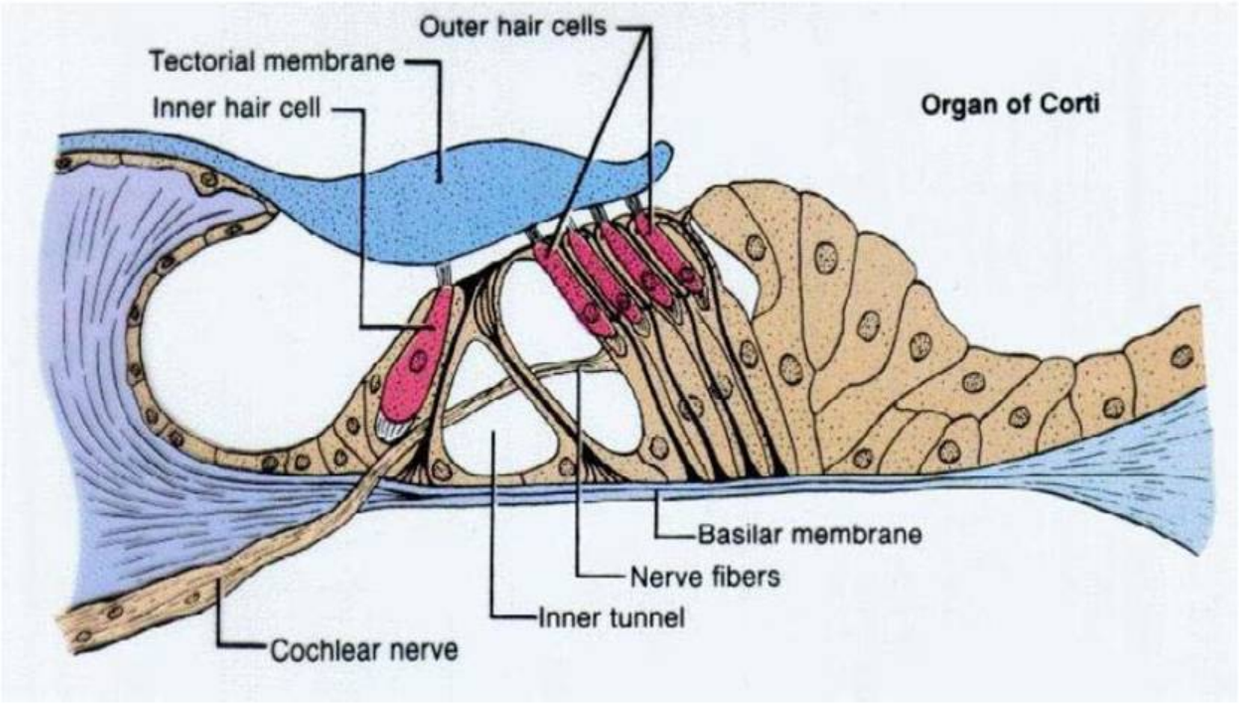

Figure 1. The Organ of Corti The organ of Corti is attached to the basilar membrane on the side of the aqueous fluid of the scala media. It is comprised of the supporting cells for the hair cells, the hair cells themselves, and the tectorial membrane (TM).

The Organ of Corti is made up of the Basilar Membrane, hair cells, support cells, Deiter, Hensen and Claudius cells, and the Tectorial Membrane. The hair cells can be divided according to their position in respect of the cochlea canal, whether outer or inner. The outer cells are more numerous and are placed along three lines; their hairs contact directly with the Tectorial Membrane and are very sensitive, are mainly stimulated by the efferent medial olivocochlea system of control. Acetylcholine (Ach) is their principal chemical mediator. The internal hair cells are arranged in a single line, don't have direct contact with the Tectorial Membrane, are less vulnerable and are supplied by afferent medial olivocochlea nerves, whose first nerve cell is within the Organ of Corti, itself enclosed within the bony labyrinth inside the cochlea. The glutamate is the main neuro–transmitter of the Internal Hair Cells. Given their afferent innervations they make up the actual sensorial cells.

The mechanical-electrical transduction of the cochlea takes place through a series of bio-chemical and bio-mechanical mechanisms. The sound impulse is transmitted from the movement of the stirrup bone on the oval window to the endolymph fluid creating a deformation of the Basilar Membrane on which the Organ of Corti rests with its hair cells that also create a deformation of the auditory cells who in turn are partially in direct contact with the Tectorial Membrane and so generating a deformation wave in the Basilar Membrane (travelling wave) as a result of the sound wave. The amount of deformation that the travelling wave

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produces along the Basilar Membrane will be evident at different points according to the frequency of the topical tone sound. The result of such mechanical modifications by the Basilar Membrane and hairs is the releasing of neuro-receptor neurohumours located in their synaptic vesicles inside the Hair Cells and so generating the bio-electrical impulse. The Basilar Membrane has different physical and elastic properties along the cochlea spiral from its base, through the intermediate part, to the apex. Even resonance properties vary along the cochlea. This makes one part of the Basilar Membrane resonate and deform according to the frequency of the sound rather than another part of the Basilar Membrane and consequently the Organ of Corti, the activating groups of Hair Cells and their nerve fibres based on the different frequencies contained in the sound. The part of the Basilar Membrane that is most sensitive to low frequency sounds is the apex of the cochlea whilst the part most sensitive to high frequencies is the widest part of the coil that is the base of the cochlea.

The first neuron of the auditory system is contained in the Corti Gland inside the cochlea where we find T cells whose peripheral extensions come from the Internal Hair Cells whilst the central extensions together make up the eighth cranial nerve and connect to the pontini bulb centres. It is important to keep in mind, according to the most recent theories, that inside the Organ of Corti at the External Hair Cell level there is an important active magnifying process of the signal that produces significant amplification, definition and resolution in the frequency of the sound inputs and a notable refinement of the auditory threshold. The fine longitudinal and transversal motility of the Outer Hair Cells, both spontaneous types and those stimulated externally, motility modulated by the efferent olivocochlea system, are the basis of such important functions. From this it can be deduced that a loss of Outer Hair Cells would produce a series of auditory problems more critical and complex in respect of damage to the Inner Hair Cells. Hearing loss (reduction of auditory function) connected to changes in analysis, peripheral translation and conduction of apparatus is defined as neurosensory and gives way to distortions in frequency, intensity such as recruitment, a phenomenon that distorts the subjective sound intensity (loudness), in phase, exertion and auditory conformation.

Outer Hair Cells are cells that belong to and are controlled by the efferent system more than sensor cells. They are more sensitive to auditory stimulation in respect of Internal Hair Cells which are anatomically connected to the afferent or sensorial system as previously stated. The particular sensitivity is mainly mechanical in nature and Is connected to 1) the presence of direct tectorial hair connections between stereohairs and the Tectorial Membrane and 2) their "active" vibratory motility, electrically and chemically mediated, that translates into acoustic phenomenon that can be picked up and recorded by a microphone positioned in the external auditory canal: the Otoacoustic Emissions.

3. What OAE are

The discovery of otoemissions is attributed to the English physics professor David Kemp at the end of the ‘70s. He is merited with first putting forward the idea and then introducing clinical diagnosis using investigative methodologies capable of non-invasive exploration, in

humans, the Organ of Corti functions and in particular the Outer Hair Cells. The basis of this methodology has produced a series of new and surprising evidence regarding the cochlea physiology that integrates, contradicts and supersedes the consolidated theories of von Békésy, Nobel Prize winner in 1960.

The direct contact between the stereo cilias of the Outer Hair Cells and the Tectorial Membrane create mechanical-electrical type reactions that transfer to the entire cell connected by ATP (Adenosin-TriPhosfate). The typical cytoskeleton-like network of muscle (actina–miosina) of which the cell is made, makes use of the electric charge originated at the level of the stereo cilia and moves either slowly or rapidly. These movements are modulated and regulated by the medial olivocochlea system, a true servo-system of control through various synaptic neurohumours and in particular Acetylcholine. The function of Outer Hair Cells is fundamental in conferring on our hearing the elevated threshold characteristics, the increased dynamics between minimum audible threshold and the perceptible maximum and frequency selectiveness.

A cochlea system with dysfunctional Outer Hair Cells rapidly loses these properties even if in theory the Inner Hair Cells are healthy. The information received mechanically from the Outer Hair Cells is transmitted in electric form as well as in mechanical form to the Inner Hair Cells and so to our proper sensory auditory system. To stress again, the Outer Hair Cells are particularly vulnerable, their high characteristic sensitivity to which are connected elevated bioenergetic and metabolic requests such that any cochlea noxae that is infected, toxic, traumatised or suffering from a metabolic disorder can bring about a lesion and become apparent prematurely. The study of Otoacoustic emissions appears significant and effective in the majority of auditory problems of peripheral receptors.

The otoacoustic emissions (OAE) are recorded by a particular probe positioned in the external auditory canal. If it is necessary to create responses the probe, other than being a receiver that records the emissions from the cochlea, contains a transducer capable of sending stimuli to the cochlea. These days it is possible to study the OAE mainly in one of three ways:

1. Recording the spontaneous emissions produced by the cochlea in the absence of any acoustic stimulus. Such emissions are called 'Spontaneous Otoacoustic Emissions' (SOAE).
2. Recording the emissions produced inside the cochlea through the sending of temporary acoustic stimuli, such as clicks, that are able to involve synchronously and globally a large number of the acoustic cells from the base to the apex. These emissions are known as 'Transient Otoacoustic Emissions' (TEOAE).
3. Cochlea emissions created by pairs of tonal stimuli of differing frequency for intermodulation phenomena, so-called 'Distortion Product Otoacoustic Emissions' (DPOAE).

Apart from the SOAE method of recording whose clinical value is unfortunately less, we shall focus on the TEOAE and DPOAE recording methods. The first method involves sending a series of clicks from a probe and recording the acoustic response from the hair cells. The acoustic response is normally represented graphically by oscillations based on a time period

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(milliseconds), as well as by a spectrogram that traces the size and frequency of the response. The DPOAE instead operates by way of sending a pair of pure tones (F1 and F2), with very small value frequency differences between them for example F1=1000 Hz, F2=1220 Hz, a ratio of F2/F1 = 1.22. The two tones, so-called primary tones, give rise to distortions in the cochlea deriving from their combination. The phenomenon of the combination of tones is mostly connected to the peripheral processing mechanisms of the signal which is still not wholly understood but that resides in the internal ear and in particular is connected to the active processes of the cochlea. So if two tones of differing frequency are sent simultaneously, the ear might perceive one or more tones superimposed that are the sum of the two tones or else are the difference (simple, cubic, quadratic, etc.) of the two primary tones. The response traces the form of a DP-gram, showing the extent of the response derived from the frequency of the primary tones.

Nowadays the major diagnostic clinical function is mostly engaged in the TEOAE and DPOAE being the spontaneous emissions less subject to interpretation despite having a notable scientific interest. Dedicated software systems permit the execution of a rapid measurement statistically adapted to the cochlea response. As regards the DPOAE it is interesting to note that it establishes a modern method to survey one of the more characteristic psychoacoustic phenomena: combination tones. The study of DPOAE in particular allows the design of cochlea responses in an audiometric-like way, frequency by frequency, on a graph that shows on the vertical axis the frequencies of stimulation and on the horizontal axis the intensity levels of the received Otoacoustic emissions showing immediately if the audiological threshold is within normal limits or not.

The operating range is important in identifying the dysfunction of the cochlea in Ménière's disease, in evaluating damage from noise, in ototoxic type changes, in the study of some genetic and immunological cochlea alterations, in the differential cochlea diagnosis against retro cochlea diagnosis and the identification of new pathologies such as Auditory Neuropathy. Finally, the range of neonatal auditory screening establishes the most sensitive and specific means of recognising premature infantile deafness. Auditory screening is carried out at birth before the new-born baby is discharged from hospital normally the second day after birth and, given the simplicity and speed of testing, is the best method for definitive diagnosis or alerting and preparing for further diagnosis and rehabilitative therapy within a few months and before the child's first birthday, a period of great neuroplastic and linguistic activity. It's therefore possible to control and limit the damage from auditory sensorial deprivation, language disorders, communication and behaviour disorders.

OAEs provide objectivity and greater accuracy, representing a non invasive tool for the assessment of OHC and the functionality of the cochlear amplifier, as demonstrated by experimental and clinical studies [3-5]; furthermore, the cochlear effects of exogenous factors, such as ototoxic drugs, solvents and high-level sound exposure [6-8], can be monitored by OAE. It has been suggested that OAEs may provide early indication of cochlear damage before evidence for NIHL appears in pure-tone audiometry [9-10]. Recently, TEOAE have been used to study in tinnitus subjects with normal hearing to assess whether a minor cochlear or efferent dysfunction might play a role in tinnitus [11].

One of the few limitations of OAE is related to the extent of hearing loss that we can explore: infact, already for cochlear hearing loss above 50 dB the OAE, just because otoacoustic emissions are produced by the activation of CCE, are no longer evoked.

4. TEOAE recording

To record the TEOAE signals the Otodynamic Analyzer (ILO92, Otodynamics Ltd, Hatfield, United Kingdom), was widely used, by inserting a SGS-type general purpose TEOAE probe into the external ear canal. The TEOAE recordings were carried out in a standard hospital room, corresponding to the usual clinical setting for these measurements. The automated differential non-linear test paradigm was used: the stimulus was characterized by a train of four clicks, three with the same amplitude and polarity, followed by a fourth one with a 3-fold amplitude and opposite polarity with respect to the preceding ones. The 80 μs clicks presented at 50/s were 75–85 dB SPL. The responses were obtained evaluating an average among 260 stimuli trains (1040 clicks) stored into two different buffers (A and B) for a total of 2080 clicks. The value of the automatically computed correlation or reproducibility between the two obtained waveforms (A and B) of an OAE signal is named Repro or whole waveform reproducibility (REPRO) (Pearson correlation coefficient *100) (see in Figure 2, on the right, Repro=99%).

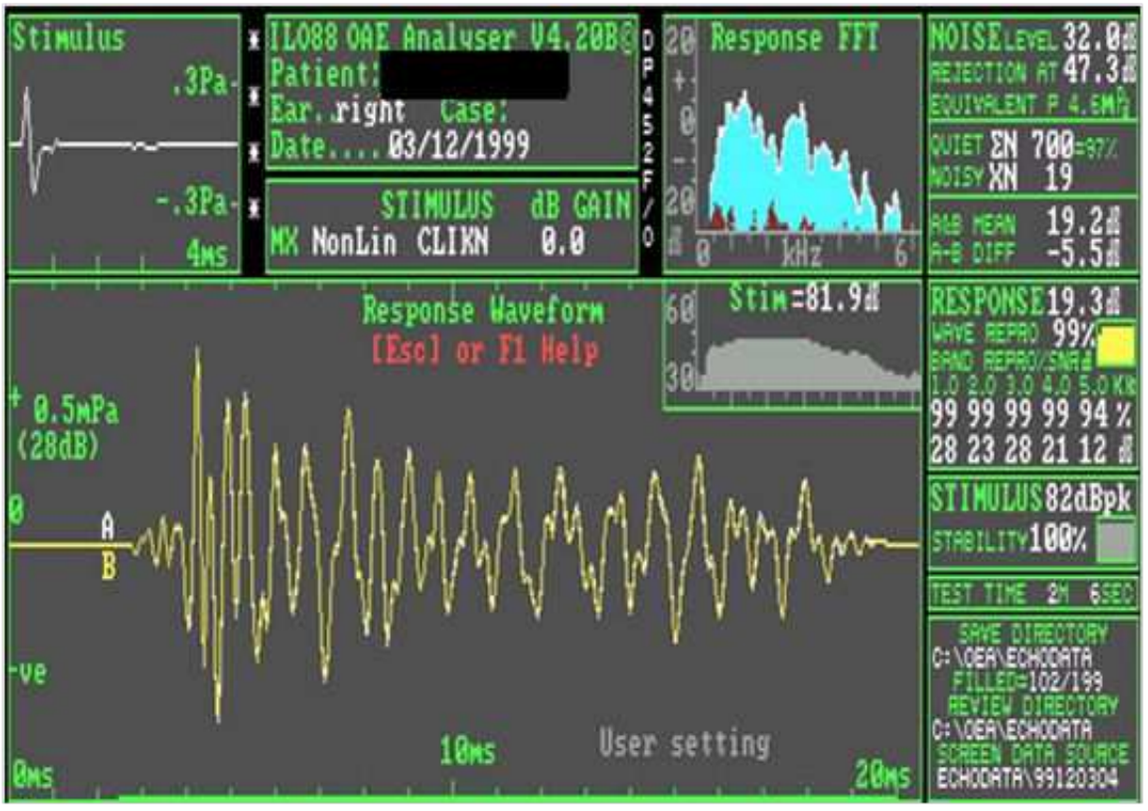

Figure 2. TEOAE signals (ILO92, Otodynamics Ltd)

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5. Broad band measurement of ear immittance and perspective for improving TEOAE detection

The most innovative application of micro-electro-mechanical systems (MEMS) technology to acoustic sensors is the manufacturing of thermo-acoustic velocimeters based on the two-wire anemometric transduction principle. These new sensors allow to capture directly the acoustic particle velocity signal v, and thus, by coupling and assembling them with standard microphones which are instead sensitive to the pressure signal p, a new generation of pressure-velocity (p-v) micro-probes is nowadays made available (see Figure 3).

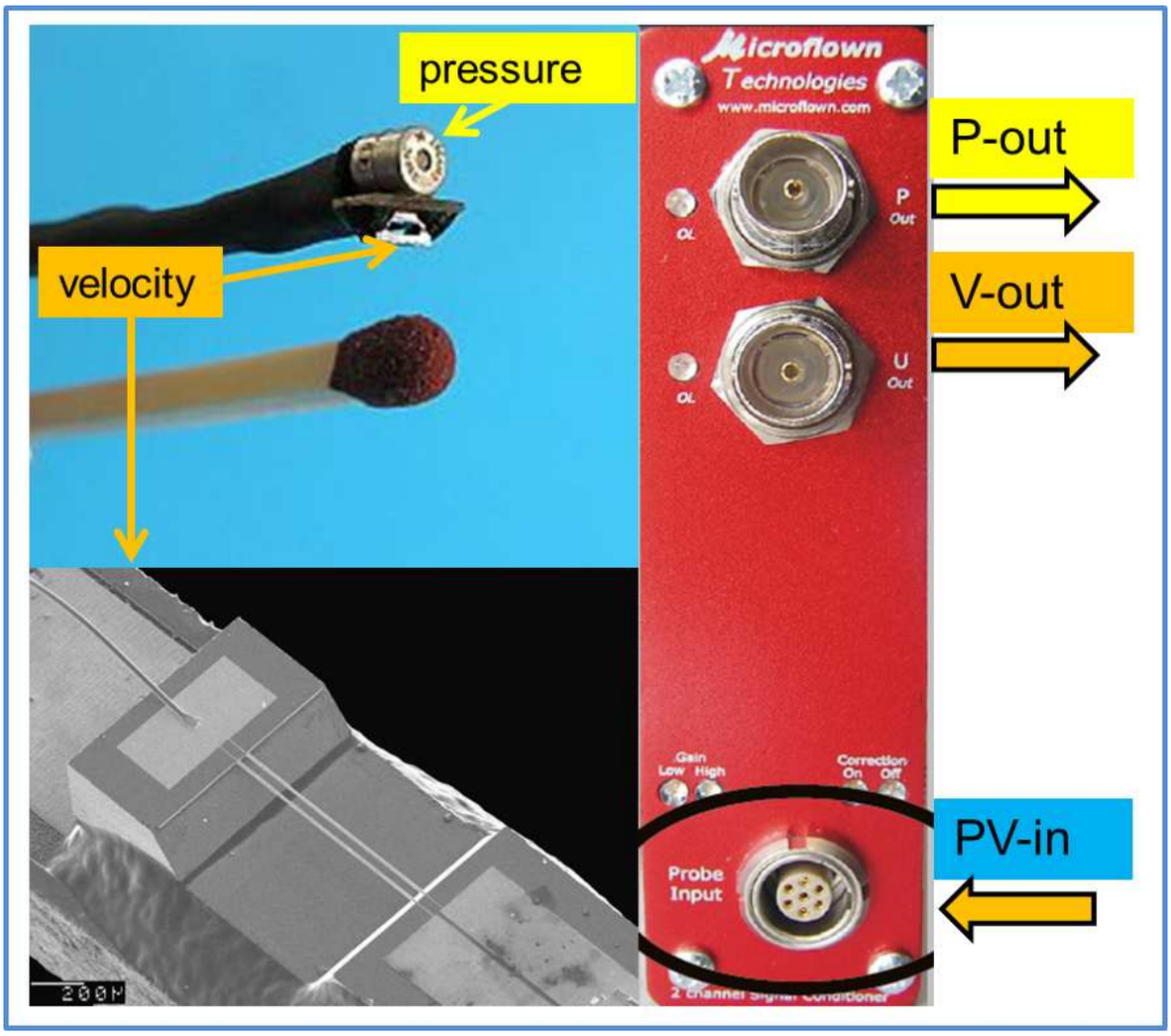

Figure 3. A p-v sound intensity micro-probe consists in the assembly of a miniaturized pressure microphone and a MEMS technology based velocimeter in a single measurement system. While the pressure sensor is a standard electret one, the velocity signal is transduced thanks to the differential anemometric principle applied to two closely spaced heated wires 10 μm apart, 1mm long and 5μm large suspended in parallel in order to form a bridge. The wire composition is 200 nm platinum (Pt) on a silicon nitride (Si3N4) substratum 150 nm thick. The captured pressure and velocity analog signals are conditioned through a common probe input and handled in output as two separate voltage signals. (The commercial system shown in the figure is by courtesy of Microflown®: www.microflown.com).

These micro-probes are clearly the ideal device for carrying out advanced direct measurements of the sound field energetic properties like sound intensity j=pv or acoustic impedance Z=p/v. To this aim, an accurate calibration procedure [12] is needed (see Figure 4).

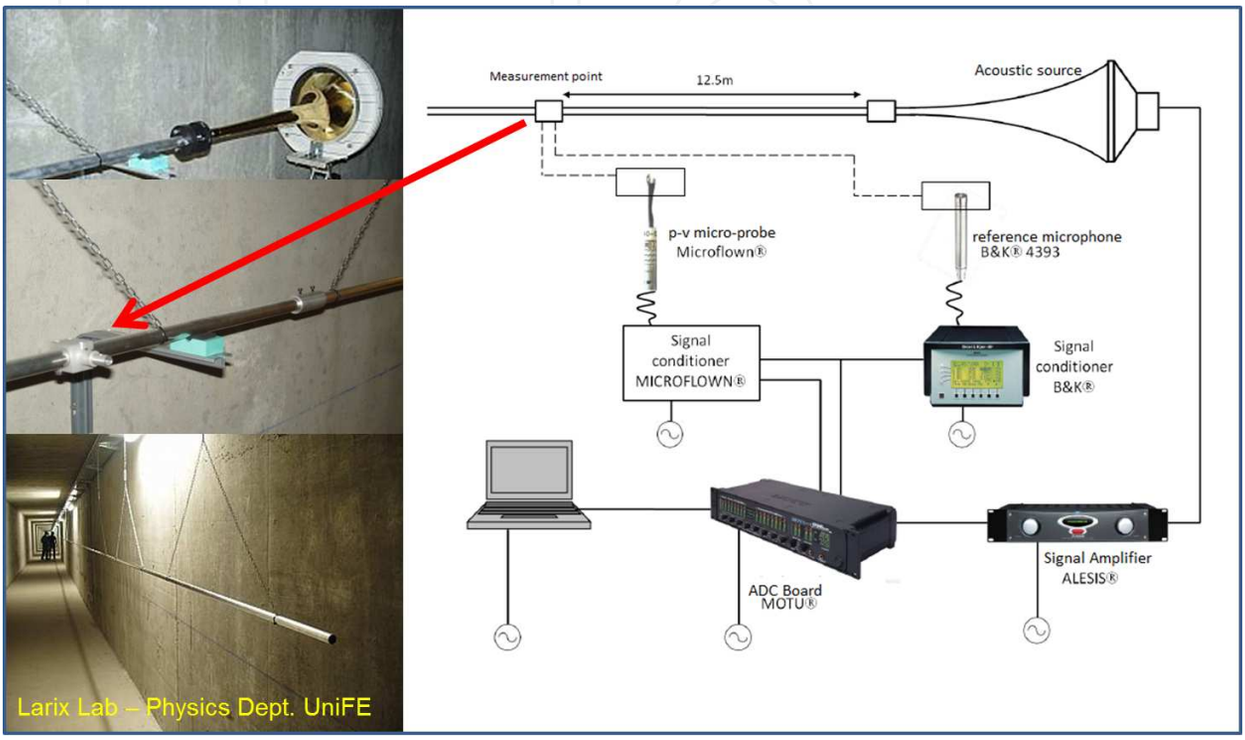

Figure 4. The facility for sound intensity micro-probes calibration installed at the Larix Lab of the Physics Department of University of Ferrara consists in a 48 m long wave guide where a progressive plane wave is generated through a bi-conical loudspeaker in the [50, 10000] Hz frequency range. The p-v micro-probe under calibration is inserted at a distance of 12.5 m from the source and is calibrated by comparison with a reference pressure microphone using the correction function Γ(ω) defined in Equation 13 of Ref. [12].

Of course, the calibration filtering process can be implemented at post-processing level but, with few engineering effort, the calibration filters can also be programmed at hardware level so making, in particular, the measurement of acoustic impedance, a completely automatic task. The technological innovation driven by MEMS application to acoustic sensors can be easily transferred to audiometric devices so transforming for instance a traditional tympanometric probe in a new setup for p-v tympanometry (see Figure 5). The main advantages of a p-v tympanometric test with respect to a traditional one are: a) the direct measure of ear immitance for more precise results; b) the test is completely non-invasive for static pressure external pumping is no longer necessary (p-v test measurements are performed in standard pressure conditions); c) the test produces wideband results in the typical frequency range of multi-tonal tympanometry [100, 1200] Hz; d) the p-v audiometer provides sophisticated sound energy analysis capability for hearing models validation (see Ref. [13]).

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Figure 5. A p-v tympanometer is designed as a laptop based dual channel analyzer (lower left) able to record both the Impulse Responses (IRs) of pressure and velocity signals captured with the p-v tympanometric probe shown in the upper part of the figure. Once the p-v IRs of the ear canal have been measured in atmospheric pressure condition (lower right), the system calculates the external/middle ear specific immittance and displays its magnitude in dB relative to the frequency dependent baseline Y_0 obtained by plugging up the probe.

As an example of results obtained with p-v tympanometry, wideband p-v tympanograms measured in dB for 26 left and right normal ears belonging to 13 voluntary students are clustered and reported in Figure 6.

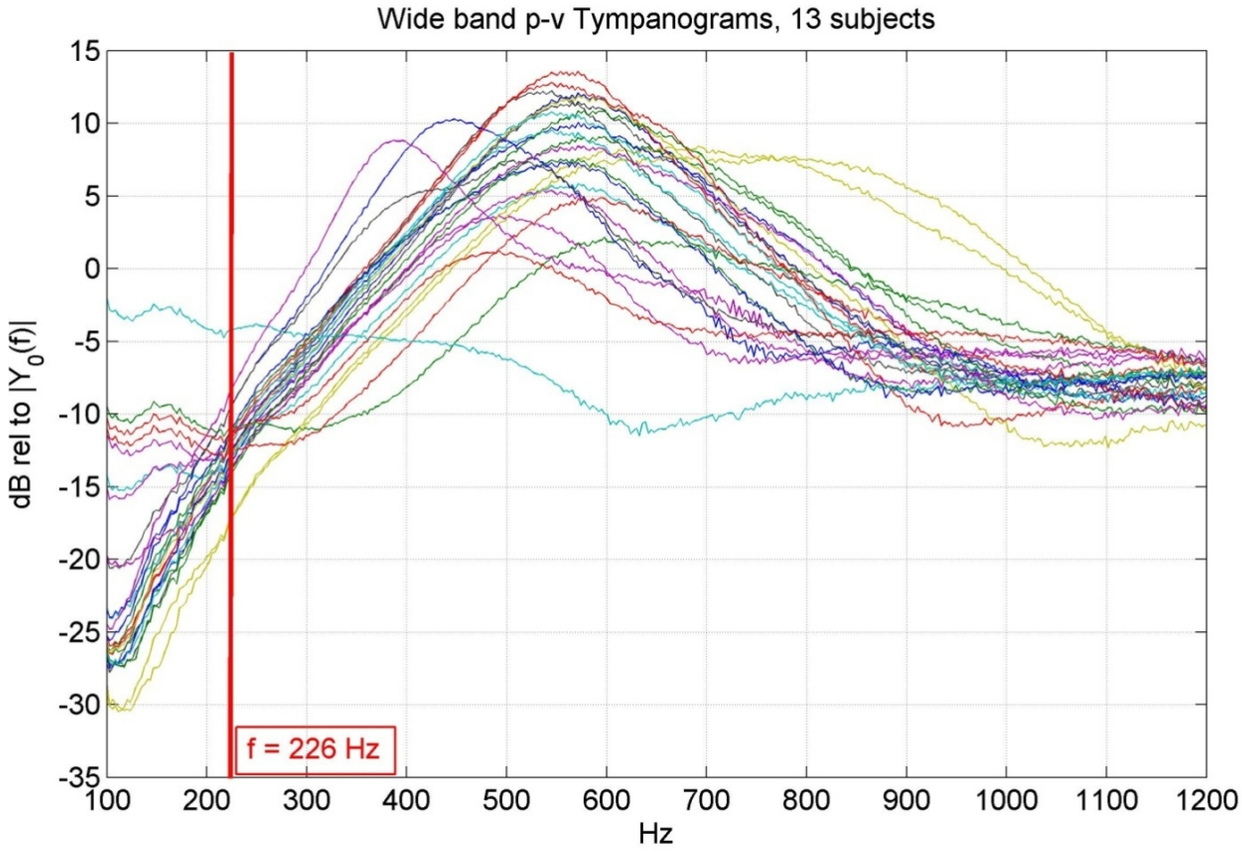

Figure 6. Wideband p-v tympanograms measured in dB for 26 left and right normal ears belonging to 13 voluntary students. One clearly see that all tympanograms converges between -10 and -15 dB for the standard frequency of 226 Hz used in traditional tympanometry. The mean value found at -12.7 dB can thus be considered the "normal" value of the immitance magnitude measured by p-v tympanometry at 226 Hz.

As the primary data collected by the p-v tympanometry are basically the measurement of the pressure and velocity ear canal IRs, a completely new perspective also for OAE studies is also opened. Specifically for the TEOAEs which could be simply detected as the non-linear byproducts of DSP algorithms used in the ear-canal immitance function calculations.

6. TEOAE post-processing analysis

The Recurrence Quantification Analysis (RQA) and Principal Component Analysis (PCA) have been carried on TEOAE waveforms [14-17] (Zimatore et al. 2000, 2001 2002, 2003) to extract new descriptors that could enlighten an early diagnosis of hearing loss.

In the last few years, a new parameter has been introduced to analyse TEOAE, to improve the specificity of diagnostic tests and to reduce inter-subject variability. The work was concentrated on the analysis of the TEOAE focusing on their dynamics by the Recurrence Quantification Analysis (RQA). RQA is a post-processing analysis that is extremely fit to non-stationary signals and represents a valid alternative to Wavelet analysis used by other researchers. In fact,

the embedding procedure allows to expand a mono-dimensional signal into multidimensional space, thus permitting the identification of fine peculiarities of the sampled series that in turn are described by few global parameters allowing for a synthetic patient description.

RQA in summary:

- RQA introduces few parameters descriptive of the global complexity of a signal, starting from what is called "recurrence plot"
- RQA descriptors are calculated on the basis of the number and location of dots in the recurrence plot
- RQA dynamic features are independent from signal amplitude

The results obtained demonstrate how proposed new global index can recognize even mild hearing loss and that an assessment of the severity of cochlear damage can be realized.

To build the recurrence plot, the time behavior of the original signal was represented by a series of 512 points equally spaced in time (e.g. {a1 a2 …. a 512} where ai represents the value of the signal corresponding to the i-th time position). Then, the series was arranged in successive columns (the columns number is defined by the "embedding dimension" parameter, N), each-one obtained by applying a delay in time (lag parameter) to the original sequence, in this way an "embedding matrix" was created.

Finally, the recurrence plot was built, drawing a black dot (named "recurrent point") in the represented space if the distance between the corresponding rows (the distance between the j-th and the (j+1)th row is of the embedding matrix was lower than a fixed value (radius). In the obtained plot, the horizontal and vertical axes represented the relative position of the 512 points into the TEOAE waveform. RQA descriptors were then calculated on the basis of the number and the location of dots in the recurrence plot. In particular, percent of recurrence (Rec) is the percentage of recurrence points in a recurrent plot; percent of determinism (Det) is the percentage of recurrence points which form diagonal lines and it indicates the degree of deterministic structure of the signal; entropy (Ent) is the Shannon entropy of the probability distribution of the diagonal line lengths and is linked to the richness of deterministic structure [16-17] (Zimatore et al. 2002 and 2003). The presence of horizontal and vertical lines in the recurrence plot shows that part of the considered signal matches closely with a sequence farther along the time (for more details see http://www.recurrence-plot.tk).

In TEOAE analysis the delay in the embedding procedure (lag) is set to 1; the number of the embedding matrix columns (embedding dimension) is set to 10; and the cut-off distance (radius) is set to 15; to eliminate the initial linear ringing, the first 2.8 ms of the recorded TEOAE signals are excluded.

Comparing Figure 7 and 8, it is clear that recurrence plots distinguish between normal hearing and impaired hearing TEOAEs especially in terms of a reduction in the deterministic structure.

As a further step of the post-processing analysis, the well known Principal Component Analysis (PCA), was applied on the obtained RQA descriptors. Briefly, PCA is a common statistical technique which provides the possibility to reduce the starting data set dimension

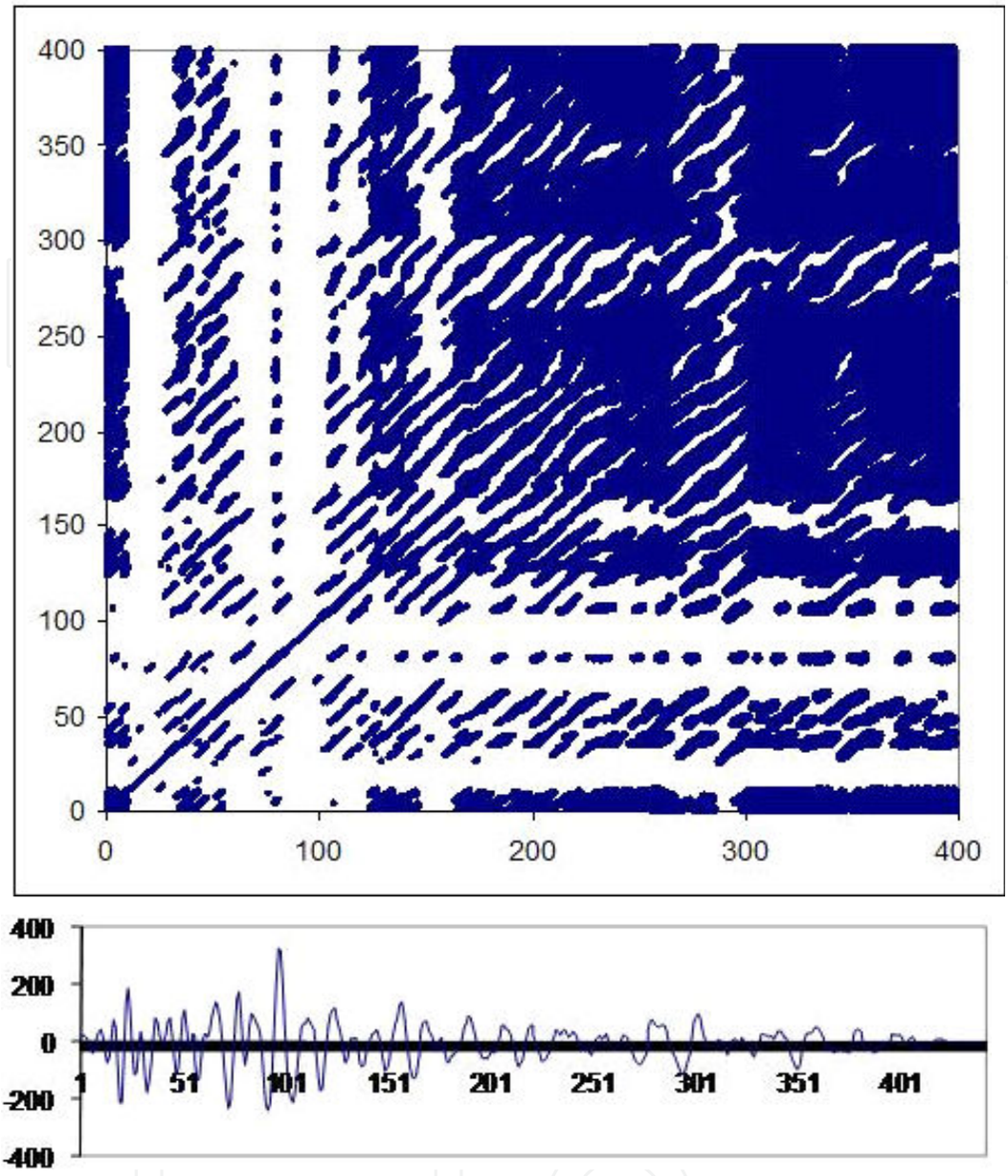

Figure 7. Recurrence plot (top) of a typical TEOAE recorded in a Normal ear (%Det=88.89) (bottom)

without consistent loss of information and with a separation of the different and independent features characterizing the data set. PCA describes the original data set with a lower number of new parameters named main components (PC1, PC2) which explain more than 90% of the total variability in the data set. Having, by construction, PC1 and PC2 zero mean and standard deviation equal to 1, if a set of TEOAE signals from normal ears are studied, 96% of them will fall within a circle centered in the origin of the PC1/PC2 plane, and with a radius equal to 2 (reference circle in figure 12). The PC1/PC2 plane is defined starting from a representative data set made by 118 signals measured from normal hearing subjects [18]. The representative data set was used to define the circle in the PC1/PC2 plane in which the majority of TEOAE signals recorded in normal hearing subjects will fall. Mathematically, the parameter RAD2D is defined

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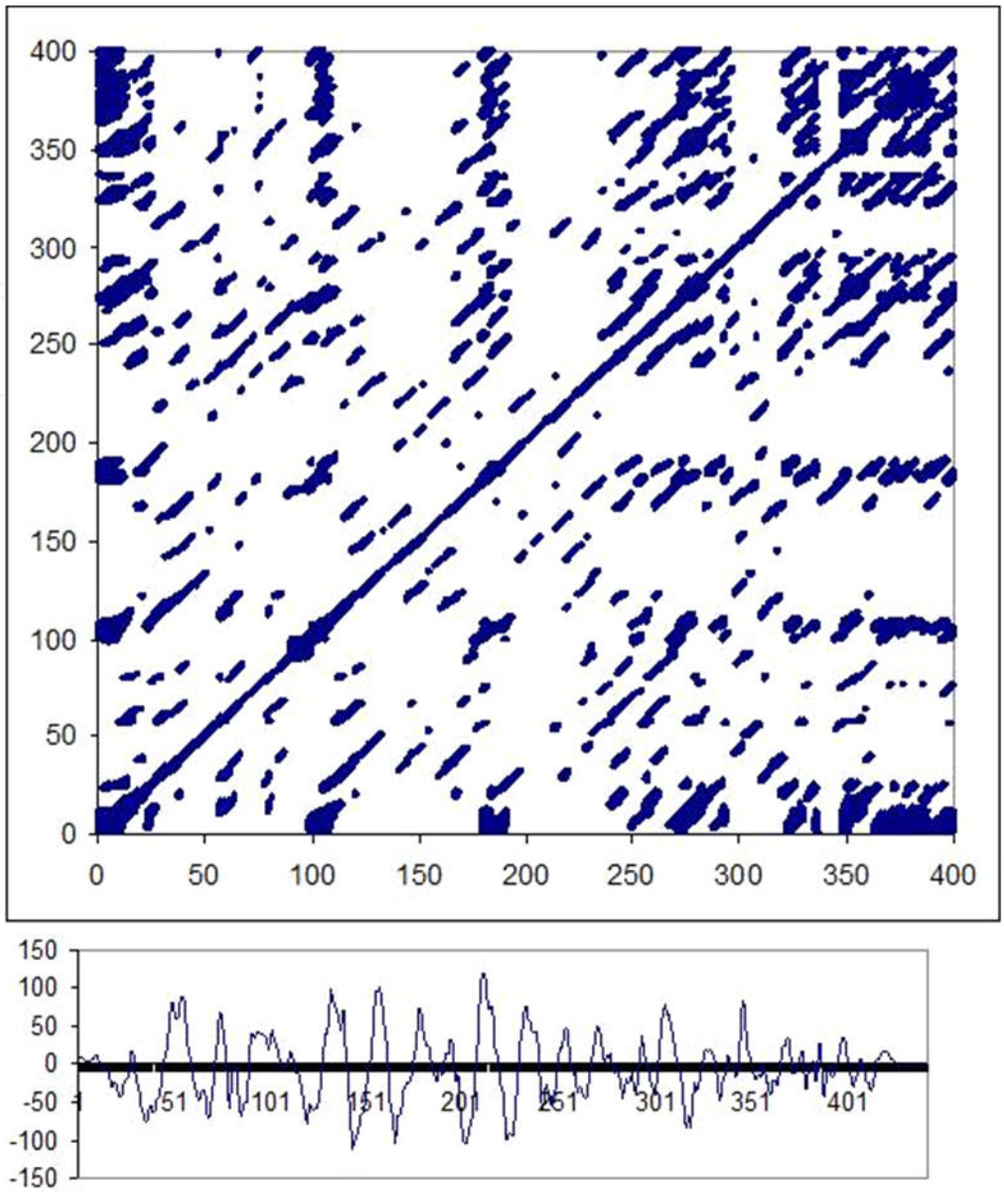

Figure 8. Recurrence Plot (top) of a representative Impaired Hearing (IH) TEOAE waveform (bottom) (% Det = 62.89)

in the PC1/PC2 plane as the Euclidean distance of one point representing a TEOAE signal from the plane origin.

The relation correlating the RAD2D obtained for all the measured signals with the entity of cochlear damage is tested. Specifically, RAD2D was evaluated for real TEOAEs by applying the same procedure as for simulated signals combining RQA and PCA techniques.

Furthermore, the post-processing analysis proposed is useful in screening of adults, in longitudinal studies, in test to evaluate the efficacy of new pharmacological treatments, in conservation program in presbycusis and in protection program in noise induced hearing losses.

Figure 10 illustrates REPRO plotted *vs* RAD2D considering 30 subjects from Florence area (Italy). The examined ears will be classified as normal hearing (NORM) or mild hearing losses

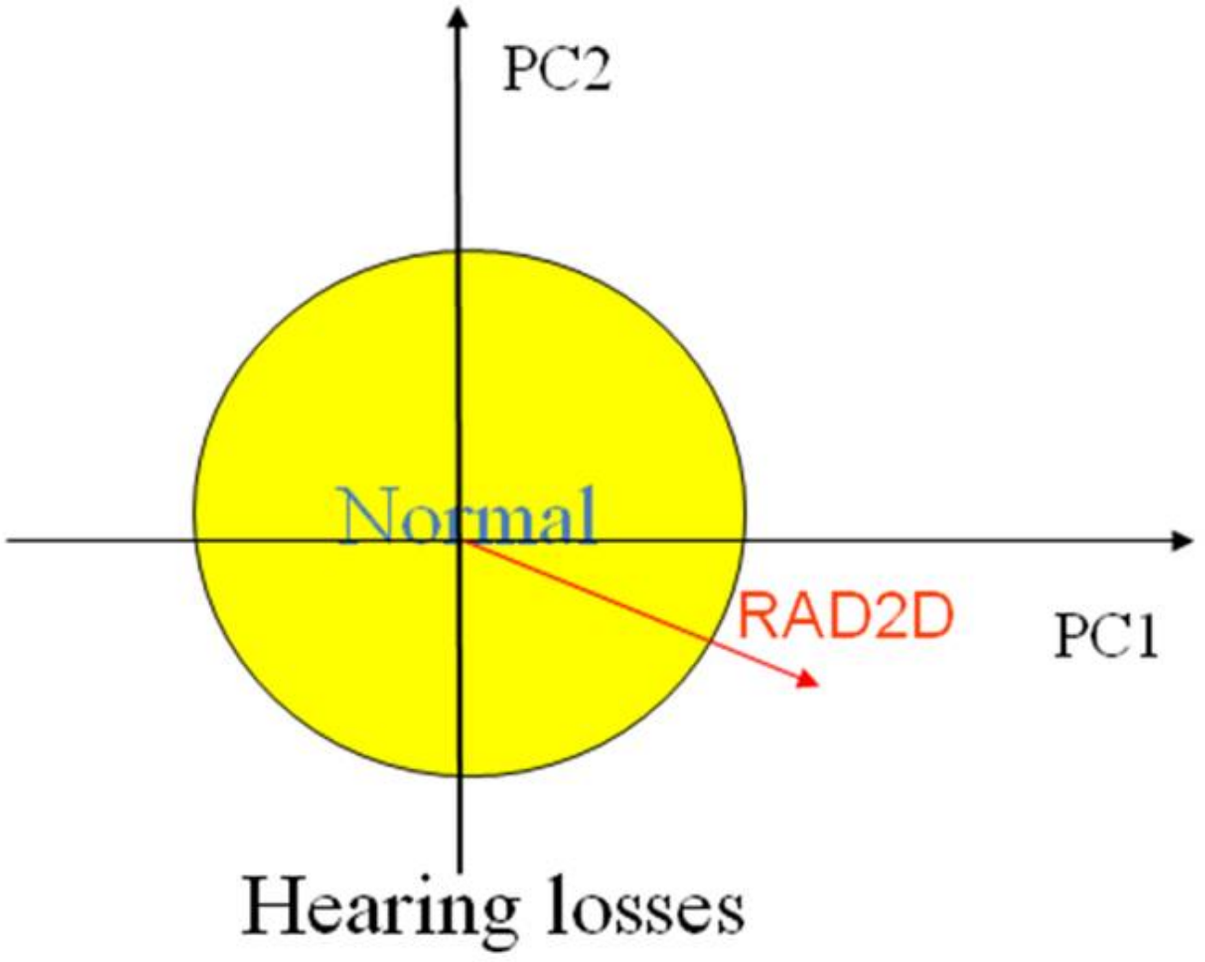

Figure 9. RAD2D is defined in the Principal Components plane as the Euclidean distance from the plane origin; the points representing the normal TEOAE signals fall in the yellow reference circle and TEOAE signals recorded form subjects with hearing losses fall outside.

(MHL) or (severe) hearing losses (HL) ears according to their pure tone thresholds at 0.250, 0.500, 1, 2, 3, 4, 6 and 8 kHz. The three groups according to the maximum hearing threshold level are: NORM, with threshold <10 dB at all audiometric frequencies, MHL, with threshold <20 dB at all audiometric frequencies and >10 dB at least at one frequency, and HL, with threshold >20 dB at least at one frequency. In Figure 10 the HL patients (white circles), in the MHL patients (blue diamonds) and in NORM subjects (black diamonds): each point corresponds to the recorded TEOAE waveform. A very simple and immediate description is available by observing the areas identified by threshold of REPRO (the horizontal line at 70%) and of RAD2D (the vertical line at 1.78). The points above the horizontal line indicate pass signals. To the left side of the vertical line, the points indicate signals that fall inside the normality circle, that is pass signals;. the main result is illustrated in the right upward rectangle of Figure 9 where the ears that have both high REPRO and high RAD2D are shown: these points-signals indicate 8 ears (3 HL, 4 MHL and 1 NORM) screened as pass by REPRO but identified as "fail" by our TEOAE parameter (possible false-negative of ILO test).

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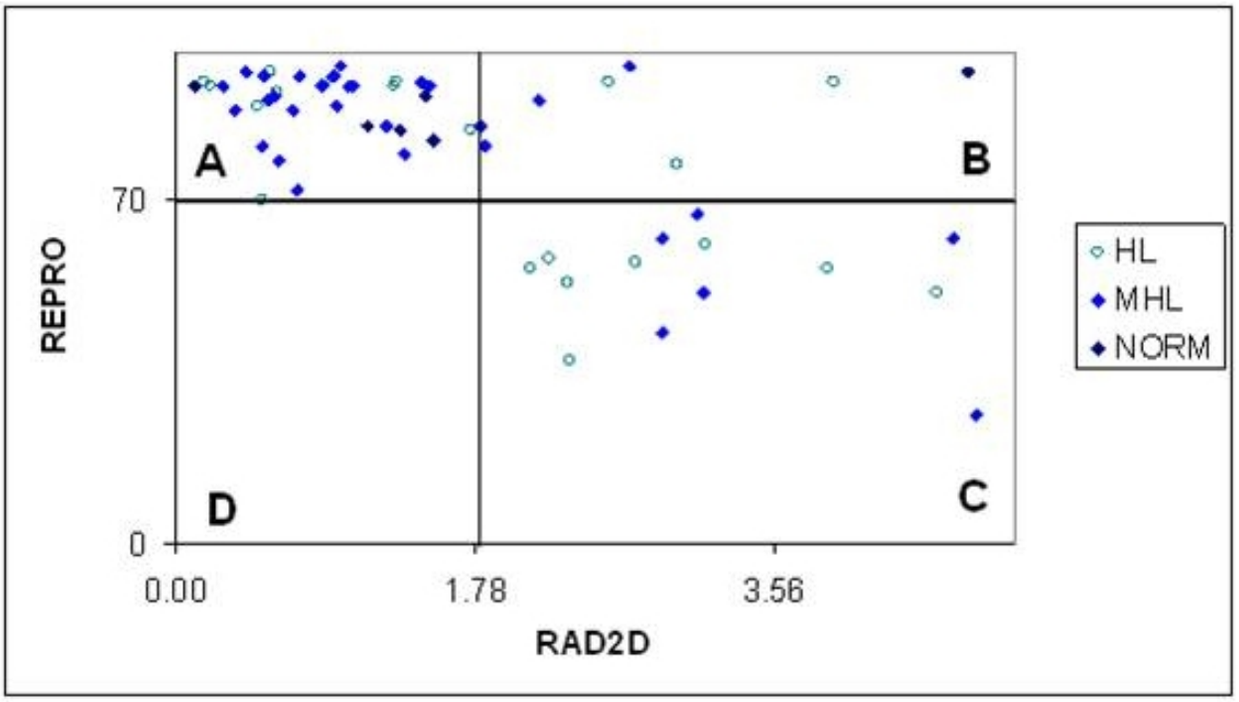

Figure 10. REPRO *vs* RAD2D from RQA parameters of TEOAE signals

The 8 points-signals that fall in the B area correspond to 8 different subjects: 6 are hunters or they shoot for hobby and 2 work often with tractors or lawn mowers. The combined use of the two global parameters REPRO and RAD2D can enlighten points corresponding to the subjects with high risk of environmental noise exposure.

In this chapter the application of technique such as RQA is proposed because, it allows the quantification of the *fine-structure* of TEOAE signals without any *a priori* hypothesis and any data manipulation; moreover, the dynamical structure of signals can be investigated without taking into account the signal-amplitude differences.

7. TEAOA simulation by mechanistic model

An electronic model of human hearing system is used to test and improve new hypothesis of cochlear mechanisms and to anatomically distinguish different contributions to ear pathologies [18-19].

An electronic model of human hearing system can be used to test and improve new hypothesis of cochlear mechanisms and to anatomically distinguish different contributions to ear pathologies.

The considered ear model is directly inspired to the so called “travelling wave” representation of the cochlear function mechanism and is able to simulate the TEOAE responses; the electric model of the whole ear, originally introduced by Guiguère and Woodland [20-21] and used in

TEOAEs analysis [15, 18, 22], has been implemented into PSpice®. PSpice® is a standard electrical simulation tool for dc, transient and ac analyses [23] (see Figure 11). The input circuit can be defined by using a graphical interface or by compiling a list representing the circuit topology. The outputs of the system are current and voltage values within the circuit which can be displayed in both tabular and graphical formats. PSpice® has been already used to study an electric model of the cochlea [24] due to the possibility to relate the model parameters to physical and physiological issues. In [24], the used lumped parameter model is entirely passive, made of a resistive network combined with two capacitances in order to model the Reissner's membrane and the OHC in the Corti Organ.

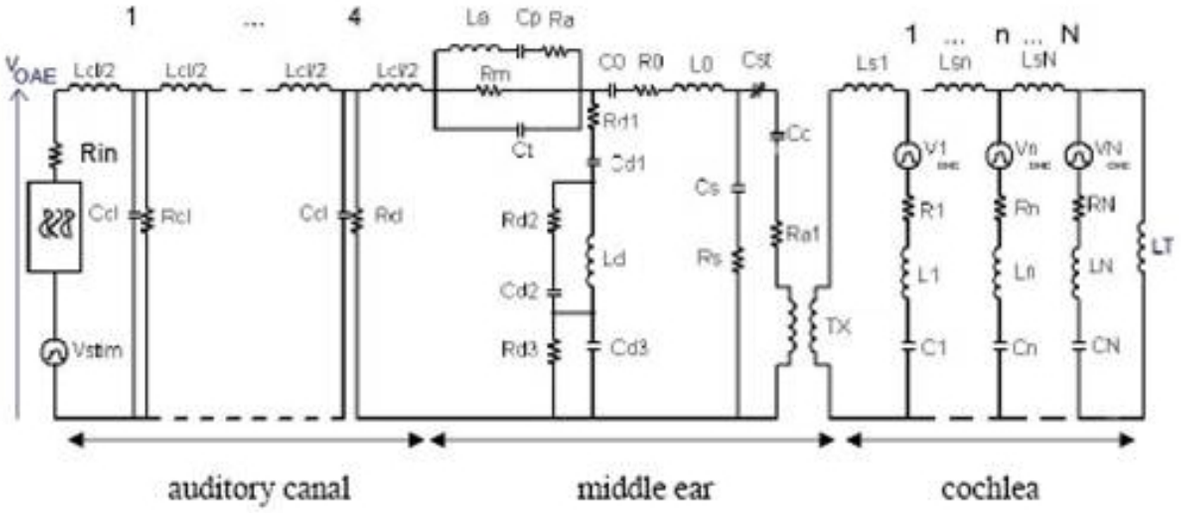

Figure 11. The electronic ear model

The considered ear model is depicted in figure 11 and encompasses the human ear anatomy from the auditory canal to the OHC within the cochlea. The auditory canal is represented by a cascade of four T-sections, corresponding to the segmented form of a uniform transmission line, while the middle ear is modeled as a complex electrical network based on its functional anatomy [25]. An ideal transformer connects the middle ear to the cochlea, to represent the acoustic transformer ratio between the eardrum and the oval window [20-21]. Finally, the cochlea is modeled as a non-uniform and non-linear transmission line, divided into several sections from the base to the apex, each one consisting of a series inductor, a shunt resonant circuit (composed of a resistor, an inductor, and a capacitor), and a non-linear voltage source. In the electro-acoustic analogy, the series inductors represent the acoustic mass of the cochlear fluids; the resistors, inductors and capacitors forming the shunt resonant circuits represent the acoustic resistance, mass and stiffness of the basilar membrane, respectively, and the non linear voltage sources represent the OHC active processes. Finally, the helicotrema is modeled by the inductor LT. The initial values of the electric ear model components are those reported in Table 1 of [20] and also used in [22]. Correspondingly, the cochlea was represented by 128 and 64 partitions [19]

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To verify the hypothesis that TEOAE are strongly modulated by the middle ear [17], some elements in the middle ear section were varied according to the experimental study of Avan and colleagues [4]. The first change is the addition of a stapes capacitor (C_{st}) to the middle-ear section of the circuit, as already considered by [20] Giguère and Woodland (1994a) and by [25]. When C_{st} has a large value, its impedance is small, corresponding to small tension in the stapedius muscle (C_{st} equal to infinity corresponds to no stiffness in the resting condition). Conversely, when C_{st} is small, its impedance is large, corresponding to high muscle tension. Then, changes in the tympanic membrane stiffness (C_0, C_{d1}), to account for changes in the middle ear pressure, and in the tympanic membrane mass (L_0, L_d), to simulate an additive mass, have been considered [4]. Furthermore, a dead cochlea condition has been simulated by de-activating the voltage sources in all cochlear sections.

The role of middle ear effects is a hot topic in the OAE field, and would be of high interest to audiology and hearing researchers.

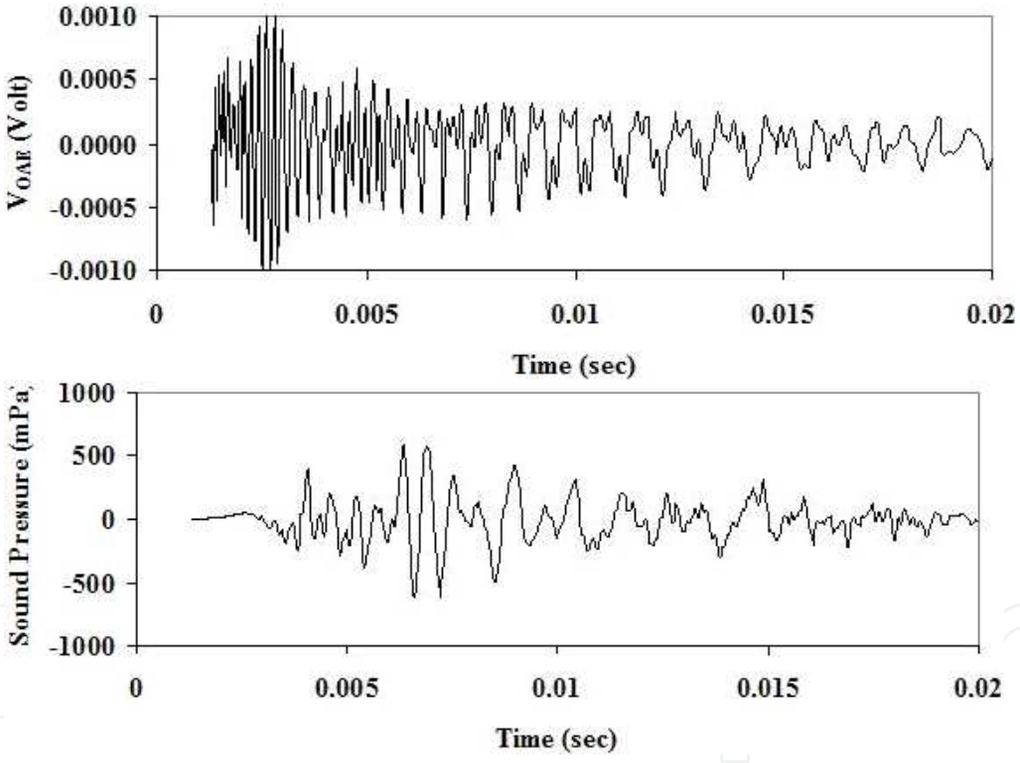

Figure 12. TEOAE Simulated (top) and real (bottom) in normal ear

Figure 12 (top) reports a typical simulated signal, and a real TEOAE signal recorded from a normoacousic subject is reported in figure 12 (bottom). In both simulated and real signals, recording starts after 2.5 ms from the initial external excitation (t = 0), to get rid of the initial ringing. Both signals show oscillations lasting up to 20 ms, with higher frequencies having shorter latency than lower frequencies, in agreement with the latency-frequency relationship typical of TEOAEs. In fact, according to the place–frequency (tonotopic) effect characteristic

of the basilar membrane, each element of the membrane acts as a resonator at a frequency inversely proportional to its distance from the oval window.

A very important goal in prevention and clinical applications is to improve the specificity of diagnostic tests and to reduce inter-subject variability in TEOAE signals. A new pass/fail test could be useful for screening but the quantification of cochlear damage is of great interest in research programs. To determine the amount of damage, an ear model can be used to simulate different levels of cochlear damage by silencing a growing number of cochlear partitions. The relation between a new parameter and the number of silenced partitions in the model was evaluated.

From the comparison between the real and simulated RAD2D values it is possible to extrapolate the corresponding number of "hypothetical silenced partitions". In this way, since each partition corresponded to a specific portion of uncoiled cochlea and to a specific number of outer hair cells, a descriptor of OHC integrity is obtained [26].

8. Conclusion

A very important goal in prevention and clinical applications is to improve the specificity of diagnostic tests and to reduce inter-subject variability in TEOAE signals. The availability of new micro-probes able to pick up both the pressure and the air particle velocity signals inside the ear canal, while allowing to update the standard multi-tonal tympanometry with the wideband implementation of p-v tympanometric non-invasive tests, points also to record and analyze TEOAEs as the non-linear by-product of DSP algorithms used in the ear-immitance function computing process. Furthermore, to prevent and to mitigate noise and aging effects on cochlea, a new post-processing procedure could be employed in *longitudinal studies* [27] as well as to test the efficacy of new pharmacological treatments and the opportunity to follow a subject over time.

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