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Review Article

Internal Medicine Section

Review of Infrared Carbon-Dioxide Sensors and Capnogram Features for Developing Asthma-Monitoring Device

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ABSTRACT

Introduction: Asthma is one of the most common heterogeneous respiratory chronic diseases and fourteenth most imperative illness in the world in terms of duration and extent of disability. The existing method for early identification of asthma is based on health care provider's physical assessment and spirometer or peak flow meter which is manual and unreliable if patients are non-cooperative. Therefore, capnography, which measured the respired carbon dioxide concentration, has been proposed as a patient independent method for the assessment of asthma.

Aim: This study aims to critically review, investigate, and compare the specifications of different infrared CO_2 sensors and capnogram features to develop an asthma-monitoring device.

Materials and Methods: A rigorous and extensive search was carried out on Google scholar, the Web of Science, PubMed, and Scopus and several index terms (CO_2 sensor, infrared sensor, CO_2 measurement, asthma detection, capnograph, and capnogram) were employed to identify appropriate CO_2 sensors, technology, and capnogram features to develop asthma monitoring device.

Results: The review revealed that the COMET CO_2 sensor is the most suitable and reliable for developing a capnograph device owing to its weight (7 g), output range (0-99 mmHg), warm-up time (2-15 s), and response time (0.028 s). Furthermore, slope and time-frequency components measured from alveolar phase and complete breath cycle respectively are found the most significant features to screen asthma severity level. Further, the effects of pressure and temperature on CO_2 values were tested using Proteus software. Finding reveals that the CO2 values changed drastically from 17,835.19 parts per million (ppm) to 86,321.29 ppm as the pressure changed from 16.53 kPa to 81.53 kPa at a constant temperature (25°C). With a change in temperature from 25 to 27°C, the CO2 values were found to change from 16,812.19 ppm to 17,249.13 ppm at a constant pressure (16.53 kPa). Based on the review, a CO_2 measurement device using COMET equivalent CO_2 sensor was developed.

Conclusion: The developed device is capable of the assessment of cardiorespiratory condition instead of asthma severity level due to lack of significant capnogram features, which still remains to be integrated into the device.

Keywords: Arduino, Assessment, Capnography, Cardiorespiratory disorder, Parameter

INTRODUCTION

A capnogram shows the concentration of Carbon Dioxide (CO_2) in the respiratory gases of human lungs. An accurate capnogram measurement and features can provide valuable information about cardiorespiratory disorders, e.g., Chronic Obstructive Pulmonary Disease (COPD), asthma, pneumonia, and Congestive Heart Failure (CHF) [1-3]. Of these, asthma has the second highest incidence among respiratory disorders and is considered the fourteenth most common illness in the world [4]. Over the last few decades, asthma has become a serious threat to human life and has attracted significant research interest in its early diagnosis. A total of 334 million people are affected by asthma, of which 14% are children and 8.6% young adults [4]. Asthma is no longer considered a disease of well-developed countries because it equally affects the population of developing and under-developed countries, and its prevalence is increasing at an alarming rate [4].

In Malaysia, asthma affects around 10-13% of the total population, as per the national health and morbidity survey, with Malays, Indians, and Chinese constituting 67%, 12.9%, and 7.3%, respectively [5]. On the other hand, a survey conducted by the Asthma Council of Malaysia indicated that 66% of asthmatics have never undergone a lung-function test, owing to a shortage of diagnostic devices [5]. Additionally, existing diagnostic devices are patient dependent, require patient co-operation, and cannot be used with children under five-year-old. Hence, a significant need exists for an effort-independent method, e.g., capnography, to assess the respiratory function of these patients.

The major challenges for developing such an effort-independent device include identifying the best monitoring technology and optimal parameters with sufficient sensitivity and specificity to assess the respiratory function and its changes. We believe that capnography and the parameters derived from a capnogram can meet this challenge. Hence, a rigorous and extensive search was carried out from July 2017 to January 2018 by employing standard english language (UK style) with Google Scholar, the Web of Science, PubMed, and Scopus using different keywords (CO_2 sensor, infrared sensor, respiratory CO_2 monitoring device, asthma monitoring device, capnograph, capnogram) to identify appropriate CO_2 sensors, technology, and capnogram features. Based on our literature review, we propose a hand-held capnograph device that can be used as an asthma-monitoring device in the home environment and assist in following the progression and management of asthma.

To date, several studies have made great strides towards identifying and quantifying cardio-respiratory conditions, specifically, asthma, using a capnograph [1-3,6-21]. However, commercially available time-based capnographs are bulky, costly, inadequate for estimating the lung's Ventilation-Perfusion (V/Q) status, and incapable of estimating physiological dead-space components. In addition, the starts of the expiration and inspiration phases are not reliably distinguished in a capnogram because of the presence of dead space and rebreathing, respectively [22,23].

During the last decade, only a few studies [24-32] have been conducted to overcome the limitations of existing capnography and developing capnography using mainstream and sidestream techniques in line with cardiorespiratory analysis. Santoso and Dalu Setiaji developed a sidestream Infrared (IR) capnograph and successfully tested it during a laparoscopic surgery [24]. However, the chosen microcontroller had limited data memory, program memory, and a Universal Asynchronous Receiver-Transmitter (UART) serial-communication device that restricted the program and communication mode. In addition, the device used two displays, which increased the system complexity and the device computation cost. Moreover, a different CO_2 sensor would be necessary to avoid false readings because the current sensor is not internally calibrated with respect to changes in atmospheric pressure and temperature [24].

Bautista C et al., designed and tested a microcontroller-based wireless capnograph using a Sprint IR sensor and LED display, which was found to be poorly correlated with the cardiorespiratory condition [25]. Other researchers reported the development of capnography using the MG811, Sprint IR, and CDM4160-H00 modules [25-32]. However, sufficient verification is needed to confirm the precision of the device. Further, in terms of technology, we prefer to use a sidestream technique since it is simpler, more convenient, and has no sterilization problems compared with the mainstream airway adapter. It can be used when a patient is in an unusual position and is the predominant form of monitoring in hospital settings [1,22,24]. Hence, we propose a handheld capnography device based on sidestream technology that incorporates software to calculate the capnogram features, which can be used to assess cardiopulmonary conditions, specifically asthma, in home environments.

When developing a capnograph, choosing an appropriate CO_2 sensor plays a vital role and remains challenging in line with the application, monetary value, accuracy, sensitivity, and specificity [33]. Several CO_2 sensor technologies are available to measure CO_2 during respiration. Among them, a low-cost yet sensitive technique is Non-Dispersive Infrared (NDIR) spectroscopy [34]. Therefore, we reviewed a wide range of low-cost NDIR CO_2 sensor modules with their corresponding specifications [Table/Fig-1] [35-47].

This paper is structured as follows. Section 2 compares the specifications of the different infrared CO_2 sensors. Section 3 presents capnogram features that correlate with cardiopulmonary diseases. Section 4 elucidates the preliminary findings of the pressure and temperature study. The proposed capnograph for asthma assessment is described in Section 5. Conclusions are presented in Section 6.

COMPARATIVE STUDY OF CO_2 SENSORS ALONG WITH THEIR SPECIFICATIONS

A comparative study has been carried out on the specifications of infrared CO_2 sensors to identify the optimum CO_2 sensor. These specifications include the operating voltage, output range in percentage, operating temperature, sensitivity, weight, approximate cost, applications, and warm-up and response times. These specifications were selected to identify the best CO_2 sensor as per the application, and to develop an accurate and low-cost capnograph that can be used to assess cardiorespiratory diseases. The most commonly used infrared CO_2 sensors, along with their specifications, available in the market is listed in [Table/Fig-1].

The power requirements play a significant role when developing a hand-held capnograph, since greater power consumption may require the use of power-supply circuits that make the device bulky, expensive, non-portable, and complex. In addition, the maximum power supply reflects on the device's expected use, including the environment, available resources, and device-failure impact.

$$Percentage\,(\%) = \frac{Output\ of\ sensors\,(mmHg)}{Current\ barometric\ pressure} \times 100 \qquad (1)$$

$$CO_2\,(1\%) = 10000\ ppm$$

where the current barometric pressure is considered 760 mmHg.

Moreover, since the output of human respiratory CO2 measurements falls between 35,000 and 50,000 parts per million (ppm) (3.5%-5%) at sea level [48] and conversion takes place using Equation (1), only limited sensors can be used to detect human respiratory CO_2. In addition, the sensor's output measurement units should be mmHg and percentage, since they are preferred and more appropriate than ppm for this application. The sensor weight has a great impact on the bulkiness of the device; hence, it should be as light as possible to develop a more compact device.

The warm-up and response times of the sensor play a key role in developing an accurate and rapid device. Hence, their values should be as small as possible to minimize the changes to the capnogram waveform shape. Furthermore, the cost and intended application of each sensor listed in [Table/Fig-1] reveals that, although the CAPM, COMET, and Sprint IR sensors are more expensive than the other sensors, they are more capable of detecting human respiratory CO_2.

After critically analysing the specifications of the listed sensors, we suggest using COMET, CAPM, MH410, Sprint IR, or COZIR-WR for measuring human respiratory CO_2. The warm-up and response times of the MH410, COZIR-WR, and Sprint IR sensors are greater than the COMET and CAPM.

Thus, we consider the COMET and CAPM CO_2 sensors to be more appropriate, reliable, and precise for developing a capnograph. Further, we have discussed significant capnogram features that may possibly use for monitoring asthmatic conditions.

CAPNOGRAM FEATURES

Several features, e.g., such as end-tidal carbon-dioxide partial pressure ($PetCO_2$), Respiratory Rate (RR), time spent at $PetCO_2$, duration for which the CO_2 partial pressure remains at its maximum value, exhalation duration, Hjorth parameters (activity, mobility, and complexity), end exhalation slope (α angle), Slope Ratio (SR), and Area Ratio (AR), have been proposed as indicators for cardiopulmonary diseases by several researchers [1-3,6-21]. In addition, the $PetCO_2$ and RR features have been proposed as predictors of extubation post-laparoscopic surgery [24]. The capnogram features as observed with oesophageal intubation, Obstructive Diseases (OD), Restrictive Diseases (RD), and normal health are presented in [Table/Fig-2].

[Table/Fig-2] illustrates the capnogram and features associated with cardiopulmonary diseases. Howe TA et al., evaluated three parameters (slopes of phase II and III, α angle) as measures of an asthmatic condition and found that the slope of phase III and the α angle were highly correlated with an asthmatic condition than the slope of phase II [19]. Mieloszyk RJ et al., reported four features (exhalation duration, $PetCO_2$, time spent at $PetCO_2$, and exhalation slope) that can differentiate COPD normal and COPD/CHF and advocated that these features might be useful for screening other cardiorespiratory disorders [1]. Kean TT et al., presented 13 features associated with capnograms, e.g., A1 and A2 (area), S1 and S2 (slope), SR (slope ratio), AR (area ratio), α angle, HP1 and HP2 (activity), and HP1 and HP2 (mobility) [18]. Of these, AR, SR, and HP1 (activity) were more highly correlated than the other features for differentiating asthmatic and non-asthmatic conditions.

Guthrie BD et al., reported a strong correlation between $PetCO_2$ and an asthmatic condition. However, further investigation is required on large samples to generalize their findings [15]. In addition, Kazemi M et al., claimed that the capnogram frequency components can reflect the asthmatic condition [9]. They found that non-asthmatic capnograms have one component in their power-spectral density (PSD) estimation, in contrast to asthmatic capnograms, which have two components. They also reported that the frequency component for the asthmatic patient has a larger amplitude than normal, which increases with the asthma severity level. However, implementation of their finding in real time remains challenging.

CO_2 Sensor	Operating Voltage (Volt)	Range (in % CO_2)	Operating Temperature (°C)	Sensitivity/ Accuracy (%)	Weight/Size (Approx. in grams)	Approx. Cost (in $)	Warm-up time (s)	Response time (s)	Application	References
COMET-I, II	5	0-13.8	5 to 55	±0.42%	<7.0	400	2-15	0.028	CO_2 partial pressure, respiration rate, end-tidal CO_2, inspired CO_2, inspiration and expiration times	[27,35]
CAPM	5	0-21	0 to 40	±0.28%	>10	500	2-10	<20	CO_2 Measurement and respiration rate	[36]
MG 811	6	0.035-1	-20-50	Highly Sensitive,	60	43.55	300	<60	Air Quality Control Ferment Process Control Room Temperature CO_2 concentration Detection	[32,37]
MH410	3.5-5.5	0-100	-20-50	0.05%	20	80	90	<30	Widely Used for CO_2 Detection	[38]
MISIR	3.5-5.5	0-0.5	0 to 50	±0.005%; ±3% of reading	10	115	120	<20	CO_2 Detection	[39]
OGS-410	5-6	0-0.2 (Standard) 0-0.5	0 to 50	85 V/W	5	125	<1120	30	Indoor air quality monitoring, Obstructive Sleep Apnea monitoring, Industrial control, Climate Control for Automobiles, Combustion Control for Furnace Greenhouse	[40]
TGS4161	5.0	0.035-1	-10 to 50	approx. ±20% at 0.1% CO_2	50	50.01	43200	90	Indoor air quality control, CO_2 monitors	[41]
Sprint IR	3.3 V-5 V	0 to 100	0 to 50	±0.007%; +/- 5% of reading	8	230	<60	0.05	Measurement of CO_2 concentrations, Metabolic Assessment and Analytical Instrumentation.	[6, 25]
IR Prime 2	3 to 5	0-0.5	-30 to 60	±3% of range up to 50% of range	1[27, 28]8.0	266	<60	<30	To be used to read CO_2 gas	[42]
K30	5.5-14	0-1	0 to 50	±0.003% at ±3% of measured value	7	85	<60	20	Air handling units; Alarm sensor housings; Fresh air ventilators; Air conditioning in cars; Kitchen appliances, fans Automatic window openers; Combustion controls	[43]
K33	6-14	0-1	-40 to 60	±0.003%; ±3% of measured value	6	249	<180	60	Measure up to 10,000 ppm (1%) carbon dioxide, temperature, and relative humidity in remote locations.	[44]
COZIR-WR	3.2 to 3.4	0-5, 0-20, 0-65	0 to 50	±0.007%; ±5% of reading	20	109	<10	4-120	CO_2 detection	[45]
CO_2 Sensor 27929	6.5-12	0.035-1	0 to 70	High Sensitivity	4	43.55	>20	>10	Gas level over-limit alarm; Stand-alone/background sensing device; Environmental monitoring equipment	[46]
Digital CO_2 Sensor EE893	4.75-7.5	0-0.2/0.5/1	-40- to 60	0-0.2%: < ±(0.005% at ±2% of measuring value)	10	299	15	105	Data loggers; Handhelds; Wireless transmitters; Building management; Demand controlled ventilation	[47]

[Table/Fig-1]: Different types of non-dispersive infrared CO_2 sensors and their specifications.

Capnogram features	Cardio pulmonary diseases	Authors
Slope of Phase II and III, and α angle	Asthma	Howe, et al. (2011)
Exhalation Duration, $PetCO_2$, time spent at $PetCO_2$ and exhalation slope	COPD, CHF	Mieloszyk, et al. (2014)
A1 and A2 (area), Area ratio (AR), S1 and S2 (Slope), SR (slope ratio), AR (area ratio), α angle, HP1 and HP2 (activity), HP1 and HP2 (mobility)	Asthma	Kean et al., (2010)
$PetCO_2$	Asthma	Bridgette et al., (2007)
T_e, T_i, T_{tot}, S1, S2, SR, A_A, D_A	Extubation outcomes during mechanical ventilation	Rasera et al., (2015)
Power spectral density (PSD)	Asthma Severity	Kazemi et al., (2013)
PetCO2 and RR	Laparoscopic Surgery	Santoso and Dalu Setiaji (2014)

[Table/Fig-2]: Capnogram features associated with cardiopulmonary diseases.
HP: Hjorth's parameter; T_e: Expiratory time; T_i: Inspiratory time; T_{tot}: Respiratory cycle total time; S1: Initial slope; S2: Slope of phase III; SR: Slope ratio; A_A: Ascending angle; D_A: Descending angle; PetCO2: Maximum CO2 values; COPD: Chronic obstructive pulmonary disease; Congestive heart failure (CHF).

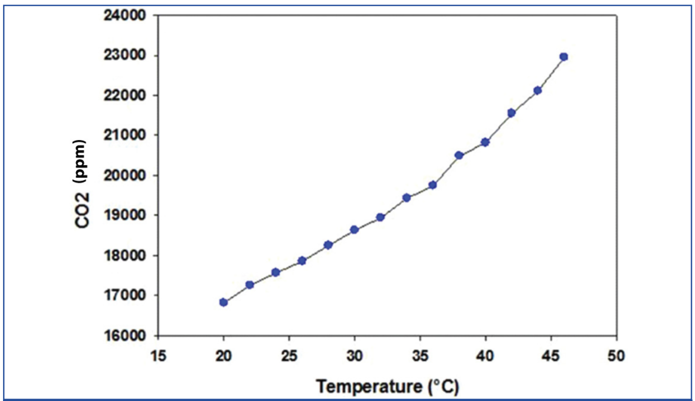
The capnogram features also have a strong correlation with other physiological conditions (extubation outcomes and laparoscopic surgery) as presented by Rasera CC et al., and Santoso D et al. [21,24]. Hence, we propose a user-operable and handheld capnography device incorporated with a capnogram feature for assessing the asthmatic condition, which can be used in a home environment. Hence, extracting features from the capnogram while developing a capnography device is significant, as this can provide valuable information about the cardiorespiratory status.

EFFECT OF PRESSURE AND TEMPERATURE ON A CO_2 SENSOR

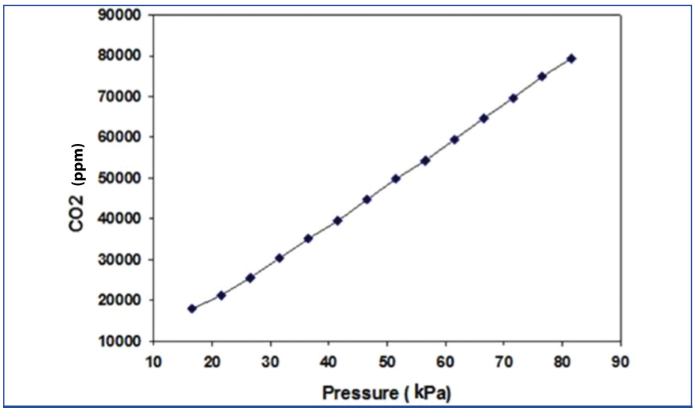
A simulation study was performed to understand the effect of pressure and temperature changes on the CO_2 output using Proteus software. Equation 1 was used to analyse the effect of the pressure and temperature on the CO_2, as presented in Equation (2) [49].

$$\rho(t,p) = \rho\left(\left(25^\circ C, 1013\,hPa\right) * \frac{p}{1013} * \frac{298}{273+t}\right) \tag{2}$$

To calibrate the pressure and temperature effects, we first changed the temperature while keeping the pressure constant (16.53 kPa). It was observed that the CO2 output changed corresponding to the change in temperature from 20 to 46°C, as illustrated in [Table/Fig-3]. In contrast to the temperature, when we varied the pressure from 16.53 kPa to 81.53 kPa while keeping the temperature constant (25°C), the CO2 output changed drastically from 17,853.19 ppm to 86,321.29 ppm, as illustrated in [Table/Fig-4]. The results confirmed that both pressure and temperature have a significant effect on the CO_2 output. Hence, they should be considered when developing a respiratory CO_2 measurement device and should be set internally when designing a CO_2 sensor by incorporating barometric pressure and temperature sensors. These sensors assist in compensating the CO_2 reading, based on the current temperature and barometric pressure, to avoid false readings or alterations in the capnogram shape after a certain time interval. Furthermore, capnogram features should be incorporated into the capnograph device to correlate with the asthmatic condition, as discussed in the next section.



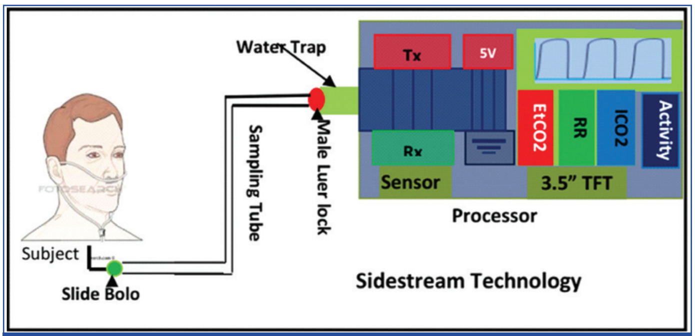
[Table/Fig-3]: Temperature vs. CO_2 output.



[Table/Fig-4]: Pressure vs. CO_2 output.

PROPOSED CAPNOGRAPH FOR ASTHMA ASSESSMENT

Upon critical review, we propose a user-friendly, inexpensive, and handheld capnography device based on sidestream technology for assessment of cardiorespiratory conditions, as presented in [Table/Fig-5] [50]. A minimal set of parameters to assess cardiopulmonary was reported by the proposed device, including end-tidal carbon dioxide ($PetCO_2$), Respiratory Rate (RR), inspired carbon dioxide (ICO_2), and Hjorth's parameter (activity) as these features have the potential to differentiate pulmonary conditions, reported by Kean TT et al., Brown LH et al., Lamba S et al., Guthrie BD et al., and Kesten S et al., [2,7,8,15,51]. Each part of this has been explained in a subsequent section.



[Table/Fig-5]: Block diagram of proposed asthmatic device.

CO_2 Acquisition Unit

The CO_2 acquisition unit comprises five major components: a nasal cannula, water trap, pump, motor, and CO_2 sensor. The nasal cannula (7 feet long) was placed between the water trap and the subject's nose to transport the CO_2 samples. The water trap was used to trap the moisture and the subject's secretions while maintaining the shape of the CO_2 waveform. In addition, hydrophobic (0.2 μ hydrophobic porous) and particulate (200 microns) filters were integrated with the water trap to eliminate the remaining water vapour from the gas sample while maintaining a laminar flow, which minimizes the distortion of the CO_2 waveform.

Thereafter, CO_2 samples were drawn from the cannula to the CO_2 sensor at the speed of 50 mL/min using a pump and Direct-Current (DC) motor, so the proposed device can be used at a higher respiratory rate (150 bpm). Furthermore, an NDIR CO_2 sensor was used to continuously measure the amount of CO_2 during expiration and inspiration [52]. The sensor has three-pin UART communication at the Transistor-Transistor Logic (TTL) level for transmitting and receiving the CO_2 data from the sensor to the processor and vice-versa.

Significance of CO_2 sensor: The COMET CO_2 sensor equivalent sensor was used for acquiring the CO_2 signal from the subject through a medical face mask or nasal cannula, as per the recommendation of Acker J et al., [27]. The sensor is highly selective and sensitive to CO_2 gas [53,54]. This sensor is selected for its unique specifications (weight, response time, warm-up time, output range, sampling rate (100 Hz), and operating voltage range). Furthermore, signal pre-processing was performed to limit the bandwidth of the CO_2 signal.

Pre-processing: The CO_2 sensor output was amplified using an amplifier (AD 8553) and then passed through a low-pass filter at f_L=10 Hz with two poles in agreement with earlier study [55], and a high-pass filter at f_H=0.1 Hz with two poles to limit the bandwidth and increase the sharpness of the CO_2 signal.

Processor

The Arduino Mega 2560, an open-source microcontroller board, was used to process the CO_2 samples for computation and transmission purposes [56-59]. It receives expired CO_2 data from the CO_2 sensor and transmits those values via the computer's serial port, which is not possible with the Arduino Uno [60], for a higher baud rate (19200, 115200). The Arduino Integrated Development Environment (IDE) was used to develop the program for the acquisition, filtering, feature extraction, and display of the CO_2 signal [61,62]. The technical detail and implemented algorithm can be found elsewhere [50]. Furthermore, a post-processing was performed which includes Finite Impulse Response (FIR) band-pass filter of two poles with bandwidth (0.1-10 Hz) to limit the bandwidth and the moving average filter (span, 8) for capnogram signal smoothing were employed [50].

Display Unit

A high resolution 3.5" display {Adafruit Thin-Film-Transistor (TFT)} was used to display the capnogram and other features. It can be driven by a minimal power supply (3 V). Moreover, it has a built-in controller with RAM buffering, which reduces the processor's computation time [63]. The data is transferred to the display unit via a Serial Peripheral Interface (SPI). The SPI mode requires only five pins (SPI data in, data out, clock, select, and DC). The implementation is simple, fairly flexible, and easy to port to various microcontrollers. It also allows the use of a micro Secure Digital (SD) card on the same SPI bus, which is not supported by other organic LED displays. Hence, this display module (TFT-3.5") was used to develop a small, handheld and user-operable capnography device.

Signal Post-Processing

The acquired CO_2 signal will be transferred to the Labview® system-design software via serial communication in order to extract more precise and significant feature to classify the asthma severity level [64,65]. Here, we will extract the time-frequency component of each breath using a wavelet transform because it provides time-localized spectral information for the signal as a distribution function in terms of time and frequency. These distributions are useful for displaying the time-frequency content of the capnogram during severe asthma conditions. Here, a Haar wavelet transform will be applied to extract the detail and approximate coefficients for the slope of phase III for each breath signal; the transform can reduce the detail coefficients of the first decomposition level by 40% [66]. This helps to improve the feature-selection performance and the classification steps of the decision-support system. Finally, a support vector machine classifier model will be applied to classify the asthma severity level based on the features.

CONCLUSION AND REMARKS

This study investigated and compared previous research work on non-dispersive infrared CO_2 sensors. A wide range of sensors were identified, and their corresponding specifications were extensively reviewed. These specifications included operating voltage, operating temperature, weight, approximate cost, response time, warm-up time, output range, and applications. Through this study, it was found that both the COMET and CAPM CO_2 sensors could be more appropriate and reliable for developing a home-based asthma-monitoring device, because of their output range which falls between 0-99 mmHg and 0-150 mmHg, respectively weight, and warm-up and response times. Additionally, they measured the respiration rate, end-tidal CO_2, inspired CO_2, and inspiration and expiration times. Therefore, by using the COMET equivalent CO_2 sensors, a small, hand-held, precise, and quantitative capnography device has been developed. On the other hand, adding an amalgamation of capnogram features, e.g. the slope of phase II, α angle, slope ratio, area ratio, and frequency components, while developing the device will provide a breakthrough in understanding respiratory distress, specifically asthma. Moreover, Kazemi M et al., You B et al., Yaron M et al., Howe TA et al., Kean TT et al., conducted correlation studies on 30, 20, 128, 30, 16, and 73 asthmatic patients, respectively, in offline mode, and concluded that measuring the slope, α angle, slope ratio, and frequency components from the expiration phase of the capnogram signal could provide significant information about the asthmatic condition [9-11,16,18]. Hence, the viability of the claimed features while developing a capnograph device should be verified in future work.

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