“The Common-Mode Rejection of the Ear and its Influence on the Hearing of Born and Unborn”

by Asbjørn Krokstad

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Asbjørn Krokstad

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NTNU
Norwegian University of Science and Technology

Faculty of Information Technology, Mathematics
and Electrical Engineering
Department of Electronics and Telecommunications
Acoustics Research Centre

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THE COMMON-MODE REJECTION OF THE EAR AND ITS INFLUENCE ON THE HEARING OF BORN AND UNBORN

Asbjørn Krokstad, NTNU, Trondheim

Introduction.

The analysis presented here was initiated by S. J. Karlsen, M.D., and T. Bull-Njaa, M.D., at Aker University Hospital in Oslo. The author was asked to estimate the risk of hearing damage for a fetus when using endoscopic lithotripters for ureteral stone removal during pregnancy. Karlsen and Bull-Njaa had measured sound pressure levels from several types of lithotripters in a water tank. Impulse peak levels up to 188 dB at a distance of 15 cm were measured.

A paper presenting measurement data for seven types of lithotripters and a simple analysis of the risk of hearing damage for a fetus, was published in Journal of Endourology in 2001 [2]. The paper was awarded the Astra Tech Prize 2001 for the best research paper of clinical importance. The term “Common-mode rejection” was not introduced in that paper, but in a lecture presented at a meeting of the Acoustical Society of Norway in 2003.

This paper is repeating some aspects of the analysis of damage risk of hearing loss, with an extended analysis of acoustical problems. The analysis may give some physical insight into basic hearing mechanisms both for airborne sound and for sound in fluids (liquids), as in the case of a fetus.

This paper does not claim to extend our basic knowledge of hearing. But, using an analogy from electronic circuits may hopefully facilitate the understanding of some acoustical features of the ear which has been sparsely discussed in the audiological literature.

The most important simplifications in this study are:

- The development of the hearing organ of the fetus during pregnancy is not discussed.
- As the hearing ability under normal situations is reasonably well documented for both adults and children, the paper is mainly trying to quantify the consequences of *the great change of acoustical environment at birth*: a change from being embedded in amniotic fluid (“water”) in the uterus, to normal functions in air after birth.

- Only acoustical and mechanical changes are analysed, not neural effects. The displacement amplitudes of the basilar membrane (place dependent) is the main quantity in focus of our interest here.
- As damage risk criterion for the fetus, a transformation of criteria for adults is used, based on the relative dimensions of heads for adults and newly born babies.
- For the main signal path, the displacement of the tympanic membrane is used as an indication of the sensitivity of hearing for an incident wave,
- Nonlinear effects are not taken into account.

For the estimation of damage risks, worst-case situations are used.

Common-Mode and Common-Mode Rejection.

The term “Common-mode rejection” is borrowed from operational amplifiers [1]. An important feature for these amplifiers is *the differential stage*, where the output signal is the difference between the outputs from two amplifier branches, see Fig. 1. This stage will amplify signals that are present with inverted phase at the two inputs, or even a signal which is presented to only one transistor as long as the the second input is kept at a constant voltage. But signals which are in-phase at the input terminals, will theoretically give no output. Using matched components, the stage will cancel in-phase input signals as

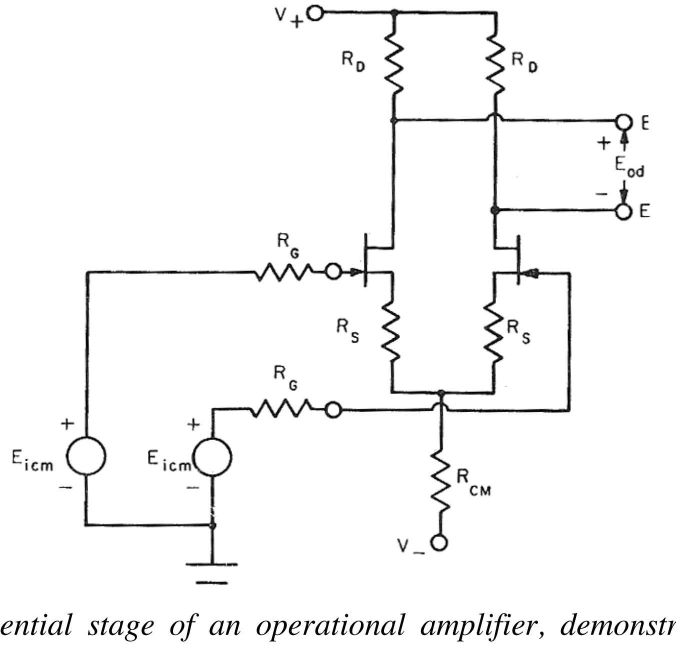


Figure 1 Differential stage of an operational amplifier, demonstrating common-mode input.

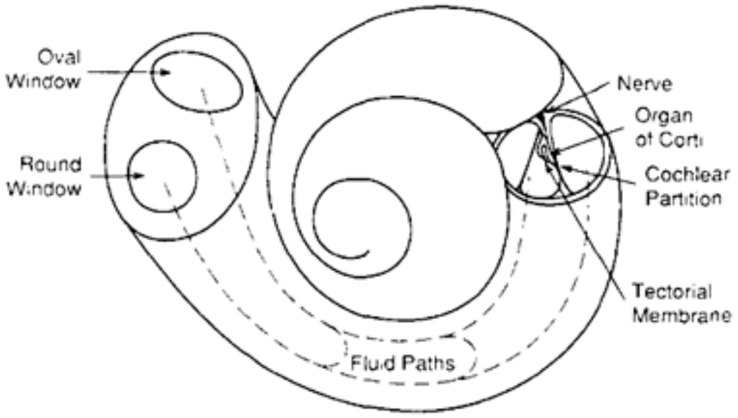


Figure 2 Illustration of the cochlea with the organ of Corti. (from en.wikipedia.org/wiki/image:Cochlea.png)

well as temperature drift and variations in power supply (common-mode input), making it possible to use direct coupled amplifier stages even near DC (0 Hz).

The *common-mode rejection ratio* is the ratio of differential gain to common-mode gain, and is a measure of the efficiency of this cancellation. A high common-mode rejection requires a perfect match between components and also that the two branches are kept at equal temperature.

What does this have to do with the ear? The cochlea of mammals is a marvellous differential analog-to-digital converter (ADC). The fluid-filled cochlea is divided longitudinally into the *scala vestibuli* and the *scala tympani* (see Figs. 2 and 3) by the *basilar membrane* bearing *the organ of Corti,* which includes outer and inner hair cells, the ADC of hearing. The *scala media*, separated from the scala vestibuli by the very thin *Reissner's membrane*, may dynamically be considered as a part of the scala vestibuli, even if the fluid in the scala media, the *endolymph,* is more viscous than the *perilymph,* the fluid in both the scala vestibuli and the scala tympani. The *oval window* is the excitation area of the scala vestibuli from the *ossicles: malleus, incus,* and the *stapes (stirrup)*, which transmit the movement of the *tympanic membrane* to the inner ear. The *round window* connects the scala tympani to the middle ear (*tympanic cavity)* for pressure release.

Excursion of the basilar membrane, and thus excitation of neural activity in the auditory nerve, depends mostly on the local pressure difference between the scala vestibuli and the scala tympani. The local excitations will produce waves in the fluid-filled cochlea and a frequency- and place-dependent displacement of the basilar

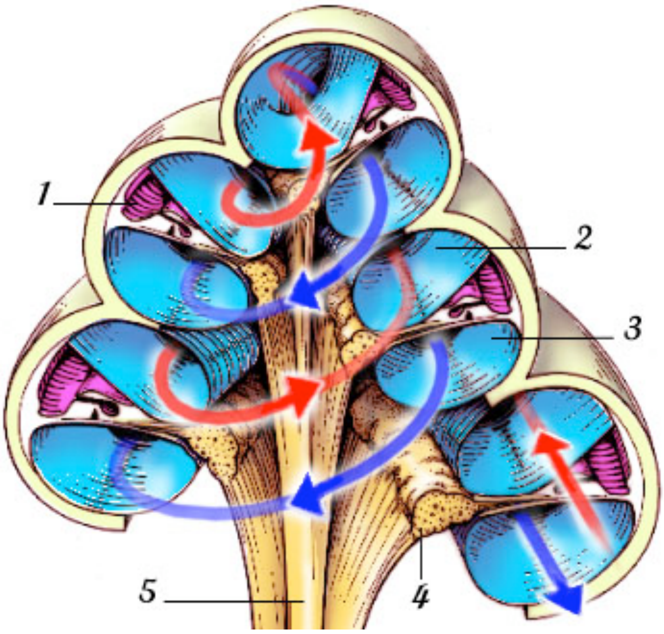


Figure 3 A cut showing the cochlea's differential nature. Arrows show differential excitation. For common-mode input both arrows are in the same direction. 1. Scala media. 2. Scala vestibuli. 3. Scala tympani. 4. Ganglion cells. 5. The 8th cranial nerve. (from: http://www.iurc.montp.inserm.fr/cric/audition/english/cochlea/cochlea.htm)

membrane. These aspects of cochlear mechanics have been studied from the time of Helmholtz by ingenious methods of measurements and by numerical analysis. For the simplified discussion in this paper we only need to stress that for the important range of excursions, mechanical responses are linearly dependent on excitations. Reduced excitation means reduced cochlear responses, and also reduced loudness of sound.

In the linear range the responses to an extended excitation of a part of cochlea may be found by adding the space distributed response (Greens functions) to local excitations.

About dimensions

In wave physics dimensions are expressed in *wavelengths* as justification for simplifications. In volumes with linear dimensions smaller than a quarter wavelength ($\lambda/4$), the sound pressure amplitudes are nearly constant over the volume. "Small" (in wavelengths) objects have little influence on wave propagation in a medium. A table will clarify propagation characteristics and wavelengths of compressional waves in the body, see Table 1.

Material	Density kg/m3	Speed of sound m/sec	Character-istic imp. Pc	Wavelength at 10 kHz	Sound pressure level reduction to air (dB)
Air	1.3	340	442	34 mm	0
Fat	950	1440	1368000	144 mm	-64
Blood	1025	1570	1609250	157 mm	-65
Muscles	1070	1580	1690600	158 mm	-66
Bone	1700	4000	6800000	400 mm	-78

Table 1. Material data for compressional waves in and outside the body tissue. (Data from ref. 9).

Audible sound covers the frequency range up to about 20 000 Hz, but very little information is found for the range above 10 000 Hz, which in Table 1 is used as the highest frequency, and the smallest wavelength, of importance for communication purposes. Some typical dimensions of parts of the body are: (refs. 3, 4, 6 and 7)

> Head of an adult: a sphere of diameter 170 mm.
>
> Head of a "newborn": a sphere of diameter 120 mm.
>
> Ear canal (Meatus): 25 mm long, elliptical cross-section 9 mm and 4.5 mm diameters.
>
> Tympanic cavity: linear dimensions < 11 mm.
>
> Ossicles: the smallest bones in the body.
>
> Cochlea: length of the channels is 32 mm, curled to a cochlea of diameter 8 mm at the basal turn.

The brain is acoustically a viscous fluid in a bony shell. Blood, fat and muscles have nearly equal acoustical data, and not very different from the brain. Cavities which are normally filled with air, as the middle ear cavity (*tympanic cavity),* nose, mouth and throat, are causing some difficulties for a simple model. Table 1 demonstrates that:

> The reflections coefficients between different body tissues inside the body are moderate, but are large at boundaries towards air. Our body is a reverberation chamber: very little sound energy is crossing the boundaries going in or out. Due to great internal losses, and dimensions which are small in terms of wavelength, the "reverberation times" are short.
>
> Acoustically the head is at least 4.5 times smaller inside than from the outside.

Most middle and inner ear elements, such as the cochlea, the ossicles, and the tympanic cavity, are small compared to in-body wavelengths over the frequency range of interest.

For sound crossing the boundary of the body from in-body to the air, the boundary (skin) will have a particle velocity amplitude nearly twice that of the incident wave, and the transmitted wave in air will have the same velocity amplitude.

The sound pressure amplitudes at the boundary and in the air are in that situation very small (theoretically reduced by a factor of about 3 000).

For sound crossing from the air into the body, the sound pressure amplitude at the boundary is nearly twice that of the incident sound (+6 dB), while the particle velocity is small at the boundary and inside the body (reduced by a factor of about 3 000).

Basic hearing (refs. 3, 5 and 8)

The intended function of the basic hearing is of course to detect and analyse airborne acoustical waves for sound perception, and evolution has optimised the hearing organ for this function.

The main path: Sound waves in air → sound pressure at the tympanic membrane → movements of the tympanic membrane and malleus → coupled to incus, stapes and the oval window. The lever effect of the ossicles is increasing the force amplitudes by a factor 15, or 23 dB. The velocity amplitudes are decreased with the same factor.

Only the scala vestibuli is excited. The basic hearing is thus based on a pure differential excitation of cochlea.

Being excited from the oval window, the cochlea is functioning as a folded transmission line (through the scala vestibuli and the scala media to the *helicotrema*, which is an opening, into the scala tympani propagating the waves back to the round window). The transmission line is tapered and has a distributed and frequency selective “leakage” from the scala vestibuli through the basilar membrane to the scala tympani. This marvellous mechanical element is performing a running short time Fourier analysis of the input signal, displaying the spectrum as a place distribution of displacement amplitudes of the basilar membrane. *This function is the basis for communication of man. Distributing acoustical signals to a large number of independent neurons makes it possible to extract frequency and time information in several stages for neural processing.*

The main path has a supplementary route from the tympanic membrane to the oval window. Movement of the tympanic membrane produces a sound pressure in the tympanic cavity, a pressure which is exciting both the oval and the round window, and thus both the scala vestibuli and the scala tympani. The tympanic cavity is normally air-filled, but even then the dimensions (about 11 mm) are much smaller than the wavelengths, also for high frequencies. The excitations of the two windows are therefore in phase, so this path gives *a typical common-mode excitation of the cochlea*.

Improper functioning of the ossicles is known to give conductive hearing losses in the range of 60 dB, which may be the sum of common-mode rejection and mismatch between air and fluid, a mismatch which is reduced in the main path by the force transformation of the ossicles by the factor 15, or 23 dB. *This leaves about 40 dB as common-mode rejection, which is a reasonable estimate.*

Direct excitation of the whole body of cochlea by a wave.

Even a very simple analysis may reveal important physical features, see Fig. 4. A plane wave of amplitude A, incident at an angle φ from the local plane of the basilar membrane, is exciting sound waves locally in the fluid of both the scala vestibuli and the scala tympani. In a plane wave (which is an acceptable approximation for all waves in the far field) the pressure amplitudes are independent of position and thus equal in the two channels. Pressure differences, and thus forces on the basilar membrane, are due to phase differences between the local pressure amplitudes in the two channels. If the incident direction is in the plane of the basilar membrane, the phases are equal and the difference zero.

Due to small dimensions and constant pressure amplitudes, the forces may be visualized as concentrated in the "centre of gravity" in each channel. d is the distance between the centres of the two channels, see Fig. 5. The time delay, τ, between those two centres is :

$$\tau = d \ \sin \varphi / c$$

c - speed of sound

Using the representation of periodic signals as vectors in a complex plane, Fig. 5 illustrates the relationship between the two signals.

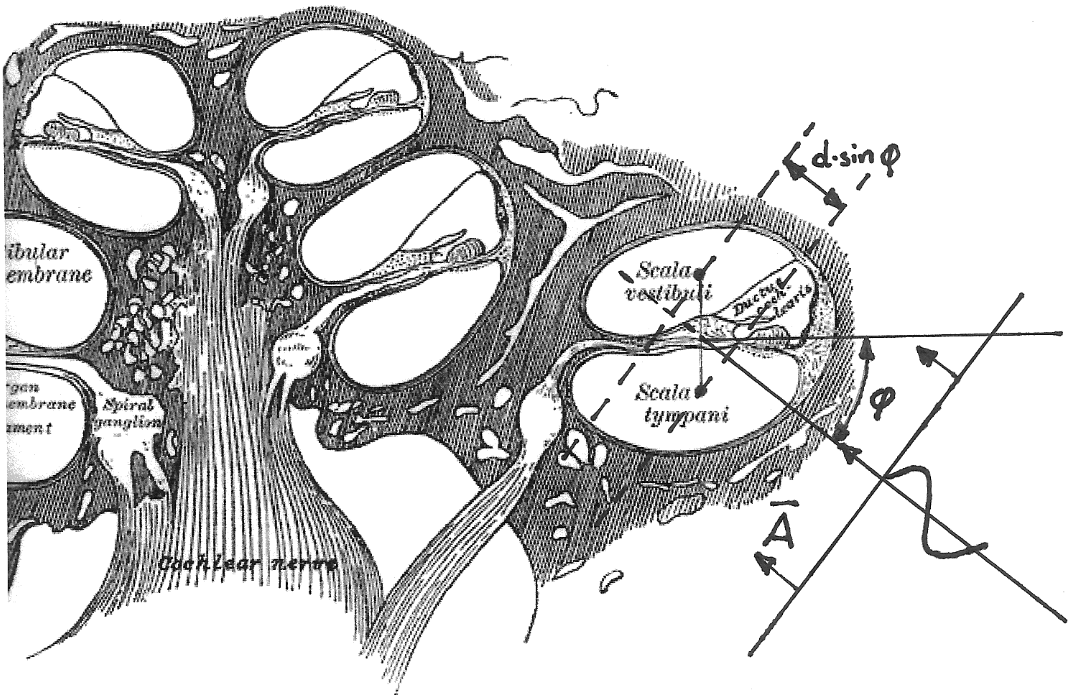


Figure 4 An incident plane wave in the temporal bone is exciting the whole body of cochlea. The wave front forms an angle φ to the plane of the basilar membrane. Distance between the centres of the channels is d. (Illustration of cochlea is from en.wikipedia.org/wiki/image:Gray928.png)

The phase angle, Φ, between the two vectors, which represent the pressure amplitudes in the two channels, is:

$$\Phi = 2\pi \frac{d \cdot \sin\varphi}{\lambda} = 2\pi f \frac{d \cdot \sin\varphi}{c}$$

f – frequency, c - speed of sound, λ - wavelength

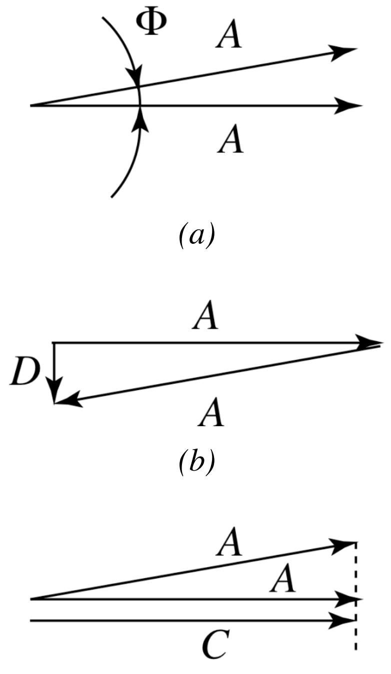
The amplitude of the pressure difference component:

$$D = 2 \cdot A \cdot \sin\frac{\Phi}{2}$$

The common-mode amplitude:

$$C = A \cdot \cos\Phi$$

The cochlea is small: the distance *d* between the centres of the two channels is about 1 mm. The wavelength at the highest frequency of interest is about 300 mm (waves partly in bone and partly in perilymph). The phase difference angle Φ is, for all frequencies, very small, even when the direction of a wave is normal to the basilar membrane ($\varphi = \pi/2$; $\sin\varphi = 1$). Under these conditions the *sine* function may be substituted by the *angle*, and the *cosine* function by *1*.



(a)

(b)

(c)

Figure 5 Phase-vectorial representation of the excitation of the two cochlear channels from an incident plane wave of amplitude A and an angle φ relative to the local plane of the basilar membrane, leading to a phase difference of Φ *between the two sound pressures (a). In (b), the difference signal, of amplitude D, is illustrated. The common-mode amplitude, C, is illustrated in (c) as the projection of one vector onto the other.*

The differential local excitation of cochlea by a wave is then:

$$D \approx A \cdot \frac{2\pi \cdot d \cdot \sin\varphi}{\lambda} = A \cdot \frac{2\pi \cdot f \cdot d \cdot \sin\varphi}{c}$$

The common-mode excitation is the amplitude of the incident wave:

$$C \approx A$$

$$\Rightarrow D / C = 2\pi \cdot f \cdot \frac{d}{c} \cdot \sin\varphi$$

Two examples:

1) $f = 10\,000$ Hz, $c = 1500$ m/sec, $d = 1$ mm, $\varphi = \pi/2$
$\Rightarrow D = 0.042\ C$
$\Rightarrow$ 20 lg D = 20 lg C - 27 dB

2) $f = 1000$ Hz, $c = 4000$ m/sec, $d =$ 0,5 mm, $\varphi = \pi/4$
$\Rightarrow D = 0.0006\ C$
$\Rightarrow$ 20 lg D = 20 lg C - 65 dB

A differential excitation from an incident wave may have an influence at high frequencies if the common-mode rejection is greater than about 30 dB.

At medium and low frequencies the common-mode excitation is totally dominating, and resulting responses depend totally on the symmetry between channels.

Practical consequences for hearing.

For airborne sound the sensitivity of the main signal path is optimized, both by the impedance matching by the ossicles, and by giving an ideal differential (unsymmetrical) excitation of the cochlea at the oval window. A direct excitation of the cochlea body by waves generated in the body, or generated in air and transmitted to other parts of the body than the ears, will give two terms:

> A *differential term* which is dependent on the direction of the wave, and is frequency dependent. The symmetry plane (the plane of the basilar membrane) will vary a little from section to section of the cochlea, but a wave in the direction of the axis of the cochlea will give near maximum differential excitation of all parts of the cochlea.
>
> A *common-mode term* with an amplitude as the incident wave, no directivity and no dependence on frequency.

The common-mode component will be cancelled in a completely symmetrical system. Details that destroy the symmetry are the endolymph-filled scala media, and the fact that the round window radiates directly to the tympanic cavity, while the oval window is loaded by the ossicles. Acceleration of the whole cochlea (by movements of the scull) normal to the membrane will result in a differential excitation of the basilar membrane. For an acceleration in the plane of the basilar membrane, only common modes are excited.

The part-cancellation of noise from in-body sources will greatly improve the signal-to-noise ratio of the hearing. Imagine a situation where airborne sound, such as speech or music, is accompanied by the sound of one's own heartbeats. The fact that we do not hear sound produced and propagated in our own body, indicates that the common-mode rejection is quite great, 40 dB or greater.

It is also important that the differential function of the cochlea reduces the possibility of excitation of the basilar membrane for airborne sound penetrating the skin and propagating in the body, as if the source was inside.

The localization of sources in air depends on the acoustical signal processing of the pinna, and thus demands signals transmitted the ordinary path.

The curling of the cochlea into 2 ¾ turns prevents a direct coupling of a wave in the temporal bone to the fluids in cochlea. Signals which are not exciting the cochlea at the oval window, will be analysed by the cochlea in a way different from the Fourier analysis that is normally performed. The spectral distribution of the signal will be changed in a way which is not easily predicted. The time information, which is the basis of the precise discrimination of pitch, is, however, still available to the neural system.

For a deliberate excitation of the cochlea using a vibration exciter directly to the scull (bone conduction), it may be of benefit to notice that the simple analysis indicates that pressure waves in the direction of the *axis of cochlea* will be more efficient producers of audible sound than waves normal to the axis. To produce as great differential excitation as possible, a gradient field with zero pressure in the plane of the basilar membrane will be especially efficient.

Two anti-phase transducers (a dipole) may have benefits as sources of bone conduction if a proper placement is found.

The hearing of the unborn (fetus).

The original problem attacked was to estimate the possible risk of hearing loss for a fetus due to impulsive sound by the use of intrauretal lithotripters in pregnant patients, as these sources give peak sound levels as high as 188 dB near the head of fetus. The hearing ability of a fetus of course has broader interest, and several experimental studies of the development of hearing during pregnancy, and of auditory experiences of fetus which are claimed to be remembered after birth, have been reported [10].

This theoretical study is mainly limited to a systematic comparison of the environmental conditions for hearing of a fetus in a late state of pregnancy, to normal conditions after birth.

All information about the condition of a fetus is given and controlled by the physicians in the project of lithotripsy.

“Normal” conditions:

> The frequency range of hearing for sound in air is about 20 - 20000 Hz, corresponding to range of wavelengths 7 - 0.017 meter.
>
> The ear canal resonance ($\lambda/4$) is in the frequency range 2500 - 3500 Hz.
>
> Air-filled tympanic cavity (middle ear cavity).
>
> The ossicles transmit displacements of the tympanic membrane to the oval window with the force amplitude increased by a factor 15, and the velocity amplitude decreased by the same factor.
>
> Differential excitation of the cochlea from the oval window to the scala vestibuli only.
>
> Pressure release at the round window to the air-filled tympanic cavity.

Conditions of the fetus:

> The fetus is embedded in amniotic fluid (“water”, in this paper called “fluid”) in the uterus.
>
> Wavelengths correspond to the frequency range 20 - 20000 Hz: 75 - 0.075 meter.
>
> *The ear canal (meatus) and the tympanic (middle ear) cavity are fluid-filled.*

Compressional sound waves from in-body sources have several possible routes to the fetus, and may be propagated with a relatively moderate reduction due to losses and due to partial reflections. In fluids (“water”), losses due to absorption are small, but in porous materials such as the placenta, and also muscles and fat, losses must be taken into account.

For reaching the cochlea three paths are analysed:

1) The ordinary path

The amniotic water in the tympanic cavity greatly increases the impedance loading of the tympanic membrane. Both the stiffness of the middle ear cavity, and the moving mass of the tympanic membrane, being loaded by fluid on both sides, are greatly increased.

The amplitudes of displacement of the tympanic membrane due to an incident wave in fluid may be calculated in a simple way. The tympanic membrane represents only a small obstruction to compressional waves in fluids. *The velocity amplitude of the tympanic membrane will be nearly equal to the particle velocity amplitude of the wave in the fluid.*

For a point source (which is small compared to the wavelength), the displacement amplitude, χ, is given by:

$$\chi = \frac{p}{2\pi f \cdot \rho c}\sqrt{1+\left(\frac{c}{2\pi f \cdot r}\right)^2}$$

p - sound pressure amplitude, f - frequency
ρc - characteristic impedance, r - distance from source

At distances from the source that are greater than the wavelength, the relation between pressure and displacement is independent of the distance, and the wave behaves as a plane wave. The vibration amplitude of the tympanic membrane at 1000 Hz for a fluid wave pressure amplitude of $1.4 \cdot 2\cdot10^{-5}$ Pa, (at the threshold of hearing) can be calculated to $\underline{2.8\cdot10^{-15}\ \mathrm{m}}$. Wilska, [4], has determined the amplitude of the tympanic membrane at the same pressure amplitude and the same frequency, for ordinary conditions (waves in air).

The displacement amplitude in air is 71 dB greater than in fluid.

Due to the small distances from the temporal bone, the vibration amplitude of the tympanic membrane for a fluid-filled middle ear will be even smaller.

The fluid environment and fluid-filled middle-ear will, for the ordinary path of hearing, represent ***a protection factor*** *of the fetus against sound of more than -70 dB at 1000 Hz, and from sources outside (in air) of more than 65 dB. (6 dB less due to boundary reflection at the surface).*

Under ordinary conditions 1000 Hz is in the stiffness controlled range of the tympanic membrane (the middle ear resonance frequency is at 1500 Hz). Displacement amplitudes in the frequency range below resonance are, under normal hearing, proportional to the sound pressure amplitudes. In a fluid environment the *velocity* amplitudes are constant and the displacement amplitudes are increasing at low frequencies.

The protection factor at 100 Hz can therefore be calculated to -50 dB for in-body sources, 20 dB less than at 1000 Hz.

For frequencies well above the middle ear resonance, the displacement amplitudes in normal conditions are reduced by f^2, compared to f for the fluid-filled ear.

The ear canal resonance increases the sensitivity under normal conditions by 10-15 dB at 2500-3500 Hz. The resonance frequency is moved upwards to 13 000-14 000 Hz for the fluid-filled ear canal, and the damping due to radiation and losses at the walls is increased, so the influence on the transmission to cochlea is reduced. The reduction of the protection factor by 6 dB/octave at higher frequencies starts at about 3000 Hz, and is about 10 dB down at 10 000 Hz.

The displacement amplitudes of the tympanic membrane are in the fluid environment of the fetus reduced by about 50 dB at 100 Hz, increasing to 70 dB at 1000-3000 Hz and reduced to about 60 dB at 10000 Hz.

The normal threshold of hearing is at 100 Hz lifted by about 20 dB relative to the threshold at 1000 Hz, so the threshold of hearing of the fetus for the normal path is in the range 60-70 dB sound pressure levels for all frequencies up to about 10000 Hz.

2) Transmission directly to the cochlear windows

The sound pressure amplitude in the fluid-filled tympanic cavity will be a few dB higher than the free field pressure amplitude of the incident wave, and, as the linear dimensions are much smaller than the wavelength, will be nearly constant, both in amplitude and phase. The oval and round windows will transmit the pressure to the scala vestibuli and the scala tympani nearly without reduction. It is thus a very small mismatch between the exciting wave and the fields in the cochlear channels. The phase differences are very small, so the excitation of the basilar membrane is a typical common-mode signal.

For normal hearing the air-filled cavity represents a compliance that reduces the transmission of bone conducted sound to both windows, especially at high frequencies. Radiation through the meatus is also reducing the pressure in the cavity. This path gives a greater force on both windows of the fetus than for ears under normal conditions. The displacement of the basilar membrane is dependent on the common-mode rejection. For both windows the acoustical loading is now dominated by the fluid on both sides. The effect of the stapes loading of the oval window, which destroys the symmetry, is less important.

The common-mode rejection is increased, and a rejection of more than 40 dB will certainly be obtained, especially in the basal turn of cochlea. An increased outer load on both windows will, for a given excitation, reduce the displacement amplitudes of the basilar membrane.

3) Excitation of the cochlear body

For the body embedded in fluid and with fluid-filled cavities, the propagation of waves is less disturbed than in normal conditions. Due to reduced dimensions of the cochlea of the fetus, the differential excitation may be neglected. The whole-body excitation is common-mode. The rejection factor is improved by the fluid load of both windows.

The distributed excitation, for most of the frequency range with small phase differences, will result in a displacement pattern of the basilar membrane which is very different from the pattern obtained when exciting the oval window only.

The tonotopic organization is destroyed so it is reasonable to assume that this path will contribute signals that are similar to modulated noise.

In-body sources

The most important in-body sources are the heartbeats and respiratory sounds.

The heart is a relatively large, and certainly strong, muscle producing a large volume displacement. The fundamental frequency for the mother's heartbeats is about 1 Hz, but the spectrum is rich in harmonics, which even is heard when using a stethoscope. The heartbeats of a fetus are of 2-3 times higher fundamental frequency.

Numerical values of the sound pressure levels in the body have not been available to the author. But, it is quite clear that the sound pressure levels do not exceed 90 dB at low frequencies, and 80 dB at medium and high frequencies, due to the fact that the heartbeats are not heard in air outside the body. The sound pressure levels are reduced by 64 dB crossing the boundary from fat to air, and a sound pressure level higher than 16 dB may have exceeded the threshold of hearing for a broad band signal.

Of the signals that are produced by the mother for communication purposes, speech and singing are the most interesting. Vowels, voiced consonants and singing are produced by tightening the vocal chords. The speech sound waves are propagating both outwards, into the air, and down into the lungs, exciting the chest which is giving a measurable radiation at low frequencies (which normally is masked by the radiation from the mouth) [11]. Vibrations may of course generate compressional waves in the body. The source strength of a trained voice (opera singers) may be high (> 100 dB at 1 m). For untrained voices, and in daily speech and singing, the levels are in the range 70-80 dB at a distance of 1 m.

Sources outside the body

Sources with a vibrational contact with the body fat, muscles or bone may be treated as in-body sources. (Example: a guitar body). For airborne sound, the sound pressure amplitudes at a body boundary are increased due to reflection by 0-6 dB, depending on frequency, and the pressure amplitudes are continuous across the boundary. The sound pressure levels in air are reasonable approximations of levels in the mother's body, and even of levels at the head of the fetus.

The calculation of displacement amplitudes may be based on the far field approximation (only the first term in the formula for point sources). The in-body velocity amplitudes and displacement amplitudes are both reduced by a factor 3100 (-64 dB), the same as for the far field of in-body sources.

Sources outside the body may be treated as in-body sources; assuming the pressure level to be equal or a little higher.

Fetus summing up

There are two important questions the analysis tries to answer:

1) Is it possible that intrauretal lithotripsy in a pregnant patient may damage fetal hearing?

2) Is it possible that babies may recognize sound that was experienced as a fetus?

The first is the original problem. It is of course a very special problem, since about 0.07% of pregnant patients develop urolithiasis. Problems with high level sources inside the body of pregnant women are not a common problem. But, extending the problem also to include external sources, to ask generally if there is any risk of inflicting a permanent noise induced hearing damage to the fetus; and if, what would be a reasonable noise level limit that gives a small risk?

Only a part of the second problem is discussed here: is the fetus hearing sound from important sound sources at a level and a signal-to-noise ratio that are sufficiently high to identify the source; and is the neural representation of the sound so similar to the airborne sound after birth that it is possible to recognize some features of the signal?

Intrauretal lithotripsy is the only internal source known to the author, which may give levels that represent a damage risk to a fetus. The spectra of the short impulses used cover the whole frequency range, which implies that a level reduction in any frequency range will reduce the peak level and the risk. Sharpening the normally used risk criterion for peak impulse levels (140 dB) by 10 dB to 130 dB corresponds to a correction for linear dimensions by a factor of 3, from a diameter of the head for adults of 170 mm, to a fetus head diameter of about 60mm. The mean head diameter of newly born is 120 mm. The sharpening should therefore cover a great part of the late stage of pregnancy.

Compared to airborne sound, the displacement amplitude in the normal path to the oval window is reduced by more than 60 dB over most of the frequency range.

The limiting level giving a small risk of hearing damage by the normal path is 190 dB. The limit is practically impossible to exceed due to cavitation near the source.

The direct excitation of both the oval and the round window directly by sound waves in the fluid is the critical path. (Excitation of the basilar membrane through the shell of the cochlea is smaller than the excitation through the windows).

Due to small dimensions compared to the wavelengths, the differential term may be neglected. The reduction of excitation depends mostly on the common-mode rejection, which in this situation is greater than normal (in air), especially at high frequencies.

Assuming a rejection of 50 dB, the transformed criterion will be 180 dB.

This level has been exceeded by some types of lithotripters 150 mm from the source in water. Taking losses and partial reflections in the path into account, the limit will not be exceeded, and the risk should be small. *There are, however, some assumptions behind these calculations which are not properly proved. When treating pregnant patients it is recommended to use equipment giving the lowest sound levels, and to use sufficient intervals between impulses for allowing the hearing of the fetus to recover.*

Damage risk from external sources (airborne sound)

In general sound environments the impulse criteria must be supplemented by criteria involving both levels and duration. Even if it has been criticized, the ISO 1999 which is based on the energy equivalent level, may be useful. The ordinary used limit, $L_{Aeq} = 85$ dB should be sharpened to 75 dB.

The critical path to the cochlea of the fetus is the direct excitation of both oval and round window from the fluid-filled tympanic cavity. The excitation of the basilar membrane depends on the sound pressure level in the tympanic cavity and of the common-mode rejection. Due to reflection at the body boundary, 6 dB is added to the free field level in air.

Free field levels in air which should represent a small risk of hearing damage to a fetus are then:

$$L_{Aeq} < 119 \text{ dB (8 hours)} \qquad L_{max\ impulse} < 174 \text{ dB}$$

The damage risk is greater for the mother than for the fetus.

A few sources, such as aircrafts and guns, may radiate sound exceeding these limits, but such sources a rare in daily life. The fetus is well protected against noise induced hearing damage.

May a fetus receive sound impressions which may be recognized after birth?

Stories are told about babies that recognize music and voices heard during pregnancy. Such observations are difficult to prove, and also difficult to reject. Ref. 10 presents a summary of scientific studies of the question. Ultrasound imaging is now giving an opportunity to study responses of fetuses to sound stimuli. Available publications also deal with the development of hearing during pregnancy. That is not a topic for this paper, which mainly discusses acoustical problems and the change of acoustical environment at birth.

Important:

> A fetus may hear sound if the levels are above the threshold of hearing, which is at least 40 dB higher than for normal hearing.
>
> The ordinary path, giving differential excitation of the basilar membrane through the oval window only, is reduced in sensitivity by about 60 dB due to the fluid-filled tympanic cavity and meatus.

Only sound of levels 70 dB and higher is thus processed by the fetus as in normal hearing, and even then with a distortion of the place distribution of spectra due to high levels of direct excitation of the round window or the whole cochlea.

> Direct common-mode excitation of both the oval and the round window is probably the dominating path of fetal hearing.
>
> Excitation of the whole cochlear body by waves in the temporal bone will be less dominating than excitation at the windows, but will contribute to a distortion of the place distribution of spectra.

For normal hearing of airborne sound, the differential excitation of the oval window is dominating in sensitivity and is of a level about 60 dB over the common-mode excitation of both windows, and nearly the same over excitation of the whole body of cochlea.

For the fetus the direct excitation of the cochlea through both windows is giving higher levels than excitation of the oval window only.

Speech sounds and singing of the mother, and sound from external sources, have to compete with noise from internal sources, as heartbeats, respiratory sounds and sounds due to movements. These noise spectra are dominated by low frequencies, even below the interesting range for communication, but the sources are interfering with speech and music over nearly the whole frequency range.

> ***The place display of the spectrum of the input signal along the basilar membrane is distorted by high level excitation both at the round windows and distributed over the body of cochlea.***
>
> ***The time information is maintained, so pitch and signal envelopes may be determined.***

Spectral information is the main source for discrimination between speech sounds. To discriminate between voices, pitch is very important. Music recognition is mostly based on pitch variations and rhythmical information carried by envelope patterns.

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Conclusions

Our ears are designed to reject sources inside our body.

The differential form of the cochlea, cancelling waves which are exciting both the scala vestibuli and the scala tympani, is emphasizing airborne sound relative to in-body sources. Functionally this may be described by common-mode and common-mode rejection.

A fetus is protected against sound from all types of sources.

Embedded in amniotic fluid in the uterus and with a fluid-filled middle ear, also the normal path to the cochlea is protected, sufficiently to eliminate all risk of hearing damage.

A fetus may hear sound both from in-body sources, from sources in contact with the body, and from outside sources. The hearing level will be reduced by 50 dB or more.

The display of the spectrum of the signal along the basilar membrane and the organ of Corti is, for a fetus, greatly distorted by high levels of excitation of the cochlea from outside the oval window. The time information is kept intact.

> It is advisable not to care too much about the auditory environment of a fetus. It is well protected both against hearing damage and against exciting auditory experiences.
>
> But one can not care too much about the auditory environment *after birth*. The hearing organs are then well developed and ready to receive suitable input for training and to start filling up the memory by auditory events.

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