

LESSON TO LISTEN



Part I

Know how to hear: a public health matter

At first reading this title might appear immoderate to some of you. But if just for the time of this article our readers would mind to lend an attentive ear, it won't take long for them to understand that what from outside is seen as a mundane auricle, is in fact a complex and very delicate organ towards which we should be always considerate. Thanks to our ears we do not perceive only information that are vital for our survival, but also speech finds it real sense for existence. Last but not least, this organ with the help of our brain is gifted with unique properties that make us feeling intense emotions when listening to song or music. Like our sight, our hearing is a precious asset that we have to protect. Get your ears damaged may make your life hell. This is why in January 2004, Christian Hugonnet¹, who is famous for his FISM², organized during his "Week of Sound" a specific conference with the title "Lesson to listen: be liable for your ears".

by Jean-José Wanègue

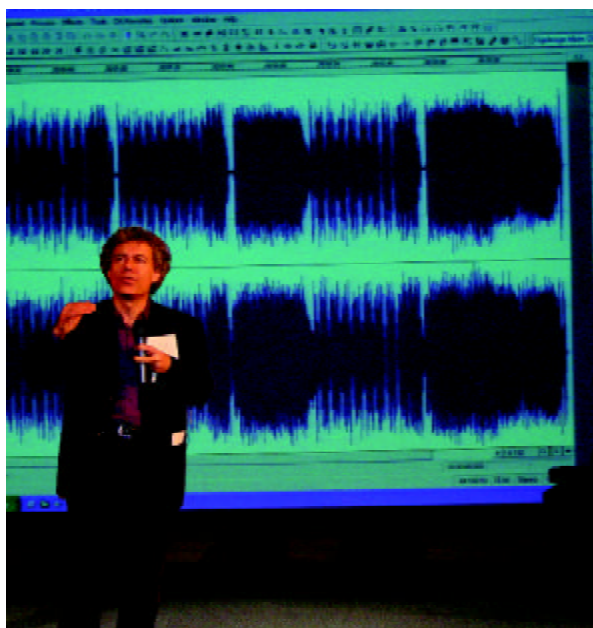
**Pro Sound Systems,
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Turn down that music!

As Christian Hugonnet so rightly said in his introduction of this conference, sound is everywhere and sound invites itself everywhere at all time, being words, music or noise. Our life is immersed in a multitude of sounds we are not conscious of any more. Within this cacophony there are privileged moments that we dedicated to music listening. Technical and industrial progresses having achieved their works, every one of us has access to numerous solutions to listen to his favorite music depending on the time of the day and his location.

It can go from a simple earphone system to a high-end loudspeaker cabinet, as well as rock concert, classical music recital or some good smoky noisy night-club. Within this abundance of solutions, it is fre-

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Christian Hugonnet animating the "Lesson to Listen" conference during the "Week of Sound"

quent that a kind of competition for loudness has been opened as the public wants to feel stronger sensations. It is clear that this evolution may expose our ears to rough treatment. Prolonged listening with headset or loudspeakers at high level may cause severe irreversible lesions for which most of the time we are not conscious of. Of course the very first people to be concerned with this and who also are particularly affected are the youth who in their quest for strong sensations and due to lack of awareness are exposing themselves to high risk that can lead to some forms of temporary or permanent deafness. Faced with that situation, French health authorities took legal measures to limit the sound level of all electronic appliances (mainly walkman) that are connected to headset or earphone. The output sound level has been limited to 100 dB SPL³ (July 24, 1998 departmental order). In March 1998 a departmental order has defined the average authorized sound pressure level in discothèque and night club to 105 dB (A)⁴. Later came the turn for the public concerts with a departmental order dated from December 1999. It says that

average authorized sound level should not exceed 105 dB SPL and peak levels should not go over 120 dB. The problem with these regulations is that these levels are more or less respected. So it has been found that during a concert, peak levels had reached 139.5 dB which is equivalent to a jet engine. Many countries have now such regulations. But regulations are useless if you can not enforce compliance with them. It means that a long education work has to be down to make all concerned people aware about them and to be

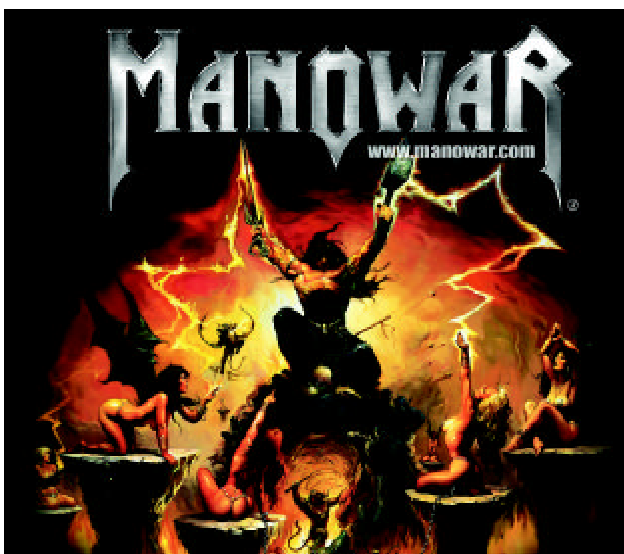
conscious of the circumstances when they put their ears at risks. And as we will see, this is not limited just to youth people, but also musicians, sound engineers, and everybody in his everyday life. So it is our own responsibility to know where is our tolerable limit above which we would seriously put in danger our invaluable hearing asset. Easy to say you would answer when you know that unfortunately we are not equal facing this problem for many reasons and it is true that it could be difficult to find out what

to do with all these sound level measurement units. Moreover risks are not the same depending how long you are exposed to a more or less intense sound or depending of its dynamic range. One can easily understand that if there is a passage within the Berlioz's Fantastic Symphony that peaks at 110 dB, it has certainly not the same consequences as a Manowar band concert who has been listed in the Guinness record book for the loudest concert ever heard.

To understand to what risk we expose ourselves when from innocuous musical greediness we let ourselves being lured into a decibel bulimia, the promoters of this conference invited doctor Drystan Loth (senior lecturer and medical practitioner), Yann Coppier (musician and professor at the Music ATLA school) and Thierry Garacino (musician and sound engineer). More than a conference, this event was a real workshop where Yan Coppier and Thierry Garicino conducted convincing demonstrations with an excellent pedagogical approach.

Flash-back to few definitions

Rapid air pressure variations in the vicinity of our ears cause an auditory sensation. These variations of pressure are generated by physical disturbances in an elastic material under the effect of energy released in this material or transmitted to this material. Sound waves are propagated by means of local oscillations of air particles around their equilibrium position and going from one to the next. Larger variations of pressure correspond to a louder sound. Interesting enough is the fact that the word "Sound" designates at the same time the physical vibrations that generate the sensation and the sensation itself. The sound waves we capture and detect carry a certain amount of energy. They are characterized by three main parameters: pitch, loudness and timbre. It is accepted custom to say that the



Rock and decibels: Manowar, a music that mustn't fall into anybody's ears.

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Yann Coppier (left) and Thierry Garacino (right) during their tutorial gave a chance to the audience to participate to a workshop that lot of school of music would like to have

pitch of a sound is simply a measure of its frequency. The loudness of a sound is the subjective perception we have of its intensity. The timbre is related to all characteristics that make sounds with identical pitch distinguishable.

For the time being we will mainly focus on loudness which is associated to intensity, but it shouldn't be considered as identical. It is true to say that we can be easily confused with these terms like loudness, intensity, volume. So let's clarify it now. As sound is a result of air pressure variation, it is logical to start with pressure unit which is the Pascal (1 Pa = 1 N/m²). The average atmospheric pressure is about 100 000 Pa (1.013 x 10⁵ Pa). We will quantify the sound in stating the pressure variation relative to the atmospheric pressure. The human hearing sensitivity is quite high. Our threshold of hearing corresponds to a pressure variation of 20 μ Pa (20 x 10⁻⁶ Pa).

ment of sound intensity is a function of listener's position with regard to the position of the source. In absence of reflection or reverberation it obeys the inverse square law. It means that if at a distance of r you have a sound intensity I ($I = P/4\pi r^2$), at a distance of $2r$ this intensity will be one-fourth, and at a distance of $4r$ it will remain only one-sixteenth (6.25%). The threshold of pain is reached when the pressure variation is situated at about 20 Pa (see figure 1).

This value has been selected as the reference (P_0) for the creation of a scale of sound pressure at the specific frequency (pitch) of 1000 Hz. The sound intensity that carries such a sound wave is $I_0 = 10^{-12}$ Watts/m². In the air, the measure-

Our hearing system is rather sensitive to pressure variations than to absolute pressures. So it appeared logical to use ratio for measurement. It means that at any time we will compare a given value to a reference value. Furthermore, since the study of Gustav Fechner (1860/1912) we know that sensation (sound, light, pressure, pain) increases as the logarithm of stimulus intensity. So to take into account this physiological property and to be able to cope with stimulus intensities that can vary in a very wide range (from 1 to 10¹², even higher sometime) it makes sense to use a logarithm scale and to have decibel as unit. Thus if we double the sound power going from one loudspeaker to two loudspeakers, the auditory sensation will only increase by 3 dB, whatever is the original power.

3 dB = 10 log (P_2/P_1) with $P_2 = 2 \times P_1$

If now we go from 2 to 4 loudspeakers, again we increase the auditory sensation by another 3 dB, which at the end makes 6 dB difference relative to the original power delivered with 1 loudspeaker. If now we want a specific sound to be perceived twice as loud, its intensity must increase by a factor of 10. This corresponds to intensity increase of 10 dB. But

two sounds that have the exact same intensity might be perceived with different loudness as the frequency might differ. Since our hearing sensitivity significantly varies with frequency, Fletcher and Munsen have plotted a set of equal loudness curves reflecting this variation of sensitivity. We also call these curves ISONIC curves (see figure 2).

The unit for these curves is the phon. So now if we hear a sound at 100 Hz

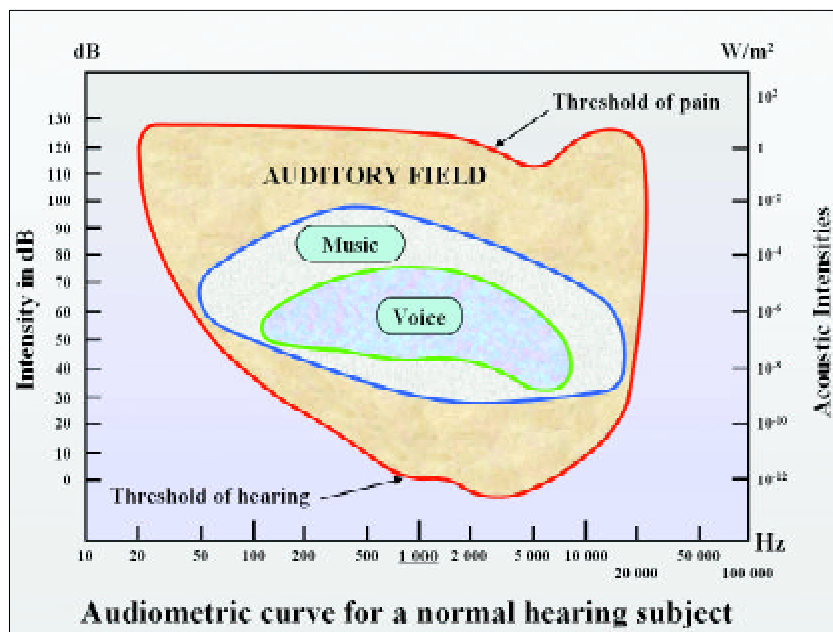


Figure 1: The auditory field is the area bounded by the threshold of hearing (0 dB) and the threshold of pain (120 dB).

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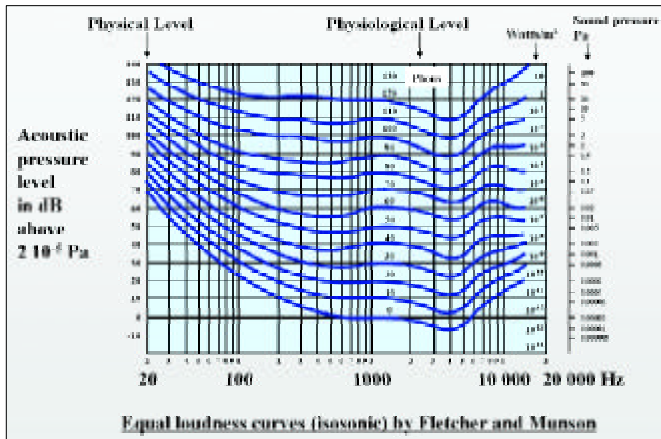


Figure 2: Fletcher and Munsen have plotted this diagram where curves represent equal loudness as perceived by average human hear (Isoconic curves)

that is perceived as loud as a sound at 1000 Hz with a loudness of 40 dB, then this sound is said to have a loudness of 40 phons. Each time we have a 10 phons increase for a given sound, the perceived loudness is doubling. It is usually said that the just noticeable difference for sound intensity is 1 dB. In fact this value varies with the frequency and the sound intensity. Loudness is an important parameter as it should never reach the threshold of pain. But it is also important to take into consideration the dynamic range. For a sound or a signal, the dynamic range is the difference between the loudest and quietest portions. Our hearing system has a dynamic range of about 120 dB. Each music instrument has its own

loud but as usually they have a wide dynamic range, they are not necessarily harmful for our ears due to the alternation between the fortissimo (*fff*: very very loud) and the pianissimo (*ppp*: very very soft). On the contrary music with a low dynamic range will generate an average sound level that will be rather stable offering no period to let the ear finds some rest and get relief. As later on Yann Coppier and Thierry Garacino will explain in their presentation on the evolution of their dynamic range,

dynamics and by extension each music will have a specific dynamic range depending of the score and the composition of the orchestra for which it has been written. On top of that the conductor may have some influence. In music the dynamic range may approach 90 dB. Some music can appear quite

amplifying them. At 3000 Hz, the global amplification factor reaches 20 dB (figure 4).

In its vibration the eardrum (tympanic membrane) transfers the aerial vibrations to the tiny ossicles that are located in the middle ear. The whole set hammer (or malleus)-anvil (or incus)-stirrup (or stapes) works as an impedance adaptor in order to transmit almost all the captured energy to the inner ear through the oval window⁵. Without this ossicular chain that can be also regarded as a lever, 98% of the energy would be lost. In order to protect the inner ear against loud sounds, there is a mechanism that thanks to tiny muscles that are tying the hammer and the stirrup to the wall of the tympanic chamber. This mechanism

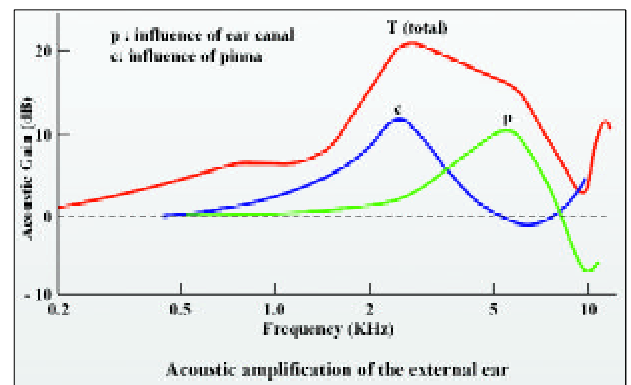


Figure 4: Overview of the auditory system

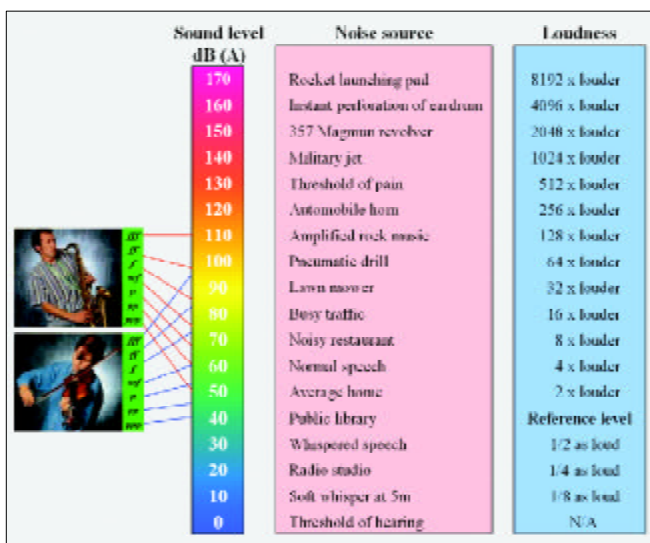


Figure 3: Few examples of sounds with their respective loudness. To double the perceived loudness, sound intensity has to be increased by 10 dB

compression of dynamics (not of data) which really spread out with the “free” FM radio stations proliferation in the 80’s, tends to become widespread in music recording.

How ear and hearing work

The outer ear (pinna, auditory canal and tympanic membrane) is set to capture the sound waves while acoustically

can be activated by reflex or voluntarily. It will reduce the transfer function of the ossicular chain and enables a decrease of 30 dB of the intensity. When sound level reaches 80 dB these muscles will work by reflex (ossicular reflex) to reduce the pressure transmitted to the inner ear. Unfortunately it doesn’t work for very loud sounds and for impulse sounds, as well as for frequencies above 2000 Hz. This is why we have to be very careful with sharp sounds. Furthermore their action is limited within in time.

In the inner ear we find two specific sensory organs. There is the vestibule with its 3 semicircular canals which serve as the body’s balance organ. The second organ is the cochlea which might be regarded as the microphone of the body. It is a snail-shell like structure with 2

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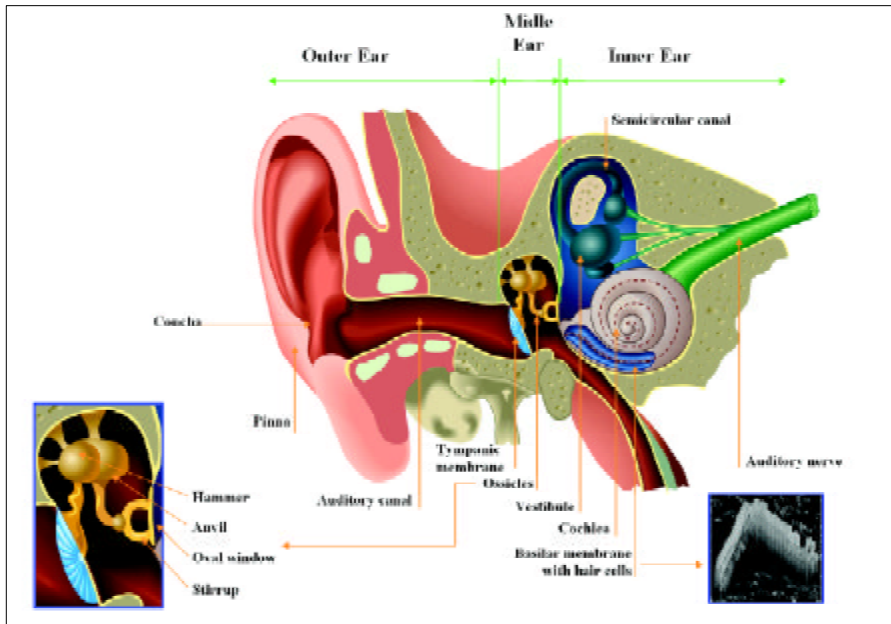


Figure 5: Overview of the auditory system

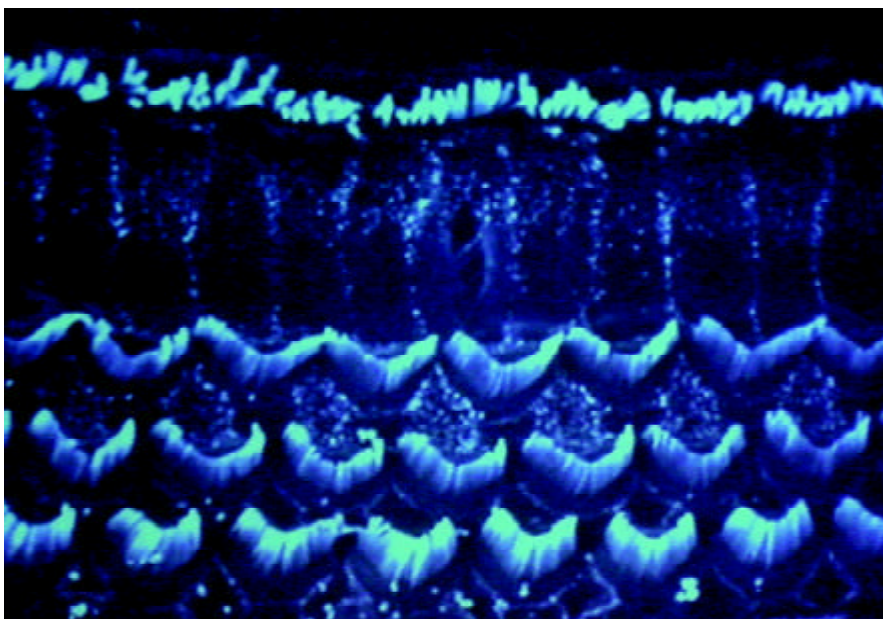
$\frac{1}{2}$ coils that are rolled up around an axis within which gets the auditory nerve. As the sound vibrations are transmitted to the inner ear by the ossicles as mechanical vibrations, they become fluidic vibrations that later on will be converted into electrical impulses. At this point we will only concentrate our interest on the organ of Corti which is the auditory neuro-sensory part of the cochlea. This organ is sitting on the basilar membrane and

is composed of sensory cells that are called hair cells due to their resemblance to hair.

There are about 15 500 hair cells that are innervated by the auditory nerve. There are two types of hair cells that are arranged along four parallel rows. A first row is made of the inner hair cells that are about 3 500 (IHC). The three other rows are made of the outer hair cells which account for 12 000 (OHC). When a sound wave is captured, it

is transferred to the inner ear thanks to the amplification (reduction) mechanism of the ossicular chain. Through the oval window the vibrations will be transformed in pressure changes in the cochlea which is filled with fluid. This will result in an oscillation mechanism of the basilar membrane which will selectively vibrate. This membrane works similar to a cascade of low-pass filters. Depending of the frequency, the vibration has a maximum effect at a different point along the basilar membrane (passive tonotopy). The base will have its resonance with sharp frequencies, while the apex will have its resonance with low frequencies (see figure 6).

This mechanism has been discovered by Georg von Békésy in 1928 who was rewarded by a Nobel prize in 1961. Where this membrane oscillates, it makes the inner hair cells to lean back and forth. As these IHC are in contact with the nerve fibres, it will generate electric impulses that will be transmitted to the auditory area of the brain. The outer hair cells are contributing to a kind of sound reinforcement or reduction depending on the sound intensity and the pitch thanks to a feed-back process stimulated by the brain. This mechanism would sharpen the pitch resolution for high frequencies. So depending of the frequency of the sound, a specific portion of the basilar membrane will oscillate with in turn a specific hair cells portion to be at



Electronic scanning microscope picture of hair cells: - top row: inner hair cells- bottom rows: outer hair cells

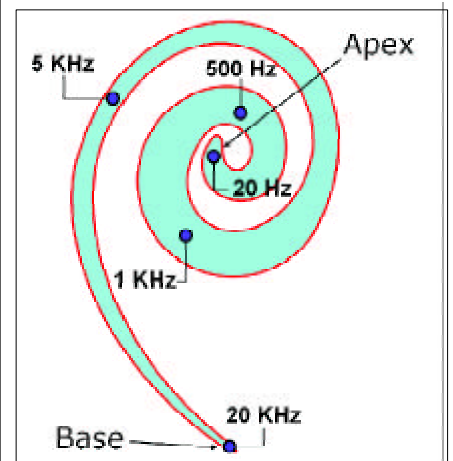


Figure 6: Due to its geometry the basilar membrane works like a cascade of low-pass filters

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work. It is easy to understand that in case of loud sound exposure, this organ of Corti, and more specifically these hair cells can be damaged and thus no more information can be transmitted to the auditory nerve. What is important to bear in mind is that the amount of IHC and OHC is ridiculously small when compared to the millions of photo-receptors we have on our retina. Hair cells are not able to proliferate.

Tinnitus song

Dr. Loth emphasized on the fact that hair cells are fragile and more particularly the outer hair cells. They are made of tiny muscle fibres that are susceptible to get tired. At the end they loss their elasticity and on the long run they can not anymore transmit the sound vibrations coming from outside. When our auditory system is exposed to very high loud noise (persistence of high sound pressure, explosion or

these symptoms are detectable. May be the first recommendation that all of us should adopt is not to put his ears at risk. The dangers in connection with noise depend on the sound level and the duration of exposure. The typical case is the person who goes to a discothèque and who will be exposed to sound-pressure levels that often exceed 100 dB. Three very significant phenomena may be observed in such situation and right away they should be taken for serious. We can get the feeling of a filled ears (sense of fullness) or blocked ears. We can also ear typical sounds that are called tinnitus which for a vast majority manifest as ringing noise in the mid or high frequency. They can also manifest as high pitch whistling, or as waterfall noise, or low pitch sound. Tinnitus is an auditory perception in the absence of any sound stimulation in the cochlea. When the auditory cells have been destroyed, the corresponding nerve fibres are not any more under control and they begin to permanently and anarchically to discharge electrical impulses that induce phantom noises.

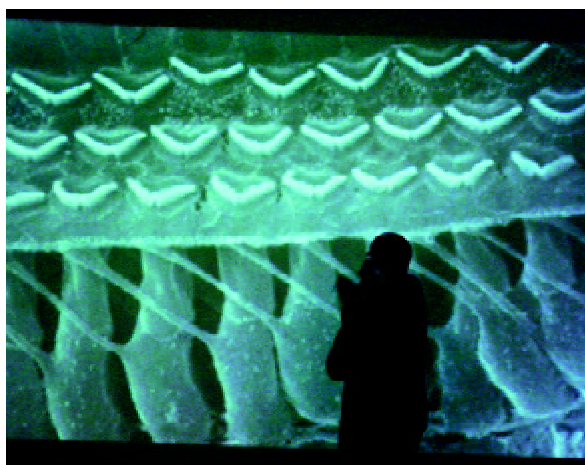


Dr. Drystan Loth while explaining how ear works and the damages that may occur to hair cells that we can see on the screen.

blast) the fluidic vibration might act like an absolute tidal wave that can destroy everything on its way and tear down some of these invaluable hair cells. As soon as these cells are destroyed they won't be replaced as like our neuron they can not proliferate⁶.

Their destruction and their auditory after-maths consequences are incurable. So it is better to know how this happens, what are the symptoms or warning signs if any, and how should we behave when

Whatever is the perceived symptom, it is a clear signal that tells you your hear is hurting. Under the effect of these intensive strengths the ear cells begin to swell to a point that they may blow up. Faced with these symptoms, Dr. Loth is categorical. Get out right away and find a quiet place to give your ears a rest. Usually these symptoms will rapidly disappear after few hours. But it may take also few days before normal hearing returns. The immediate consequence to high sound-



In the heart of the ear with Dr. Loth. Electronic scanning microscope view of hair cells: it is there where dB can really cause great damages.

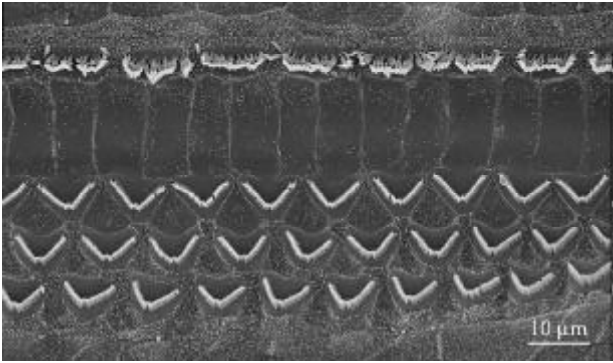
pressure exposure is a hearing loss known as temporary threshold shift (TTS) if the organ of Corti can be restored.

But if hair cells and neurons die, then the hearing loss becomes permanent and we have a permanent threshold shift (PTS). Unfortunately a vast majority of the public is not aware of this and often the victim doesn't want to mention his discomfort (that could be believed as momentary) or to be considered as fragile person. As a consequence to this excess of shyness or pride, Dr. Loth had received in many circumstances patients for whom the irreparable damage had been reached. And that is he had once the case of a young man who after few hours spent in a discothèque began to hear tinnitus. His friends declared not to hear anything that peculiar, so he decided to stay. But faced to the persistence of the trouble he decided to knock up a earplug with some tissue. After three weeks the tinnitus were still there. The audiogram immediately revealed that he had a dramatic threshold shift above 2000 Hz reaching a loss of sensitivity of 80 dB around 6000 Hz. After a medical treatment he could partially recuperate his auditory ability (about 30 dB) but his tinnitus were still there. It means that at about 20 years old he had already the hearing ability of a 60 year-old person (see picture 7).

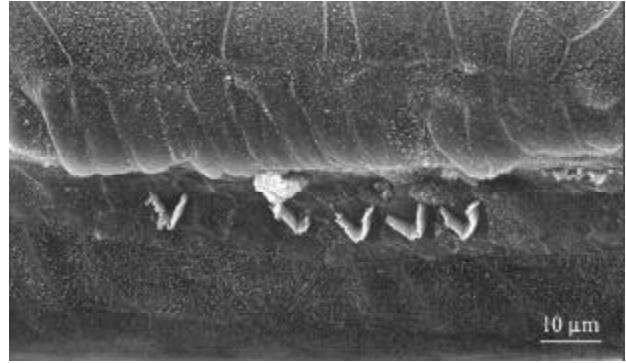
We even daren't imagine what could

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Scanning Electron Microscopy (SEM) surface views of the organ of Corti of rats



Normal Organ of Corti: the four rows of auditory sensory cells, with inner hair cells and outer hair cells, are present. The inner hair cells (IHC) are arranged along one row (top row) whereas the outer hair cells (OHC) are arranged along three parallel rows (bottom rows). The hair fasciculus of the IHC are rectilinear while those of the OHC are arranged with a W-shape. Picture made with a SEM by Marc Lenoir – INSERM U583.



Organ of Corti after acoustic trauma: of a rat that has been exposed to sound of 130 dB at a frequency of 8000 Hz during 15 mn. We can see a massive destruction of hair cells. Only five OHC could survive to this acoustic trauma. Picture made with a SEM by Jing Wang – INSERM U583.

have been the extent of the damage without this makeshift protection. Added to this hearing loss, one might experience some very hampering intensity distortion phenomenon for which we have not yet clear physiological explanation as Dr. Loth recalled it. In other words the more the sound level increases, the more the distortion turns up, and the more acute is the hearing trouble. This phenomenon makes

sometime hearing aids difficult to tolerate. With the availability of digital hearing aids it is now possible to limit this phenomenon. What we should remember from this testimony is that as soon as the very first symptom shows up, it is imperative to go in a quiet place. In case of persistence of the symptoms, don't wait to consult an ENT specialist (ear-nose-throat) as soon as possible. Treated in the

following 24 hours, the patient has a fair chance to totally recover his normal hearing level after an auditory trauma. After 3 days the chances become very low, and passed 3 weeks you may fear permanent after effects (PTS). ■■

Footnotes

¹Christian Hugonnet is the chairman of the "Week of Sound" weeklong event.

²FISM : Internation Forum for the Multichannel Surround Sound techniques and applications.

³dB SPL : Sound Pressure Level = measure of acoustic pressure

⁴dB(A): weighted decibel measurement according to curve (A) to take into account the response of the ear while SPL measurements are based on absolute reference.

⁵It is not quiet sure that the whole of what we hear is transmitted to the inner ear through the ossicular chain. Leipp (1977) describes a direct aerial transmission process between the eardrum and the round window, particularly for frequencies above 10 KHz.

⁶After 10 weeks of fetal gestation, we get our final count of hair cells.

PS2 will feature the concluding part of this Lesson to Listen in the December 2004 issue.

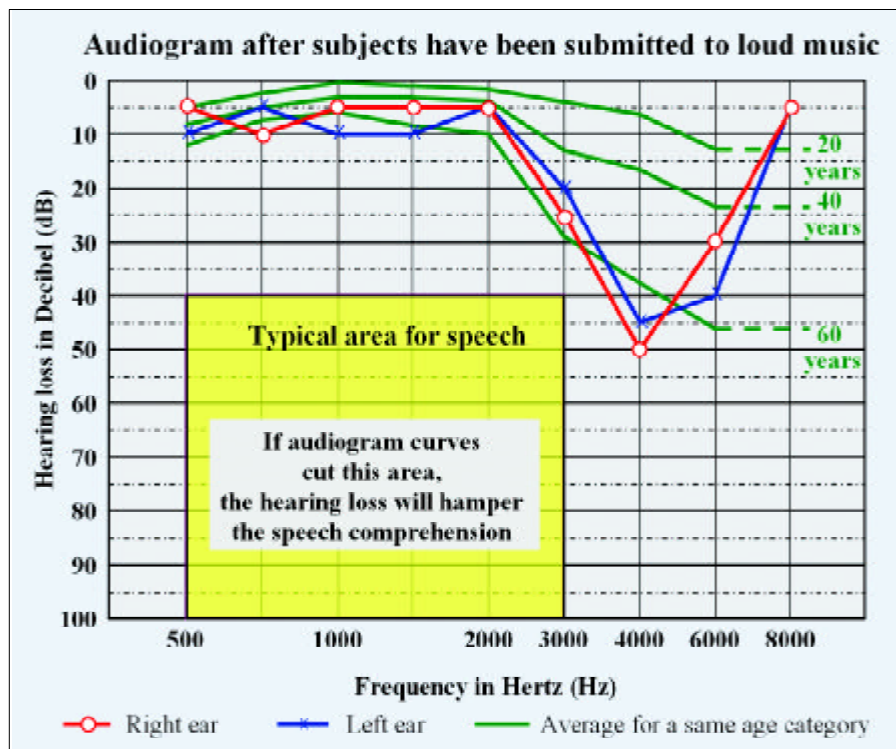


Figure 7: Loud music can severely hamper hearing performance, mainly in the 4000 Hz region.