## PART 1

# Decibel (dB)

The decibel is a logarithmic scale used to describe the ratio of two values of a physical quantity, $Q_2$ and $Q_1$. The comparison in decibels (dB) is given by:

$$10\ \log\left[\frac{Q_2}{Q_1}\right].$$

The decibel scale is used to facilitate the description of quantities which vary within a very broad range of values. The following table helps us to understand the definition above:

| $Q_2/Q_1$ | Comparison in dB | $Q_2/Q_1$ | Comparison in dB |
|---|---|---|---|
| 1 | 10 log1 = 0 | $10^3$ | $10\ \log 10^3 = 30$ |
| 2 | 10 log2 ≈ 3.01 | $10^6$ | $10\ \log 10^6 = 60$ |
| 10 | 10 log10 = 10 | $10^{12}$ | $10\ \log 10^{12} = 120$ |

The factor of 10 multiplying the logarithm makes it decibels instead of bels.

# Audible Sound

The word «sound» refers to audible sound unless otherwise stated. Audible sound is a pressure wave with frequency between 20 Hz and 20 kHz and with an intensity above the standard threshold of hearing. Since the ear is surrounded by air, or perhaps water, the sound waves are ***longitudinal waves***. Details will follow, however, the normal ranges of sound frequency, pressure, intensity and wavelength are summarized in the table below:

| | | | |
|---|---|---|---|
| Frequency | 20 Hz - 20 kHz | musicians call it ***pitch*** (τονικό ύψος) | i.e. between the points where the actual threshold of hearing and the threshold of pain (120dB) meet |
| Intensity | $10^{-12}$ W/m$^2$- 10 W/m$^2$ | i.e. 0 to 130 dB | "dynamic range of hearing" i.e. from the standard threshold of hearing to the threshold of pain |
| Pressure | $2\ 10^{-5}$ Pa - 60 Pa | $\approx 2\ 10^{-10} - 6\ 10^{-4}$ atm | pressure is to be understood as the amplitude of the pressure wave |
| Wavelength | 17.2 mm - 17.2 m | for $\theta_{air} = 20°C$, where $v \approx 344$ m/s | The well known relation holds: $v=\lambda f$, v: velocity, λ: wavelength, f: frequency |

For air temperature, $\theta_{air} = 20°C$, where the speed of sound is $v \approx 344$ m/s, the audible sound waves have wavelengths from 17.2 mm to 17.2 m. The speed of sound depends on temperature, humidity, variations of atmospheric pressure and pollution…

# Sound Intensity – Standard Threshold of Hearing

***Sound intensity***, I, is defined as the sound power per unit area:

$$I = \frac{P}{A} = \frac{\text{sound power}}{\text{area}},$$

measured in W/m$^2$ or W/cm$^2$. Usually I is measured in air and at the listener's location. Many sound intensity measurements are made relative to a ***standard threshold of hearing*** sound intensity, $I_0$:

$$I_0 = 10^{-12}\ \text{W/m}^2.$$

Notice that $I_0$ applies for the human ear and for the frequency of 1 kHz. Usually, I is measured within the dB scheme, relative to $I_0$:

$$I(dB) = 10\ \log\left[\frac{I}{I_0}\right].$$

Thus, $I_0$ takes the value 0 dB. The use of powers of 10 provides a manageable range of numbers to encompass the wide range of the human hearing response, from $I_0$ to the ***threshold of pain*** at some $10^{13}$ $I_0$, i.e. from 0 dB to 130 dB.

## Just Noticeable Difference (JND)

One of the reasons that decibel is a convenient unit, is the following:

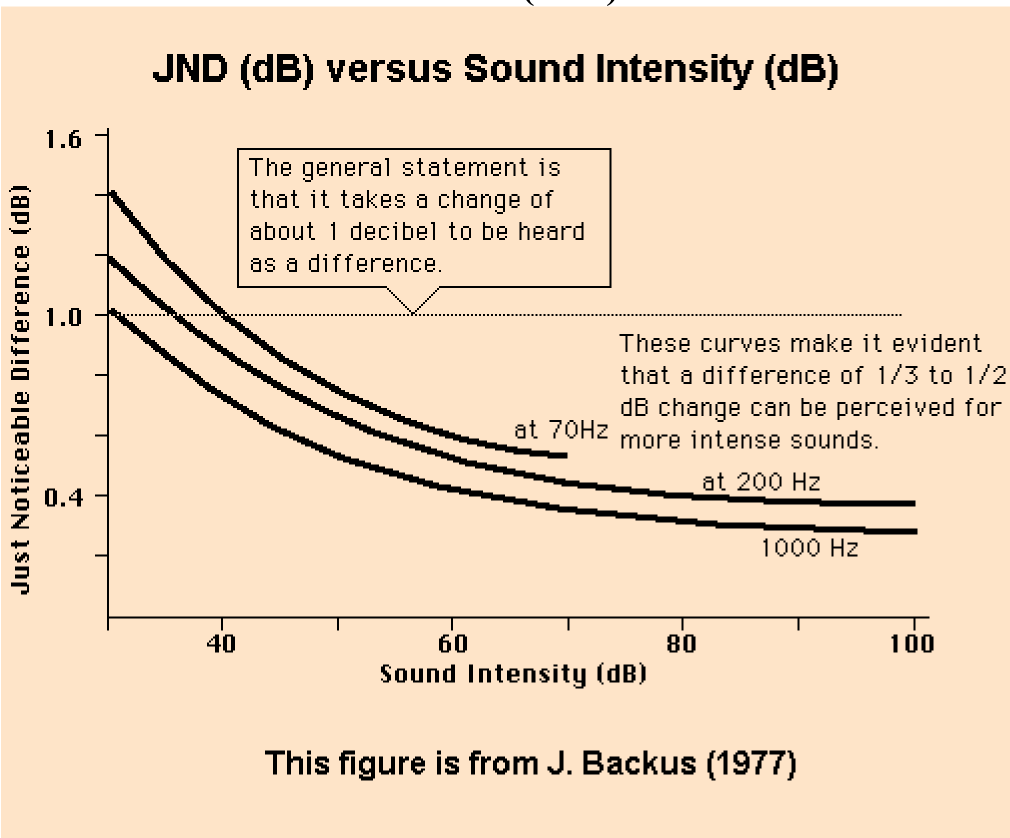
***About 1 dB*** is the ***Just Noticeable Difference*** (***JND***) in sound intensity for the normal human ear:

JND ~ 1dB

Notice that this holds only for soft sounds around 30-40 dB, at low and midrange frequencies.

It may drop to 1/3 dB - 1/2 dB for loud sounds.

Figure from [2]:

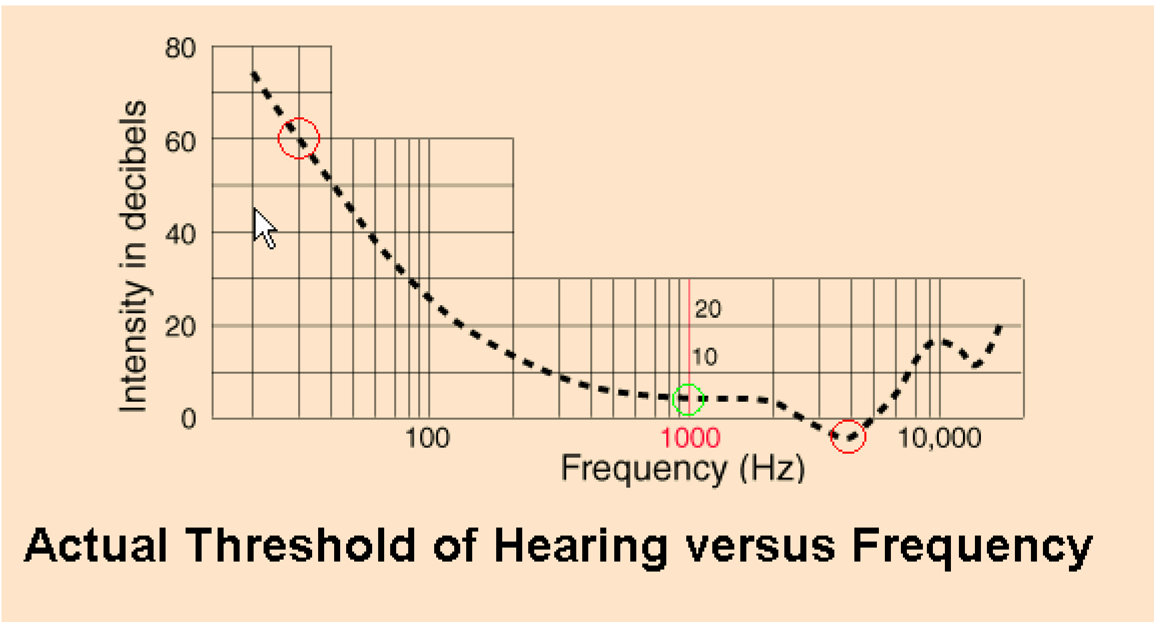



## Actual Threshold of Hearing – Threshold of Pain

$I_0$ (0 dB) is a convenient level of reference, but the ***actual threshold of hearing*** at 1 kHz is more like

$$I_a = 2.5\ 10^{-12}\ \mathrm{W/m^2}$$

or about 4 dB. The measured threshold of hearing curve shows that the sound intensity required to be heard is quite *different for different frequencies* (Fig. 2).



There is marked *discrimination against lower frequencies* so that about 60 dB is required to be heard at 30 Hz. The maximum sensitivity at about 3.5 to 4 kHz is related to the *resonance of the auditory canal*.

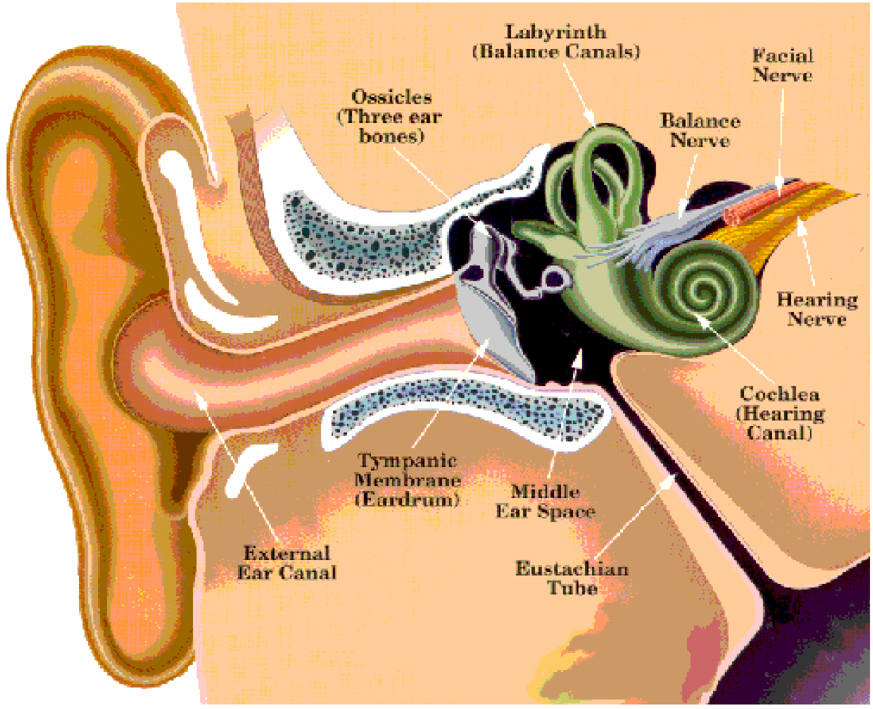
The nominal ***dynamic range of (human) hearing*** is from the ***standard threshold of hearing*** (**0 dB**) to the ***threshold of pain***. A nominal value for the threshold of pain is **130 dB**, but that which may be considered painful for one may be welcomed as entertainment by others. Generally, younger persons are more tolerant of loud sounds than older persons because their protective mechanism is more effective. This tolerance does not make them immune to the damage that loud sounds can produce.  Some sources quote **120 dB** as the threshold of pain and define the audible sound frequency range as ending at about 20 kHz where the ***actual threshold of hearing*** and ***the threshold of pain*** meet. Something analogous can be also defined for the low frequencies, and finally the audible sound frequency range is from 20 Hz to 20 kHz. This remarkable dynamic range of hearing is enhanced by an effective ***amplification structure (I)*** which extends its low end and by a ***protective mechanism (II)*** which extends the high end.

***Amplification structure (I).***

The ***outer ear*** (***pinna*** and ***auditory canal***) and ***middle ear*** (***tympanic membrane*** and ***ossicles***) contribute something like a factor of 100 (i.e. $\approx 2 \cdot 15 \cdot 3$) or about 20 dB of amplification under optimum conditions. The contribution of the specific parts is analyzed below (notice that the numbers here are just representative, not precise data):

The ***pinna*** (πτερύγιο) due to its larger area, contributes a factor of 2. Notice that the ***auditory canal***, due to the one-side-closed tube resonance, enhances the frequency range 2 kHz -5 kHz.

The ***tympanic membrane***'s area is some 15 times larger than the area of the ***oval window*** which is the door to the ***inner ear*** (***labyrinth*** and ***cochlea***), thus contributing a relative 15 times "area amplification".  Finally, the ***ossicles*** (hammer, anvil and stirrup) contribute a lever-type (μοχλός) amplification by a factor of 3 when listening to soft sounds.




Outer, Middle and Inner Ear

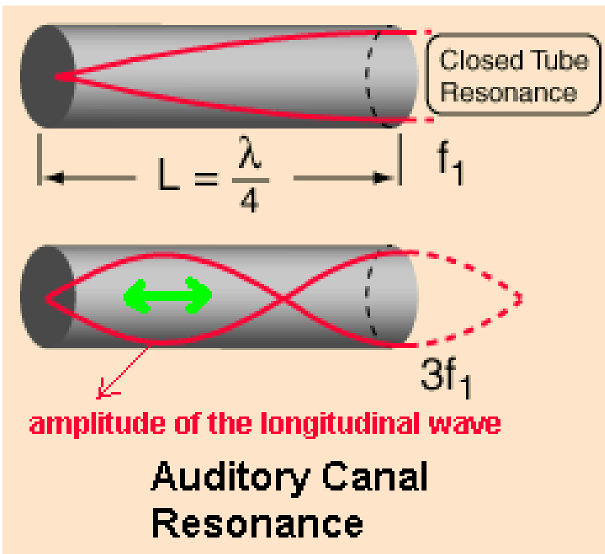
It is necessary now to give a little piece of physical information. Details about ***resonant frequencies*** will follow later. At this point we merely point out that an one-side-closed tube of length L allows standing waves with wavelength, λ:

$$L = n\,(\lambda/4), \quad n = \text{odd } (1,3,5,\ldots)$$

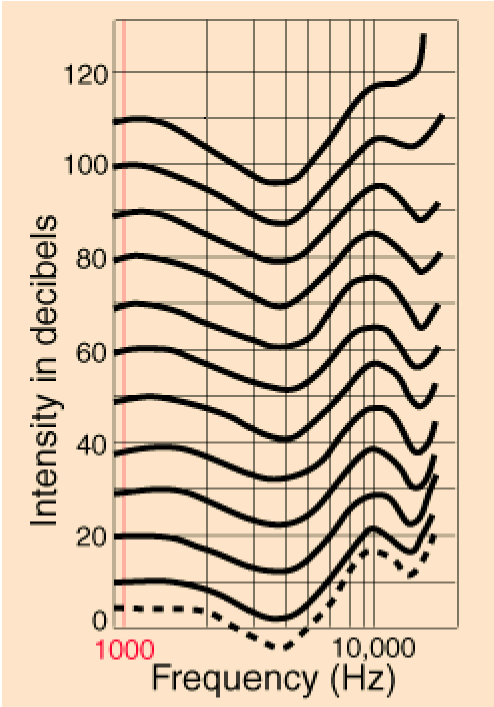
i.e. allows frequencies:

$$f_n = n\,f_1, \quad f_1 = v/(4L),$$

where v is the speed of sound. Here $f_1$ is called the ***fundamental*** frequency and $f_n$ is called the ***nth harmonic***. Notice also that sound is a ***longitudinal wave*** (the ear is usually in air or water).

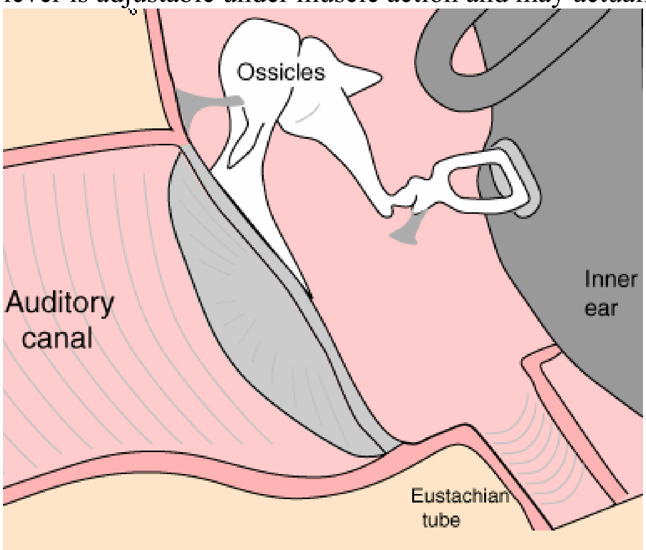


**Auditory Canal Resonance – Frequencies of maximum sensitivity of human hearing.** The figure on the left shows the frequencies of maximum sensitivity of human hearing. These can somehow be modelled as one-side-closed tube resonances of the auditory canal. There is a significant ***dip*** in the range ***2 kHz - 5 kHz*** with a ***peak sensitivity*** around ***3.5 kHz - 4 kHz***. The observed ***peak*** at about *3.7 kHz* at body temperature is associated with the resonance of the auditory canal and corresponds to a tube length of 2.4 cm. There is another enhanced sensitivity region at about *13.5 kHz* which may be associated with the ***3rd harmonic resonance*** of the auditory canal (it is somewhat above the calculated 3rd harmonic of a closed cylinder). The high sensitivity region at 2 kHz – 5 kHz is very important for the understanding of ***speech***.

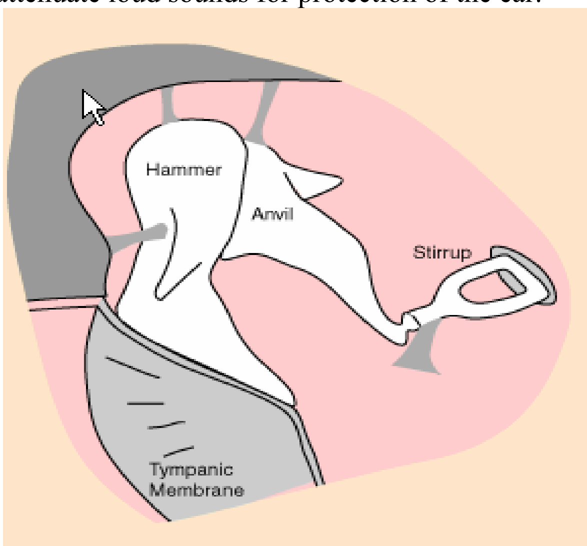



**Frequencies of maximum sensitivity of human hearing**

The ***tympanic membrane*** (τύμπανο) receives vibrations travelling up the auditory canal and transfers them through the tiny occicles to the oval window, the port into the inner ear. The tympanic membrane is some 15 times larger than the oval window, giving an amplification of about 15 compared to the oval window alone. The ossicles, achieve an amplification by a factor of about 3 under optimum conditions, by lever action. The lever is adjustable under muscle action and may actually attenuate loud sounds for protection of the ear.

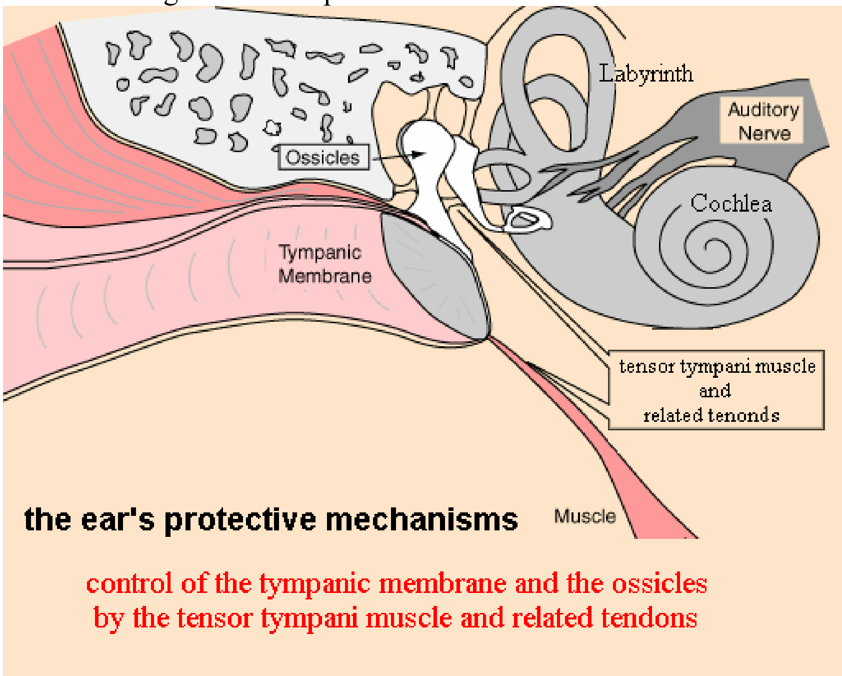


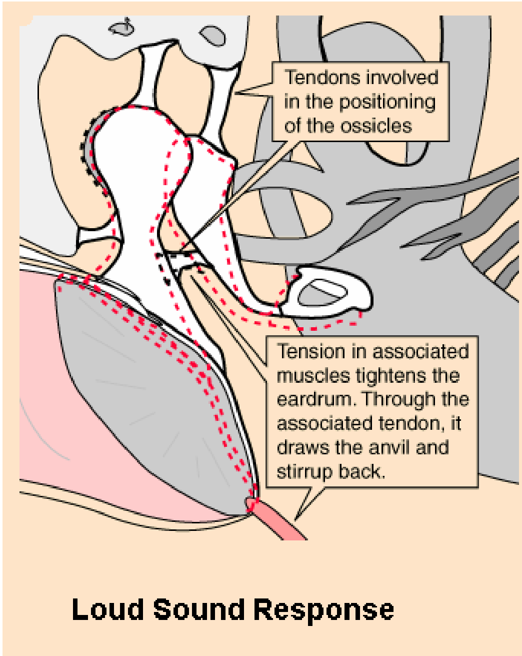

**tympanic membrane**




**ossicles**

***Protective mechanism (II).*** In response to loud sounds, the tensor tympani muscle tightens the tympanic membrane (τύμπανο) and through the tendon between the hammer (σφύρα) and anvil (άκμων) shifts the stirrup (αναβολεύς) backward from the oval window of the inner ear. This shifting of the ossicles reduces the transmitted force to the inner ear, protecting it. However, it is a relatively slow mechanism and cannot protect the ear from sudden loud sounds like a gunshot. The process is less effective in older ears.




***References***

[1] Basic source of information was the site http://hyperphysics.phy-astr.gsu.edu/hbase/sound/ and related links.
[2] Backus, John, The Acoustical Foundations of Music, 2nd Ed, W W Norton, New York, 1977
[3] Rossing, Thomas D., The Science of Sound 2nd Ed, Addison-Wesley 1990
[4] Stevens, S. S., & Warshofsky, Fred,eds. Sound and Hearing, Time-Life Books, NY, 1965. Excellent illustration of inner ear and discussion of inner ear process.
[5] Private Communication: Toufektsis Orestis, Graz Musical Academy. Ορέστης
[6] http://www.audiologyawareness.com/hhelp/howhr.htm

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