University of Windsor
64-412 Research Project Report

Objective Percussion Technology for the Diagnosis of Pulmonary Pathologies

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Submitted on:	August 21st, 2006

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August 22nd, 2006

Dear Drs. Maeva and Maev,

Please accept this report entitled "Objective Percussion Technology for the Diagnosis of Pulmonary Pathologies" as my submission for completion of the 64-412 research project requirements.

During these past two terms, I worked alongside Dr. Shofman in the Centre of Imaging Research and Materials Characterization. With Dr. Maev and Dr. Svet as principal investigators, we worked on the development of a Portable Pulmonary Injury Diagnostics Device. We sought to apply age-old percussion techniques and objectify them to obtain an accurate picture of the human chest.

My involvement in this research project has provided me with valuable experience. My submitted report outlines the tasks with which I have been directly involved within the scope of the entire project.

I would like to express my gratitude for being able to contribute to such an interesting and significant project.

Sincerely,

Yann Gagnon
100770982

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Abstract

Percussion is a procedure that has been used by physicians for hundreds of years, where the human body is struck with fingers or an instrument, and the resulting sounds are subjectively analyzed by the physician. A two-dimensional mental image is then interpreted to reveal the location and relative sizes of pathologies. The current project aims to objectify these percussion techniques using modern technology to obtain a reliable and accurate image of the human body, and to develop a portable, relatively inexpensive device. This report principally deals with the tasks I have accomplished in the context of the development of this Portable Pulmonary Injury Diagnostics device.

I – Introduction

Traditional percussion techniques have been extremely useful and are still used today as a preliminary diagnostical tool. However, the accuracy of the diagnosis is highly dependent on the experience of the physician and the availability of a quiet locale. Though percussion sounds have been extensively classified and describes, the human ear remains a subjective instrument of analysis.

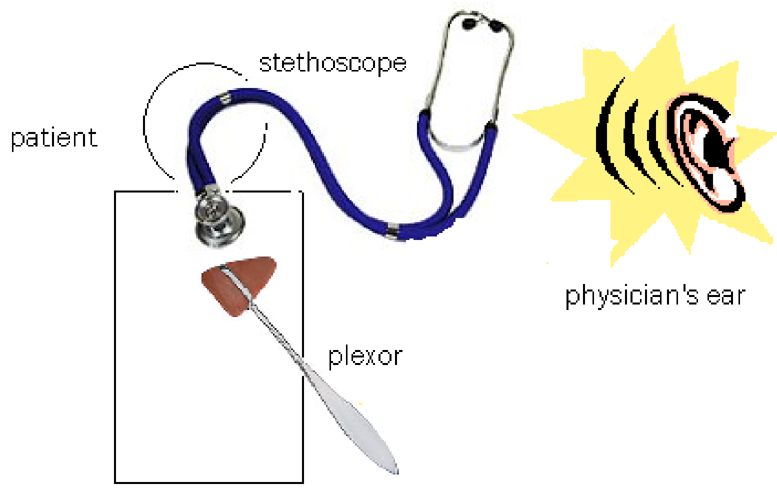

Figure 1 – Elements of Traditional Percussion

The body of the patient is excited, usually with the use of a plexor. Though it is not the most inconsistent part of the traditional percussion process, it is still subjective, especially between different physicians. Next, the acoustical response of different stethoscope can differ greatly. Finally and most importantly, no useful diagnosis can be made without the experienced and well versed ear and brain of the physician.

The following block diagram exemplifies how we can objectify the process to obtain quantitative results.

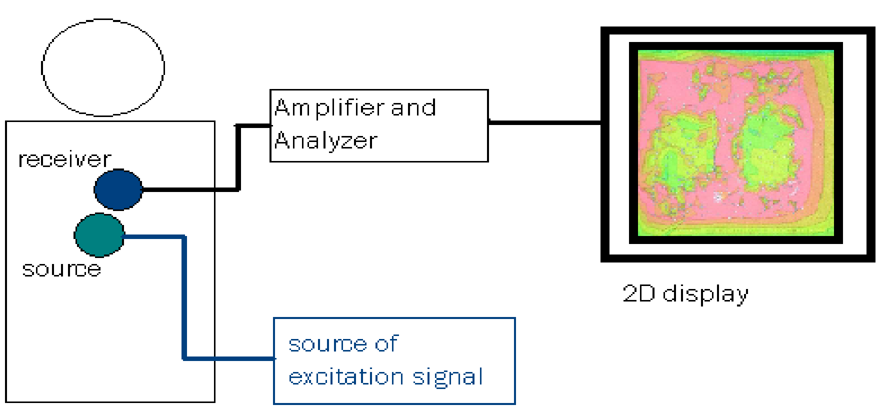

Figure 2 – Objectifying Percussion Techniques

As we will see, new possibilities are now available in terms of excitation signals and methods of measurements, as well as advanced signal processing.

II Construction of a Model of the Human Chest

1. Preamble

This section is mostly devoted to the model design and manufacturing, assembling of experimental setup, practical tests of objective percussion techniques and comparison of its different modifications.

Though objective percussion is intended to the medical treatment of humans, the initial experiments must be carried out on an experimental model for several reasons:

- Stability for all stages of the experiments.
- Availability at any time required.
- Invulnerability to some unexpected factors accompanying any research.

The search of a suitable model, also referred to as a phantom, was undertaken. There are many different models used to investigate various properties of the human lungs. The following are some applications of lung models in research:

· Penetrating and non-penetrating ballistic impacts
· Administration of inhaled medication
· Anatomical models for teaching aids
· Medical Imaging (X-ray, CT, MRI)
· Radiation Therapy
· Study of breathing processes
· Particle deposition

These models can be in the forms of mathematical, computerized simulations and physical models. We note that for each application, the focus is on a specific set of relevant physical properties. And so, an appropriate model can completely ignore certain properties while it must accurately replicate others.

In our case, we are interested in the acoustical properties, with a focus on elastic properties, density, absorption and interface effects. We must make sure that our model reflects these accurately and consistently. With this in mind, we list the following goals for our model:

• Similar density to that of actual lungs (0.2 to 0.3 kg/m3)
• Similar elasticity to real lungs and chest.
• Good acoustical coupling between different parts of the model.
• Flexibility for introducing defects (pneumothorax, hydrothorax)

Since other models are meant for other applications and focus on a different set of physical properties we set out to find a good model. The perfect model would of course encompass all possible physical properties accurately. But since this is impossible, we seek a model which replicates the physical properties we are interested in and has the features we need. When considering existing models, it quickly becomes clear they do not satisfy our requirements, and this is expected since we have a completely different application.

2 - Model Design and Construction

The entire model resides inside a plexi-glass box with sides and bottom of thickness 14mm. This plexi-glass box is 300mm wide and 400mm long with a depth of 160mm. It was carefully fabricated so that it would be leak proof.

The lung tissue is a structured aggregation of small air-filled cavities with elastic and dissipative walls. This is why we choose the plastic foam as a basic material for the model.

Figure 3 - Piece of foam to create lungs in model. The metallic cylinder was used to create holes for pathologies.

In order to simulate the presence of water in tissue and consequently density, some necessary amount (near 25% by volume) of water was added and uniformly distributed in the foam. We quickly noticed that the water-based model was not stable: the water migrated to the lowest parts of the model due to gravity which drastically changed the acoustical properties by formation of non-uniform distribution of density. Therefore, some glue-like agent would have to be found. The glycerol solution of agar was proposed to soak the foam and solve this problem.

Glycerol was used for the replication the density and acoustical properties of the lungs. We also used agar, a galactose polymer and an excellent thickening agent in a glycerol an dissolve it in the glycerol. Glycerol provides the density we seek and will not leak down the phantom. Further, it does not evaporate over time keeping a stable specific weight and mechanical stiffness of the phantom. Another useful property of the glycerol is viscosity:

it helps to enlarge vibration energy loss up to reasonable levels, much closer to that of real lungs than with a water based model.

A small amount of water is used to initially solve the agar to compose a mixture which has a melting point of 85 degrees Celsius. When the mix cools, the agar forms a net-like structure of polymer molecules. As a result, a low concentration of agar enhances the viscosity and higher concentrations lead to the formation of an elastic jelly-like substance. Then we heat the glycerol to approximately 90 degrees Celsius and dissolve the agar/water mix into it. Once allowed to cool, the mix solidifies to a gelatin-like composition below 32 degrees and provides the elasticity desired. Gravity no longer redistributes the density throughout the model. A preservative, sodium benzoate, is previously added to the mixture to maintain its stability against microbial decay. A piece of foam 300mmx400mm and 120mm thick was used and soaked in the glycerol/agar mixture to give it a density of approximately 0.25kg/m^3. This piece of foam is the main part of the model and will simulate the lungs. Particular attention was paid to ensure that the mixture was distributed uniformly throughout the foam for consistent modeling.

We waited for the glycerol/agar mixture in this piece of foam to solidify and then introduced two types of defects in it. The first type is a fluid-filled cavity, in this case water, which simulates a hydrothorax. The second is an air filled cavity, which simulates a pneumothorax. The cavities were made by drilling out cylindrical spaces in the foam. Four different sizes (same diameter, different depths) of each type were cut out of the lungs and a latex bladder was used in the case of the hydrothorax to contain the water. Good acoustical contact between the hydrothorax and the lungs was ensured since the surfaces are soft and pressed well towards each other.

Next, the chest wall model was worked out and manufactured. We replicate the muscle mass surrounding the lungs with a stiff fibrous material (air filter) filled also with the same glycerol-gelatin solution, but of higher concentration. In this we insert wooden baguettes that are about 20mm wide, 8 mm thick, 300mm long. They were spaced about 2cm away from each other. The cross-sections of our model wooden ribs were made to be close to the actual cross-section of human ribs.

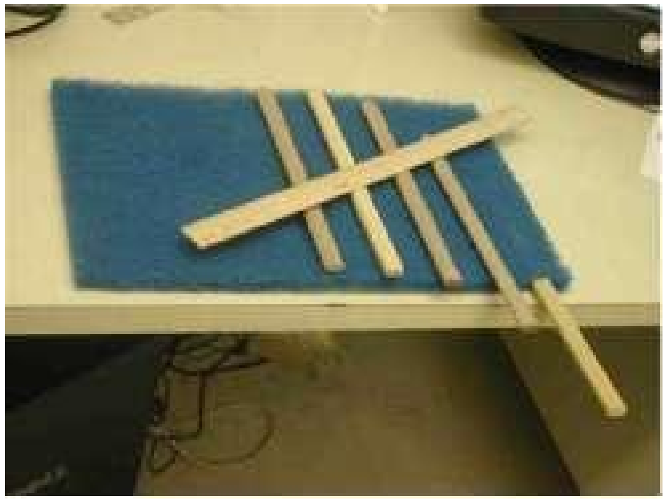

Figure 4 - Construction of Chest Wall

The chest wall model was completely soaked in the higher concentration glycerol/agar mixture. This resulted in the sought after stiffness to replicate the muscle mass of the chest wall.

The chest wall was placed above the lungs in the plexi-glass box. Next we use our glycerol/agar mixture again and spread it on top of the ribs to have a thin but very smooth layer for which to lay our "skin" onto. This layer is important so that the skin makes good and even contact with the rest of the model. Another reason is that a smooth skin will provide a consistent and good acoustical contact with the microphones used for measurements.

The skin is simply an appropriately sized piece of natural leather, with markings to map out the placement of the ribs, hydrothoraxes and pneumothoraxes.

Tracks were affixed to both sides of the plexi-glass box that run length-wise along the model. Perpendicular to both of this is an L-shaped piece of aluminum that allows us to place various drivers, sources or microphones at precise locations.

Figure 5 -- The completed phantom, with percussion hammer and microphones

III - Measurements Methods and Equipment

Two different sources of sound are used in this experiment. The first is an electric hammer, which consists of a solenoid which drives a striker in a plastic housing. This percussion hammer replicates the tapping a doctor would perform. This solenoid is fed by a square waveform and produces a consistent tapping over time. A special spring loaded holder was constructed to ensure that the same force was applied by the hammer onto the model for each measurement.

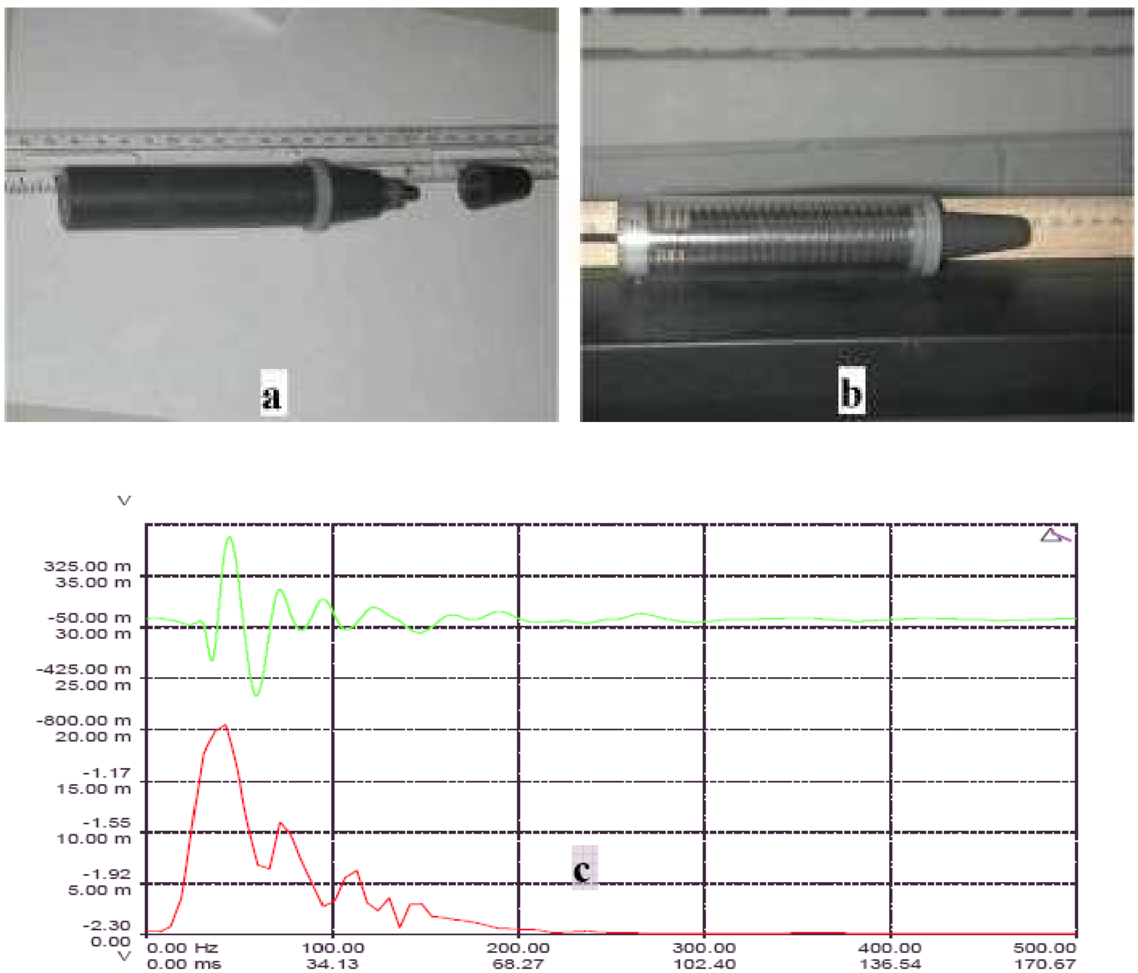

Figure 6 (a) The percussion hammer is seen partially disassembled, (b) in its spring loaded housing on the right, (c) the driver's signal and their spectrum measured at a distance of about 20 mm

The second source is a modified loudspeaker which mechanically drives the surface of the model. In order to minimize sound irradiation to the air which could be superposed to the measured signal on the model, the loudspeaker diaphragm was cut out and sound deadening foam was placed on the loudspeaker housing. Both a multi-tone signal and a built-in pink noise signal were fed one at a time in trials to this loudspeaker. Because of the stronger decay of higher frequencies, a custom "violet" multi-tone signal was designed and used for some experiments. This violet multi-tone signal contains enhanced higher frequencies. Frequencies from 30 to 500 Hz were represented in steps of 5 Hz.

Figure 7 - The electro-dynamic driver in its holder on the model. The green foam is the sound deadening material and the grey plastic cylinder is the striker.

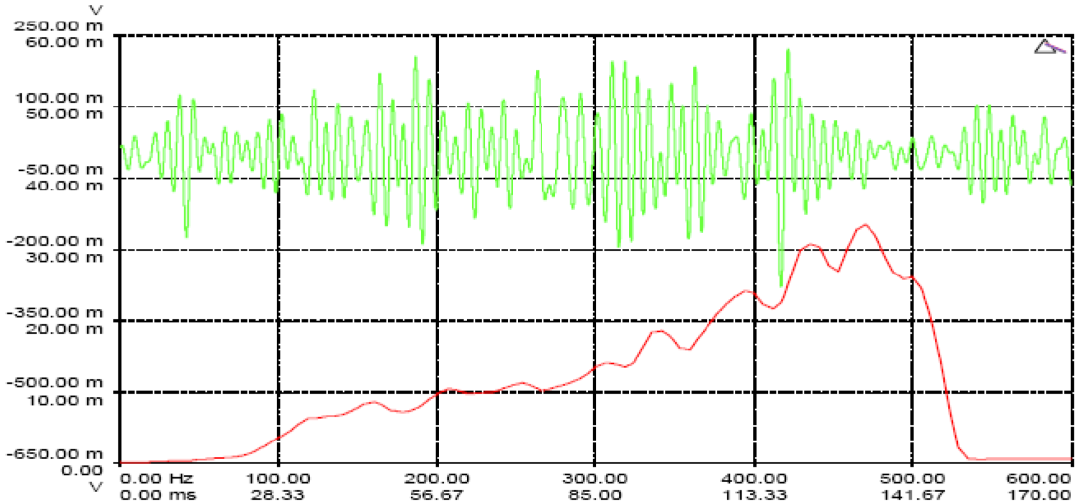

Figure 8 - Violet multitone signal received in 20 mm vicinity of actuator and its spectrum.

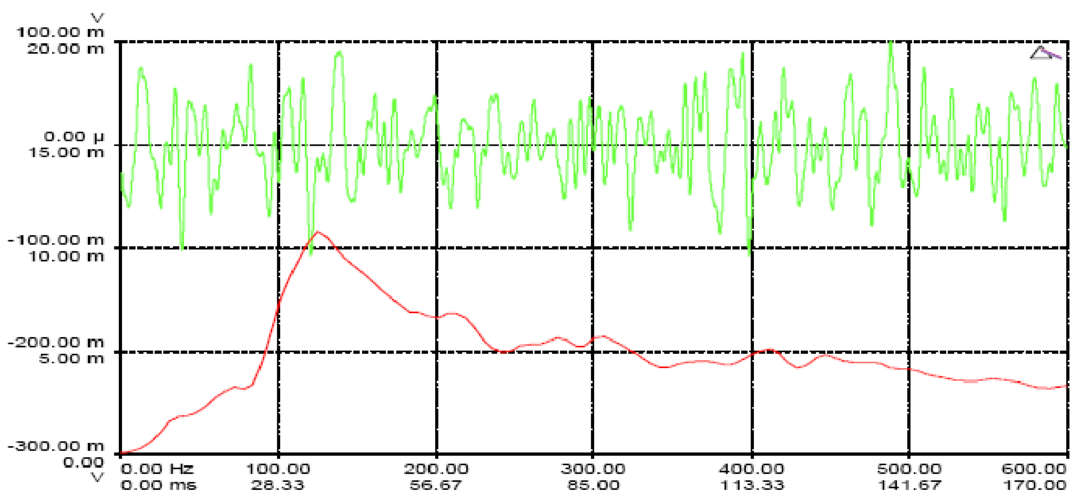

Figure 9 - Pink noise signal received in 20 mm vicinity of actuator and its spectrum.

The microphones are two Behringer ECM8000 units chosen for their extremely flat frequency response in the low frequency range (20-1000Hz). These are condenser type microphones which require separate power supplies but make up for this slight inconvenience with great frequency response and quality. The microphone housings were removed and the condenser units were installed in the output of conical concentrator. This cone was constructed to work exactly like the bell of a stethoscope.

Figure 10 - The active circuitry of the ECM8000 mounted on the side of the model.

At first, a membrane was used but it was quickly found that the membrane became a high-quality resonator and therefore suppressed much of the interesting spectrum. The conical unit was kept without the membrane and was found to be optimal for our use. We also did some measurements with a neonatal stethoscope with the condenser unit of the microphone attached to the head. The open conical "bell" side of the head was used. With both the conical unit and the stethoscope, acoustical gel was used to ensure perfect coupling.

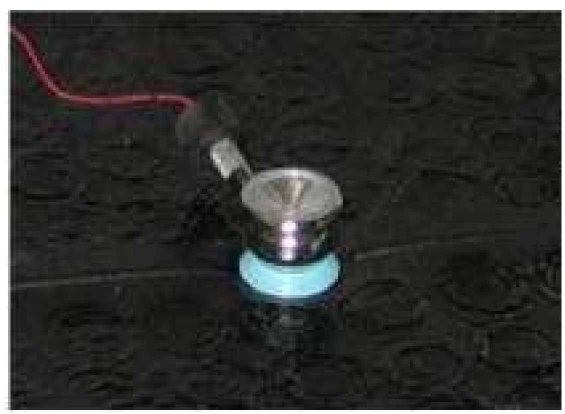

Figure 11 Left: Conical unit with plastic membrane and microphone. Right: Neonatal stethoscope with microphone attached..

*T*he Behringer ECM8000 microphones require phantom power for proper operation and this was achieved with two ART Tube MP professional microphone tube preamplifiers. These provide the 48V phantom power needed for the microphones. In this context, phantom power refers to the superimposed DC voltage used on the audio line to power the condenser unit. These preamplifiers also allow for 56dB of amplification before sending the signal to the spectrum analyzer. High quality XLR cables were used for all connections.

Figure 12 - ART TubeMP preamplifiers and phantom power supplies with XLR connections

The main piece of hardware in this experiment is the PrismSound dScope Series III spectrum analyzer. The dScope interfaces through its own Windows application and exportation of data to Microsoft Excel is achieved with the built-in scripting capabilities of the software. It functions as both a two channel signal generator and as a two-channel analyzer for our purposes. As a signal generator, the software allows us to use and modify any of the signals we wish to use: square waves (for percussion hammer), sine waves, multi-tone, noise and sweeps (for electro-dynamic driver). As an analyzer, it allows us to monitor two analogue inputs and record the data with the software and our own script. We perform a fast-Fourier transform to obtain the frequency spectrum of our measurements. The dScope interfaces well with our XLR connections used with our preamplifiers and microphones.

Figure 13 - dScope III spectrum analyzer

A major part of my work was to write scripts in the VBScript programming language. Some scripts were used to create custom waveforms to probe our model. The rest were used to automate the measurements, which was a huge time saving measure. Automatic export of the data to MS Excel was possible. A special script was devised for every combination of excitation signals and measurement modes we used.

IV - Measurement Techniques

Several sets of measurements, each consisting of about 200 pixels (cells) throughout the phantom were performed. Every set can be described in terms of its spatial mode (positioning of devices) and its type of radiated signal (short burst or noise or custom waveform). We have used three different modes of measurement, characterized by their different spatial arrangements of the source and the sound receiver.

Two of these modes are separated modes of measurement, where one of the two devices remains immobile and the other is moved. The most convenient location for the immobile device is the centre of the phantom. Of course, two different separated modes are possible: a mobile receiver (the source remains immobile at the centre) and a mobile source (receiver remains immobile at the centre). This second scenario is an exact repetition of Dr. Syrnev's methodology used during his investigations.

The combined mode consists of positioning the source and the receiver as close together as possible. Together, they scan the phantom as a single unit and so that their relative position remains same.

We used different types of acoustical signals to make an experimental selection of the optimal signal(s) to be used in future work. The short burst signal was created by an electro-mechanical "hammer", specially designed to replicate the action of a doctor's fingers tapping on a patient's body. The other types of signals were created by an electrodynamical actuator, which we also refer to as an acoustical driver.

The acoustical driver can be fed any waveform built into our signal analyser's wave generator and any custom made functions. We used a pink noise signal created by the analyser, a "violet" noise signal designed by our team, and linearly frequency modulated (LFM) sine signals of both short (about 1 second) and long (about 30 second) durations. The pink noise was used because its maximum spectral density of energy lies in the low frequency band, which is the band of interest in our experiments. On the other hand, a white noise signal has most of its energy in the useless frequency range between 1 and 44 kHz hence it was not used in our experiments. The violet noise signal (overall range from 30 to 530 Hz , with enhanced high frequencies) was developed and then applied to overcome the strong absorption of higher frequency components when the sound propagates through the phantom.

Most of the experimental data was obtained with the use of the short burst and the pink and violet noise signals..

We call the combination of our **spatial modes** of measurement and the **type of signal** used our **configuration** for that specific set of measurements. With 3 spatial modes and 3 types of signals, 9 configurations were possible. However, most of the experiments were performed according to only 3 configurations. There were several reasons not to try all theoretically possible combinations. For example, if the distance from the source to the receiver is practically zero (combined mode) then the higher frequency components do not decrease unlike what happens in the separated mode. It is the only way to measure the high-frequency response, so the best kind of signal is pink noise. Since the short burst signal has a spectrum in the range of 0 to 300 Hz, we are not able to measure the spectral response for frequencies greater than 300Hz. A small series of measurements was performed in the combined mode using the short burst signal. Only the low-frequency response could be measured.

In principle, it is possible to also scan the phantom with a mobile source using any of the noise signals. Measurements with the percussion hammer as the immobile source were also possible. However it quickly became clear that these other configurations did not yield anything new when compared to the 3 configurations chosen for the main data analysis

V - Results

The extensive measurements performed on the two different phantoms showed that spectral characteristics of the modeled pathologies and the modeled "healthy tissue" differed from each other but not fundamentally so. Sometimes the spectra measured on different areas of the healthy lungs varied considerably and this can mask the spectral particularities of the pathologies. In this case, only statistical data processing is able to reliably reveal the pneumothoraxes and hydrothoraxes.

Detailed measurements demonstrated that the spectral variations from one "healthy" area to another were caused by acoustical reflections caused by the boundaries of the foam. The second phantom contained absorptive layers on the side and bottom of the foam forming the model.

Unfortunately we could not achieve complete elimination of the interference effects. In order to minimize them, a phantom with only two modeled pathologies was built. A pneumothorax and a hydrothorax, both of diameter 90mm and depth 50mm, were situated as far as possible from the boundaries and each other. In terms of eliminating undesirable reflections, this model comes the closest to an actual human or animal body because of the lack of abrupt boundaries, corners etc. This allowed a much better demonstration of the diagnostic capabilities of objective percussion using any of the measurement modes and any type of probing signal discussed in this report.. As an example, the result of a 1-dimensional scan of the modeled hydrothorax is represented in the Fig.14 . The image consists of the spectra measured on the rib which crosses the hydrothorax close to its diameter. Each of the measurements were taken 1 centimeter from each other and the immobile receiver was set about 20 cm away from the pathology. The percussion hammer was a mobile source and provided a short burst signal for these measurements.

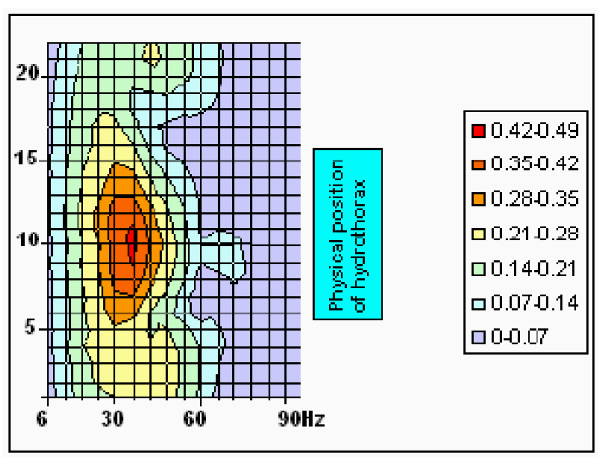

Figure 14 A one-dimensional percussion image of the hydrothorax obtained by scanning along the rib. The vertical axis represents the position of the source while the horizontal axis represents the frequency and the colour scale represents the amplitude.

In the case of the more complex phantoms, advanced signal processing techniques was necessary to detect the spectral particularities of the lung pathologies. The development of such algorithms, including matched filtering algorithms was beyond the scope of my work and was performed by Dr. Svet and his team. The specific results will therefore not be included in this report, however, the conclusions drawn from it will be, for the sake of completeness.

VI – Conclusion

· The foregoing research showed the possibility of revealing lung pathologies such as pneumothoraxes and hydrothoraxes based on objective percussion methods.

· The exact localization of pathologies and their degrees can be defined only on the basis of the construction of a two-dimensional percussion image. In our opinion, the data obtained from the measurements performed in isolated points are not representative. Such isolated measurements are probably useful in extreme cases when the volume of gas or liquid is quite large. In this case, for real patients in real environmental conditions, a single-point measurement is only enough to confirm the presence of a serious pathology but not give explicit details.

· Diagnostics of pneumothoraxes and hydrothoraxes can be accomplished by spectral analysis of percussion signals. Spectral features of these two kinds of pathologies are different.

· The higher precision of localization and gas percentage determination in pneumothoraxes can be achieved on the basis of so called matched treatment algorithms.

· The spectral algorithms of the percussion image construction previously proposed allows the exact localization of pneumothorax with a precision of at least 5-6mm and also the estimation of the volume of the gas.

· The noise signal or other artificial signal with a large enough basis seems to be preferable because it allows the achievement of a more stable spectra. Furthermore, the more stable spectra allows us to perform further correlation measurements in separated mode.

· The use of a short burst signal is especially useful for a calibration-like mode, but under certain conditions it can also be used for the localization of pathologies.

· The higher frequency band within audible range proved to provide very informative results, especially for hydrothoraxes.

· Objective percussion can be performed in two ways: a combined mode of measurement (actuator and receiver placed at same point) and a separated mode of measurement (actuator and receiver are each placed at a different locations, where one remains stationary and the other is mobile). The separated mode allows two configurations: a mobile receiver or a mobile source (Sirnev's methodology).

· Pneumothoraxes can be reliably diagnosed both in combined and separated modes. Different volumes (from 50 to 200 cm3) of air can be distinguished which corresponds to a range of 20% to 80% in terms of severity of the pathology.

· Diagnostic reliability of hydrothoraxes also appears to be good for large volumes of liquid with the use of the combined mode of measurement with the noise signal. The separated mode of measurement used with the burst signal did not indicate well the difference of size of hydrothoraxes. Therefore further developments of signal processing algorithms are necessary for this mode.

· The experimental material obtained does not allow us to draw a complete conclusion concerning the optimal measurement mode, combined or separated. Both modes are informative, but the separated mode of measurement supplies with several additional diagnostic parameters notably the speed of sound propagation which is very sensitive to type of tissue. It appears to be advisable to use both modes of measurement in further research and development.