Development and Feasibility Studies of a Device for Early Prediction of Asthma Attack

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1 Introduction

Asthma is a disease of the bronchial tubes in the lungs (the "airways") [1]. The commonly known symptoms of asthma attack are coughing, wheezing, chest tightness, and shortness of breath [2]. There are three major features of asthma: (1) Airway obstruction, (2) Inflammation, (3) Airway Irritability. Asthma is a serious threat to mankind. According to WHO (World Health Organization), 9 people die every day across the globe because of asthma and an estimated 300 million people worldwide suffer from asthma. It is estimated that the number of people with asthma will grow by 100 million by the year 2025 [1]. Thus, the diagnosis and control of asthma are of utmost importance.

Paredi et al. (2002) have proposed a temperature sensor to measure rate of the exhaled breath temperature. They have shown that the faster rise of exhaled breath temperature is an indicative of inflammation in conducting airways [3].

Popov et al. (2010) have developed an exhaled temperature measuring device for assessment of inflammatory processes in the conducting airways [4].

Dieffenderfer et al. (2016) have proposed a multimodal sensing platform using an array of sensors for an asthma predictor to monitor environmental pollutants, heart rate, breath rate, wheezing sound, expiratory airflow, three-axis acceleration, and many more [5].

However, the above devices are bulky, operationally complex, and have incorporated multiple sensors, and therefore, the common people are reluctant to use them.

Siemens have manufactured a device that detects the early signs of airway inflammation by measuring the concentration of nitric oxide (NO) in the patient's exhaled breath [6]. Star et al. (2007) have developed a NO sensor using carbon nanotube that can detect an asthma attack before its onset [7]. However, the presence of NO in exhaled breath for NO detection is not at all full proof as its concentration may change due to other factors also. High expense is an additional disadvantageous factor.

Hence, the objective of the present work is the development and performance characterization of an asthma predictor that would be simple, relatively inexpensive, and easy to use to meet the needs of mankind. It will serve asthmatic patients all around the globe, enabling them to take early precautionary measure.

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The proposed single sensor-based device measures primarily the respiration temperature of the subject. Simple programs were embedded in an Arduino controller to derive clinically significant asthmatic indices to foresee possible asthma attack.

2 Theoretical Background

Olson (1958) reported the electrical analog of the ventilatory system [8]. Schmidt et al. (1998) have described the respiratory system using the electrical RC-model. The respiratory tract is analogous to electrical resistor (R) and alveolus represents the electrical capacitor (C) [9].

An oxygen deficiency in the blood stream of an asthmatic patient occurs due to the formation of mucus in the respiratory tract. The presence of the mucus reduces the cross-sectional area of the tract causing a restricted ventilatory flow leading to higher breath rates to meet the required oxygen demand. Moreover, during expiration air leaving the lungs is cooled as it passes through the respiratory tract through direct transfer of heat to the airway mucosa [10]. The excessive mucous layer in the respiratory tract of the asthmatic patients reduces this heat transfer efficiency resulting in higher exhaled breath temperature. The slope of time–temperature response curve is higher for asthmatic patients.

During exhalation, breath temperature rises and during inhalation, breath temperature falls. For mathematical reasons, it was determined that the temperature slope from the beginning of exhalation to 63% of the plateau temperature best characterized the rate of increase, i.e., was the maximum [11] (Fig. 1).

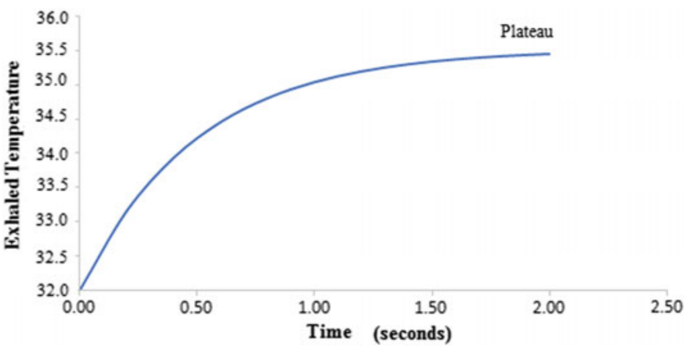

Fig. 1. Exhaled temperature versus time curve

The exhaled breath temperature changes exponentially with time. The shape of the curve depends upon the time constant (τ). In one time constant, the response reaches 63% of its final change. The rate of temperature increase ($\Delta T(t)/\Delta t$) calculated between the beginning of exhalation and 63% of the total temperature increase proved to be the more reproducible parameter to characterize the curves. The response is of the form

$$T(t) = To\left(1 - e^{-\frac{t}{\tau}}\right) \quad (1)$$

To = temperature at steady state

$$\frac{dT(t)}{dt} = \frac{1}{\tau} \times To \times e^{-t/\tau} \quad (2)$$

t = time after exhalation starts, τ (time constant) = R × C

As the value of t in Eq. (2) will increase, the slope will decrease hence we can say that with increase in time slope is decreasing.

$$\frac{dT(t)}{dt}(max) = To/\tau, \ at\, t = 0 \quad (3)$$

$$\frac{dT(t)}{dt}(min) = 0, \ at\, t = \infty \quad (4)$$

3 Materials

The components used in the proposed hardware system are: (a) LM35 (Temperature Sensor), (b) OP-AMP (IC-741), (c) Arduino (UNO), (d) 16 × 2 LCD, (e) breathing mask, (f) resistors, and capacitors (passive components).

4 Methodology

4.1 Overview of the Method

The proposed system uses LM35 as the temperature sensor that provides electrical signal (mV) replicating the respiration temperature. A conditioning circuit using an amplifier and a low-pass filter processes the signal and feeds to the Arduino Uno controller. The Arduino (using embedded algorithms) evaluates the desired parameters and displays them on the LCD. The block diagram and prototype of the system are shown in Fig. 2 and Fig. 3, respectively.

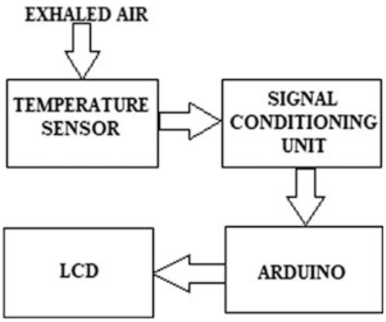

Fig. 2. Block diagram

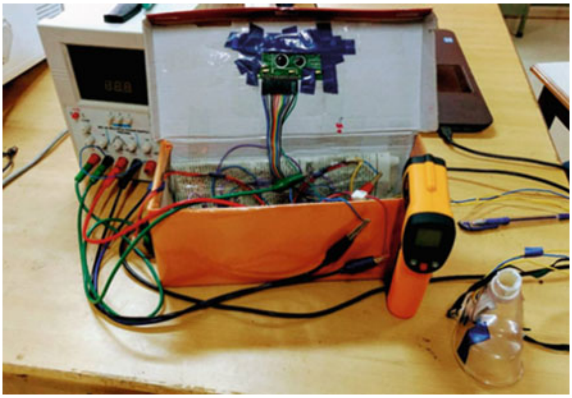

Fig. 3. Prototype of the system

4.2 Principle

The device works on the basic knowledge that the exhaled air has a higher temperature than that of the inhaled air. The temperature sensor follows the breath temperature. Arduino executes programs to evaluate (a) respiratory rate of the concerned subject. The rate of respiration of a normal adult person is 12 to 25 breaths per minute; the same for asthmatic patients is greater than 25 breaths per minute. (b) temperature and (c) rate of rise of the exhaled breath. The differences in parameters have been exploited in predicting asthma [3, 12].

4.3 Procedural Steps

The procedure for evaluating asthma-specific parameters is as follows:

1. The electrical output from LM35 is amplified with a gain of 11, $V_o = \{1 + (R_f/R_i)\} * V_i$, where V_o is output voltage, V_i is input voltage, R_f is feedback resistor, R_i is input resistor. R_f is 100 kΩ and R_i is 10 kΩ.

2. The amplified signal is fed to an active first-order low-pass RC filter of unity gain in order to remove the noise from the final output. The cutoff frequency of the filter is around 5 Hz (frequency = 1/(2ΠRC)). Value of R is 3.3 KΩ and value of C is 10 μF.
3. The final output obtained from the low-pass filter goes to the A4 pin of Arduino Uno. This input received is converted by an ADC in the range of 0–1023 which is further mapped on to a scale of 0–5 V using a conversion factor of 0.0048828 (= 5/1024).
4. The Arduino executes the program to evaluate (a) respiration rate, (b) temperature, and (c) slope (rate of rise of exhaled breath temperature) and the results are displayed on a 16 × 2 LCD screen.

4.4 Program Algorithm

The output of the low-pass filter is fed to the Arduino Uno which executes a preloaded code to determine the asthma-specific parameters. The pseudo-code of the algorithm processed by the microcontroller is given.

```
INITIALIZE slope, rate and count1 to zero.
WHILE time is less than 60 seconds do
    Read data from pin A4 of Arduino into variable a
    Convert a into temperature and store in variable c using regression equation
    Delay for 300 milliseconds
    Read data from A4 pin of Arduino into variable b
    Convert b into temperature and store in variable d using regression equation
    IF d is greater than c then
            count=1; sp=(d-c)/300; slope=maximum of (slope, sp)
    END IF
    IF c is greater than or equal to d then
            count1=count+1
    END IF
    IF count1=2 then
            rate=rate+1; count=0; count1=0
    END IF
END WHILE
PRINT rate, slope and temperature
```

5 Results and Discussion

5.1 Calibration of Temperature Sensor Along with Signal Conditioning Unit

The electrical signal from the overall temperature sensing system is calibrated against a set of predetermined temperatures using an infrared thermometer. The data pairs are plotted to get a calibration curve (Fig. 4) and a regression equation is established as Y = (0.1048 * X) + 0.4441 using Microsoft Excel, 2016, where Y is voltage in Volts and X is temperature in °C.

5.2 Performance Study of the Device

136 healthy male subjects and 53 male asthmatic subjects were studied who belonged to the age group of 20 to 25 years. The device measures breath rate, breath temperature, and rate of rise of exhaled breath temperature of all the subjects. The exhalation and inhalation breath pattern of the subjects were also observed using the Arduino serial plotter. The different temperature values in the serial plotter are actually digital values of the input voltage (converted into temperature) converted by the 10-bit ADC of the Arduino Uno. The breath pattern is a temperature v/s time graph. One complete breath cycle consists of exhalation and inhalation. Temperature rises during exhalation and temperature falls during inhalation. A sample breath pattern is shown in Fig. 5. The Table 1 shows the data obtained from only ten subjects due to space constraint.

The subjects under consideration in Table 1 labelled as ASTH were asthmatic. The breath rates obtained were all in the range of (29–33) breaths per minute. This satisfies the theoretical criteria that breath rate of asthmatic patients should be greater than 25 breaths per minute [12]. The subjects under consideration in Table 1 labelled as HLTHY have no medical history of respiratory diseases. The breath rates obtained are found to be in the range (16–23) breaths per minute. This also satisfies the theoretical criteria that the breath rate should lie between 12 and 25 breaths per minute [12]. However, the breath rate might change with different geographical locations and different age groups.

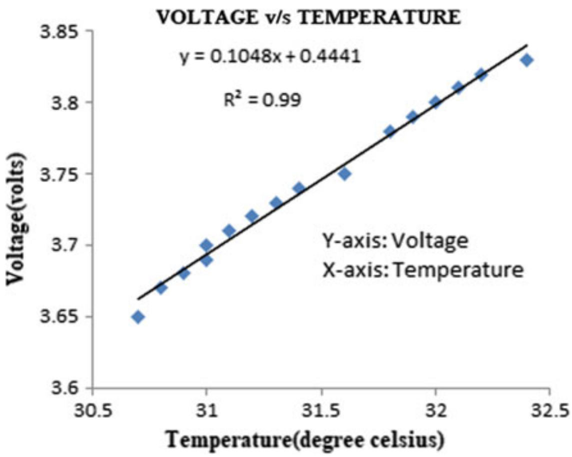

Fig. 4. Calibration curve

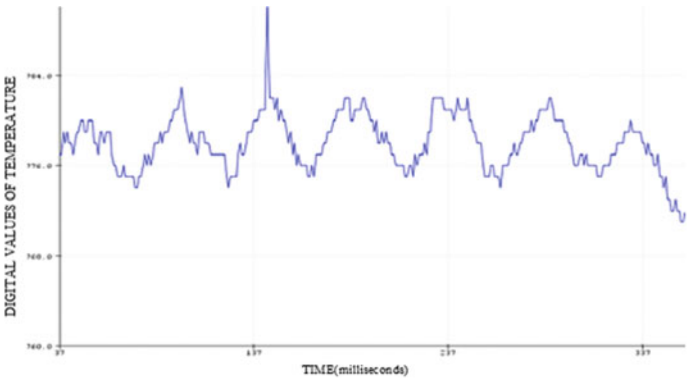

Fig. 5. Exhalation and inhalation breath pattern

Table 1. Values of the asthma-specific parameters of Asthmatic and healthy subjects

Age		Breath rate		Breath temperature (°C)		Rate of rise of exhaled temperature (°C/s)	
ASTH	HLTHY	ASTH	HLTHY	ASTH	HLTHY	ASTH	HLTHY
22	21	34	20	35.71	33.94	1.0310	0.4361
22	20	31	18	35.32	34.56	0.9136	0.4355
23	24	29	16	35.55	34.45	0.9197	0.5052
22	22	30	21	36.11	34.21	0.9256	0.5120
22	20	35	17	35.96	33.96	1.0520	0.4361

The results obtained by performance study of the device as shown in Table 1 indicate that the device is clinically fit for asthma prediction. The device is found to consume 410 mW of power which is close to the power consumed, 500 mW and 800 mW, by some available asthma predicting devices [4, 13].

6 Conclusion

A single sensor-based, inexpensive, and easy-to-adopt asthma attack predictor has been presented. The sensor, fitted inside a breathing mask, tracks the respiration temperature. The temperature pattern is processed by a set of simple algorithms, embedded in an Arduino-UNO controller, to calculate the breath rate, exhaled breath temperature, and its rate of rise of a subject to warn the patient. The device consumes only 410 mW of power. However, the use of Arduino Pro Mini will reduce the power consumption drastically to 0.115 mW. Its predictive performance is clinically satisfactory.

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