Design and Evaluation of a Low-cost Piezoelectric Device for Remote Diagnosis of Respiratory Diseases

Rohan Palanki[1], **Justin Poiroux**[1], **Srinivas Palanki**[2*]

[1]*Department of Chemical & Biomolecular Engineering*
University of South Alabama
Mobile AL 36695
E-mails: rohanpalanki@gmail.com, justinpoiroux@gmail.com

[2]*Department of Chemical Engineering*
Lamar University
Beaumont TX 77710
E-mail: spalanki@lamar.com

[*]*Corresponding author*

Received: June 08, 2015 **Accepted: November 09, 2015**

Published: December 22, 2015

Abstract: *In this research, a piezoelectric film was utilized to develop a low-cost biomedical device for diagnosis and management of breathing disorders. First, it was shown that when a commercial polyvinylidene fluoride (PVDF) film was subjected to airflow generated from human breath, the voltage generated increased with decreasing film thickness. Then, a device was fabricated that records a patient's breathing pattern and sends this data to a remote email address via the Raspberry Pi, an inexpensive computer. It was shown that the breathing patterns could be recorded in a reproducible manner with this device. Next, the efficacy of the device to detect breathing disorders was tested. A restrictive ventilatory abnormality was simulated by tying a crepe bandage around the chest. It was shown that this device could successfully distinguish between breathing in a normal patient and the breathing of a patient with a restrictive ventilatory abnormality. It is possible to fabricate this device for less than \$100, thereby making it accessible to a large number of patients with chronic lung diseases.*

Keywords: *PVDF film, Respiratory, Remote diagnosis.*

Introduction

Lung diseases such as restrictive ventilatory abnormalities kill about 4 million people every year in the United States [9]. These diseases are chronic in nature and require repeated visits to the doctor's office or hospital for proper disease management. Current diagnostic devices include the use of spirometry, which is a lung-function test that measures the volume of air taken in and exhaled as a function of time. This device costs \$2,000-\$5000 and is typically available only in the doctor's office. However, for proper management of lung diseases, it is necessary to make frequent measurements of lung function (e.g. daily measurements), so that this information can then be used to make adjustments to medication as well as life-style. Thus, there is a need to develop a low-cost biomedical device that patients can use at home instead of making frequent (and expensive) trips to the doctor's office. Furthermore, if this device can automatically send breathing pattern data to the doctor's office from the patient's home, remote diagnosis of respiratory diseases is possible. An inexpensive device that is easily affordable while offering accurate measurements [13] would provide a significant improvement to the lives of people with chronic lung diseases.

Nield et al. [5] studied the inhalation and exhalation patterns of patients with obstructive ventilatory abnormalities, restrictive ventilatory abnormalities, and normal patients and showed that the breathing patterns of these three groups were substantially different. To capture the breathing patterns of a patient, it is necessary to use a material that converts mechanical energy to electrical energy. There is current interest in harvesting energy from ambient mechanical vibrations for developing self-powered electronic devices [2]. Previous attempts to capture energy from low speed airflow have made use of piezoelectric cantilever beams [11] and windmills [8]. Recent developments in nanomaterials have made it possible to utilize piezoelectric nanomaterials as the functional elements to scavenge low-density energy directly from activities such as breathing. One such material, polyvinylidene fluoride (PVDF) film, exhibits the strongest piezoelectric response of any commercially available polymer. Due to this piezoelectric property, PVDF films are used in the manufacture tactile sensor arrays, inexpensive strain gauges and lightweight audio transducers [14]. Sun et al. [12] fabricated a PVDF film via reactive ion etching and used this material in a microbelt configuration for harvesting energy from simulated respiration. Luis et al. [3] developed a smart sensor based on capacitive sensing to monitor the respiratory rate in patients with sleep apnea. Cao et al. [1] developed a wireless portable system for monitoring respiratory diseases, which measures respiratory airflow, blood oxygen saturation and body posture using micro-hot-film microsensors integrated with Bluetooth transmitters for diagnosis of sleep apnea, chronic obstructive pulmonary disease and asthma. A comprehensive review of wearable sensors is available in the review article by Patel et al. [7]. Another approach involves the measurement of respiratory system impedance using forced oscillation technique in a tube-shaped fluid-communicating member, a support member and an actuator [4]. However, there are no results in the literature where a commercial PVDF film has been utilized for harvesting energy from breathing for diagnosis of lung function abnormalities.

The objective of this research was to demonstrate a proof-of-concept of a low-cost piezoelectric device for remote diagnosis of respiratory diseases. To achieve this goal, a commercial PVDF film was evaluated to see if sufficient voltage could be generated when subjected to airflow from human breath. Then, a low-cost device was fabricated that could be used to reproducibly capture voltage from human breath. Finally, a computer program was written that sends this voltage versus time plot to a remote email address that could be accessed by a physician's office, thereby demonstrating that this device could be used for remote diagnosis of respiratory diseases. This paper is organized as follows: Section II lists the materials and methods used in the design and evaluation of this piezoelectric device. Section III describes the experimental results of the device and its efficacy in detecting breathing disorders. The conclusions of this research are summarized in Section IV.

Materials and methods

PVDF film of thickness 110 μm, 52 μm, and 28 μm (Precision Acoustics), Peak Flowmeter (Assess LR), Multimeter (Fluke), Alligator Clips, Electrical Tape, Scissors, Ruler, Masking Tape, Plexi-Glass, Plastic (PET) Bottle of base diameter 2", Peak Flowmeter mouthpiece of diameter 1.5", Electrical Wires (Radio Shack), Soldering Iron (Weller), Crepe Bandage (Ace), SolidWorks Software (Dassault Systems), Raspberry Pi Computer (Adafruit), Breadboard (Radio Shack).

The two surfaces of a PVDF film of thickness 110 μm and size 5.4 cm $\times$ 5.4 cm were attached to a voltmeter using alligator clips. A peak flow meter was used to blow air at a rate of 75 l/min onto the film and the peak voltage generated was measured using a voltmeter. This experiment was repeated with a PVDF film of thickness 52 μm and 28 μm. Five measurements of voltage were taken for each PVDF film thickness to ensure that the results were reproducible.

Each component of the device was first designed in SolidWorks [10]. First, a base plate with five prongs was designed so that the PVDF film could be looped in such a way that alligator clips could access both sides of the film. Then, a tapered cylindrical tube was designed to accommodate the base plate so that the air from human breath could be directed to the PVDF film for maximum vibration. Finally, the entire assembly was designed to fit in a small bottle with no base to protect the PVDF film. Electrical wires were soldered to alligator clips and these were attached to both sides of the PVDF film. The electrical wires could then be connected to a voltmeter or to the Raspberry Pi for voltage measurement.

A computer program was written in Python on the Raspberry Pi. Fig. 1 shows the flow diagram used for the program. First, the basic modules (time, operating system, general purpose input output (GPIO), email and Matplotlib) were imported into Python. The function "SendMail" was defined, whose purpose was to deliver a set image via Simple Mail Transfer Protocol (SMTP). Next, variables were defined for time and voltage readings, which are saved in a text file and plotted using the "Matlibplot" function. To record the voltage data, it was necessary to convert the analog voltage signal to a digital voltage signal. This analog to digital conversion was accomplished by defining the "readadc" function. Finally, it was necessary to develop a subsystem that switched on and off the data recording process. An "on-off" button in conjunction with a "while loop" was used to accomplish this task. When the button was pressed in the "on" position while breathing into the piezoelectric device, an analog voltage was generated. This voltage was converted to a digital signal via the "readadc" function. Voltage versus time data was recorded in the variables defined for this purpose and a plot was generated by the "Matlibplot" function. This plot was sent to a specified email address by the "SendMail" function via SMTP. The plot could, then, be accessed by opening the email at a remote location in a smart phone device or computer.

Institutional Research Board (IRB) approval was obtained for conducting breathing tests. A pulmonologist was contacted to determine if the biomedical device developed in this project could be used as a rapid diagnostic tool for respiratory ailments. The pulmonologist suggested that the breathing patterns of a restrictive ventilatory abnormality, a common lung disease, could be simulated in a healthy person if a crepe bandage was taped around one of the researcher's chest and the lung function was measured. This simulated exercise had to be conducted because IRB approval could not be obtained for testing this device on a patient with restrictive ventilatory abnormality without any data that this device could work. One of the researchers of this project breathed into this device in the same pattern that is used for testing for respiratory ailments in a standard spirometer (i.e., take a deep breath in, then breathe out rapidly into the device to empty the lungs and then take a deep breath in). Standard parameters with and without the bandage were first measured on a commercial spirometer to see if the crepe bandage adequately simulated a restrictive ventilatory abnormality. Once it was determined that tying a crepe bandage around the chest actually simulated a restrictive ventilatory abnormality, the breathing patterns with and without the bandage were compared on the piezoelectric device developed in this research. A substantial difference in the voltage signals generated with and without the bandage would provide the necessary proof-of-concept of the the proposed low-cost device.

Results and discussion

Fig. 2 shows the effect of PVDF film thickness on the voltage generated. It is observed that the peak voltage generated increases as the film thickness decreases. This is because the static structure for the thinnest film is more easily deformed by air flow as compared to thicker film, thereby leading to a higher peak voltage. Thus, the thinnest film was used in fabricating the device. A piezoelectric device was fabricated using the procedure outlined in the previous section using a film thickness of 28 μm and a film area of 10.8 cm^2. The film area had to

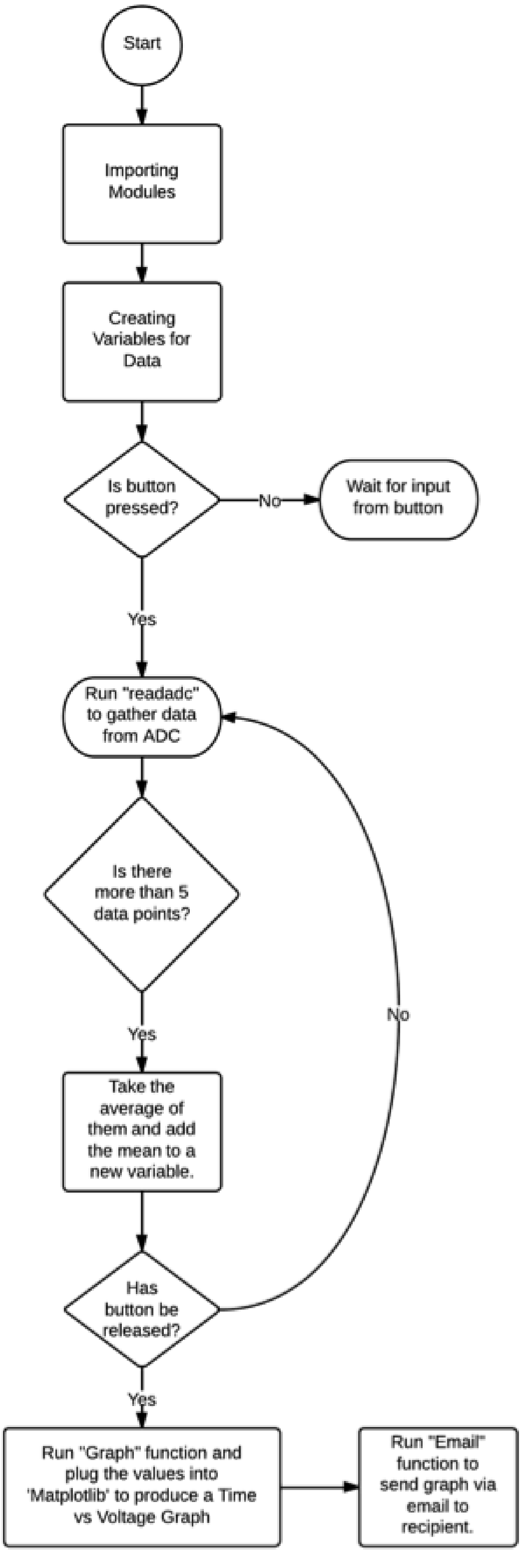


Fig. 1 Flow chart of computer program

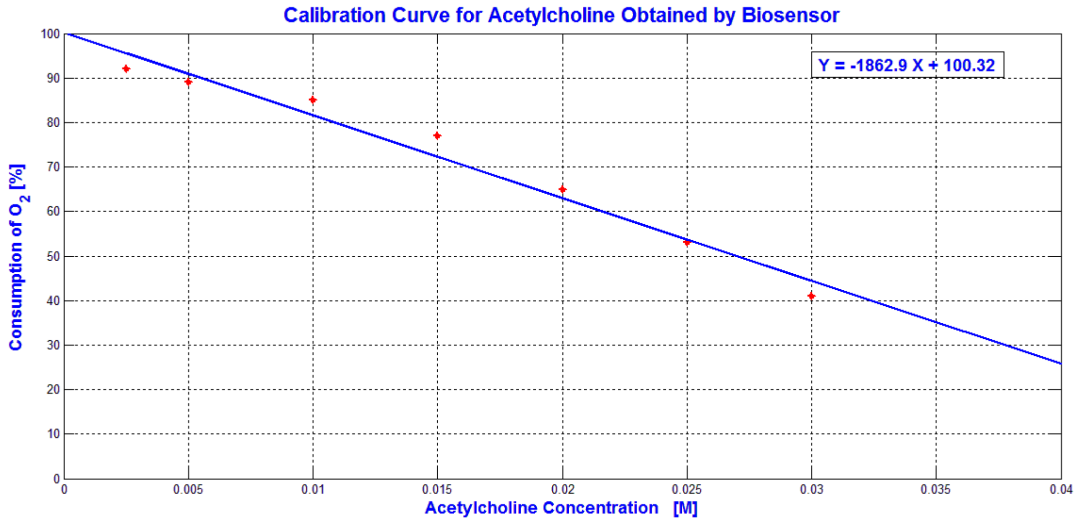


Fig. 2 Effect of PVDF film thickness

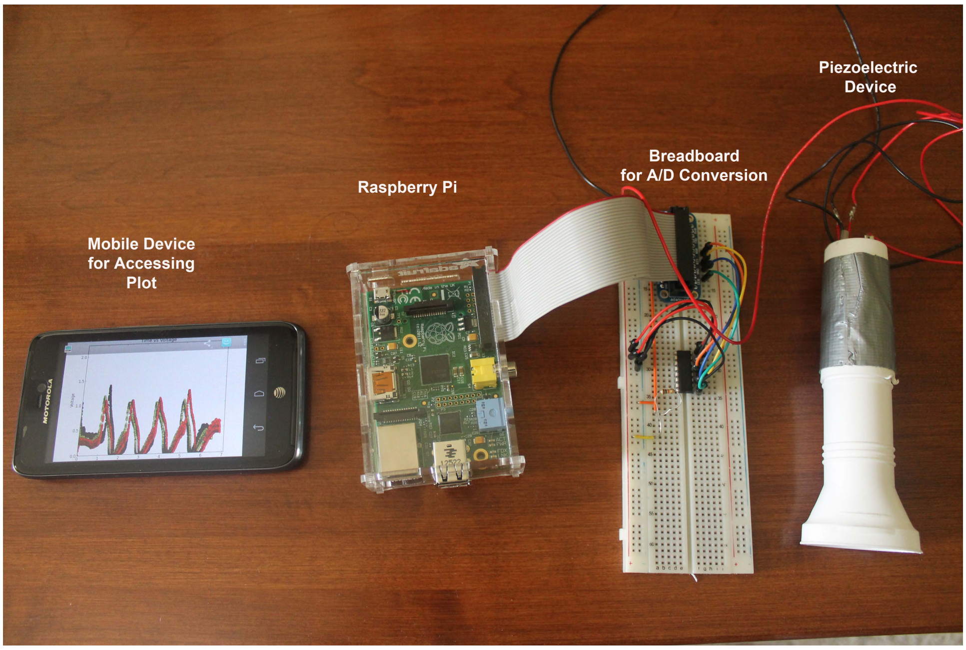


Fig. 3 Overall device configuration

be optimized so that the device was small enough to be portable but large enough to generate measurable voltage from human breath. The Python program was loaded onto the Raspberry Pi and the piezoelectric device was connected. A picture of the overall configuration is shown in Fig. 3.

One of the researchers (RP) breathed into the piezoelectric device and the voltage versus time data was sent via email to a specified email address. This normal breathing pattern experiment was repeated three times to see if the voltage data produced was reproducible. A smart phone was used to access the plot sent to the specified email address. Fig. 4 shows the voltage captured during 7 s of inhalation and exhalation. It is observed from Fig. 4 that when the experiment was repeated three times under identical conditions, there is a very strong and reproducible correlation between the voltage generated and the breathing cycle (inhalation and exhalation).

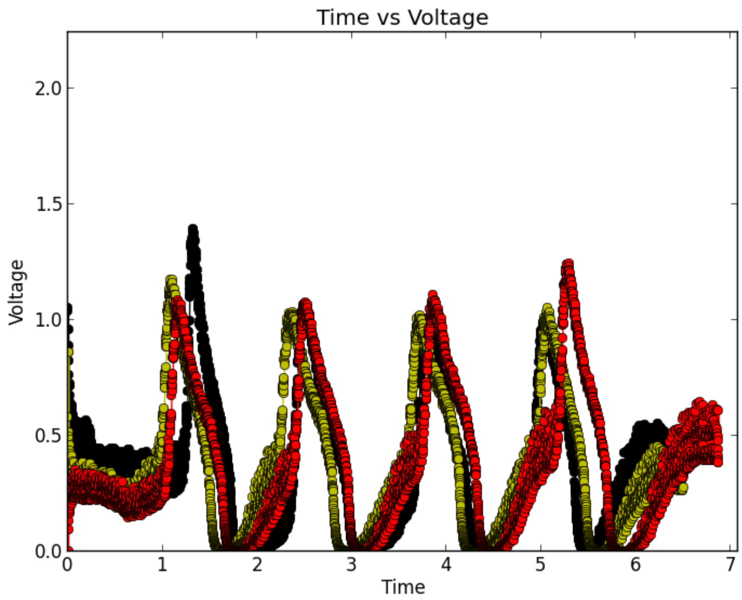


Fig. 4 Breathing patterns captured via Raspberry Pi

Table 1 Parameters from standard spirometer test

	FEV1, [l]	FVC, [l]	Ratio	PEF, [l/s]
Normal breathing	3.10	3.80	0.80	7.17
Taped breathing	2.39	3.10	0.77	5.00

Pulmonologists diagnose and track lung diseases by using a commercial spirometer to measure the Forced Expiratory Volume in one second (FEV1), Forced Vital Capacity (FVC), and the Peak Expiratory Flow (PEF). For patients with restrictive ventilatory abnormalities, the FEV1, FVC and the PEF are reduced (as compared to normal patients), whereas the ratio of of FEV1 to FVC does not change significantly. For this test, patients are asked to breathe in a certain sequence of inhalation and exhalation: deep breath in followed by a deep breath out and then a quick breath in. During this specific test, the FEV1, FVC and the PEF are measured and the pulmonologist uses this data to diagnose respiratory diseases. It was first necessary to verify that tying a crepe bandage around one of the researcher's chest adequately simulated a restrictive ventilatory abnormality. Table 1 shows the results of the spirometer test that were conducted by a pulmonologist using a commercial spirometer. Table 1 shows that FEV1, FVC, and PEF are reduced while the ratio of FEV1 to FVC is almost the same for the case where the researcher's chest was taped when compared to the case where the chest was not taped. This indicated that tying a crepe bandage around the chest while conducting the breathing test adequately simulated a restrictive ventilatory abnormality.

Now the same test was conducted using the low-cost piezoelectric device. The objective was to demonstrate that the voltage versus time data generated from the breathing pattern of a patient with restrictive ventilatory abnormalities would be substantially different from the voltage versus time data generated from the breathing pattern of a normal person. The results are shown in Fig. 5. The voltage versus time data was sent to a remote email address set up for this experiment. In Fig. 5, the magenta line indicates breathing for a normal patient and the blue line indicates breathing for a patient with restrictive ventilatory abnormality (simulated by tying a crepe bandage around the chest). It can be clearly seen that the breathing patterns for a normal patient and one with a restrictive ventilatory abnormality are completely different. Thus, the piezoelectric device is able to distinguish between normal breathing and simulated restrictive ventilatory abnormality. The dynamic data represented by Fig. 5 can be used to correlate the data obtained via a standard spirometer. This device can be used to quantify breathing patterns, and thus diagnose respiratory diseases in patients. Also, this device can be utilized to track improvements in a patient's respiratory health over time. For instance, a patient who has been diagnosed with a chronic lung disease in a physician's office could record the voltage versus time data at home using the device developed here and send it to the physician electronically every day via the Raspberry Pi. The physician can adjust the patient's medication, if necessary, based on this data without having to meet the patient again. This can lead to a considerable saving in money and time for the patient. Furthermore, daily feedback on respiratory patterns from a device that is available at home can motivate the patient to adhere to the diet, exercise and medication regiment recommended by the physician.

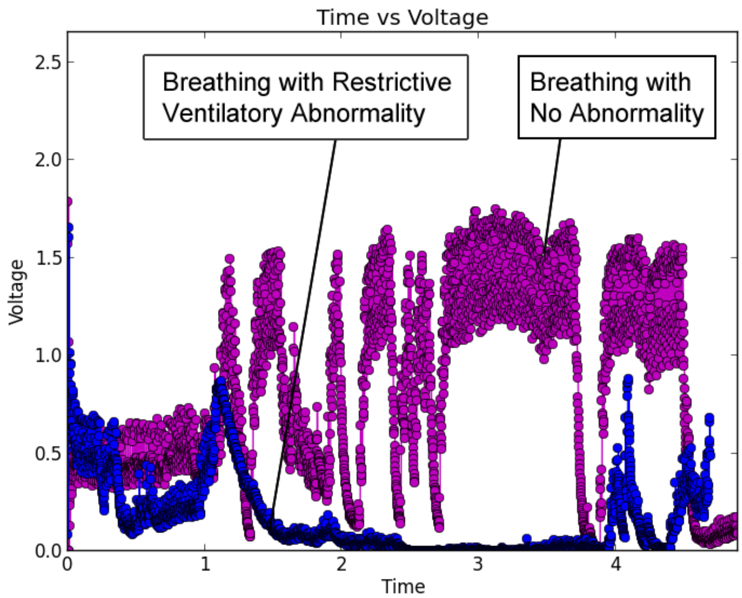


Fig. 5 Diagnosis of restrictive ventilatory abnormality

This project provides a proof-of-concept of the development of a PVDF-based device for diagnosis of respiratory diseases. A restrictive ventilatory abnormality was simulated by tying a crepe bandage around the chest of one of the researchers. The tighter the bandage, the more severe is the abnormality. By comparing the breathing patterns of the same person with and without the bandage provided the necessary proof that the device is able to distinguish between sick and well patients. Actual applicability of this device in a clinical setting requires further testing in collaboration with physician researchers. Currently, physicians use more expensive spirometers to diagnose such respiratory conditions. It is necessary to develop a correlation between the commercial spirometer readings and this device so that it is possible to determine from the voltage pattern if a patient has a respiratory disease. We envision that this device would be used by patients at home *after* they have been diagnosed with a respiratory disease by a physician. Daily voltage readings will provide a *comparative* indication of whether the patient's condition is improving without having to visit the physician's office.

Conclusions

In this paper, a proof-of-concept of a low-cost piezoelectric device for remote diagnosis of respiratory diseases was demonstrated. A commercial portable spirometer costs $2,000-$5,000 whereas the device described here can be constructed with relatively simple material for less than $100. It is envisioned that at this price point, patients can purchase this device for home use instead of making expensive trips to the physician's office. Currently, an algorithm is being developed to correlate the data generated by the piezoelectric device to standard spirometer results such as FEV1, FVC, and PEF. Furthermore, the device is being tested for its ability to diagnose obstructive respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD). A provisional patent (Application Number 61774012) for this device was filed on March 7, 2013 with the United States Patent and Trademark Office [6].

Acknowledgment

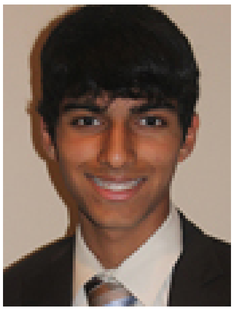
The authors would like to thank Dr. Brian Fouty from the Center for Lung Biology at the University of South Alabama for assistance with spirometer readings.

References

1. Cao Z., R. Zhu, R. Y. Que (2012). A Wireless Portable System with Microsensors for Monitoring Respiratory Diseases, IEEE Trans on Biomedical Engineering, 59, 11, 3110-3116.
2. Donelan J. M., Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, A. D. Kuo (2008). Biomechanical Energy Harvesting: Generating Electricity during Walking with Minimal User Effort, Science, 319, 807-810.
3. Luis J. A., L. M. Roa-Romero, J. A. Gomez-Galan, D. N. Hernandez, M. A. Estudillo-Valderrama, G. Barbarov-Rostan, C. Rubia-Marcos (2014). Design and Implementation of a Smart Sensor for Respiratory Rate Monitoring, Sensors, 14, 3019-3032.
4. Maksym G. N., L. Posada, H. Hanafialamdari (2013). United States Patent Application 14/398, 336.
5. Nield M., A. Arora, K. Dracups, G. W. S. Hoo, C. B. Cooper (2003). Comparison of Breathing Patterns during Exercise in Patients with Obstructive and Restrictive Ventilatory Abnormalities, Journal of Rehabilitation Research and Development, 40(5), 407-414, doi: 10.1682/JRRD.2003.09.0009.
6. Palanki R. (2013). Piezoelectric Apparatus and Method for Detecting and Evaluating Breathing Disorders, United States Patent and Trademark Office, Application 61774012, March 7.
7. Pate, S., H. Park, P. Bonato, L. Chan, M. Rodgers (2012). A Review of Wearable Sensors and Systems with Application in Rehabilitation, Journal of NeuroEngineering and Rehabilitation, 9(12), 1-17.
8. Priya S., C. T. Chen, D. Fye, J. Zahnd (2005). Flow Energy Harvesting Using Piezoelectric Cantilevers with Cylindrical Extension, The Japanese Journal of Applied Physics, 44, L104-L107.
9. Rattue P. (2012). Lung Diseases Leading Cause of Death, Most People Don't Know, Medical News Today, 7/1/2012, http://www.medicalnewstoday.com/articles/247293.php.

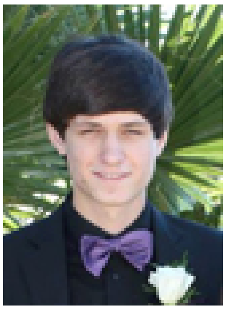
10. SolidWorks (2012). Dassault Systems, Waltham, MA.
11. St. Clair D., A. Bibo, V. R. Sennakesavababu, M. F. Daqaq, G. Li (2010). A Scalable Concept for Micropower Generation Using Flow-induced Self-excited Oscillations, Appl Phys Lett, 96, 144103, http://dx.doi.org/10.1063/1.3385780.
12. Sun C., J. Shi, D. J. Bayerl, X. Wang (2011). PVDF Micro Belts for Harvesting Energy from Respiration, Energy Environ Sci, 4, 4508-4512.
13. Yeddula S. R., G. V. Tcheslavski (2015). Design and Analysis of Low Cost Electro-dermal Response System Using Texas Instrument's MSP430 Value Line Launchpad, International Journal Bioautomation, 19(1), 79-94.
14. Zhang Q. M., V. Bharti, G. Kavarnos, M. Schwartz (2002). Poly (Vinylidene Fluoride) (PVDF) and its Copolymers, Encyclopedia of Smart Materials, Volumes 1-2, John Wiley & Sons, 807-825.

Rohan Palanki
E-mail: rohanpalanki@gmail.com



Rohan Palanki is currently a freshman in the Medical Scholars Program at Rice University and Baylor College of Medicine. His research interests are in biomedical engineering and he has been an Intel International Science and Engineering Fair (ISEF) Finalist for three years (2012, 2013, 2015). He conducted this research as part of a high school outreach program at the University of South Alabama.

Justin Poiroux
E-mail: justinpoiroux@gmail.com



Justin Poiroux is currently a freshman in the Computer Engineering Department at Auburn University. His research interests are in applications of computer technology to medical devices. He conducted this research as part of a high school outreach program at the University of South Alabama.

Srinivas Palanki, Ph.D.
E-mail: spalanki@lamar.edu

Srinivas Palanki received his B.Tech. degree in Chemical Engineering, from the Indian Institute of Technology, Delhi in 1986, the M.S. and Ph.D. degrees in Chemical Engineering from the University of Michigan, Ann Arbor in 1987 and 1992 respectively. His research interests are in the fields of process automation and alternative energy. He is currently the Dean of Engineering and Garrett Chair at Lamar University. He has published more than 120 journal and conference papers.