



Bachelor of Science in Medicine Degree Program End of Term Final Report

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Date: 07/31/17

Project Title: Pediatric Respiratory Analysis

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Summary (250 words max single spaced):

Asthma is a chronic, obstructive, inflammatory lung disease that affects 13% of Canadian children. It is the most common chronic disease in childhood seen in the emergency department. Asthma typically presents with coughing and wheezing, however parental reporting of a wheeze is difficult to interpret and inconsistent. As a result, diagnosis of asthma may be delayed or made prematurely. To address this issue a clearer definition of wheezing is needed for the lay audience, along with better education regarding breath sounds and respiratory disease.

In this study breath sound recordings from 15 healthy children and 15 wheezing children presenting to the Children's Hospital Emergency Department were digitally recorded and analyzed. Children aged two months old to eight years old were recorded using a custom stethoscope connected to a mobile phone. Analysis was based on a Fast Fourier Transform of the sound's spectrogram to create power spectrum density (PSD) curves for the breath sounds. The PSDs were used to analyze differences in amplitude and frequency throughout the breath sounds. The results identify differences in peak inspiratory and expiratory power, and different trends in the power and frequency in expiratory breath sounds that can be used to distinguish wheezing from normal breath sounds in a pediatric population. The results of this study can help better define wheezing for a lay audience and could be incorporated in mobile application that can assist families and health care professionals with identifying wheezes and asthma.

Student Signature

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Acknowledgments: I gratefully acknowledge the sole or partial funding support from the following sponsors;

H.T. Thorlakson Foundation
Dean, College of Medicine
Research Manitoba

Manitoba Medical Service Foundation (MMSF)
Vice-Dean, Research Rady FHS
Health Sciences Centre Research Foundation
Heart and Stroke Foundation

Sponsorship if different than above;

Children's Hospital Research Institute of Manitoba

MD/PHD MD/MSc. BSc. (MED) MED II Research Program

Joe Doupe Annual Event Undergraduate Medical Student Research Symposium

Canadian National Medical Student Research Symposium

Introduction

Asthma is a chronic obstructive inflammatory lung disease. Associated with coughing, wheezing, dyspnea, chest tightness, airway narrowing, and increased airway responsiveness. It is the most common chronic disease seen in children in resource rich countries.¹ The World Health Organization estimates that there are 235 million people with asthma worldwide and projects that this number will increase to 335 million by 2025.² In Canada, 8.5% of the population has been diagnosed with asthma (2010) and 13% of children are affected.^{3,4} Asthma leads to significant mortality and morbidity in children in Canada. Each year, approximately 20 children die from asthma and there is an estimated 146 000 emergency room visits due to asthma attacks. In 1994, the direct cost of asthma was estimated to be \$600 million per year with hospitalizations accounting for \$135 million each year.⁵ It is also the leading cause of children missing school.⁶ Much of the burden of disease is a result of under-diagnosis, under-treatment, and lack of caregiver and patient education leading to non-compliance.⁷ We believe that improved methods of diagnosis as well as patient and caregiver education should lead to improvements in the management of this disease. Our lab intends on creating a mobile app that will contain useful information regarding asthma, wheezing, and other respiratory diseases as a useful tool for caregivers of young children. This project aims to explore the current technology and the digital assessment of breath sound recordings to identify adventitious sounds such as wheeze.

Background

Asthma symptoms are caused by obstructed airflow resulting from decreased luminal diameter within the airway. The reduced diameter is a result of inflammatory processes, bronchoconstriction, and airway hyperresponsiveness.⁸ Inhaled corticosteroids are the primary treatment recommended for the airway inflammation in asthmatic patients. Inflammatory cells including neutrophils, eosinophils, lymphocytes, and mast cells are found in asthmatic lungs. Leukotrienes and immunoglobulin E antibodies are also associated with the inflammation.^{9,10} Airways normally respond to various stimuli by narrowing. Common triggers include cold air, histamine, exercise, upper respiratory infections, allergens, and air pollutants. Hyperresponsiveness occurs when a small stimulus is able to illicit airway narrowing or a greater degree of narrowing than expected/normal.¹¹

Asthma is diagnosed through the combination of a history, physical exam and objective measures of pulmonary function. Findings on a history include recurrent dyspnea, chest tightness, wheezing, sputum production and cough usually associated with stimuli that cause airway responsiveness. Pulmonary function tests that show a reduced FEV₁/FVC ratio (80-90% expected) with an increase in FEV₁ of 12% or more after a bronchodilator or other controlled therapy supports the diagnosis of asthma.¹² In children under the age of six pulmonary function testing is not reliable or easy to perform and diagnosis relies only on the history and physical. Findings that support a diagnosis of asthma include severe episodes of wheezing/dyspnea, wheezing/dyspnea after one year of age, three or more episodes of wheezing, chronic cough (at night or with exercise/activity), and improvement with asthma medication.¹³ In the setting of an acute exacerbation or 'asthma attack' findings on a physical exam can include tachypnea, hypoxia, wheezing, accessory muscle use, retractions, and prolonged expiratory phase. However, most children with asthma will have a normal physical exam if they are not having an exacerbation.¹⁴ The challenge is to diagnose a child prior to going to the emergency room with

an exacerbation. However, this can be difficult as not all patients or caregivers are familiar with the symptoms of asthma. An example of this is wheezing. The presence of wheezing is a trademark of asthma and strongly supports a diagnosis of asthma. Therefore, a more consistent way to identify wheezing has potential to improve the diagnosis of asthma and to treat children before they present to the emergency department.

Breath sounds are defined as any of sounds created by breathing, both normal sounds and adventitious sounds. Breath sounds can be defined with three characteristics; frequency, intensity, and timbre/quality. The frequency of a sound is measured in Hertz (Hz) defined as the number of waves per second. The frequency depends on the wavelength of the sound as well as the velocity of the sound through the medium which it is passing through. The human ear's perception of frequency is called the pitch. A normal human ear can detect frequencies from 20-20 000Hz.¹⁵ The intensity or loudness of a sound is a function of its amplitude. The amplitude is determined by the amount of energy being carried by the wave. The intensity is measured with a logarithmic decibel scale. If two sounds have the same amplitude and frequency they can still be distinguished based on the timbre or quality.¹⁶ Almost all sounds contain multiple frequencies. The pitch is determined by the fundamental or lowest frequency of the sound. The higher frequencies are called overtones and it is the characteristics of the overtones that affect the timbre of the sound.

Breath sounds are created in the airway when the airflow is either turbulent or forms vortices.¹⁷ Normal laminar flow will not create a sound. The principle of laminar flow is defined by the Poiseuille equation. In airways below a threshold diameter the flow is laminar and are not audible. Turbulent flow will occur in larger airways, where the airway is irregular or branching. During turbulent flow the air molecules collide with each other and the walls of the airway which creates sound.¹⁵ Additionally, vortices can also create breath sounds.¹⁸ When air flows out of a circular or wide opening, vortices can form. This normally occurs in the bronchial tree from the 5th to 13th generations. Normal breathing is cyclical with a 1:2 ratio in length of inspiration:expiration. Inspirations also tend to be higher pitched, and more intense than the typically passive expirations.

To hear breath sounds they must pass through the parenchyma of the lungs as well as the chest wall. These barriers act as a low-pass filter and block much of the higher frequency sound.¹⁹ The barriers also cause energy loss over the 100-200Hz range.²⁰ For classification purposes breath sounds can be divided into low (<100Hz), middle (200-600Hz), and high (600-1200Hz).²¹ Due to the passive nature and low-pass filtering effect, the full expiratory cycle is not always audible. Auscultation also includes other ambient noises from the thoracic cavity, such as heart sounds. These are most intense below 100hz, then start to fall off from 100-200Hz.

These sounds can be heard through the mouth and over the trachea and chest wall. A normal breath sound is the quiet sound heard over the chest wall or the louder and more varied noise heard over the trachea. Adventitious sounds (eg. wheezing) are superimposed over the normal breathing sounds. Generally speaking, adventitious sounds are an indicator of pathology.²² There are several different adventitious sounds recognized by clinicians. Crackles are discontinuous sounds normally heard during inspiration. Fine crackles have short duration while coarse crackles have long duration. Crackles indicate some pathology in the lung parenchyma or the airway. Cough sounds come from the coughing reflex and normally have a frequency between 50-300Hz. Rhonchi are low pitched wheezes defined by having a duration longer than 100ms (frequency <50Hz). These are indicative of secretions in, narrowing of, or

abnormally collapsible large airways. Squawks are inspiratory sounds that usually indicate interstitial lung pathology. A squawk can be from 50-400ms. Stridor is a low wheezing sound with a low frequency that originates from the larynx or trachea and is normally heard during inspiration. Stridor can occur in situations such as laryngeal or tracheal stenosis as well as diseases like whooping cough. Wheezes are musical sounds with a periodic waveform. A wheeze may be monophonic, having one dominant frequency, or polyphonic, having multiple dominant resonant frequencies. A wheeze's dominant frequency is over 100Hz and lasts longer than 100ms.²²

Wheezing is one of many adventitious lung sounds and is a hallmark of obstructive airway diseases which includes asthma.²³ The mechanism of wheezing is explained by the flutter theory. In this theory, the airway is considered a collapsible tube filled with a fluid (air) based on Bernoulli's principle. When fluid flows through a tube at a high velocity there a corresponding drop in pressure. This causes the airway to collapse decreasing the volume within the airway. This in turn increases pressure which pushes against the airway and opens it. At this point the airflow will again cause a drop in pressure and the process is repeated. The cycle of collapsing and restoring the airway is called 'fluttering' and leads to the sound we perceive as a wheeze. For this to occur the velocity of the air within the airway must reach a certain velocity, referred to as the flutter velocity. In asthmatic patients, the narrowing of the airway caused by inflammation increases the velocity of the airflow and disposes the patient to fluttering, and therefore wheezing.^{24,25} It has been suggested that polyphonic wheezes seen in asthma originate in the central airways as there tends to be few dominate frequencies. This is supported by the flutter theory as only the first five to seven generations of the airways can have airflow that reaches flutter velocity.

Wheezes are adventitious breath sounds that are important indicators of obstructive airway disease.²⁶ In asthma, wheeze can show the presence, severity, and the location of the obstruction.²⁷ The physical characteristics of a true wheeze have been defined differently on various sources. In practice, a true definition based on the physical characteristic has not been necessary since the human ear is not capable of distinguishing the duration and frequency of wheezes to that specificity. Consequently, physicians have relied on qualitative definitions such as "whistling sounds" and "musical notes"¹⁵. However, in order to move forward with electronic detection of wheezes a singular definition needs to be established. Wheezes have been reported to be 100-250ms with fundamental frequencies from 100-1000Hz.²⁸ Others have reported a fundamental frequency range from 400-1000Hz for a wheeze whereas a rhonchus had is <200Hz.²⁹ Wheezes have also been defined as lasting longer than 50ms with frequencies between 100-1600Hz.³⁰ For wheezing infants a duration of 80-250ms has been reported as well.³¹ Wheezes have been associated with a number of pathologies including infections such as croup, laryngitis, acute tracheobronchitis, laryngo/trachea/bronchomalacia, laryngeal and tracheal tumors, tracheal stenosis, emotional laryngeal stenosis, foreign body aspiration, airway compression,³² asthma,³³ and nocturnal asthma.³⁴ Wheezes can be divided into monophonic wheezes and polyphonic wheezes. A monophonic wheeze consists of single notes that start and stop at different times without overlap. Various pathologies can cause monophonic wheezes such as obstructions in the bronchial tubes caused by tumors, bronchostenosis from inflammation, muscle accumulation, or a foreign body. A rigid obstruction will cause wheezes throughout the respiratory cycle while with a less rigid obstruction the wheeze may be in only the inspiratory or expiratory phase. A fixed monophonic wheeze will have constant frequency and a random monophonic wheeze has varied frequency and lengths. Usually asthma presents

with a random monophonic wheeze. Polyphonic wheezes have multiple notes that overlap each other. These are usually caused by compression in the central airways. Usually these are only expiratory and the pitch increases towards the end of inspiration.³⁵ Definitions of a wheeze vary between guidelines. The European Respiratory Reviews published a guideline called Computerized Respiratory Sound Analysis (CORSA) in which they defined wheezes as sounds with frequency >100Hz and lasting longer than 100ms.³⁶ The dominant frequency tends to be around 400Hz. The highest recorded wheeze frequency is 710Hz.³⁷ Various methods of automated wheeze detection have been developed. Using automated detection, sounds with a determined pitch with near-periodic signals can be distinguished from those without a defined pitch. Since the fundamental frequency of a wheeze is a pseudoperiodic signal, they can be distinguished from the normal breathing sounds. In addition to a frequency criteria there must also be an amplitude criterion for the automated detection of a wheeze. With these two criteria, automated detection is usually based on the spectral appearance – a peak with sufficient amplitude within the proper frequency range is necessary. Usually a threshold amplitude is determined and this value must be exceeded for the sound to be eligible as a wheeze. Other criteria that have been used, including wheeze as a percentage of the total respiratory cycle and computing the mean frequency of wheezes and labelling them to the respiratory phase.³⁷

Identification of a wheeze relies on breath sound analysis. The art of analysing breath sounds dates to the earliest physicians. Hippocrates is documented to have applied his ear directly to a patient's chest in order to detect accumulation of fluid within the lung, a method thereafter referred to as immediate auscultation. The method persisted well into the nineteenth century without much change.³⁸ In 1816 a French physician named Rene Laennec recognized the need for a method to listen to the heart without directly contacting the patient. His solution was to roll paper into a cylinder and place one end onto the patient and his ear over the other. He found this not only improved the hygiene of the procedure but also improved the quality of the sounds he heard. Thus, the method of mediate auscultation was developed.³⁹ The tool was eventually named the stethoscope from the Greek 'sethos' for chest and 'skopein' to explore. Over the next century and a half, the design of the stethoscope was improved upon and it became the gold standard for analysis of breathing sounds.⁴⁰ Various sounds such as wheezes, crackles, coughs, rhonchi, squawks, stridor were identified and associated with different diseases. However, the analysis of breath sounds with the stethoscope was not perfect. Over the years many terms for breath sounds were used without much consensus on the defining features of a sound. A wheeze was defined qualitatively using terms such as "whistling sounds" or "rice on a frying pan". Additionally, studies have shown that there is limited consensus between expert physicians on what sound they are hearing through a stethoscope.⁴¹⁻⁴³ A more recent analysis concluded that manual auscultation with a stethoscope is not a reliable tool for assessing breath sounds in infants.⁴⁴ This demonstrated a need to standardize the terminology used in breath sound analysis and create a more objective method of analysing the sounds. The digital age brought forth advancements that could solve both problems through digital sound analysis.

Using computer software it is possible to analysis breath sounds, using more objective measures. For this project we used the Respiratory Acoustics Laboratory Environment (RALE) software created in 1990 at the University of Manitoba by Hans Pasterkamp.⁴⁵ This software looks at breath sounds in multiple ways. The first is a spectrogram which is a representation of the frequencies and power of the sound over time. The sound is divided into 100ms segments, and for each segment the power of frequencies in hertz is displayed as a color on the graph.

Additionally, for each 100ms segment a power spectrum can be displayed which is a graphical representation of the power in decibels of all the frequencies within that segment. The waveform of the segment is also displayed which shows the amplitude or sound pressure variation of the sound (measured in volts) over the 100ms segment. In the program the user scores and labels the breath sounds as either inspiration, expiration, background noise or rejected segment. Once labelled the overall power spectra data can be exported allowing for quantitative comparison of the spectra for inspiration and expiration. Given that asthmatic children typically wheeze during expiration, there should be noticeable differences in the sound spectrum in expirations from children with normal breathing sounds and those with wheezing.

As digital medicine has become more popular so too has digital analysis of breath sounds. Digital analysis overcomes some of the disadvantages of subjective auscultation as sounds can be analyzed objectively based on the properties of the sound, permanent records of the sounds can be kept, and more meaningful results for physicians and patients can be extrapolated from the data. However, a major caveat to digital breath analysis is the lack of guidelines or standardization. To combat this problem and provide a framework for digital breath sound analysis, a European project called Computerized Respiratory Sound Analysis (CORSAs) was funded. This publication established guidelines for recording, digitalization, analysis, and reporting of breath sounds in addition to providing definitions of various adventitious breath sounds.⁴⁶ The standard method for recording sound is with either a microphone or contact sensor at the mouth or chest with a high-pass filter with a cut-off range between 50-60Hz. The sound undergoes direct digitalization and is stored on the computer device used to make the recording. The sound should be converted from analogue to digital at 12, 14, or 16 bits per sample with a sampling rate ranged between 4kHz and 22.5kHz. Discrete Fourier Transform using the Fast Fourier Transform algorithm is typically used for spectral analysis. The segments usually are 20-50ms with sampling rates around 10kHz and signal block lengths of 256, 512, and 1024.⁴⁷ According to CORSAs a wheeze should be defined as a sound greater than 100Hz and longer than 100ms. Typically, the dominant frequency is 400Hz but it can range widely from 80-1600Hz. In addition, it is reported that asthmatics without a wheeze will have increased higher frequency sounds, causing the median frequency to be elevated. This is likely due to changes in air turbulence which results from mucosal changes in asthma.⁴⁸

Given the importance of wheeze in the diagnosis and management of asthma, it is extremely important to have accurate reporting and records of wheezing, especially in young children who cannot report wheezing themselves or have traditional pulmonary function tests performed on them. It has been shown that parental reporting of wheeze is unreliable.^{49,50} In adults, independent observers do not have strong agreement.^{51,52,53} In infants the reliability of the stethoscope has also been shown to be poor.⁵⁴ Also, the International Study of Allergy and Asthma in Childhood (ISAAC) showed parental reporting of wheeze decreased by 40% after they were shown a video of a wheezing child.⁵⁵ The results of these studies show that two factors can contribute to delayed, missed, or false diagnosis of asthma. The first being parental education and reporting of a wheeze, and the second being the reliability of a physician's auscultation. Digital sound analysis could be an elegant solution to both problems, particularly if implemented in an e-Health format such as a mobile app. Such an app could provide two functions. The app could act as an educational tool which contains video and sound files that show caretakers what different adventitious breath sounds look and sound like, which will help them identify the sounds and allow them to report more accurately to their physician. The second function can be implemented by both the caretaker and the physician. By using a

stethoscope-like attachment parents would be able to record their child's breathing and save the recording in the app, which can then be shown or sent the physician to be reviewed. Additionally, if physicians in the emergency room were equipped with the app they could also record the child's breathing and make a more objective diagnosis of a wheeze. For this application to be valid it must be shown that this method can accurately identify wheezing.

Various methods of digital wheeze detection have been suggested, most of which rely on a spectrum analysis. One method is a joint time-frequency analysis in which a peak in the frequency domain which corresponds to one of the fundamental frequencies of the wheeze is detected. A monophonic wheeze will have one peak while polyphonic wheezes have multiple. A second analysis over time is needed to confirm a wheeze when other sounds also have a peak frequency.⁵⁶ Another method of wheeze detection uses wavelet packet decomposition. First a wheeze is detected and extracted in the frequency domain, followed by an inverse transformation, reconstruction of the signal, and a time detection.⁵⁷ A continuous wavelet transform has also been successfully used for wheeze detection.⁵⁸ Another method is described automatic wheeze detection and quantification of spectral analysis based on a threshold frequency for the peak of a wheeze.⁵⁹ CORSA states that wheezes should be defined in digital analysis based on pitch and duration. Pitch, or the dominant frequency, being >80-100Hz and the duration being 100ms or longer.⁶⁰ Notably no wheeze has been recorded with a pitch >1600Hz.⁶¹ For automated wheeze detection, CORSA states that identification based on detection of peaks in the frequency must also use an amplitude threshold in which the sound must exceed. Generally, most previous systems used to detect wheeze rely on detecting individual peaks in the frequency at one instance in time. This method has been successful; however, it may be less useful for the pediatric population less than 5 years of age. In older children and adults, the airway has fully developed and is stiffer. This means that as it flutters and creates a wheeze the minimum and maximum endpoints remain the same. This creates the typical monophonic or polyphonic wheezes with clear peaks in the power spectra. In young children, however, the airways are much more flaccid, and instead of wheezing at a few specific frequencies, the wheezes occur across multiple frequencies. Because of this there appears to be less individual peaks in the power spectra but rather a more generally increase in power over a wide range of frequencies. This makes it possible to demonstrate wheezing by creating a power spectra using the average power at each frequency using a recording of multiple inspirations and expirations that may better capture the trend of wheezing in young children.

The goal of this paper is to show that recordings made through a mobile app in an emergency room setting can be used to accurately identify wheezing in children. Using RALES, the recording is broken into inspiration, expiration, and background noise. The spectral data is then extracted and the average power of the frequency over time is calculated. As wheezing is primarily an expiratory sound, the average power of dominant frequencies in a wheezing child's expiration should be higher than the average power of expiration in a child with a normal airway. The results show that recording a child's breathing using a device connected to a mobile phone app can identify wheezing through manual spectral analysis of expiratory breath sounds. This opens the door for the development of an automated method of detection for recordings made this way and may provide an opportunity to improve our diagnosis of asthma in young children.

Methods

Population

The breath sounds of 30 children aged zero to seven presenting at the Children's Hospital emergency room in Winnipeg, Manitoba were collected. During the assessment, the physician determined if the child had either normal breath sounds (non-respiratory related ER visit) or abnormal breathing. After the child's assessment, the caregivers were asked if they would be willing to participate in the study. If willing, the physician informed our team that the child is willing to participate in the study and we took written/signed consent from the child's caregiver before any assessment for the study. At that time the physician reported on the child's suspected diagnosis and informed us if the breath sounds were determined to be normal or abnormal. Specifically, our criteria for abnormal breathing were the presence of nasal flaring, tracheal tug, intercostal indrawing, stridor, prolonged expiration, crackles, or wheezes on auscultation. The caregiver was asked to respond to a short verbal questionnaire. The questions included entrance complaint, coughing, wheezing, shortness of breath, and response to bronchodilators or corticosteroids both while child has a cold and when the child does not have a cold.

Breath Sound Acquisition

Breath sounds were recorded using a custom stethoscope consisting of a pediatric bell connected to an electret microphone by plastic tubing. The microphone was connected to an iPhone 6 plus, and using the default iOS camera software video of the child breathing was recorded using the stethoscope as the audio channel. The app iRig Recorder⁶² was running in the background and an over-the-ear headset was used to listen to the breath sounds while recording. The child was placed in a position that he or she felt comfortable in, most commonly lying on the bed or on their caregiver's lap. Children who could follow directions were asked to sit upright and breath normally during auscultation using the custom stethoscope. The lungs were auscultated in eight locations (four posteriorly and four anteriorly) for at least 10 seconds per location (Figure. 1). The stethoscope was placed such that on the right anterior side the right upper lobe and right middle lobe were auscultated and on the left anterior side the upper and lower portions of the left upper lobe were auscultated. Posteriorly, the upper lobe and lower lobe were auscultated on each side. This was done to best simulate potential community use of this analysis so special precautions were taken regarding environmental sound or positioning of the child.

Analysis

The video recordings were transferred to a Windows laptop as an MP4 file. The audio was extracted from video and converted to a WAV file using Goldwave⁶³. The conversion was done with a sampling rate of 10240Hz to a PCM signed 16-bit format with a mono channel. These sound files were analysed using R.A.L.E. View.⁶⁴ Figure 2 shows a screenshot of the R.A.L.E. View program with a processed breath sound file. The 100ms segments within the file were tagged manually as background sound, inspiration, or expiration. To ensure accurate labelling the sound was analysed by simultaneously watching the video recording so that inspirations and expirations could be easily identified based on the movement of the child's chest wall. Additionally, sound unfit for analysis was rejected. Crying, coughing, talking, and

other none breath sounds from the child were rejected. Extraneous environmental sounds such as static and other interference from moving the microphone were rejected.

After processing, data from R.A.L.E. View was exported for analysis. The power spectrum density was plotted for the audio file (Figure. 2). The graph shows the inspiration, expiration and background noise for the overall recording. Typically there's a frequency peak after 200Hz, followed by a loss in power (200-500Hz) that plateaued after approx. 800Hz. Quantitative features were then extracted from the PSD and they were compared between the "normal" breath sound and the "abnormal" (wheezy) breath sound groups.

Features (Figure. 4.)

FEAT_A – Amplitude: The difference in inspiratory and expiratory peak power was found for each child (measured as inspiratory peak – expiratory peak).

FEAT_{B,E} – Gradient: The second measure was the downward trend of PSD that occurred after the peak and bulk of the breath sound. This was best measured from 400hz-700hz using a linear line of best fit.

FEAT_{C,F} – Gradient: Similarly, the upward trend in the PSDs from 200hz – peak power was measured and analysed.

FEAT_{D,G} – Angle: Lastly, the angle between the upward and downward gradients was calculated for both the inspiratory and expiratory curves from the PSD

Once all these features were extracted for each subject, they were compared between the two groups (healthy and wheezy subjects) using the Mann-Whitney-U statistical analysis method and box-plots of the significant results.

Results

The breath sounds of thirty children presenting to the Children's Hospital in Winnipeg Manitoba were recorded. The children were grouped into one of two groups: healthy/control group or the wheezing group. Fifteen children were identified as having normal breathing by the attending emergency physician and fifteen were identified as wheezing. The age, height, weight, and sex were recorded for the subjects with a goal of having approximate equivalence between the two groups. Ages of the children ranged from two months old to eight years old. The mean age of the wheezy children was 2.4 ± 2.2 years old and for healthy children the mean age was 2.0 ± 1.7 . The basic demographics of the subjects are show in in Table. 1.

Each breath sound was analyzed using R.A.L.E. View™ where sounds were labelled as inspiration, expiration, or background. Interfering sounds such as static, vocalizations from the child, parent, or researcher were marked to be excluded (Figure. 2). Once labelled, data was extracted from the program and used to generate PSD graphs. These spectrograms display the average power of the breath sound for every frequency from 0-1200hz taken over the entire duration of the recording. Each graph contains three curves (inspiration, expiration and background) for each recording (Figure. 3). For all children, the average power was highest over the first 0-50hz for both inspiratory and expiratory sounds with a consistent downward trend in power moving towards 100hz. The background sounds followed a similar trend but at lower power. Similar background noise was observed between the two groups.

There was a noticeable difference in the expiratory spectrograms between the wheezing and healthy children. In the healthy children there was a tendency for the power of the breath sounds to level off between 100-200hz and then remain level or increase between the 300-500hz range. The inspiratory curves were similar between the healthy and wheezy subjects, however, there was stark contrast in the expiratory curves. The expiratory spectrograms for wheezy children showed marked increases in power, usually over the 300-500hz range, often to the point of having a higher average power than the inspiratory sounds (Figure. 4).

For each PSD, the peak inspiratory frequency and peak expiratory frequency after 200Hz was recorded. We used 200hz as the cut-off as there was higher background noise in the lower frequency range including heart sounds, that interfered with the breath sounds.

Given that differences were not normally distributed and that we had a low sample size a Mann-Whitney-U statistical analysis was performed. The results of the feature comparisons are shown in Table. 2.

This analysis showed four out of the seven features indicated significant difference between the healthy and wheezy groups (Feat_A, Feat_C, Feat_D and Feat_E had p-value <0.05). The majority of the features were from the expiratory curve, confirming our initial observation that the expiratory PSD for a child who is wheezy has significantly higher power in the 200-500hz range relative to the inspiratory sound than children with healthy breath sounds.

We found no significant difference in the angle for the expiratory curves. The difference in expiratory angle from 200hz – peak power was significantly different between the two groups ($p < 0.01$). Additionally, there was again no significant difference in the inspiratory slopes between the healthy and wheezing children from 200hz-peak amplitude. The angle created for the expiratory sounds were significantly different between the two groups ($p < 0.01$). Once again there no significant difference in the angles for the inspiratory peaks between the two groups. Boxplots demonstrate the difference between normal and wheezing children for features A, C, and D and the lack of differences for features F and G (Figure 5).

Discussion

The goal of our study was to show that there are quantifiable differences between breath sounds in normal and wheezing children who present to the emergency room detectable through digital breath sound analysis. We believe that digital sound analysis could be incorporated into an educational mobile app designed to assist parents recognize and manage the signs and symptoms of asthma as well as other airway diseases. This made our approach different than previous wheeze detection studies. Instead of using complicated, large, state of the art recording devices, rooms designed for recording sound, and building perfect conditions for recording we wanted to simulate what recording would be like for a parent at home to see if it is still possible to detect wheezing. Based on our results we do believe that this is a viable endeavor.

The population we targeted was young preschool children. Once children reach age six the diagnosis of asthma becomes easier. Wheezing in these children is more obvious, and they can describe it themselves. Spirometry also becomes a useful tool for identification of asthma at this age. Before six years of age, wheezing can be harder to identify and can be easily confused with many other breath sounds young children commonly create. As a result, many children who

likely have asthma go undiagnosed, and at the same time many children who do not have asthma or other serious diseases go to the emergency room unnecessarily. An educational mobile application could help these issues by presenting parents with examples of what wheezing and other adventitious breathing look and sound like with videos. It could contain useful information about what could be causing it, when to go see a doctor, or when to go to the emergency room. Adding the ability to record breath sounds with the application and detect wheezes would add to the apps function. The wheezing detection could potentially be automatic, or if too difficult, recordings could be saved and sent to physician for complete analysis. This would make it much easier for physicians to know if a child was wheezing during an episode of respiratory distress. This function would only be possible if we could first prove that our method of recording and analysis could be used to identify a wheeze, which we now believe it does.

For our analysis, we converted the recordings to power spectrum density curves. Multiple variables within the curves showed significant difference between normal and wheezing children which could be used to identify a wheeze. The most recognizable difference was in the difference in inspiratory and expiratory peaks between the two groups. We defined a peak as the maximum amplitude occurring after 200Hz. There was consistently loud sounds for inspirations, expirations, and background noise, all of which dropped off significantly after over the first 200Hz. From 200Hz to 500Hz we saw the breath sounds plateau or slightly increase in amplitude, and then start to fall off again. Normally expirations are passive processes and produce quiet breath sounds, while inspirations are active and loud. Therefore, the difference in peaks is quite noticeable as demonstrated with our control group. However, in the wheezing children the expiratory peak was much higher, usually higher than the inspiratory peak. Our analysis of the slopes and angles of the PSD also revealed variables that could be used to help identify a wheeze. The measurement of the angles from 200Hz to the peak amplitude demonstrated that wheezing children have a significantly different angle in the curve over this range than the healthy children. In fact, on average the wheezing children had a rise in the curve over this region while the healthy children had a drop. This reflects the increased power in expiration of the wheezing children. We also found that the inspiratory angle was not significantly different between the groups. The expiratory angle, however, was significantly different in wheezing and normal children. We believe that a combination of these measures could be used to identify wheezing from healthy breath sound recordings.

To secure better identification of wheezing we measured two other variables which did not yield significant results. The first was the angle of drop in the curve after the peak and the second was the curvature of the PSD after the peak. We were unable to find a significant difference in either of these variables. Nevertheless, we believe digital analysis of breath sounds present a promising method for detecting wheezes which could assist parents and physicians with recognition of wheezing in young, preschool, children.

In the future, this study can be expanded through the analysis of more variables from the sound to improve our ability to identify wheezing. Additionally, we will begin a similar process for children presenting with other adventitious sound such as crackles or with other common pathologies such as croup. We would like to have a database with examples for what each looks and sounds like to incorporate into an application that can be used by both families and healthcare workers to improve recognition of different respiratory diseases and to better inform families about what actions should be taken. The ability to distinguish breath sounds through digital analysis would be a powerful asset in such an application.

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Figures & Tables

Table 1: Summary of participants including mean age, height, and weight with the standard deviation. The sex ratio is also reported.

Group	N	Age (Years)	Gender (M/F)	Height (cm)	Weight (kg)
Wheezy	15	2.4±2.2	10/5	94.4±21.5	15.9±4.6
Healthy	15	2.0±1.7	8/7	86.5±17.3	12.4±4.3

Table 2: Summary of comparisons for each variable. Peak is the difference in amplitude for inspiratory and expiratory breath sounds. Inspirations and expirations are broken down into three variables; angle from 400hz-700hz, the angle from 200hz-peak amplitude, and the angle of the peak measured as the angle of intersection between the first two lines. All angles are measured in degrees and the amplitude is measured in decibels. The p Values were measured using Mann-Whitney-U statistical analysis and results were considered significant with p Value less than 0.05.

	Features	Mean _{Normal}	Mean _{Wheezy}	P-value (MWU)
Peak	FEAT _A	11.85	-1.21	<0.01
Expirations	FEAT _B	-4.09	-4.34	0.575
	FEAT _C	-1.42	1.95	<0.01
	FEAT _D	177.81	173.71	<0.01
Inspirations	FEAT _E	-4.72	-4.09	0.04
	FEAT _F	1.32	1.15	0.115
	FEAT _G	173.97	174.79	0.967

Figure. 1: Diagram of locations for auscultation. Eight locations were auscultated, two anteriorly and two posteriorly.

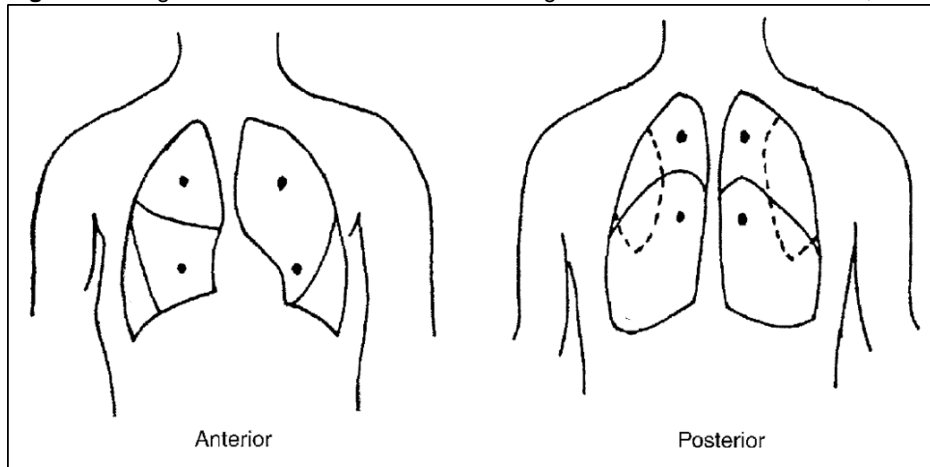


Figure. 2: R.A.L.E. View Screen Capture of manual processing of the recording. The R.A.L.E. View Software. Breath sounds were analysed using RALE View. Recordings were converted with a 10240Hz sampling rate to a PCM signed 16 bit format .wav file with a mono channel. In RALE View the sounds were marked as either inspiratory or expiratory, as demonstrated in the flow graph. The recordings was broken down into 100ms intervals and for each interval a waveform and power spectrum can be seen. The primary graph seen is a spectrogram which displays the frequency on the y-axis (measured in hertz), time on the x-axis (measured in ms), and power at each frequency is defined by the color (measured in dB). In addition to making inspirations at expirations, sounds were marked to be either analyzed (green), excluded (red), or as background sound (black).

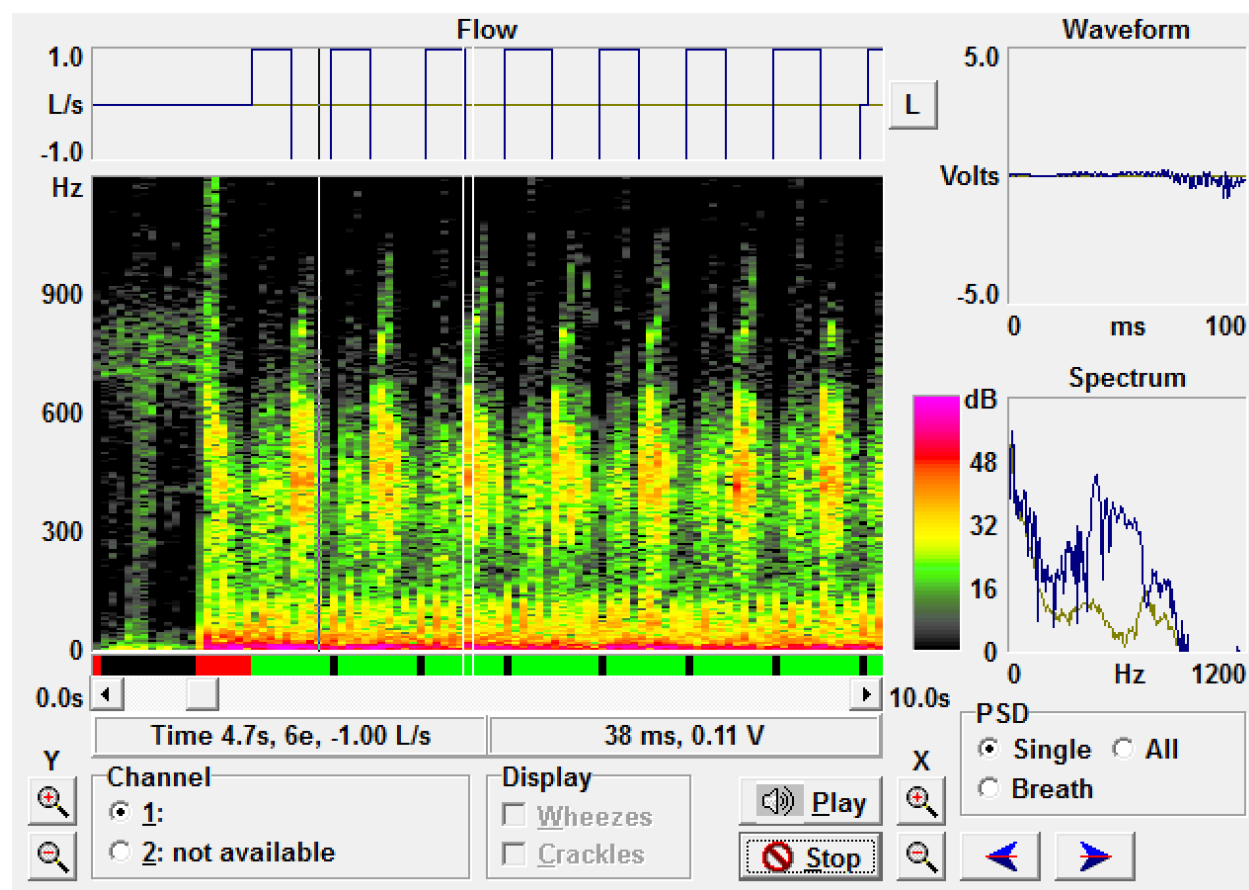


Figure 3: Power Spectrum Density of a recording. Each PSD displays three curves, one for background (black), one for expirations (red), and one for inspirations (green). The graph displays power (dB) as a function of frequency. The curves are produced by taking the average power for each frequency over the entire breath sound.

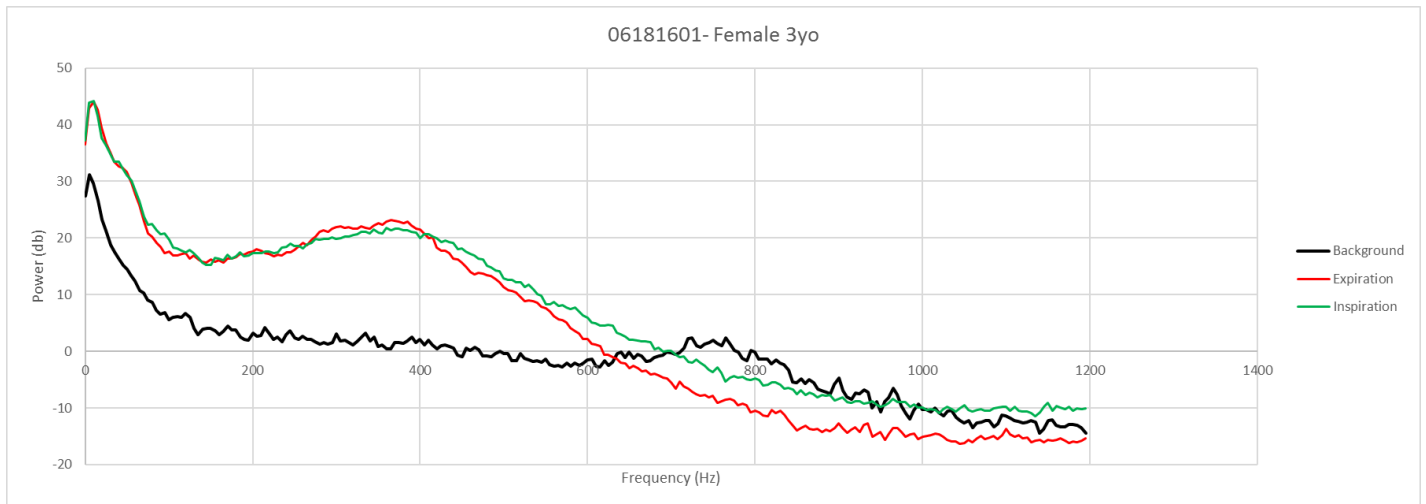


Figure 4: Comparison of a normal and wheezing PSD. (A) depicts the PSDs for a normal breathing child and (B) depicts a wheezing child. The seven features are labelled: $FEAT_A$ – Amplitude, $FEAT_{B,E}$ – Gradient: the downward trend of PSD that occurred after the peak and bulk of the breath sound. $FEAT_{C,F}$ – Gradient: Similarly, the upward trend in the PSDs, $FEAT_{D,G}$ – Angle: Lastly, the angle between the upward and downward gradients.

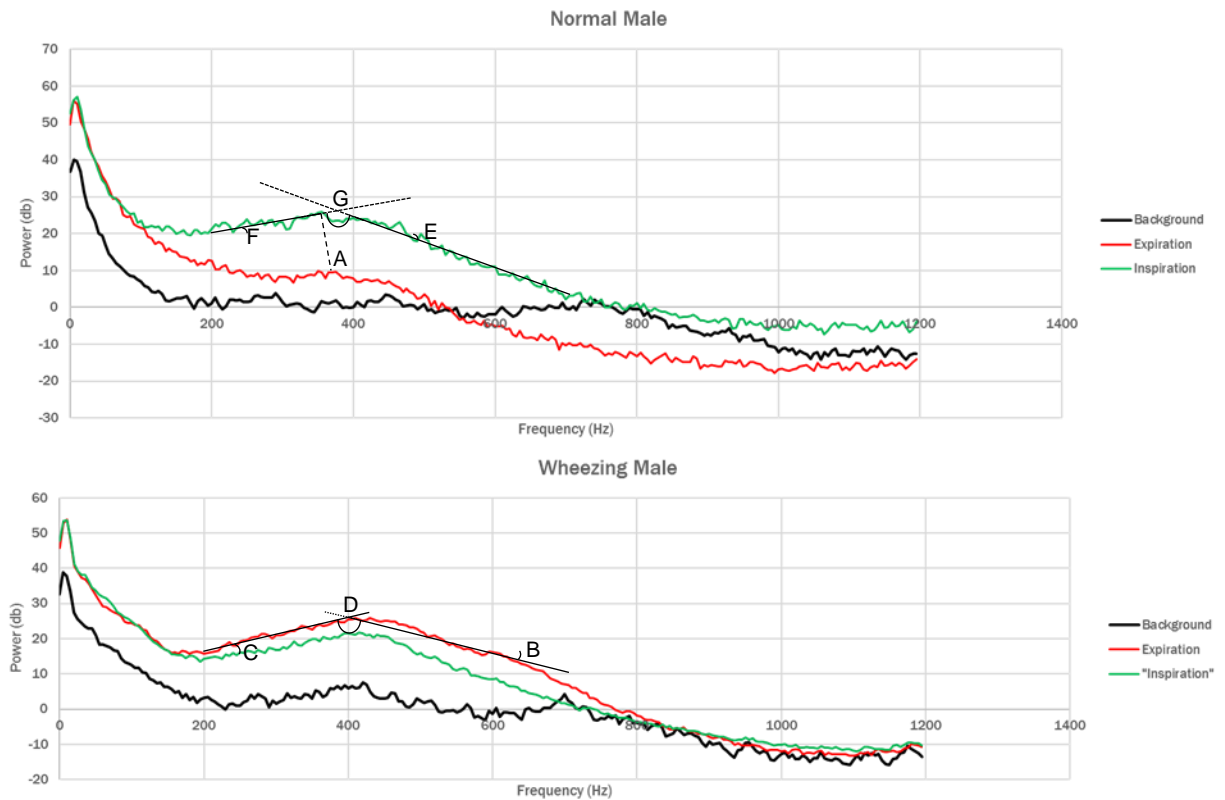


Figure. 5: Boxplots depicting comparisons for FEAT_A, FEAT_{C,E}, and FEAT_{D,G}.

