

Acoustic Coupler for Acquisition of Coronary Artery Murmurs

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Abstract

The aim of the study was to design and evaluate a coupler/microphone system for recording weak murmurs from stenoses in the coronar artery. The suggested design is based on the use of a high quality microphone, coupled to the chest through a small air cavity. Since the determination of the exact frequency range of interest related to murmurs is part of the purpose of the study, one of the goals of the design was to achieve a high signal to noise ratio in a broad frequency range. The high cut off frequency of the coupler is determined by the acoustic impedance of the chest and the design of the coupler, while the low frequency behavior was determined by the properties of the microphone, electronic circuits and inadvertent leakages in the acoustical coupling. The requirement for the microphone and pre-amplifier was a low inherent noise level. The setup was used for collection of heart sounds in a clinical trial including 463 patients referred for elective coronary angiography.

The preliminary results show, that it was possible to record heart sound in the diastolic period with a sound pressure level approximately 30 dB above the noise floor of the microphone and recording system in the frequency range from 200-700 Hz. The capability of the sensor to record diastolic heart sound in the relevant frequency range indicates that the sensor is suitable for recording of coronary murmurs.

1. Introduction

Previous studies have shown [1] [2] that it is possible to make a detection of Coronary Artery Disease based on the weak murmurs originating from the heart. These murmurs are very weak compared to the sound of the closing valves in the heart and are easily masked by other noises from within the body and by external noise. A dedicated coupler and recording system was developed to assess the properties of the heart sound, e.g. frequency content and sound level of the heart and potential murmurs.

The proposed design of the coupler was used to carry out a large number of recordings on patients referred for

elective coronary angiography. The purpose of carrying out the recordings were twofold: to record and estimate the properties of the heart sound and the evaluate the proposed design for at coupler.

2. Methods

Models describing the fluid flow in the blood vessels estimate that the noise related to murmurs can be found at frequencies up to 2 kHz [3], thus a recording system should be able to record heart sound in the frequency range from zero hertz to this theoretical upper limit. The suggested design of the coupler is based on standard measuring microphone, mounted in plastic housing. A small cut out is made in the front of the coupler to create an air cavity in front of the microphone when the coupler is attached to the skin.

To evaluate the design, the heart sound was recorded from 463 from patients referred for elective coronary angiography at the Copenhagen University Hospital (in danish *Rigshospitalet*). The recordings were carried out by trained project nurses. The heart sound was recorded while the patients were laying in a supine position. The patients were asked to stop breathing for a period of eight seconds to avoid respiration sounds during the recording.

2.1. Equipment

A sectional drawing of the proposed design of a coupler is shown on figure 1. The microphone mounted inside the coupler, is a standard prepolarized measuring microphone from G.R.A.S. (Type 40AD). The microphone has a flat frequency response almost from DC (zero hertz) to 10 kHz, which covers the range of interest. Another reason for choosing this particular microphone is the low noise level of 16 dB(A) re 20 μ Pa. The pre-amplifier from DPA (Danish Pro Audio) has small dimensions thus suitable for the purpose of constructing a compact and lightweight coupler. The preamplifier was customized to fit the measuring microphone. The pre-amplifier has unity gain, and operates thus as an impedance converter to convert the high impedance of the microphone to a low output impedance

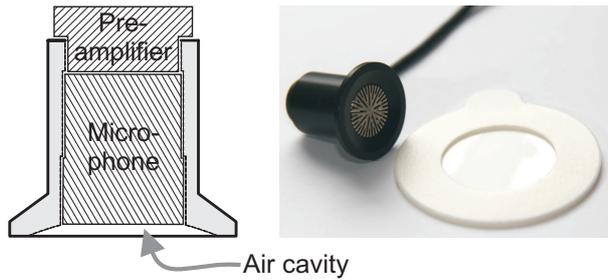


Figure 1: Sectional drawing of the coupler and microphone setup together with a picture of the coupler and patch.

which makes it possible to transfer the signal to a recording system.

The high frequency cut off is determined by the volume of air inside the coupler, hence when decreasing the volume of the cavity, the cut off frequency will increase. However some restrictions apply to the geometry of the cavity, firstly the distance between the microphone and skin must be sufficient so that the skin does not touch the microphone while recording heart sounds. Secondly the diameter of the coupler determines the “pick up area” of sound, where a large area will pick up more sound. This is due to the border condition, where the rim (where the coupler rests on the skin) is restricting the skin from moving and transmitting sound. With a small diameter the border condition will have a larger influence on the pickup area compared to coupler with a larger diameter [4].

The suggested design consists of the coupler with a diameter of 20 mm and an air cavity that has the shape of a cut out of a spherical shape. The distance between the skin and microphone, positioned in the top of the spherical shape, was 1.2 mm and the volume of the coupler was calculated to be approximately 300 mm³. The cut off frequency of the coupler is determined by the compliance of the air in coupler and the acoustic impedance of the chest. The latter is still to be investigated and is already work in progress [5]. The coupler was attached to the chest using a double adhesive. This way the microphone does not need any further support during recording and handling noise is avoided. A picture of the coupler and adhesive is shown on figure 1.

The lower frequency cut of frequency is determined by the microphone and recording system. The rear vent of the microphone is sealed from the air cavity, to avoid a roll off at low frequencies. The recording system consist of an analog frontend, external soundcard and power supply which meet the criteria of patient safety according to the standard IEC 60601-1[6]. The system is recording with a sampling frequency of 48 kHz and 24 bit resolution. It is a requirement for both microphone, pre-amplifier and recording system, that it has large dynamic range to handle

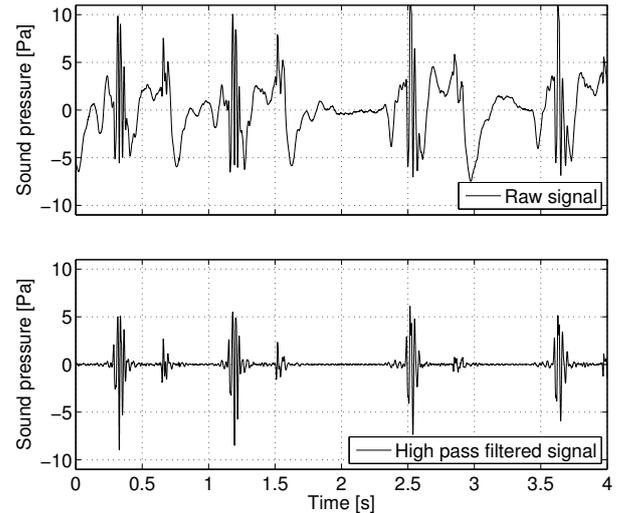


Figure 2: The top figures shows the raw signal without any filtering. The figure at the bottom shows the same signal but high pass filtered.

the S1 and S2 hearts sounds as well as the low level noise from potential murmurs.

3. Results

The recording system is capable of measuring low frequencies almost down to *DC* (zero hertz), this means that the raw signal from the heart sound recordings contains a summation of the signals that include among others the contraction of the heart muscle and airflow in trachea related to breathing. The latter has been avoided by asking the patient to stop breathing for short durations while recording. The plot at top of figure 2 shows the raw signal of sound recordings during one of the breathing breaks. The signal has large amount of low frequency components which are not likely to originate from the heart or possible stenosis. By applying a high pass filter (2nd order Butterworth, $f_c = 25\text{Hz}$), it is more easy to recognize the heart sound and properties like S1 and S2 becomes visible as shown in the bottom part of figure 2.

3.1. Saturation of recording system

Each day before any measurements were carried out, the microphone was calibrated and the result stored on the computer of the recording system. The average calibration value was afterward calculated to 13.72 Pa/V. Considering that the maximum input to the A/D converter is ± 1 Volt, the maximum equivalent sound pressure is 114 dB. Any signal beyond this level will saturate the A/D converter. The heart signal of the patient shown on figure 2 is chosen by random, but provides a general idea of the level of the

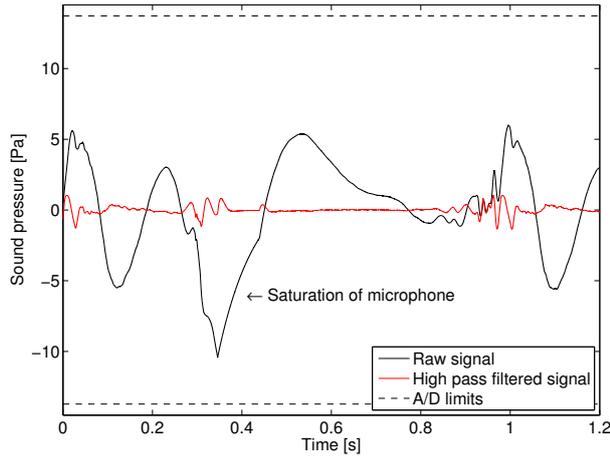


Figure 3: When the microphone becomes saturated, the raw acoustic signal looks like an exponential decaying function.

raw input signal to the A/D converter. However some patients will saturate the input because of a strong heart sound combined with signal related to the contraction of the heart muscle. A simple analysis which counts the number of patients where the sound signal reached ± 1 revealed that seven patients had reached the limit of the A/D converter.

The acquisition system can also become saturated without reaching the limit of the A/D converter. If a static pressure is present inside the cavity of the coupler the membrane in the microphone will be displaced and constant DC will be added to the signal. The displacement of the membrane limits the dynamic range of the microphone, thus the microphone and the input of the recording system can become “saturated”. Figure 3 shows the “saturation”, where the raw audio signal looks like an exponential decaying function when the saturation occurs and further the figure shows, that the signal is far from saturating the A/D converter. This is because of an electronic passive first order filter on the input of the recording system. The cut off frequency of the filter is $f_c = 0.16\text{Hz}$ which removes any frequency components below this limit (including DC) from the input of the A/D converter. During the the recording of 463 patients, the microphone became saturated on 27 recordings. Since the microphone can become saturated without the A/D converter being saturated and vice versa, there might not be any correlation between the two types of saturation. Consequently the total number of recordings where saturation occurred is 34 or in 7% of the recordings.

3.2. Frequency content of the heart signal

Out of the 463 datasets two cases are selected to evaluate frequency range and sound pressure level. The first

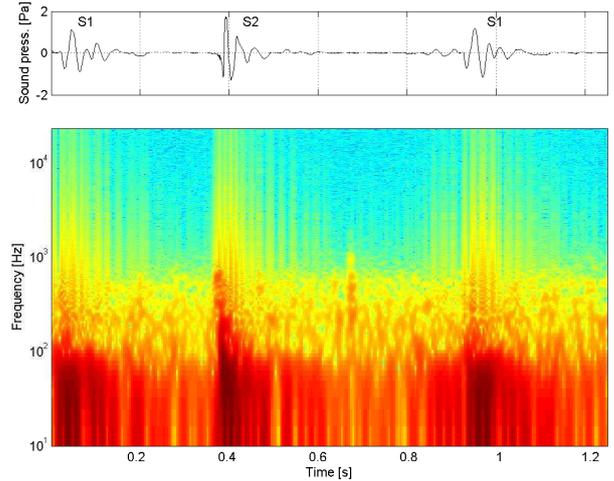


Figure 4: Spectrogram of a heart cycle. The top figures shows the time plot of the same signal as shown in the spectrogram.

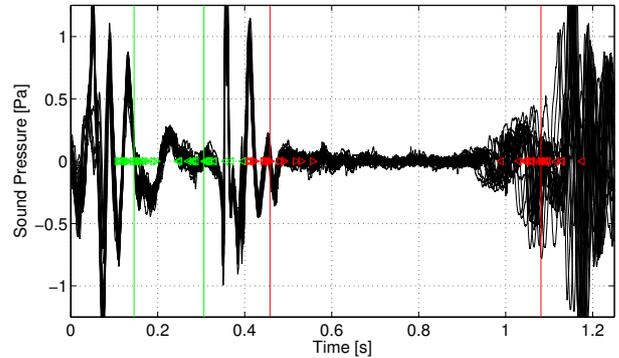


Figure 5: Segmentation of the heart signal. The green arrows indicate the systolic periods while the red arrows indicate the diastolic periods. The green and red lines are the average positions.

patient (a) has significant stenosis in the coronary arteries and an angiography showed a total of seven stenosis ranging from 40% to 100% occlusion. The three most severe stenosis had lengths of 5.81 mm to 7.46 mm. The second patient (b), turned out not to have any stenosis with an occlusion above 50%, hence this patient was considered healthy. During a heart cycle the “*lub-dub*” sound of the heart valves closing at S1 and S2 excites most of the frequency spectrum as shown on figure 4 from patient (a). The spectrum shows that most energy is found at low frequencies and particular in the systolic and diastolic period frequency content above 1 kHz is limited.

To analyze the systolic and diastolic periods separately, each heart cycle is segmented into four parts: S1, a silent systolic period, S2 and a silent diastolic period as shown in

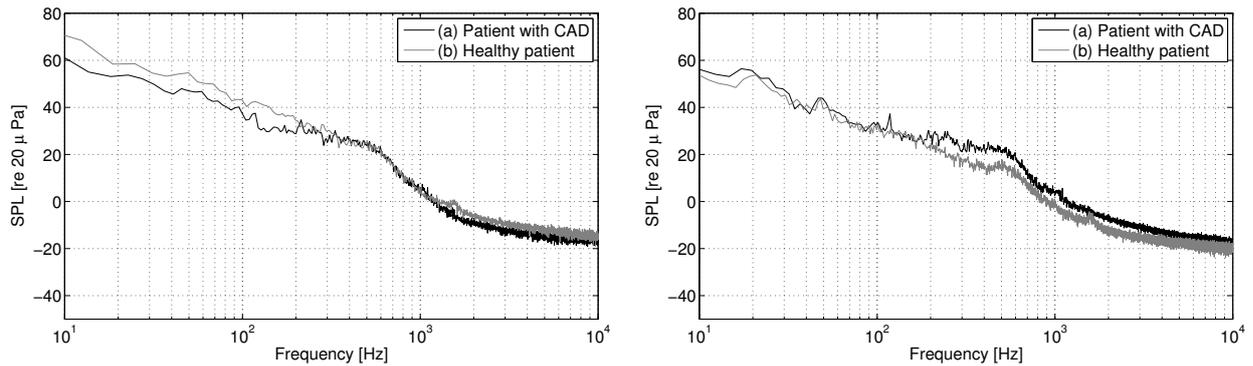


Figure 6: The systolic (left) and diastolic (right) periods from the two patients.

figure 5. The segmentation process uses properties of the heart signal, e.g. S1 and S2 and the difference of the length of the two periods in between [7]. An FFT analysis is made of each segment, and the segments are averaged in the frequency domain. Figure 6 shows the frequency analysis of the systolic and diastolic periods from patient (a) and (b). The figures show only little difference between the CAD and healthy patient. In the systolic period a level difference is visible from 200 Hz and down, while the difference in the diastolic period is seen as an increase sound pressure between 200 and 600 Hz for the patient with CAD. The level of the background noise at higher frequencies is identical to the level of the microphone, pre-amplifier and recording system. Figure 6 confirms that most energy is found at low frequencies, and a significant roll off occurs at around 700 Hz.

4. Discussion and conclusions

The coupler and recording system proved to be able to record heart sound from almost zero hertz to around 1 kHz with a low noise level. This indicated that the system is able to record weak sound from the heart, e.g. CAD murmurs. A minor part of the recordings were saturated, either because the combination of heart sound and contraction of the heart muscle exceeded the level of the A/D converter or because the microphone saturated due to a static pressure. The latter suggest that static pressures and low frequencies should be controlled by adding a vent to the air cavity of the coupler. It is still to be investigated whether the cut off is solely related to the coupler, is a natural attenuation of heart sounds when they are transmitted through the tissues of the ribcage or a combination of both.

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