A Commercial Nocturnal Asthma Monitor

Progress Report

Group number: Group 26

Group members:
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Course: BME 401

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Need:

Nocturnal asthma (NA), a nighttime exacerbation of asthma symptoms, affects 47-75% of the several hundred million asthmatics worldwide[1,2]. NA is not a necessary complication of asthma, and is indicative of an improper management of the condition. The prevalence of the disorder is ill-defined, largely due to a lack of awareness that the sufferer is even affected. Unfortunately, the consequences of this disorder—especially for children—are very serious. NA causes nighttime awakenings and lower-quality sleep overall[3], and is thus significantly correlated with other symptoms resulting from sleep disturbance such as depression, anxiety, and "developmental, emotional, and behavioral problems"[2,4,5]. However, there is currently no objective, home-based monitoring system for nocturnal asthma.

Scope:

Given the particular prevalence and negative effects of NA in children, we propose to design a commercial, home-based device capable of continuously monitoring symptoms and alerting parents or caregivers if intervention may be required (i.e., during an asthma attack). The product will not be diagnostic for asthma, and is intended for children who have already been diagnosed with asthma and may suffer from NA. Our device will also not disrupt the child as she/he sleeps, and will be easy to configure and use since its audience is not medically trained.

Design Specifications:

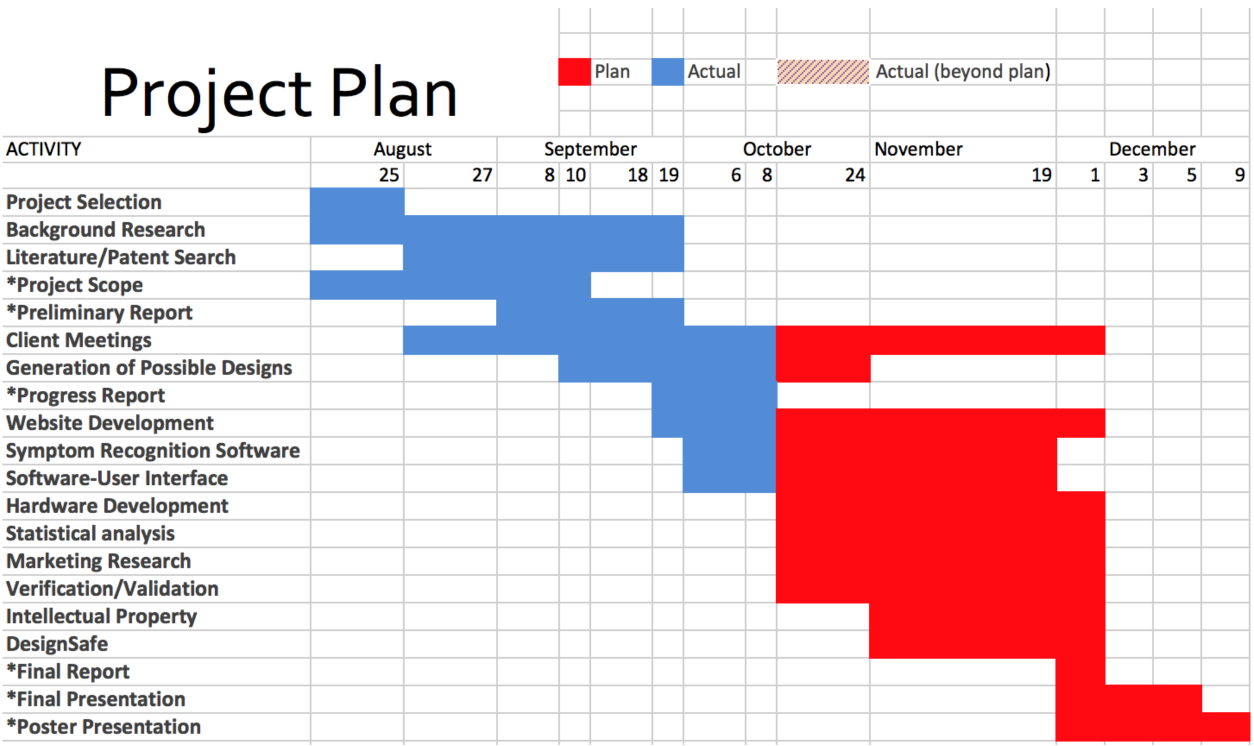
Table 1

Specification	Metric
Cost	Less than $200
Size	w x d x h less than 30 x 30 x 60 cm
Weight	Less than 3.6 kg
Accuracy	Sensitivity greater than 70%. Specificity Less than 2 false coughs/hr
Recording time	Greater than 12 hours
Sampling rate	At least 30 kHz
Audio alert volume	0 dB minimum and 80 dB maximum
Transmitter range	300 m open field range
Operating noise	Less than 30 dB

Other design considerations:

The device will be intended for children between the ages of 5-18 and is not diagnostic for asthma. It must not harm the child during monitoring and must not disrupt his/her sleep. If the child must be constrained, it must be minimal to still allow for undisturbed sleep. The device must alert parents or guardians at the onset of an asthma exacerbation, and so the device must recognize coughs in real-time or near real-time. The device should also be easy to maintain and to operate every day of the year.

Updated Design Schedule:



Organization of Team Responsibilities:

William Padovano has been focusing on developing a Matlab implementation for audio cough detection and will continue developing this software. He will then work on the software that will be uploaded onto the microcontroller in the prototype. In addition, William is in charge of researching and seeking intellectual protection for this project. David Kim will also work on the software for the prototype. Additionally, he is responsible for assessing the sensitivity and specificity of our solution. Chris Beyer is in charge of researching and purchasing the hardware for the prototype. He will also maintain the product web page.

Possible solutions:

Because a parent or guardian must be notified when a child is experiencing a nocturnal asthma exacerbation, each of the systems described below will include a radiofrequency transmitter that sends a warning signal to a radiofrequency receiver at the guardian's bedside. This frequency was chosen because of its large transmission range and the low cost of hardware to transmit and receive it. The design and features of this receiver are outlined in the "description of chosen design" section. The following subsections outline solutions that were not included in the Pugh chart due to significant drawbacks as well as potential solutions that are analyzed in further detail in the analysis section.

Discarded solutions:

The most obvious way to detect coughs is through continuous audio monitoring by parents, in a fashion similar to a baby monitor. However, this solution is severely lacking because it would require parents to be awake for the duration of the night to listen for and record coughs. The volume of the receiver could be turned up to awaken the parents when a child starts coughing, but this is clearly also not ideal because a single cough is not indicative of an asthma exacerbation. Another considered solution is a plethysmography band that could be worn around the child's chest each night. Although this method could provide a measure of breathing pattern, it would require fitting a tight band around the child. This would be uncomfortable for the child, and would likely disrupt his/her sleep. An even greater issue, though, is that the band would need to be calibrated each time it is put on and perhaps even require recalibration throughout the night[6]. The plethysmography band would also need to be placed directly on the child's skin to avoid loss of the signal through padded clothes, which means that the band would need to be cleaned routinely. These inconveniences and shortcomings led us to disregard plethsymography without further analysis in the Pugh chart.

Due to the similarities between the goals of our device and those of baby monitors, we also considered developing a system that could interface with existing baby monitors. In particular, we could take advantage of a baby monitor's microphone(s), signal transmission system, and receiver. However, we realized that producing a single system that could commandeer the functionalities of the huge number of different baby monitors would be very difficult. Due to the relatively low cost of microphones and radiofrequency transmitter/receivers we felt that the design challenges associated with producing such a device would outweigh the convenience of using preexisting hardware.

Electroencephalography (EEG) was considered as a means to detect nocturnal arousals, which are a problematic symptom of NA. For instance, alert patients tend to exhibit stronger beta-wave patterns, which are characterized by low voltages (~5mV) and high frequencies (typically 14-30Hz).[7] **Supplemental Figure 1** in the appendix details these waves as well as other waveforms.[8,9] Although the value of information concerning nocturnal arousals from this modality is high, EEG is not suitable for our project due to large discomfort and low signal-to-noise ratio (SNR), since the recording is susceptible to motion artifacts. It also does not monitor coughs or wheezes that a child may experience without waking up.

Electromyography (EMG) electrodes placed on the intercostal muscles were also considered to monitor cough, as EMG has been used previously for ambulatory cough monitoring[10]. However, we found during testing that a cough signal was very difficult to distinguish from normal abdominal movement, such as bending slightly to one side, as is shown in **Supplemental Figure 2.** Even with dry electrodes, EMG would also be very uncomfortable for the child because these electrodes are significantly bulkier and heavier than gelled alternatives.[11] The additional weight comes from adding pre-amplifiers at the electrode site to overcome high impedance at the skin-electrode junction. The pre-amplifier subsequently amplifies noise from the junction and decreases SNR.[11] Further, since the electrodes would be directly on the body, they would require cleaning after use, which is an added inconvenience.[12]

Lastly, the possibility of placing a sound sensor in the child's pillow was discussed. Although it would seem that placing the audio sensor closer to the mouth would increase audio volume, the attenuation coefficients of cotton and other materials used in pillows are significantly higher than that of air. Indeed, Ryan and Regan found the sound attenuation through a pillow to be 20 dB for frequencies below 1 kHz, which contrasts the 0.5 dB attenuation over 10 feet in air. Attenuation for higher frequencies through a pillow is even greater (25-30 dB).[13] Thus, the pillow sensor is clearly not advantageous to a bedside audio solution.

Solutions presented in the analysis section:

Visual. Movement detection: A bedside system that tracks nocturnal coughing by monitoring chest movement. An infrared (IR) grid of around 10,000 dots is projected onto a sleeping child and an IR camera detects the location of these dots. During a cough, the relative distances of several dots will change. The system will track these changes and, if they correspond to changes that take place during a model cough, the system will register the cough. A previous study has shown that this comparison can be performed effectively through principle component analysis, which requires relatively little computational power[14].The IR projector and camera needed for this system would likely cost around 300 to 500 dollars for a prototype, depending on the projector and camera lenses used. These lenses are important because such a system has been shown to be dependent on range, with greater ranges requiring more expensive lenses.

Visual. Breathing rate detection: A bedside system that monitors a child's breathing rate by detecting expiration. A mid-wave IR camera will sense temperature fluctuations produced by the relatively warmer air that is expelled. Such a system has been researched previously and appears to be computationally expensive due to the large amount of information represented by each video frame[15]. The camera alone would also cost around 1000 dollars for the prototype.

Audio. Wearable sensor: A wearable system composed of a small microphone that contacts the skin at the suprasternal notch to detect coughs and wheezes. This location has been shown to be advantageous because it is below the larynx, which means speech artifacts are diminished, and because it does not interfere with swallowing[16]. The microphone will be held in place by a snug-fitting necklace and will send audio information to a bedside processing unit through a flexible cable, which will also power the microphone. While the wiring may be slightly uncomfortable for the child, we believe that the need to charge the collar and the added bulk of batteries would cause an even greater inconvenience to the child and parents. It would also increase the cost of our device.

Audio. Bedside sensor: A system containing a microphone that will monitor coughs from a nearby nightstand without contacting the child. It will contain a detection algorithm that can separate coughs from speech or other sounds, such as snoring or crying. A more precise description of this system is shown in the "description of chosen design" section along with cough segmentation examples produced by a preliminary custom-made Matlab implementation.

Spirometry. Current gold-standard: A spirometer is a device that monitors several lung function parameters to diagnose respiratory illnesses, including asthma. Spirometry tests are generally only periodic, and a continuous nighttime test would likely only involve a measure of tidal volume (the amount of air that is inhaled and exhaled at rest). This parameter alone would give an accurate measure of breathing rate and respiration volume, which would provide valuable information on asthma[17]. Spirometry is an unrealistic monitoring solution, however, because it is extremely uncomfortable and expensive. It was included in the Pugh chart for the sake of comparison because it is the gold-standard for characterization of asthma.

Vibration. Wearable sensor: A wearable sensor that clips onto the collar of a child's shirt and tracks sudden movements that are produced during a cough. The inexpensive vibration sensor will have a height and width of about 3 cm by 3 cm and a depth of about 1 cm. It will be water-resistant to avoid being damaged from accidental spills and to allow for routine washing. The sensor will transmit acceleration, velocity, and displacement data to a processing unit nearby through a flexible cable that also powers the sensor.

Vibration. Mattress pad: A soft, flexible pad that fits over a twin-size bed and contains a 6x6 grid of vibration sensors to monitor vibrations that occur during a cough. The number of sensors was determined by comparing an estimated chest width and length of a child (0.25 m by 0.25 m) to the width of twin mattress (1 m)[18]. Based on these values, the density of sensors must be greater than a 4x4 grid to ensure at least one sensor is always recording vibrations from the child's chest. For safety, we chose a density 50% greater than this minimum grid size. A processing unit could be built into the large mattress covering, eliminating the need for a separate processing unit. While this solution is an improvement in comfort over the wearable sensor, it comes with a sharp increase in cost (at least 36 times as expensive).

Pulse oximetry. Finger clip: A wearable transmittance pulse oximeter that will clip onto the child's finger and continuously monitor oxygen saturation during sleep. The clip will be connected to a bedside processing unit that will detect if the child is hypoxic, or is not receiving enough oxygen. Although a pulse oximeter worn as a wristband on the body would probably be more comfortable, reflectance pulse oximetry unfortunately is not applicable for our project. The mean squared error for saturated oxygen (SpO_2) readings in transmittance pulse oximetry is 0.02%, while it has been shown to be 2.6% in reflectance pulse oximetry[19] [20]. Because the system should be able to detect moderate hypoxia near the onset of a severe asthma exacerbation (defined as SpO_2 between 90% and 95%), the sensor must be able to accurately detect relatively small differences in oxygen saturation[21]. With a wrist sensor, a potentially dangerous oxygen saturation of 93% could appear on the monitor as a normal 96% saturation or vice versa. Pulse oximetry was the second highest scoring design on the Pugh chart, with low scores only in comfort and value of information. The first weakness stems from the wires and physical contact that the oximeter must maintain with the child. The second weakness can be attributed to the fact that this device measures blood oxygen saturation, and offers a warning only after an asthma attack has begun. This method has no predictive capabilities and can only detect relatively severe asthma symptoms.

Analysis of Solutions:

An analysis of viable solutions was performed through a Pugh chart.

	Relative importance	Visual: Movement detection	Visual: Breathing rate detection	Vibration: wearable sensor	Vibration: mattress pad	Pulse oximetry: finger clip
Cost	0.66	3	1	10	4	9
Safety	0.66	10	10	8	10	10
Comfort	1	5	5	4	7	5
Ease of use	1	10	10	7	10	7
Maintenance	0.66	10	10	5	8	8
Size	0.33	5	5	10	5	10
Weight	0.33	7	7	10	5	10
Recording Time	0.33	10	10	10	10	10
Sampling Rate	0.33	10	10	10	10	8
Robustness	1	3	2	4	6	8
SNR	0.66	6	8	4	4	9
Software	0.66	3	5	8	7	8
Value of Information	0.66	5	8	5	5	3
Range	1	3	6	10	10	10
Initial setup	0.66	3	3	10	8	8
TOTAL		*93*	*100*	*115*	*109*	*123*
WEIGHTED TOTAL		57.96	63.26	71.2	73.26	78.84
	Audio: wearable sensor	Audio: bedside sensor	Spirometry	Visual breathing rate & bedside audio	Pulse oximetry & bedside audio	Pulse oximetry & vibration mattress pad
Cost	8	8	1	1	7	3
Safety	8	10	2	10	10	10
Comfort	4	10	1	5	5	5
Ease of use	7	10	1	10	7	7
Maintenance	5	10	3	10	8	8
Size	10	10	4	9	9	5
Weight	8	8	4	6	8	5
Recording Time	10	10	10	10	10	10
Sampling Rate	8	8	10	8	7	8
Robustness	9	9	10	9	9	9
SNR	6	7	10	7	9	9
Software	8	8	6	4	7	6
Value of Information	8	5	10	9	6	6
Range	10	8	10	7	8	10
Initial setup	6	6	5	3	6	8
TOTAL	*115*	*127*	*87*	*108*	*116*	*109*
WEIGHTED TOTAL	74.22	84.52	55.66	70.93	75.2	73.24
Weighted Min	10	Weighted Max	100			

Explanation of Pugh chart scores:

We placed each of our 15 categories into one of three bins (high importance, medium importance, and low importance), corresponding to weights of 1, 0.66, and 0.33. We rated comfort, ease of use, robustness (the fidelity of the signal in different conditions, such as if the child rolls over, is under covers, etc.), and range as having the highest importance, because these categories best defined how a user would actually interact with the device. The size and weight were given relatively lower importance because they do not meaningfully affect the functioning of the device. The sampling rate was also given low importance because the device will not save the actual data from recording sessions, and so the samples taken per second will not greatly impact the cost or size of our device. Lastly, the recording time was given low importance so that it would not have a disproportionate impact on the total scores, since all solutions in the Pugh chart excelled in this category.

Visual solutions:

Both visual options are intuitively safe, easy to use, and easy to maintain. They are also relatively lightweight, can record for the entire night, and have a low sampling rate requirement because human movement and breathing is relatively slow. According to current literature on the required IR sensors, the signal to noise ratio is relatively high, with both sensor types purporting to monitor subjects' breathing rates with better than 90% accuracy from about 6-8 feet away. However, both of these solutions had low scores in cost because they are very expensive. The also both received very low scores in the initial setup and robustness categories because the sensors must be carefully positioned in the room and the data collected by the devices are dependent on the child's position. If the child is under blankets or is turned away from the sensors, for example, the systems would likely have difficulty tracking his/her movements or breathing rate. The resulting need to constrain the child's sleeping position also leads to moderately low scores in comfort.

The two sensors diverged in the software, value of information, and range categories. The movement tracker must synthesize very small changes in IR dots into a representation of the subject's movements, while the breathing monitor can take advantage of different temperatures to track expiration. Though the software implementation for both of these methods is challenging relative to other sensors like vibration or sound, the movement tracker's would be harder to accomplish and would likely require greater computational power. Whereas the movement monitor's accuracy also appears to fall off sharply with distance from the subject, the breathing rate monitor's does not. Lastly, the breathing rate solution would provide a measure of both cough frequency and breathing pattern, offering a more complete characterization of a child's nocturnal asthma symptoms than tracking cough alone.

Audio solutions:

The bedside audio solution has several advantages over the wearable sound sensor. In particular, the bedside monitor excels in comfort and ease of use because it does not contact the child and does not have any potentially constraining wires. This also means that this solution will experience less wear and tear during its lifetime and thus fail less frequently than the clip-on solution, which contributes to a higher safety score. However, the wearable sensor has better range because its wires may run from the child to a distant processing unit, and it also scores more highly in the value of information category. This is because a sensor at the suprasternal notch would be able to record wheezes in addition to coughs, which would provide a more complete characterization of the child's respiratory inflammation. Both of these solutions are relatively inexpensive and, based on our preliminary data collection, require a high sampling rate of at least 30 kHz to appropriately detect coughs. They also have a moderately low initial setup score because the systems may need to learn the child's unique cough in order to work most effectively. As is shown in **Figure 1 and Supplemental Figure 3**, coughs are easy to distinguish from speech and other potential noises in the bedroom, which explains the relatively high signal to noise ratio score for audio solutions.

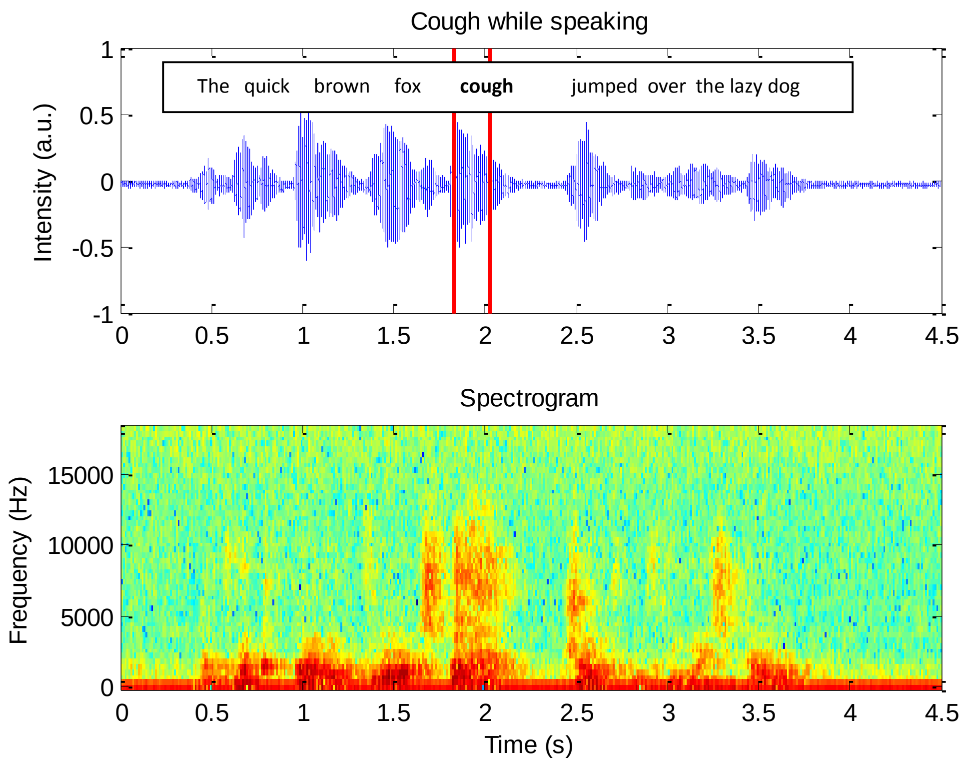


Figure 1: An example of cough segmentation using Matlab. The words and the cough are labeled in the time-series plot at the top. The red bars indicate the start and end of the detected cough. The bottom plot is the corresponding sound spectrogram.

Vibration solutions:

The SNR and value of information scores are low for both of these solutions because the detected motions are easily confused by other movements not associated with coughs, including nighttime rolling, shivering, and bending. **Supplemental Figure 4** illustrates data taken from a group member performing some of these motions. Additional complications for both designs include variations in motion between coughs and between people as well as possible attenuation of high frequency vibrations caused by the fabric of clothes. Further, the orientation of the child would likely have a large effect on the sensor readings. Although the mattress pad is much more expensive than the body clip, it still scored higher in the Pugh chart. This is because the mattress sensors surpass the body clip in some of the most heavily weighted metrics: comfort, ease of use, and robustness.

Pulse Oximetry:

Pulse oximetry was the second highest scoring design on the Pugh chart, with low scores only in comfort and value of information. As mentioned previously, a pulse oximeter can only monitor a child's more severe asthma symptoms, which could have otherwise been noticed by the child anyway. Although the monitor scored highly due to its very low signal to noise ratio and robustness, the recorded signal has little value. A pulse oximeter could be a valuable addition to an existing system but it is not practical as a solitary sensor for asthma, and its high score represents a potential weakness in the Pugh chart design.

Spirometry:

As mentioned above, spirometry has long been the standard in asthma diagnosis and characterization. The Pugh chart illustrates why: spirometry provides high-quality data on lung function with little signal noise, as is reflected in the six categories in which this solution scored a perfect 10. Spirometry ranks last overall on the Pugh chart, however, because the chosen device must be simple, relatively inexpensive, and have minimal effect on the patient's sleep. By contrast, spirometers have been shown to be too complicated for patients to reliably use independently.[2] Furthermore, data acquisition would likely entail one of two undesirable situations: requiring the patient or a caregiver to awaken during the night to administer a measurement (interrupted sleep, non-continuous data), or requiring the child to wear a mask throughout the night to obtain continuous data (a significant source of discomfort). Spirometers are also relatively expensive, further damaging their legitimacy for this application.

Combinations:

Because the monitor could potentially include more than one type of sensor, combinations of highly scoring sensor types were considered. However, these combinations failed to score higher than the bedside audio solution alone because, in general, negative qualities associated with one sensor type were not mitigated by the addition of another sensor.

Vision breathing rate & bedside audio:

While the combination of the highest-scored visual and audio solutions scored significantly better than visual alone, it still scored much worse than the bedside audio solution alone. In exchange for a significant gain in the value of information, the combined sensor is much more expensive, less comfortable, and more difficult to setup than the audio-based solution.

Pulse oximetry & bedside audio:

The combination of pulse oximetry and bedside audio monitoring scored worse than either of its component solutions. This combination received a low score overall due to issues in many significant categories, such as comfort, ease of use, and range, while receiving only a slight advantage in value of information over the solitary solutions. It also suffered from higher costs as well as lower scores in most of the less heavily weighted areas, including size, weight, and software.

Pulse oximetry & vibration mattress pad:

As with the previous combination, mattress vibration sensors with pulse oximetry also generally yielded lower category scores in the Pugh chart than the individual sensors. Although monitoring both coughing activity and oxygen saturation increases the reliability of the received information, these slight gains did not offset the disadvantages of cost, size, weight, comfort, ease of use, and maintenance.

Description of Chosen Design:

According to the Pugh chart, the bedside audio solution scored significantly better than all other options, with a weighted score of 84.52 out of the maximum possible score of 100. A visualization of the physical design for this monitor is shown in **Figure 2**. The device occupies an estimated footprint of 15.2 cm by 7.6 cm and a height of 7.6 cm. It contains a microphone—likely an electret or MEMS microphone—and an adjustable sensitivity slider. The device can be set to a higher sensitivity at the cost of lower specificity and vice versa based on a parent's preferences. It also contains an LED screen to display the number of coughs detected since the start of the sleep session, as well as a readout of coughs per minute. This will give the parent a measure of cough frequency to help gauge the severity of the child's asthma symptoms. The device also has a light that can be turned on to allow a parent to read medication labels or get a better view of the child without having to turn on lights in the room. It is powered by a wall outlet through a power cord that contains a surge protector.

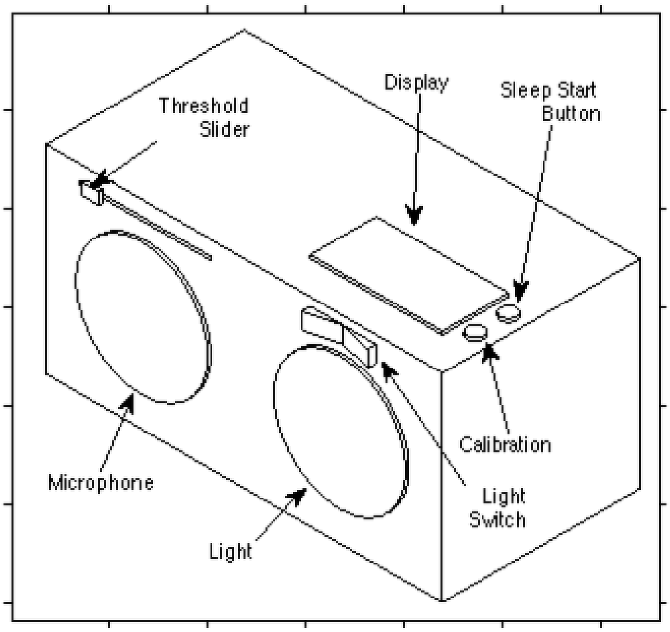


Figure 2: A model of the proposed cough monitor. Key features of the model are labeled.

Internally, the product contains a digital clock, which allows it to keep track of the time of day. This is required because, as is shown in **Supplemental Figure 5**, the median number of coughs per hour varies with time of day, which means that the minimum threshold for an asthma exacerbation also changes[22]. Once the button at the top of the device is pressed to indicate the start of sleep, the number of coughs and cough frequency values are cleared and the device begins to continuously listen to all sounds produced in the room. If the system detects significant power in a high frequency band (around 8-10 kHz) as determined by a band-pass filter, the system begins recording the sound until the power in the high frequency band drops. The frequency spectrum of this recorded segment is then calculated, which has been accomplished previously with low-power components[23]. The correlation of each frequency band of this spectrogram to the corresponding frequency band of a template cough spectrogram is taken. This template cough spectrogram would have been recorded and saved during the initial device setup, when the user calibrates the system by pressing the “calibration” button at the top of the device and coughs. If there is significant correlation in a number of frequency bands (this number is manually adjusted), then the device recognizes the sound as being a cough. The threshold can be raised or lowered by adjusting the sensitivity slider. The software to perform these calculations will likely be uploaded onto an Atmel ATmega328 microcontroller (used in the Arduino Nano).

If a high cough frequency is detected (current estimate = 10 coughs/minute), the system fires a radiofrequency pulse (likely 434 MHz or 2.4 GHz) to the receiver located in a parent’s room. A physical model of the receiving system is shown in **Figure 3**. It contains a small speaker with an adjustable volume slider as well as a warning LED to indicate an asthma exacerbation and to warn the user of low batteries. The device also contains a button that checks if it is within range of the transmitter. The LED will flash a warning if the receiver is out of range. The receiver is powered by batteries or by an optional power cable.

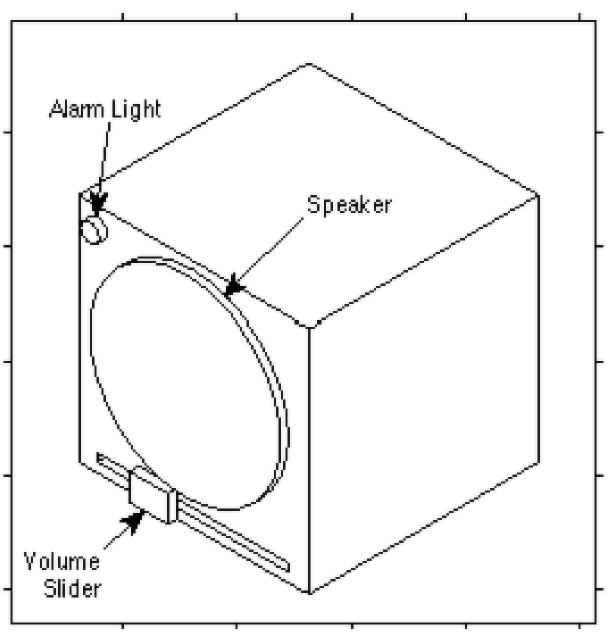
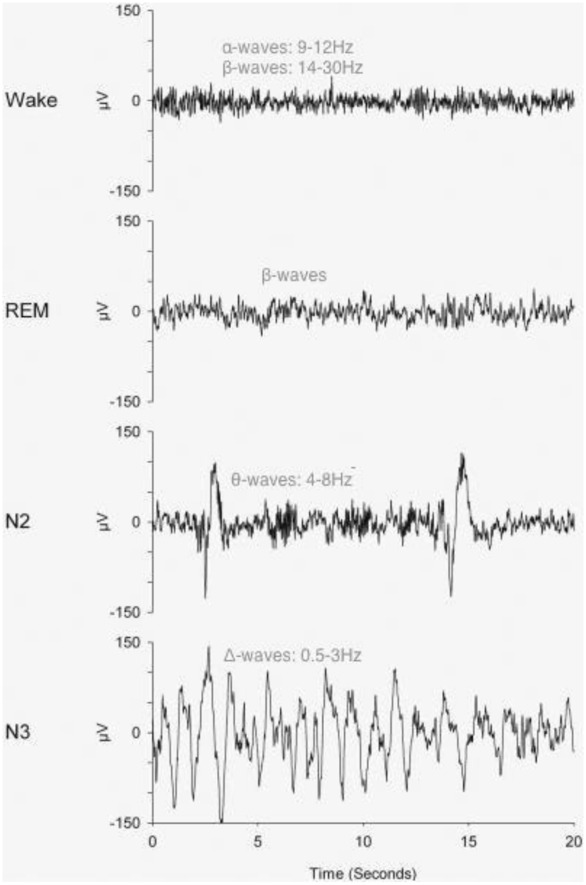
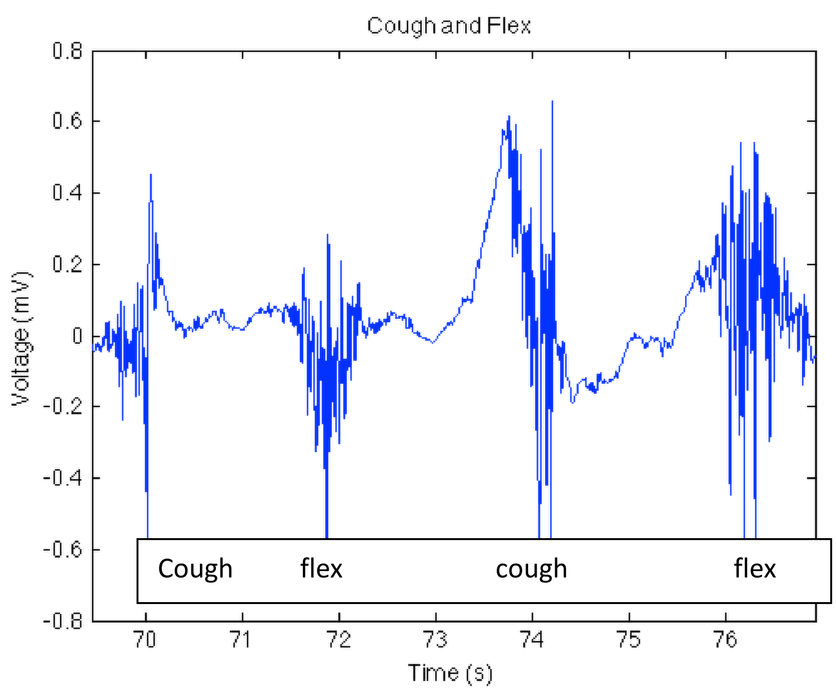


Figure 3: A model of the proposed cough receiver. Key features of the model are labeled.

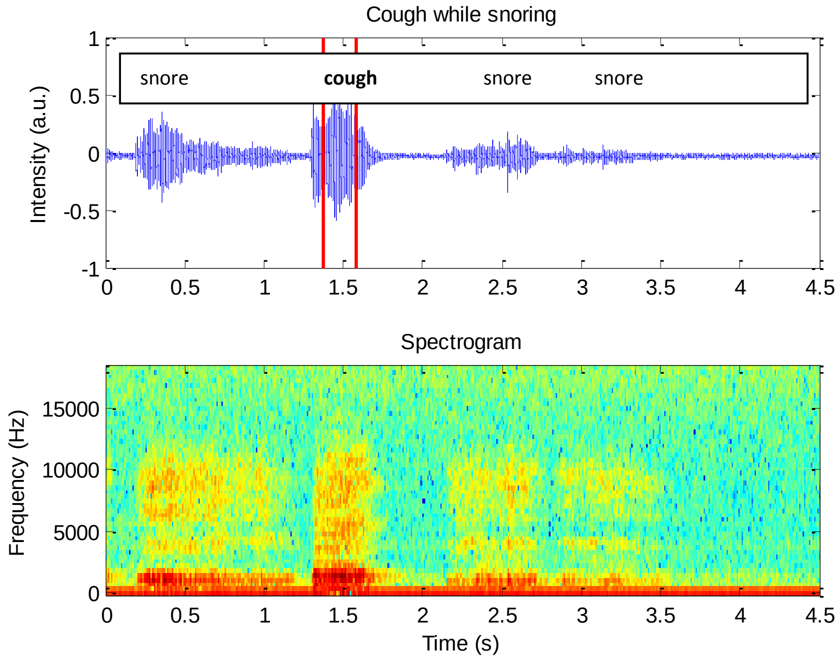
Supplemental Figures:



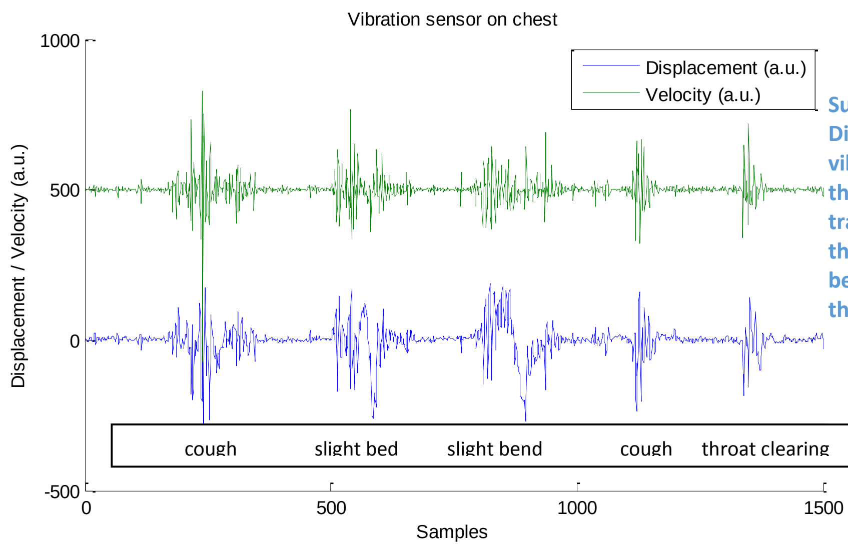
Supplemental Figure 1: EEG data taken from several sleep states of a patient: awake, rapid-eye-movement (REM), non-REM stage 2 (NR2), and non-REM stage 3 (NR3).



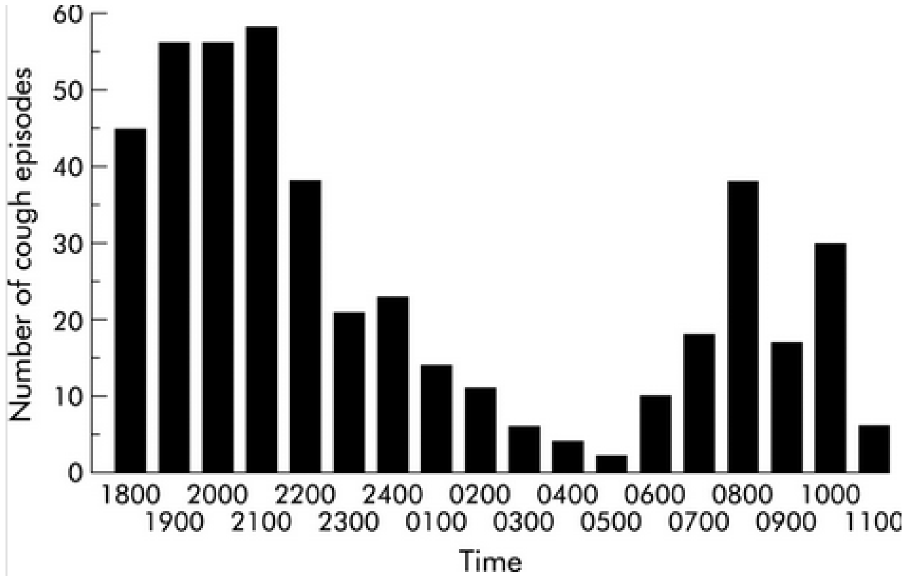
Supplemental Figure 2: EMG data taken from one of the group members showing the difference between flexing the abdominal muscles and coughing. One pair of gelled EMG electrodes was placed on the upper right quadrant of the abdominal muscle.



Supplemental Figure 3: An example of cough segmentation using Matlab during a sound recording with snores and a cough. The red bars indicate the start and end of the detected cough. The bottom plot is the corresponding sound spectrogram.



Supplemental Figure 4: Displacement data was taken from a vibration sensor that was placed on the chest. The derivative of this trace was also taken (velocity). Note the difficulty in distinguishing between coughs and a slight bend of the abdomen.



Supplemental Figure 5: A figure from a study that monitored coughs in stable asthmatic children throughout a 24-hour period. A time of 0200 means 2:00 am.

Citations:

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