The mother’s womb acoustic environment: study of the original sounds and replication for pre-term infants

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Abstract. An experimental study of the physical phenomena that regulated the sound propagation inside the human body and the amniotic fluid was carried out, by analysing the acoustic climate inside the uterus of pregnant women. The aim of this work was to reproduce the original sounds that a fetus can hear inside the mother's womb, as faithfully as possible, in order to provide preterm neonates the rich acoustic stimuli they would otherwise be deprived of. This work describes a natural and new method in the field of new-born care programs which assists early new-born development. The method involves the replication of the intrauterine acoustical environment of the mother which may play an important role in new-born development, especially those born pre-term.

1. Introduction
Several studies have shown that intrauterine environment during pregnancy is characterised by the presence of noises and sounds. These acoustic signals can propagate reaching the foetus’s ears \cite{1}. The foetus is able to perceive acoustic stimuli starting from the sixth month of pregnancy \cite{2} \cite{3}. Noises and sounds inside the mother’s womb can influence the human development. Previous researches have shown the possibility of the foetus to react to external sounds \cite{2} \cite{3} and his capability to recognise voices or sounds during the intrauterine life \cite{4} \cite{5} \cite{6}.

Sounds from the external environment to the foetus must propagate through the air and the body with different transfer functions. Indeed exogenous sounds are modified, both in frequency and intensity, when they propagate through the mother’s abdominal tissue, while endogenous sounds are modified by all the mediums they find in their path (human organs, bones, etc.). However, notwithstanding the nature and acoustic stimuli propagation modality, before reaching the foetus’s ears they must propagate through the amniotic liquid.

The target of the research was to discover the transfer functions of the several acoustic stimuli to allow the artificial recreation of the womb’s sounds lost from the pre term infant.

2. Study methodology
It is not possible to measure directly the individual intrauterine acoustic sounds during the pregnancy for obvious difficult and ethical reasons. Therefore the study focused on measuring the overall acoustic
sounds and then decomposing the sounds into their different fundamental components. Subsequently and successively, analytical mathematical models were created to describe the sounds transformation during the propagation through the physical mediums of woman’s tissue and amniotic liquid (transfer functions) and eventually the transformed sounds are recomposed. Thus, the methodology has been focused on three different steps:

- Signal acquisition;
- Post processing and transfer function analysing
- Rebuilt of the womb’s acoustic environment

3. **Signal acquisition**
The fundamental actions of this acquisition stage have been the following:

- Endogenous sounds registration by means of an intra-vaginal microphone in some of the pregnant women volunteers;
- Study of the modification of sounds during the propagation through maternal tissues, recorded by means of an intra-vaginal microphone and a series of sounds generated outside;
- Analysis of the sound modification during the propagation in liquid (amniotic fluid). Taking into account the scientific literature on underwater acoustics, this aspect has been measured in laboratory by simulations able to investigate the variation of the sound transmission with the liquid deepness (distance of the foetus’s ear from the amniotic sac). The influence of the foetus oscillation in the fluid was also studied.

The women voluntarily co-operated in this measurement study. They agreed, using previous informed consent, with written declarations that were conformed to the Helsinki Convention regarding experiments on human subjects.

The first recorded sounds were those present inside the abdomen cavity of the women (endogenous, or background sounds) when the external environment was silent.

The second series of sounds recorded, were generated by a couple of loudspeakers (see figure 1). These sounds included: pink noise, pop music, classical music and mother’s voice reading a lullaby. Both the external and the internal signals were recorded simultaneously. The measured sound levels were recorded and the endogenous signals contribution removed by logarithmic difference between the measured signals and the background noise.

![Figure 1](image-url)

**Figure 1.** Description of experimental phase for live measurements.
The relative transfer function of the mother’s voice was determined by comparing the external recording of their voice with the internal signal recorded by the probe.

The measurements for the amniotic fluid transfer function determination were carried out by recording on digital recording equipment the signal received from a condenser microphone (protected by a lattice membrane) merged into a recipient filled with a saline liquid, with characteristics similar to the amniotic fluid. Simultaneously the digital equipment recorded the sound source, which was pink noise diffused by a loudspeaker outside the recipient. The measurements were taken at variable depths of 1 cm, between 1 cm and 8 cm of fluid, to simulate the various possible foetus ear positions. Inside the water was placed also a small doll for interference simulation of the foetus.

4. Post processing and transfer function analysing

The background noise inside the abdominal cavity is composed by a time-fluctuating signal, due greatly to the maternal heart-beat and to the intestinal gurgling. The equivalent sound pressure level of this noise is generally about 30 dB(A). Figure 2 shows the equivalent levels for each frequency (averaged over the values obtained with several woman). The major part of the acoustic energy is concentrated on the middle-low frequencies.

![1/3 octave spectrum](image)

**Figure 2.** Averaged background noise level over the tested women in 1:3 octave frequency span.

The abdominal tissue transfer function is the transformation of the acoustic signals propagating through the human tissues. Figure 3 shows an example of a transfer function related to a pink noise source. From this it is evident that the sound attenuation due to the abdominal tissues is increasing with frequency. As frequency increases the column referring to the ‘inside sound’ decreases, while the outside sound remains fairly constant. The abdominal tissue attenuates more the medium-high frequencies, of which the human ear is more sensitive.

It was found during this study that the maternal voice signal propagates more efficiently with respect to other sound sources. It reaches the foetus through two different mechanisms: by the outside airborne path and by the preferential structural (body) inside path.

Figure 4 shows one case of the maternal voice analysis and its alterations. Comparing this data with Figure 3, it can be seen that the maternal voice undergoes amplification at the low frequencies, from 80 to 200Hz, and the attenuation is less sensitive at the medium-high frequencies causing a complete and audible signal transmission.
Figure 3. Example of sounds alteration from abdominal tissues in 1:3 octave bands analysis.

Figure 4. Example of mother’s voice transfer function.

Figure 5. Example of amniotic fluid transfer function.
The amniotic fluid has another transfer function on the sound transmission. This effect assumes a different behaviour depending on the different depth at which the signal arrive. From the experimental data (see figure 5) it can be observed that:

- the sound wave is not attenuated between the frequency bands from 50 to 315 Hz;
- above 315 Hz the transfer function varies according with the depth;
- between 1 cm and 3 cm depth of fluid the transfer function shows an amplification at the frequencies where the human ear is more sensitive;
- For depths above 3 cm the attenuation of sound increases proportionally with the frequency.

5. Rebuilt of the womb’s acoustic environment
A device able to acquire, sample and elaborate the acoustic signals with the aim to rebuild the proper intrauterine sounds was built. The procedure is based on:

- Signal sampling
- Decomposing the digitalised signals into their fundamental components by mean of FFT
- Transfer functions application (modification of the signals to simulate the propagation through the barriers represented by the human tissue and the amniotic fluid);
- The superposition to the transformed signals of the underlying acoustic endogenous sounds like mother’s heart-beat and intestinal mumbles (figure 6).

This process is able not only to recreate the womb sounds environment that the foetus perceives, but also to ‘personalise’ it. Indeed, by the voice acquisition of the actual mother and of her typical heart-beat whilst relaxed, it is possible to reply to pre-term not a generic acoustic environment, but the sounds effectively ‘lost’ from the womb in which the foetus grows during the pregnancy. The quality of this process strongly depends on the optimal transfer function determination and the accuracy of the sounds acquisition.

Figure 6. Typical flow chart of different sound components composition.

6. Experimental tests in Hospital
Based on the results of the research a proper device has been developed to be used in the hospitals (8). The developed device can playback the customized sounds from the mother of the pre term infant. That means there is a way to follow the daily sounds surrounding the mother, making them in relationship with her heartbeat and her voice. The device is studied to surround the pre term in the same monaural hearing environment as he’s used to listen inside the womb.
The environment inside the incubator and the external world is separated by means of an interchangeable membrane useful both for playback the sound, keep hygiene level and climate barrier. The device can be connected to all the kinds of existing incubators so it can be supplied ad an add-on. There is only the need to prepare an adaptor for one of the windows of the NICU itself.

The design and dimension of the playback device can be customized in order to be hosted below the incubator and move with it.

7. Discussion and prospects

The aim of this work is not to discuss about the characteristic of the information that reach the foetus, as they appear in the recreation process but it is important to underline the following acoustic aspects:

- High frequency sounds are attenuated more by the system abdomen-amniotic fluid in respect to low frequency sounds which leads to the question of just how important are low frequency sounds to the foetus?
- The dynamic aspect of the foetus of listening to exogenous sounds. The foetus may decide to hear more distinctly some external signals by moving closer to the mother’s abdominal wall, or to acoustically isolate itself from the outside world by moving to the centre of the amniotic sac. It has been shown that by increasing positional depth the attenuation effects of the abdominal wall and the amniotic fluid become synergetic;
- The fundamental role that the mother’s play. Their sounds are transmitted with all their fundamental characteristics, distinctly reaching the foetus and stimulating him or her for several hours in a day (the problems in the immature-borne infants linguistic acquisitions may have in this deprivation a cause?)
- The direct link that the foetus has with the maternal heart-beat. This sensation is consistently fed to the foetus listening to the endogenous intrauterine background sounds (This raises several factors: could this represent a psychological enforce; a synchronisation with the circadian mother’s rhythms and with the mother’s emotive status and an education to the recognition of external sounds as dangerous or relaxing?);
- The fact that the male voice is sufficiently transmitted through the tissues while outside (externally) the female’s voice is more difficult to be perceived. With practise the foetus will be able to recognise the male voices of the community in which the mother lives (so also but not uniquely the father’s voice). During this period a unique conscience of the mother’s voice is developed.

8. References
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