Design and Implementation of Capnograph for Laparoscopic Surgery

Daniel Santoso and Fransiscus Dalu Setiaji

***Abstract*—Capnography is a non-invasive method of monitoring the concentration of partial pressure of carbon dioxide. Nowadays, the application of capnography is a standard for general anesthesia. In this research, we design and implement sidestream capnograph based on microcontroller that can estimate the concentration of CO_2 in the respiratory gases and measure respiratory rate. The accuracy of the prototype $EtCO_2$ and RR has been verified relative to NT1D Series Handheld Vital Signs Monitor from Solaris Medical Technology Inc. in two chances of operation. The overall bias for $EtCO_2$ based on relative verification between prototype and NT1D Series is 5.58% and -1.17% respectively whereas the overall bias for RR is -0.62 bpm and -0.29 bpm respectively. The correction feature to handle interference due to presence of gases such as sevoflurane, N_2O and O_2 is also implemented in the firmware.**

***Index Terms*—End-tidal CO_2, microcontroller, respiration rate, sidestream capnograph.**

I. Introduction

Capnography is a non-invasive method of monitoring the concentration or partial pressure of carbon dioxide (CO_2) in the respiratory gases. The principles of capnography were introduced in 1943 by Luft who discovered that infrared (IR) radiation can be absorbed by CO_2 [1]. Capnography was first used in 1978 in Holland and subsequently its usefulness was approved for monitoring during anesthesia. Nowadays, the application of capnography is a standard for anesthesia for patients undergoing endotracheal intubation or placement of a laryngeal mask and while airway devices remain in place [2]. These recommendations were made primarily as a result of studies reporting anesthetic deaths and neurological injuries associated with unrecognized misplacement of endotracheal tubes, including oesophageal intubation, extubation, and disconnection from mechanical ventilation. Such incidents have caused death or brain damage as a result of hypoxia [3]-[6]. Improvements in monitoring during anesthesia, including the adoption of capnography as a standard for anesthetic monitoring helps lessen the prevalence of those incidents mentioned previously [7], [8].

Laparoscopic surgery is a technique of minimally invasive surgery of the abdomen, and it has been employed in procedures ranging across multiple surgical disciplines. The advantages of laparoscopy in comparison to open abdominal surgery include reduced surgical trauma, less pain, fewer post-operative pulmonary complications, and shorter recovery periods. Longer surgical times and higher equipment costs are some of notable disadvantages of this technique [9]. Laparoscopic surgery is most routinely performed with general anesthesia with endotracheal intubation and is considered to be the safest anesthetic technique. With induction of anesthesia relaxation of abdominal wall muscles is established therefore facilitating laparoscopic ports placement and pneumoperitonium induction. In order to achieve pneumoperitonium, the abdomen is then insufflated with CO_2. However, this approach may cause hypercapnea from systemic absorption of CO_2 [10]. The degree of hypercapnea depends on CO_2 insufflation pressure, but in routine cases under general anesthesia and controlled mechanical ventilation, hypercapnea is easily managed by increasing alveolar ventilation by 10% to 25% [11]. In cases where the degree of hypercapnea becomes unmanageable with hyperventilation alone, the pneumoperitonium can be temporarily discharged to eliminate CO_2. In uncomplicated laparoscopy, the partial pressure of arterial CO_2 ($PaCO_2$) rises on induction of pneumoperitonium and plateaus from 15 to 30 minutes later, thus signifying equilibrium. $PaCO_2$ can be reliably monitored via analysis of end-tidal gasses (capnography). Therefore capnography becomes one of the standard patient monitors for laparoscopy along with electrocardiogram, non-invasive blood pressure monitor, pulse oximetry, and temperature monitor.

In conducting this research, the team collaborated with a surgeon in a local hospital who is specialist in laparoscopic surgery. For cases treated with laparoscopic technique, patient monitoring using capnograhy has become a standard but not other cases involving general anesthesia with endotracheal intubation. In order to improve the quality and safety of the treatment, the surgeon promoted the use of capnography in all cases where capnography is recommended. Currently, there is only one capnograph, mainly used for patient monitoring in laparoscopic surgeries but actually the hospital has four operation rooms. According to the surgeon, the operational capnograph is quite expensive therefore the hospital cannot afford to have three more units to equip the rest of the operation rooms with such monitoring. Inconvenience in user interface is also a drawback of the device. For example, the user has to go through several steps only to activate / deactivate gas compensation.

In this research, we design and implement a medical device based on microcontroller that can estimate the concentration of CO_2 in the respiratory gases. The results are

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then presented in graphical display for capnography and in numerical display for end-tidal CO_2. In addition, the respiratory rate also measured and displayed in numerical mode. The emphasis of our approach is to provide a low-cost system, easy to use interface, yet maintain the accuracy within the required standards.

II. Theoretical Review

A. Physics

Methods for CO_2 concentration estimation include infrared spectrography, Raman spectrography, mass spectrography, photoacoustic spectrography, and chemical colorimetric analysis.

The infrared spectrography method is most widely used and most cost-effective. Infrared rays are emitted by all warm objects and are absorbed by non-elementary gases, while certain gases absorb particular wavelengths producing absorption bands on the infrared electromagnetic spectrum. When infrared radiation projected through a gas mixture containing CO_2, the intensity is decreased by absorption. This allows identification of absorption band and the value is proportional to the amount of CO_2 in the mixture. Infrared rays have a wavelength greater than 1 mm and thus lie beyond the visible spectrum (0.4 – 0.8 mm). CO_2 indicates strong absorption in the far infrared at 4.3 mm, therefore this wavelength within this range is used [12].

B. Sidestream vs. Mainstream Capnography

There are two types of capnography, sidestream capnography and mainstream capnography. Both sidestream and mainstream devices illustrated in Fig. 1.

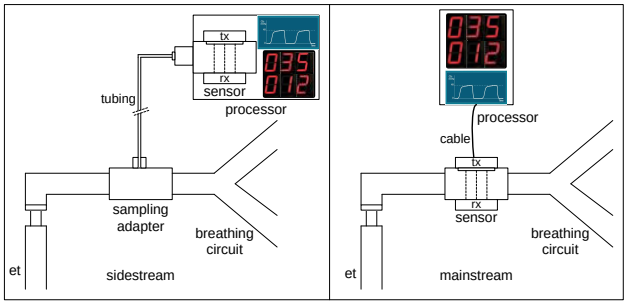


Fig. 1. Sidestream and mainstream capnography devices.

In sidestream capnography, CO_2 sensor is located in the main unit, away from the airway. A mini pump aspirates respiration gas samples from the patient's airway through a capillary tube into infrared chamber in main unit. The sampling tube is connected to a T-piece inserted at the endotracheal tube. The optimal gas flow is considered to be 50 – 200 ml/min which guarantees the capnographs are reliable in both children and adults. Contamination from the fresh gas flow source will occur if the sampling flow ever exceeds the expired gas flow. The sampling gas pump, flow regulator, sampling system, and water trap constitute multiple points for gas leakage or connection breakage. In addition, a certain delay in gas detection occurs as a result of separated sampling site and measurement site. The amount of this CO_2 flight time depends upon the size and length of the sampling tube and the rate of gas flow. The withdrawn respiration gas often contains anesthetic gases therefore the exhausted gas from the capnograph should be routed back to a gas scavenger or retrieved and reinjected through a second tube into breathing circuit to restore breathing circuit volume [13]. The sidestream capnographs allow monitoring of spontaneously breathing / non-intubated subjects since sampling of the expiratory gases can be obtained from the nasal cavity during the administration of oxygen using a simple modification of the standard nasal cannulae. Other advantages of the sidestream capnograph are no problems with sterilization, simplicity of connection, and convenience of use when patient is in unusual positions [12], [14].

In mainstream capnography, a cuvette containing the CO_2 sensor is inserted between the breathing circuit and endotracheal tube. The infrared rays pass through the respiratory gases to an infrared receiver within the cuvette and CO_2 analysis is also performed within the airway. Thus gas sampling and scavenging are not necessary. To prevent condensation of water vapor which can cause falsely high CO_2 readings, all mainstream sensors are heated above body temperature to about 40 ^oC. The heated sensing head must be distanced from patient's skin since it causes burns. It is relatively heavy thus must be supported to prevent endotracheal tube bending. Furthermore, the sensor's window must be kept clean of mucus and particles to prevent false readings. The advantages of the mainstream capnograph are faster response time, simpler mechanical system, and more certain sampling rate [15].

While both sidestream and mainstream devices continue to improve in performance, the primary criticism of mainstream technology have been mainly overcome with the introduction of solid state sources, improved optics, and miniaturization. In other hand, sidestream technology still suffers from its fundamental limitations.

C. Interference Effects

The measured absorption of CO_2 can be altered by cross interference and collision broadening due to the presence of gases such as nitrogen (N_2), nitrous oxide (N_2O), and oxygen (O_2). Cross-interference, as illustrated in Fig. 2 is the overlapping of absorption bands of other gases, may occur from nitrous oxide due to presence of strong absorption bands that slightly overlap both edges of the CO_2 band.

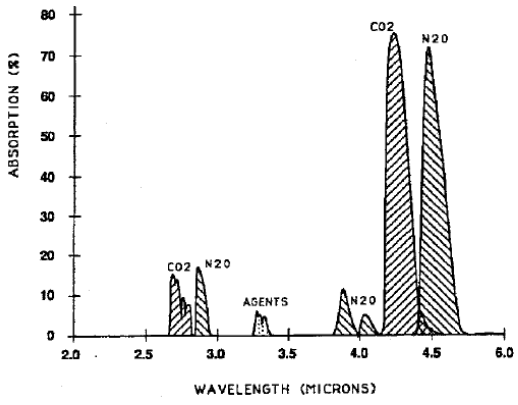


Fig. 2. The absorption spectrum of infrared for the CO_2, N_2O, and anesthetic agents [16].

The impact of this effect can vary significantly between

devices [17]. However, the use of narrow-band sources or narrow-band filters in front of the receiver with sufficiently small half power bandwidths can effectively eliminate this adversary effect.

On other side, collision broadening tends to be less device specific [17] and is a complex function of the total pressure and the presence of other gases. CO_2 displayed as a partial pressure constituent in a gas mixture and changes in atmospheric pressure and circuit pressure will alter this relationship. Pressure influences the width of infrared absorption band. As the pressure increases, more collisions occur and the bandwidth widens [18]. As a result, the absorption band is spread out and the use of narrow band sources or filters fails to correct this effect. This effect is typically compensated in system's firmware. Similarly, as pressure decreases, less intermolecular collisions occurs and the bandwidth narrows.

III. Design and Implementation

A. System Overview

Based on the close consultation with the user along with paper review, we propose a sidestream capnograph which is capable of measuring concentration of CO_2 in the respiratory gases. The device displays capnogram (expired CO_2 versus time graph), end-tidal CO_2 ($EtCO_2$) value, and respiratory rate (RR) value. The system mainly consists of three modules, the analyzer module, host microcontroller module, and display module as described in Fig. 3.

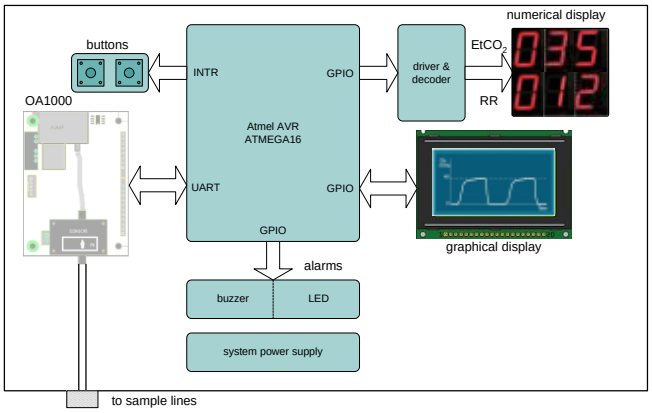


Fig. 3. Capnograph system design.

B. Analyzer Module

The analyzer module itself is an integrated system based on microcontroller that incorporates mini pump and infrared chamber as illustrated in Fig. 4.

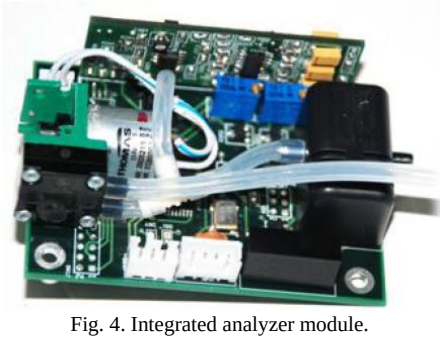


Fig. 4. Integrated analyzer module.

According to the technical specification sheet, the measurement range for $EtCO_2$ is 0 – 115 mmHg ± 5% whereas the measurement range for RR is 0 – 150 bpm ± 1 bpm. There is no requirement for periodical calibration.

The respiratory gases are sampled using mini pump with rate of 50 – 150 ml/min and then delivered to infrared chamber. Inside the chamber, the optical transmitter continuously emits non-dispersive infrared beam to the receiver at the other end. The presence of gases on the beam path causes the received intensity at the receiver to diminish. After being conditioned, transmitted intensity and received intensity are then calculated according to the Lambert-Beer's equation [19] by the microcontroller. An algorithm to calculate respiratory rate breath by breath is also incorporated in microcontroller's firmware.

The calculation results are then arranged into certain data packets and sent to host microcontroller module using UART standard in TTL level with speed of 19200 bps. Command – response scheme is used to establish communication between analyzer module and host microcontroller module, meaning that analyzer module only transmits data packet upon request from the host. For instance, to establish continuous data packet reception the command – response in Fig. 5 is used.

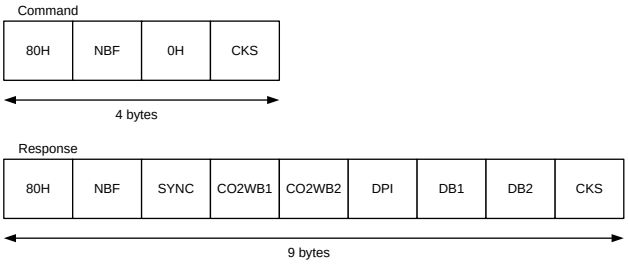


Fig. 5. Command – response for continuous data reception.

Command is four bytes data packet consisting of command type, number of bytes to follow, zero, and checksum respectively. Once this command issued by the host microcontroller module, the analyzer module replies with continuous data stream as a response at a rate of 100 Hz. CO2WB1 and CO2WB2 represent expired CO_2 versus time value while DB1 and DB2 represent either $EtCO_2$ value or RR value depending on DPI. In order to access various other functions of this module, respective data packet formats should be used as described in its manual.

C. Host Microcontroller Module

The host microcontroller module is responsible to handle incoming data stream, to decode bytes in data packet that contain measurement results, to display capnogram, $EtCO_2$ value, and RR value, and to respond to the user's input. In order to achieve those tasks, the module employs a system based on Atmel AVR ATmega8535 microcontroller running at 11.0592 MHz.

Serial port is configured to communicate with analyzer module in bi-directional asynchronous mode. The speed is adjusted at 19200 bps, as required by analyzer side. Once the "80H" command issued, the analyzer module will continuously send data packet to the host microcontroller module in certain period. For this reason, serial interrupt feature is activated. The checksum is then checked to ensure the validity of each data packet. After being verified, the data

packets rendered into the graphical representation of capnogram and numerical representation of $EtCO_2$ and RR.

There are two means for displaying measurement results, i.e. 128 x 64 pixel liquid crystal display (LCD) and 6 digits seven segment display (SSD). LCD is mainly used to display capnogram while SSD is used to display $EtCO_2$ and RR values. SSD is arranged into two identical rows for displaying $EtCO_2$ and RR respectively. Each row is made up of three digits 0.56" common anode SSD. The LCD has built in display driver and backlight. The y-axis is made up of 64 pixels while x-axis is made up of 128 pixels which is divided into two segments. Each segment is composed of 8 pages with 8 pixels each. The screen display can be accessed per pixel. An on bit in the memory represents a dark pixel on the screen. Several registers are provided to perform various control such as adjusting coordinate, data write / read, status read, etc. The LCD may be controlled through its data and control pins which are directly interfaced to the parallel ports of host microcontroller module. In other side, additional components are required for controlling SSD since it doesn't have built in drivers. BCD to 7-segment driver is employed to convert BCD codes to respective SSD digit. Since scanning method is used to alternately display data on each SSD, 1-of-8 decoder is used along with the transistor drivers. The scanning speed is quite fast so it gives illusion to human eyes that each digit is illuminated at the same time. Such scanning method significantly reduces microcontroller pins allocated for SSD interfacing yet it adds complexity to the firmware.

User's input is accommodated via two push buttons. One serves as start/stop button whereas the other serves as correction factor enable/disable button. Each button is connected to microcontroller's external interrupt pin to guarantee prompt response upon user's request. The external interrupt register is configured in such way so it responds to negative transition at external interrupt pins.

Alarms are both visual and aural. Aural alarm is implemented by using buzzer. A periodical beep will be emitted by buzzer whenever life-threatening events occurred such as when $EtCO_2$ is more than 55 mmHg. Zero reading on $EtCO_2$ and RR will also trigger the buzzer. This may indicate halted breathing, detached sampling pipe, or detached respiratory lines. Visual alarm is more like status indicator, a bi-color LED is used for this purpose. Green light indicates that readings are within normal ranges whereas red light vice versa.

The power supply for the system is built based on LM2576 switching regulator which is capable of driving 3A load. The output voltage is adjusted at 5V by choosing proper value for feedback resistors. The power supply is also equipped with crowbar circuit to prevent an over-voltage condition of power supply from damaging the circuits attached to its output.

Fig. 6 shows the steps performed by the firmware inside the microcontroller to retrieve the digital representation of capnogram, $EtCO_2$ value, and RR value from analyzer and display them on LCD and SSD respectively.

First, associated registers inside microcontroller needs to be initialized properly. Displays are set to completely blink several times to give confidence to the user that there is no dead pixel and segment on LCD and SSD that may lead to false reading. Short beep is also created using buzzer for same purpose. If there is no fault in sensor, system is ready to perform monitoring. Otherwise error message will be displayed on LCD and system goes idle. Once start/stop button pressed by the user, system continuously aspirating and analyzing respiration gas samples. The results are then displayed in real-time. The monitoring stops and displays freeze at the time user presses start/stop once more. During surgery, there is a chance that N_2O is administered to the patient. In that case the user should tell the system manually by pressing correction factor button. This compensation can be disabled by pressing the button once more.

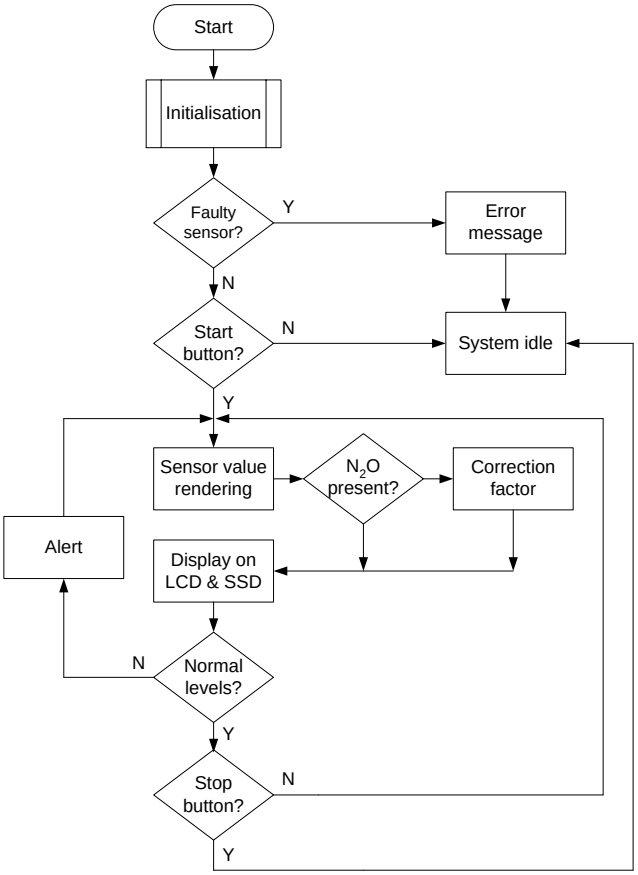


Fig. 6. The flowchart for the steps involved in programming the firmware.

IV. Result and Discussion

A prototype of capnograph has been successfully designed, implemented, and tested. Circuits are drawn with the aid of Protel DXP. The printout of circuits' layout is then printed into two printed circuit boards (PCBs). One PCB accommodates graphical and numerical display circuits whereas the other PCB accommodates microcontroller system and power supply. The size is 17 cm × 8 cm and 15 cm × 10 cm respectively. The analyzer module is fitted on top of the second PCB.

The PCBs along with the transformer, main fuse, and main switch are put together in a metal case with the size of 23 cm × 17 cm × 10 cm. PCB containing displays and buttons is vertically mounted on front cover of the box to provide convenient access to the user interface. Fig. 7 shows components placement inside the case whereas front view of the prototype is shown in Fig. 8.

Basically there are two types of test were conducted to evaluate the performance of the prototype. The first test which is called the technical test is intended to ensure there

are no significant issues regarding basic functions of the prototype, mainly associated with user interface. From this test, it was discovered that the displays are decently clear, buttons are fairly responsive, and alarms are pretty distinct. However, a short flicker was noted on numerical displays as user press one of the buttons.



Fig. 7. View inside the case.



Fig. 8. Front view of the prototype.

The accuracy of the prototype $EtCO_2$ and RR has been verified relative to NT1D Series Handheld Vital Signs Monitor from Solaris Medical Technology Inc. under real clinical conditions. Clinical testing with prototype version of the device was performed in operating room (OR). Clinical data was collected from spontaneously breathing and ventilator supported adult patients.

The prototype and NT1D Series, each with T-piece and CO_2 sensor attached to the airway adapter were connected in series to adult patients underwent operation. The readings from two devices were recorded per minute, compared, and analyzed using statistical method to obtain the measurement bias. Fig. 9 shows the prototype and NT1D Series when they were used together to perform respiratory monitoring.



Fig. 9. The prototype and NTID Series used side by side during operation.

Clinical testing was performed two times and bias of EtCO2 and RR for the prototype compared to the NT1D Series for the patients at each clinical site was calculated. The results are summarized in Table I.

TABLE I: SUMMARY OF CLINICAL TESTING

	Date	Duration (mins.)	Subject	Case	Bias	
					$ETCO_2$ (%)	RR (bpm)
1st Operation	June 7 2012	110	Female, 31 years old	Cholelithiasis and appendicitis	5,58	-0,62
2nd Operation	June 14 2012	40	Male, 40 years old	Cholelithiasis with liver abnormalitiy	-1,17	-0,29

Scatterplot for $EtCO_2$ and RR compared to the respective predicate at first operation and second operation are shown in Fig. 10, Fig. 11, Fig. 12, and Fig. 13 respectively. Line of identity is also incorporated to indicate correlation between measurement results from two devices.

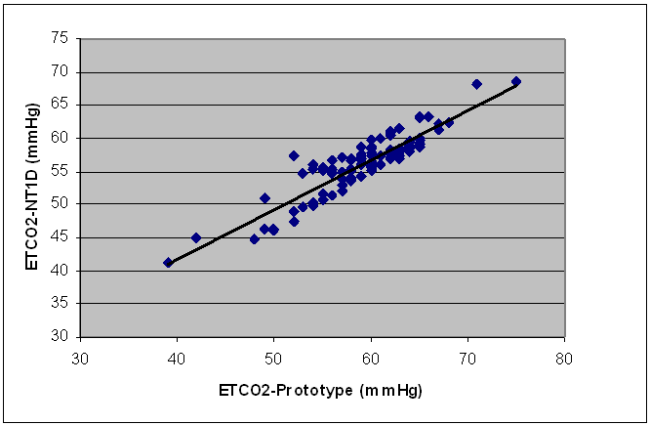


Fig. 10. $EtCO_2$ Scatterplot and line of identity for first operation between prototype and NTID Series.

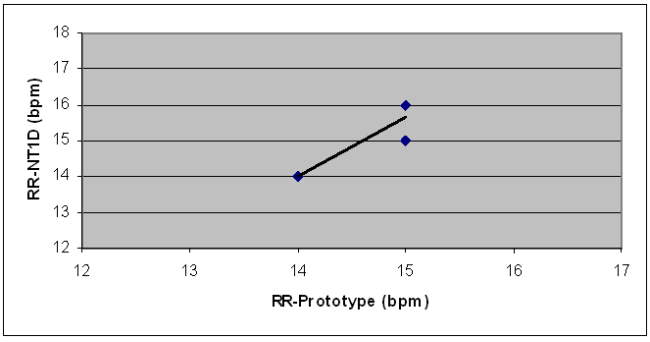


Fig. 11. RR Scatterplot and line of identity for first operation between prototype and NTID Series.

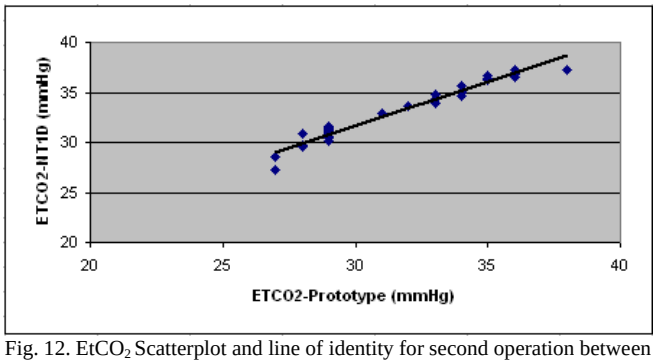


Fig. 12. $EtCO_2$ Scatterplot and line of identity for second operation between prototype and NTID Series.

On both operations, mechanical ventilator was used to create controlled breathing environment and to administer gases. The respiration rate was set to 15 bpm. Sevoflurane was used to induce and maintenance general anaesthesia. It

was administered in a mixture of N_2O and O_2. The flow-rate was continuously adjusted during operation as required.

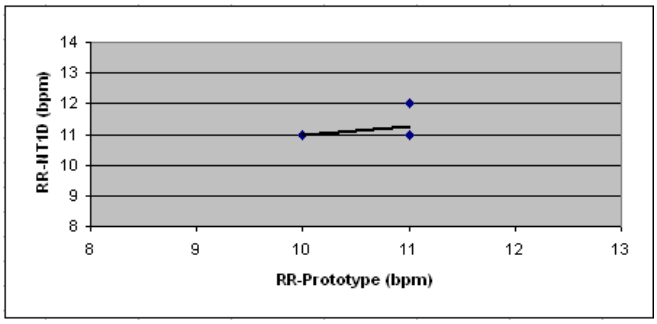


Fig. 13. RR Scatterplot and line of identity for second operation between prototype and NTID Series.

The overall bias for $EtCO_2$ based on relative verification between prototype and NT1D Series is 5.58% and -1.17% respectively whereas the overall bias for RR is -0.62 bpm and -0.29 bpm respectively. These results reveal that bias for the inter-device testing is within the tolerance that is ±5 % for $EtCO_2$ and ±1 bpm for RR. The scatterplots also indicate positive correlation between prototype readings and NT1D readings.

We also observed the effect of the usage of anesthetic gas and other gases that may affect measurement results, especially for $EtCO_2$. Among the gases, N_2O has the most significant interference effect. N_2O interference tends to cause deviation on $EtCO_2$ measurement result up to 20%. Therefore the correction feature is implemented in both devices.

V. Conclusion and Future Works

In this paper, we present a prototype of a sidestream capnograph based on microcontroller that is capable of measuring $EtCO_2$ and RR and also displaying capnogram. The prototype shows fairly good accuracy based on relative verification to NT1D Series under real clinical conditions. The correction feature implemented in the firmware is also capable in handling interference due to the presence of gases such as sevoflurane, N_2O and O_2.

In the next generation of prototype it is envisioned to replace analyzer module with newer version which has built in correction mechanism. By doing this way, the improvement in terms of accuracy can be expected.

Acknowledgment

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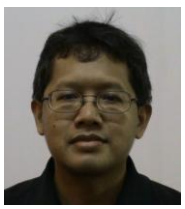
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