A System for Recording High Fidelity Cough Sound Measurements

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Abstract. **Cough sound analysis has the potential to assist with the diagnosis of lung disease. The purpose of this study was to construct and evaluate a system capable of recording high fidelity cough sound measurements. A cylindrical mouthpiece was attached to a 1" diameter metal tube with a microphone mounted tangent to the tube. Various terminations were connected to the distal end of the metal tube in order to minimize reflections and improve the total-to-background sound ratio. Terminations that were tested included: (1) assorted types of flexible tube materials, (2) various tube lengths, and (3) several types of anechoic terminations. Custom software was developed to capture and analyze the cough sound pressure waves. Simulated signals and cough sounds from volunteer subjects were recorded to characterize the response of the system. The recording system demonstrated marked improvement over prior methods in terms of expanded frequency response, minimal reflections and high total-to-background-ratios.**

Keywords: Cough, Cough Sounds, Acoustics, Lung Disease.

1. Introduction

Since the invention of the stethoscope, pulmonary physicians have used lung acoustics to assist with the diagnosis of lung disease. One respiratory maneuver which produces sound is cough, which is a symptom of many different pulmonary diseases. Even though cough may be an unwanted complication of a pulmonary disease, it has often been used by physicians as an effective diagnostic tool. Cough sounds have been analyzed in the past. These studies have shown that the acoustic information contained in a cough is correlated with various lung disease types [1-6].

Cough is an attractive maneuver for use in screening and diagnostic tests since most people are already familiar with it. Currently, many pulmonary function tests require maximal efforts by the subject. This requires specialized technician and patient training to ensure maximal effort has indeed been reached. Furthermore, the effort expended to accomplish these tests may not be reasonable in young, elderly and particularly sick patients. Cough, on the other hand, provides an easy, non-invasive maneuver which can be voluntarily performed with a minimum of patient and technician training.

In order for a respiratory screening test to be considered acceptable, the test should give consistent results in repeated trials [7]. Since sound pressure waves are dynamic signals, the "consistent" parameter is yet to be defined for cough. Researchers have shown that increased flow rates cause parallel upward shifts of sound spectral curves with no changes in the general pattern of the spectra in breath sounds measured from the chest wall [8] and from the trachea [9]. It is well known that flow-volume curves of forced expiratory maneuvers (FEM) are highly reproducible after a given effort is achieved. Since a major portion of the cough flow-volume curve is identical to the FEM curve [10], it seems plausible the acoustical energy produced during a cough is reproducible, assuming the same initial lung volume.

It has been theorized that sound expelled from the lungs is a function of the geometry and the mechanical properties of the airways. Narrowing of the airways, secretion of mucus, and changes in lung elasticity and compliance may all alter the sound produced during a cough [11]. If cough sound analysis could be used to detect and quantify these changes, it could make a major contribution to the diagnosis of lung disease.

Since in depth analysis of cough sound recordings from the mouth is still in its infancy, with the important acoustic parameters yet to be identified, it is important to make measurements with the highest possible fidelity. Unwanted noise may contaminate the sound signal if appropriate design considerations are not implemented. Reflections at the mouth opening and in the recording area should be minimized. Signal levels should be well above background noise levels to optimize mathematical analysis routines. The purpose of this project was to construct and evaluate a new system capable of recording high fidelity cough sound measurements.

2. Methods

A system was constructed to measure the sound pressure waves propagated through the mouth during cough. A cylindrical mouthpiece was attached to a 1" diameter metal tube. A 1/4" microphone (Bruel & Kjaer #4136) was mounted at a 90° angle with its diaphragm tangent to the metal tube. A 1" diameter flexible tube was attached to the metal tube opposite the mouthpiece. Anechoic terminations were developed and attached to the distal end of the flexible tube.

A software "virtual instrument" was designed using Labview to capture the sound pressure waves generated in the system. The instrument allowed the user to set the sampling frequency, sampling time, analog high-pass and anti-aliasing filters, input range, and triggering considerations. For the purpose of this study, signals were digitized at 65536 Hz with a 14 bit A/D converter (Bruel & Kjaer Type #3551). Sample time was one second, with a pre-trigger recording period of 0.05 seconds to ensure the entire wave was recorded. A high-pass filter with a cutoff frequency of 22.4 Hz, and an anti-aliasing filter with a cutoff frequency of 25.6 kHz were applied to the signal. The frequency response of the condenser microphone was 20 Hz to 35 kHz (± 1 dB). This system enabled accurate spectral analysis in the frequency domain between 50 Hz and 25 kHz. After the signal was digitized it was transferred to the computer through a GPIB interface. Custom software was developed to analyze cough sounds and simulated test signals.

To characterize the performance of various designs, a speaker (Atlas #PD-30) was coupled to the mouthpiece of the recording system to generate consistent simulated signals. In the first set of tests, a five volt peak-to-peak pulse was generated with the 3551 data acquisition unit, amplified with a power amplifier (Mitsubishi DA-M10) and the fed to the speaker. The pulse and subsequent unwanted reflections were recorded. A normalized autocorrelation function was calculated for the recorded signal. Peaks in the autocorrelation function were inspected to identify reflection time delays. Total energy within the pulse and reflections was calculated and compared to determine the amplitude of the reflections. We examined the effects of: (1) assorted types of flexible tube materials, (2) various tube lengths, and (3) several types of anechoic terminations, in order to minimize sound reflections. Flexible tube types studied were 1" diameter latex, norprene, and tygon. Lengths examined were 8', 13', and 25'. Anechoic terminations included an exponential horn and a conical wedge. Wedge placement was varied to find the point at which minimum reflections occurred. A diagram of the system is shown in Fig. 1. The optimal system (OS) was defined as the configuration that performed the best during the reflection tests.

In the second set of tests the total-to-background ratio was evaluated. The OS was compared to that of a conventional recording method (CRM). Using this method cough sounds were measured with a microphone a set distance (same as in OS, 8") from the speaker. The microphone was orientated in a perpendicular direction to the speaker in an open room. First, background measurements were recorded. Then, white noise (1.9 V_{RMS}, flat frequency spectrum to 25kHz) was applied to the speaker for a full second and recordings were made in both arrangements. Noise measurements were considered the "total" since they combined both the white noise and background sound energy. The RMS voltage was calculated for all measurements and the total-to-background ratios for each configuration were calculated.

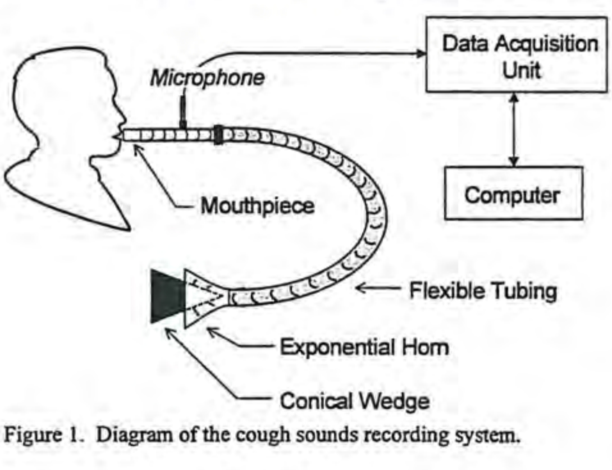

Figure 1. Diagram of the cough sounds recording system.

For the final evaluation of the OS, control coughs were recorded. Volunteers (n = 4) were all young adult (29 ± 1.9), non-smoking males with normal spirometry. Coughs were performed from total lung capacity. Power spectral density curves were computed and compared to background measurements to define the energy amplitude and range of frequencies produced during a cough. Spectrograms were analyzed to determine dynamic nature of the sound pressure wave generated during cough.

3. Results

With 8' lengths of each type of flexible tube attached to the system, the latex tube performed markedly better in the reflection tests. Though all three tubes had similar reflection times (latex (L) - 17 msec, norprene(N) - 16 msec, tygon(T) - 15 msec), reflection amplitude was much lower with the latex tube (L - 4.1%, N - 17%, T - 23%). Fig. 2 shows examples of the autocorrelation of the time signals.

The length of the latex tube also affected the reflection time lag and amplitude. Time lag increased with length (8' - 17 msec, 13' - 25 msec, 25' - 48 msec), while reflection amplitude decreased (8' - 4.1%, 13' - 1.5%, 25' - 0.04%). Although the 25' tube showed the least reflection amplitude it also exhibited the highest resistance to flow. The elevated resistance encountered during trial coughs disqualified it from consideration as a portion of the OS.

The addition of the exponential horn to the end of the tube decreased the amplitude of the reflections with the 8' latex tube (No horn - 4.1%, Horn - 1.3%). The conical wedge had little to no effect on the reflection amplitude at any position inside the exponential horn.

Results of the reflection tests indicated that the 13' latex tube

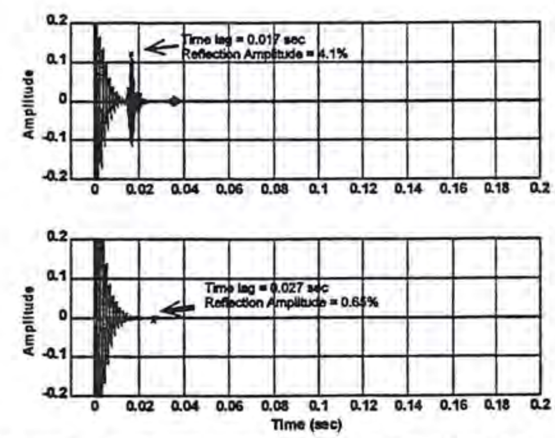

Figure 2. Normalized autocorrelation function of sound pressure wave recordings for two system configurations. Primary peak at time 0 represents initial pulse, secondary peaks represent reflections. Highest amplitude of secondary peaks (denoted with an x) indicate reflection time-lag. A) Flexible 8' latex tube with no anechoic termination. B) Flexible 13' latex tube with exponential horn attached to distal end. Note: At time 0 the amplitude is 1 for both examples.

with the exponential horn for an anechoic termination was the OS. This system exhibited a reflection time lag of 27 msec and a reflection amplitude of 0.65%. The OS improved the Total-to-background ratio by a factor of 27 over the CRM. The white noise RMS voltage was 5.202e-2 V and background was 1.713e-4 V for the OS, which corresponded to a total-to-background ratio of 304. The CRM system had a white noise RMS voltage equal to 1.480e-3 V and background level of 1.323e-4 V, which corresponded to a total-to-background ratio of 11.2.

The cough sound measurements of the volunteer control subjects were similar in terms of frequency content. The energy within the coughs slowly decayed until 7kHz where the spectrum leveled out until the maximum analysis frequency of 25kHz was reached. An example of power spectral density curves for two control coughs and a background measurement is shown in Fig. 3.

Spectrograms of the control coughs displayed the joint time-frequency energy distribution of the cough sounds. The frequency content was consistent throughout the first portion of the cough with higher energy at lower frequencies and a level spectrum at higher frequencies. Near the end of each cough the higher frequencies were attenuated and approached background noise levels. An example of a recorded sound pressure wave and corresponding spectrogram from a control cough is shown in Fig. 4.

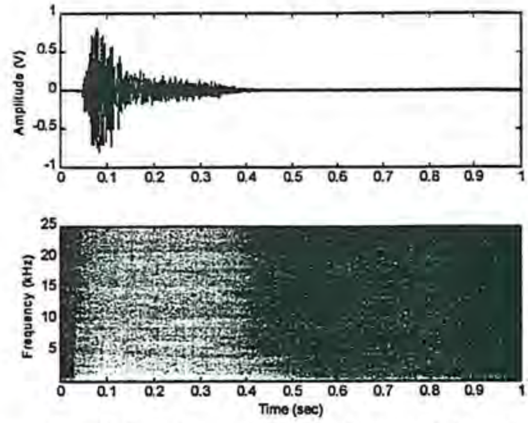

Figure 4. A) Sound pressure wave of a recorded cough. B) Corresponding spectrogram plotted on the same time axis. Intensity is represented by color. White represents high intensity, black represents low intensity.

4. Conclusions

If cough sounds are to be interpreted as a potential indicator of lung disease, it is important to make measurements with a high degree of accuracy. Reflections due to the large cross-sectional area difference at the mouth and from structures in close proximity to the subject distort the sound signal emitted from the lungs. A new system was designed and constructed to minimize the these potential sources of error.

Reflections at the mouth opening are very difficult to measure experimentally. Since the mouth opening of the human subject approximately corresponded to the size of the mouthpiece, in this system, the acoustic impedance mismatch at the mouth was theoretically minimized. A rigid metal tube was connected to the mouthpiece in order to hold the microphone while distorting the sound signal as little as possible. Flexible tubing was connected to the distal end of the metal tube to attenuate the sound signal while it traveled as a plane wave down the tube, and to attenuate reflections as they proceeded back up the tube. An anechoic termination was connected to the flexible tubing to reduce reflections. The type and length of the flexible tube also affected the amount of attenuation experienced by the signal.

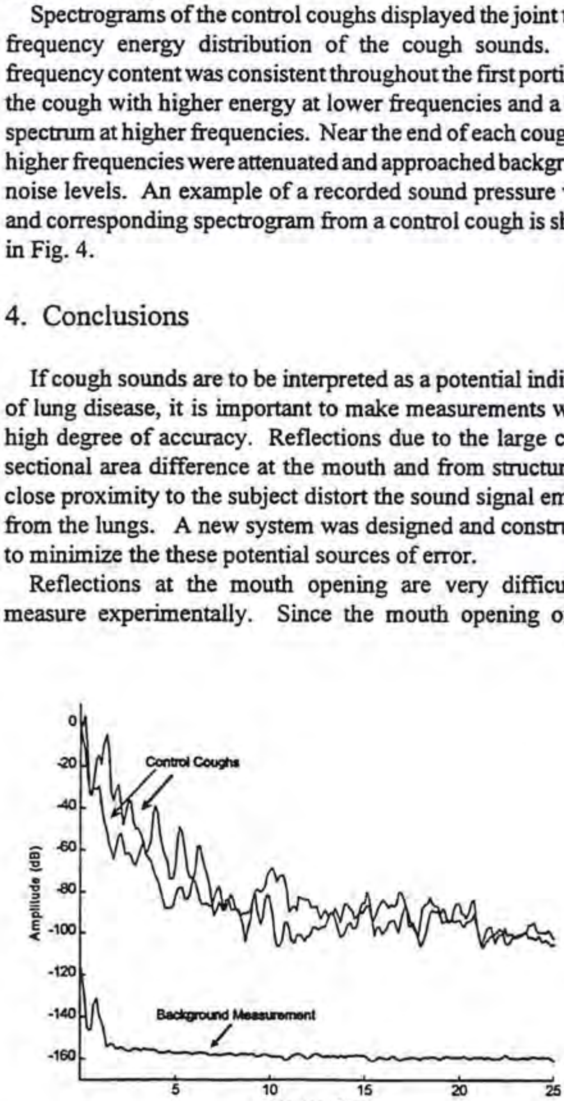

Figure 3. Power spectral density curves for control coughs and a background measurement.

The latex tube attenuated the reflections considerably more than the norprene and tygon tubing. The amplitude of the reflection appeared to be proportional to the compliance of the tube. As tube stiffness was decreased, more sound was absorbed by the tube. Longer tubes attenuated the reflections more. This allowed additional sound absorbing surface area to come into contact with the sound pressure wave as it traveled down, then back up the tube. Though the 25' latex tube demonstrated the greatest attenuation of reflections, it also presented the highest resistance to bulk air flow. While the 8' and 13' flexible tubes allowed subjects to produce relatively normal coughs, the high resistance of the 25' tube slightly "loaded" the subject and produced unnatural feeling coughs. For this reason the 13' latex tube was designated as part of the OS and used for subsequent human studies.

The open end of the latex tube provided a large acoustical impedance mismatch. To alleviate this problem an exponential horn was used. The horn allowed the cross-section of the sound's path to gradually increase to a larger size which more closely compared with the dimensions of the room. As a result it decreased the reflection amplitude in all cases and was added to the OS. A conical wedge, in addition to the exponential horn, was also tested. During testing the wedge showed no significant difference in the attenuation of reflections at any position in the exponential horn. For this reason it was not incorporated as part of the OS.

Control coughs were recorded and analyzed with the OS. The total time to perform the test and analyze the data was less than one minute. Subjects reported no discomfort when performing the test. These results indicate the system could easily be implemented as a tool to quickly screen subjects for respiratory disease.

Frequency analysis of cough sounds has shown differences between healthy subjects and those with pathological lung conditions [2,3,5,6]. An accurate characterization of the energy content within a cough with respect to frequency bands is important when developing algorithms to diagnose respiratory disease. In this study, power spectral density curves of the control coughs displayed energy content of coughs in the frequency range from 50 Hz to 25 kHz. All coughs revealed components of energy above background levels up to the maximal analysis frequency of 25 kHz. Because the energy content is still well above background level at this point, it is presumed that frequencies above 25 kHz are also present in cough sounds. As a result, higher sampling rates are needed to examine these frequencies and should be implemented in the future. Further study of the energy content between 20 kHz and 25 kHz may prove productive. This region is above the threshold of hearing in humans which suggests that if differences in sound energy occur in this frequency range for pathological conditions, the differences go unheard by pulmonary physicians. Computer analysis would be required to distinguish the energy in this frequency range.

Spectrograms of cough sound pressure waves provide frequency information at equally spaced time points throughout the cough. Dynamic change in thoracic pressures and airway flows cause the cough maneuver to be dynamic in nature. By examining the spectrogram these changes can be observed and quantified.

Since cough sounds are a function of lung anatomy and function, pathological conditions may alter the sounds with predictable patterns. If algorithms are developed which recognize these patterns, cough sound analysis can be used to assist with the diagnosis of lung disease and as an early detection tool. To accurately develop these algorithms, cough sound recordings must be made with the highest fidelity possible. Reflections, low total-to-background ratios and poor frequency response of equipment or recording methods distort the true signal of interest. In this study, a system was developed to record the cough sound measurements with design considerations that took these factors into account. In the future, this system will be used in patient trials to examine if patterns exist in the sound information of coughs from subjects with respiratory disease.

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Appendix

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