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1 Introduction

In a health care environment, mechanical ventilation is used to support patients during acute illness and surgery. Mechanical ventilation is the process by which the patient's respiratory function is artificially supported using a respirator.

During mechanical ventilation, it is necessary to ensure the adequacy of ventilation. The patient is thus monitored for several ventilatory parameters. The end-tidal CO_2 ($EtCO_2$) is one of the primary monitoring parameters. $EtCO_2$ is the partial pressure or maximal concentration of carbon dioxide (CO_2) at the end of an exhaled breath, which is expressed as a percentage of CO_2 or mmHg .

Capnography is the technique that graphs out expired CO_2 as a function of time and measures $EtCO_2$. The measuring device is called a capnometer and the waveform displayed by the capnograph is called capnogram. A sketch of a typical capnogram is shown in Figure 1.

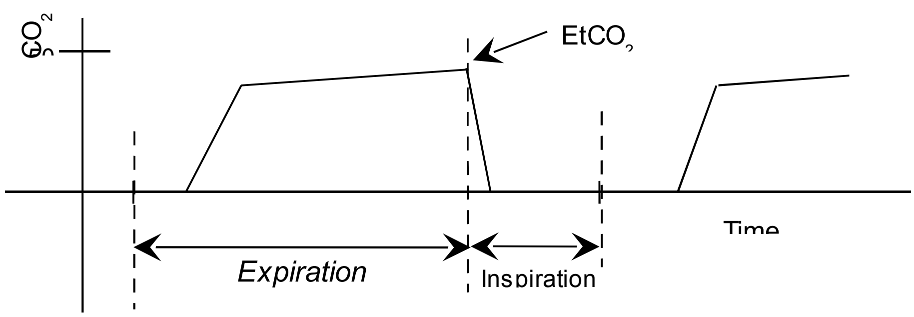

Figure 1: *Normal capnogram of a healthy human.*

1.1 The Importance of CO_2 ($EtCO_2$) Concentration Determination

The determination of CO_2 concentration is necessary to ensure the adequacy of ventilation in an artificially ventilated patient. During the respiratory cycle, the CO_2 concentration in the exhaled breath is increased as the exhalation comes to the end of a cycle. This is because the end point is the last air to leave the respiratory system and has been the deepest in the lung. The last air is called the alveolar concentration. This last peak value of expired CO_2 is accepted to be the equal to the CO_2 content of the blood and is referred to as the end–tidal CO_2 ($EtCO_2$). Consequently, it is an indicator of how efficiently CO_2 is cleared from the blood supply and is a vital monitoring parameter for the ventilated patient.

1.2 CO_2 Gas Sampling Technologies in $EtCO_2$ analysis

Many anaesthetic and ventilation units use sidestream technology for sampling the exhaled breath. In this technology, the gas sample is sampled from the ventilator circuit and the analysis occurs away from the ventilator circuit. A pump and length of tubing is used to acquire the sample from the exhaled breath . Another popular type of sampling is mainstream technology in which the CO_2 sensor is positioned directly at the patient's airway. In mainstream technology, the response time is faster and mixing of CO_2 with fresh gas is prevented to a greater extent. In practice, sidestream technology is most commonly used in the clinical setting .

Microstream technology is a comparatively new technology. It employs a unique, laser-based technology called molecular correlation spectroscopy (MCS™). The Microstream® emitter is electronically activated and self-modulating, and is operated at room temperature. The Microstream® emitter produces a focused beam of infrared energy characterized by the narrow region (0.15µm wide) of the spectrum precisely matching the absorption spectrum of CO_2. Conventional capnographs typically use a heated element called a blackbody emitter for the infrared radiation source .

1.3 The End Tidal CO_2 Analyser

The end tidal CO_2 analyser detects the CO_2 concentration in the patient's expired air using a number of methods. The technique most commonly used is based on infrared absorption. This uses absorbance spectroscopy in which the loss of infrared light is measured after having passed through the sample under study.

CO_2 absorbs infrared light at a wavelength of 4.26µm. Since the amount of light absorbed is proportional to the concentration of the absorbing molecules, the concentration of CO_2 in the exhaled breath is determined by passing infrared light through the sample and comparing the amount of energy absorbed with the amount absorbed by a sample that contains no CO_2. The result is expressed either in terms of mmHg or as a percentage of CO_2 (PCO_2/P_{atm}). Analysers using infrared technology are called infrared spectrographs and are more compact and less expensive than other technologies. These types of analysers are used in ventilation units and sometimes also as a separate unit as portable, handheld capnographs.

1.4 Ventilation rate

A typical individual at rest takes about 12-18 breaths per minute, this breathing rate can triple during hard work. Generally, 15 breaths/min (0.25Hz.) to 30 breaths/min (0.5Hz) is considered to be normal in an adult. However, an infant has a higher respiratory rate, smaller tidal volume, and a low volume of CO_2. Tidal volume is the volume of air inspired and expired with each normal breath.

The ventilation frequency is said to be 'high frequency' when it is greater than 2 Hz (120 breaths/min) and it is said to be 'low frequency' if it is below 0.25 Hz (15 breaths/ min).

1.5 Calibration of (CO_2) Gas Analysers

Gas analysers are calibrated by applying a known value to the input of a measuring system and observing/recording the system output. By applying a range of inputs and recording the outputs, a calibration curve can be plotted where the input $\boldsymbol{x}$ is plotted on the abscissa versus the output $\boldsymbol{y}$ on the ordinate axes.

The most straightforward type of calibration for gas analysers is a 'static' calibration technique. In this process, a known value is input to the system under calibration and the system output is recorded. The term 'static' refers to the calibration procedure in which the values of the variables involved remain constant during a measurement, i.e. they do not change in time. The static calibration method (also called two-point method) is the current technique for calibrating EtCO2 analysers. This method features 'zero' calibration to ambient air and 'span' calibration to a self-contained 5% (i.e. 38 mmHg) CO_2 calibration gas. Although the static method is widely accepted as a valid technique for such gas analysers, it is insufficient for describing the dynamic behavior of the analyzer.

Dynamic calibration determines the relationship between an input of known dynamic behavior and the (time-varying) measurement system output. When a time dependent variable is to be measured, a dynamic calibration is performed in addition to the static calibration. In a real time system such as $EtCO_2$ gas analysis, dynamic calibration should be performed.

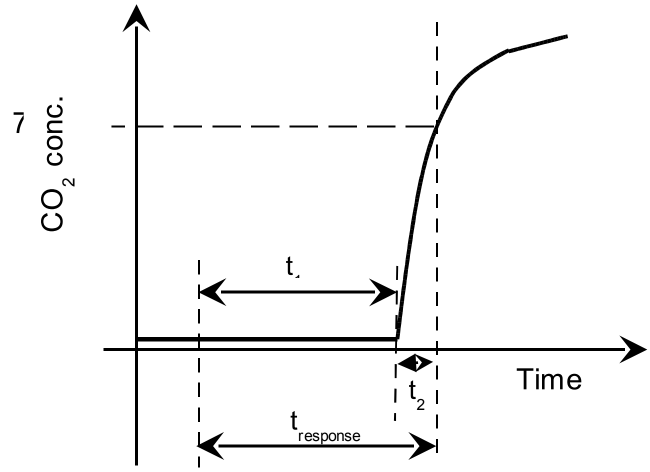

Figure 2 : Graph of a typical $EtCO_2$ waveform showing the transit time (t_1), sensor response time (t_2) and the total response time ($t_{response}$) of the sensor system.

In sidestream capnography, the CO_2 signal is delayed by the response time ($t_{response}$) as the gas is pumped along the sampling tube. Figure 2 shows a sketch of a typical waveform obtained from the $EtCO_2$ analyser. The response time, $t_{response}$, is the sum of t_1 and t_2 where t_1(transit time) is the time taken for the sample gas to move from the point of sampling to the point of measurement while t_2 (sensor response time) is time taken for the waveform to reach 70% of its final value($t_2 = t_{70}$). T_2 can also be taken as the time taken for the waveform to reach 90% of the final value($t_2 = t_{90}$) . T_{70} is generally used instead of t_{90} because the 70% point is on a steeper part of the response curve and therefore less sensitive to noise. For all practical purposes t_{90} is twice the value of t_{70} . The t_1 value generally accounts for about 89% or more of the $t_{response}$. Generally t_1 and t_2 are not specified in manufacturers' specifications. These factors should be measured as it has been observed that a long t_1 can prolong t_2 and can this result in the underestimation of $EtCO_2$. To design a system to measure t_1 and t_2 is also one of the aims of this project.

1.6 Frequency Response

Frequency response is usually presented as a plot of the output (generally amplitude) of the device versus frequency. It is used to characterize the range of frequencies in which a device is designed to operate.

In determining the frequency response of the $EtCO_2$ analyser, the maximum CO_2 concentration (i.e. the peak value on the waveform) is considered as the amplitude value while the oscillation frequency of the CO_2 signal is considered the frequency.

2 Measurement of the Frequency and Dynamic Response of an $EtCO_2$ Analyzer

Determination of the frequency response of the CO_2 analyser requires the plotting of amplitude versus frequency curve. Determining the dynamic response requires the measurement of t_1 (mechanical delay), t_2 (sensor response), and $t_{response}$ (total response time).

2.1 The Experimental Setup

The functional block diagram shown in Figure 3 describes the current prototype dynamic calibration system. In this block diagram all components other than the *Drager Narcomed 3* Anaesthetic unit comprise the simulator (the area within the dashed border line). The capnometer being investigated is the Drager Capnolog $EtCO_2$ analyser.

A specialist gas mixture of 5% CO_2 in air is used to emulate the CO_2 content of an expired breath. A separate air-line is used to flush the CO_2 from the system; this is supplied by an air compressor. The CO_2 gas is under a pressure of 725 PSI while the compressed air is at a maximum pressure of 175 PSI. The two stage regulator on the CO_2 gas cylinder and the pressure regulator on the air compressor reduce the pressure at the gas lines to a maximum of 125 PSI. As the capnograph samples at a pressure just over atmospheric pressure, 14.69 PSI, it is necessary to include a gas regulation system to reduce the pressure further along the gas lines. Two in-line pressure regulators are installed to reduce the line pressure to 29 PSI.

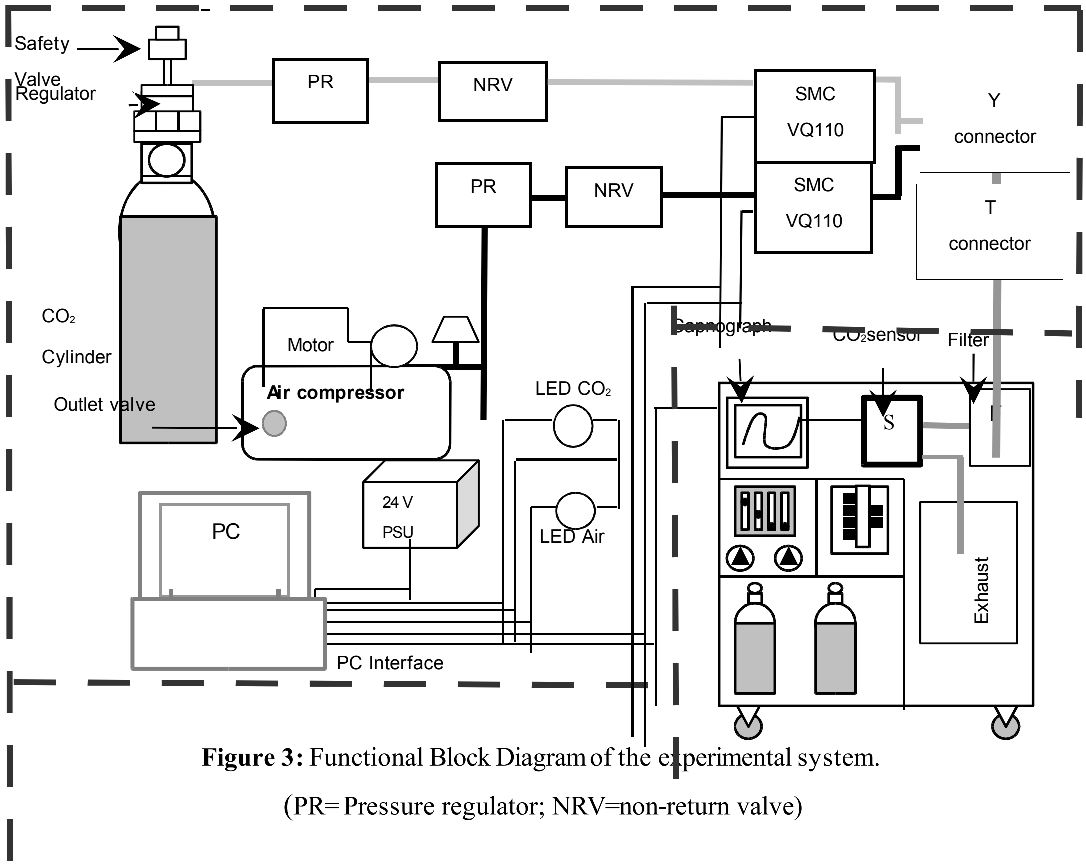

Figure 3: Functional Block Diagram of the experimental system.
(PR= Pressure regulator; NRV=non-return valve)

Non–return valves are installed to prevent back-flow and contamination. The gas channels are mixed inside the y-connector. The output gas is then passed through a T-piece that further limits the pressure of the gas mixture to the capnograph. Excess gas is vented here to the atmosphere.

A 24-volt power supply is used to power the valves. A simple LED circuit indicates when each valve is open. The valves are computer controlled using 'C' and a DAS-08 (Computer Boards Inc.) card, containing an 8254 counter timer, in order to obtain precise timing.

2.2 Data Acquisition and Analysis

For the determination of frequency response and the dynamic response of the system, a step signal is introduced to the CO_2 monitor. This is achieved by using the valve system to create a gas signal that turns on quickly (in this case 3ms, the response time of the valve). The CO_2 signal frequency is software controlled and hence straightforward to adjust.
Nine sets of data were taken, from 0.125 Hertz to 5 Hertz.

A single image of a capnogram is shown in Figure 4. It is clear from the figure that there is no amplitude or temporal information available in real time, so calibration of the data is necessary to obtain accurate amplitude information.

The primary challenge with this experiment is in data collection as the capnograph system has no means of obtaining data in the digital format necessary for analysis. Many capnograph units are completely sealed so direct data acquisition is not straightforward. As this measurement requires precise timing information, it was decided to record the capnograph trace in real-time using a digital video camera (Sony digital handycam, DCR-PC8E). The filmed traces are then downloaded to PC via a firewire interface. Each dataset, a single AVI file, is then separated into a set of bitmap images, each image corresponding to a single frame of the video sequence. With 25 frames per second, counting the number of frames allows precise timing information to be obtained.

The video sequences are subsequently analysed frame by frame in order to extract the digital waveform data.

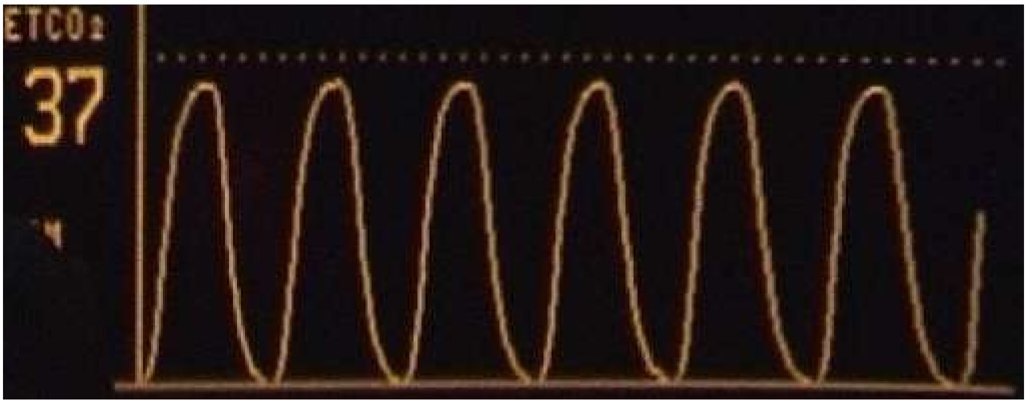

Figure 4 : *Single frame from a data-collection video sequence obtained using a Sony DCR PC-8 camera.*

2.3 Data Extraction using Image analysis

The bitmap files are processed and converted to array form using the image processing toolkit in MatLab. Three array sets are produced, the 'CO_2 magnitude' array, the 'framecount' (time) array and the 'ledstate' array that indicates the opening and closing of the valve in time. Figure 5 shows the result of this conversion process for a typical data experimental run.

2.4 Experimental Data Analysis

The arrays obtained for each data set are analyzed using MatLab code to obtain values for t_1, t_2 and $t_{response}$. For each frequency value, the maximum amplitude value of the CO_2 magnitude array is found.

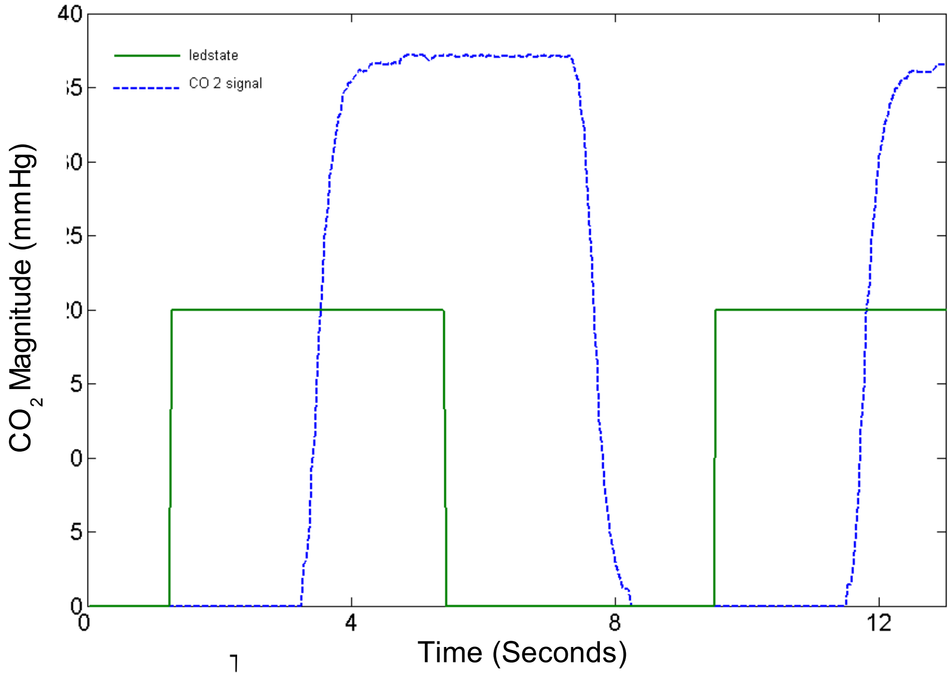

Figure 5 : *A typical waveform obtained after data acquisition using the digital video camera and Matlab.*

The measured values of t_1, t_2 and $t_{response}$ from three of the data sets are shown in table 1.

Frequency	t1	t2	$t_{response}$
0.125 Hz	2 sec	0.64 sec	2.64 sec
0.25 Hz	2 sec	0.6 sec	2.6 sec
0.5 Hz	2 sec	0.6 sec	2.6 sec

Table 1 *: Measured t_1, t_2 and $t_{response}$ for the Drager Capnolog $EtCO_2$ analyser.*

3 Results

The frequency response of the Drager Capnolog $EtCO_2$ analyser is shown in Figure 6. It is clear from this that the response of the analyser is severely degraded at respiration frequencies over 1 Hz.

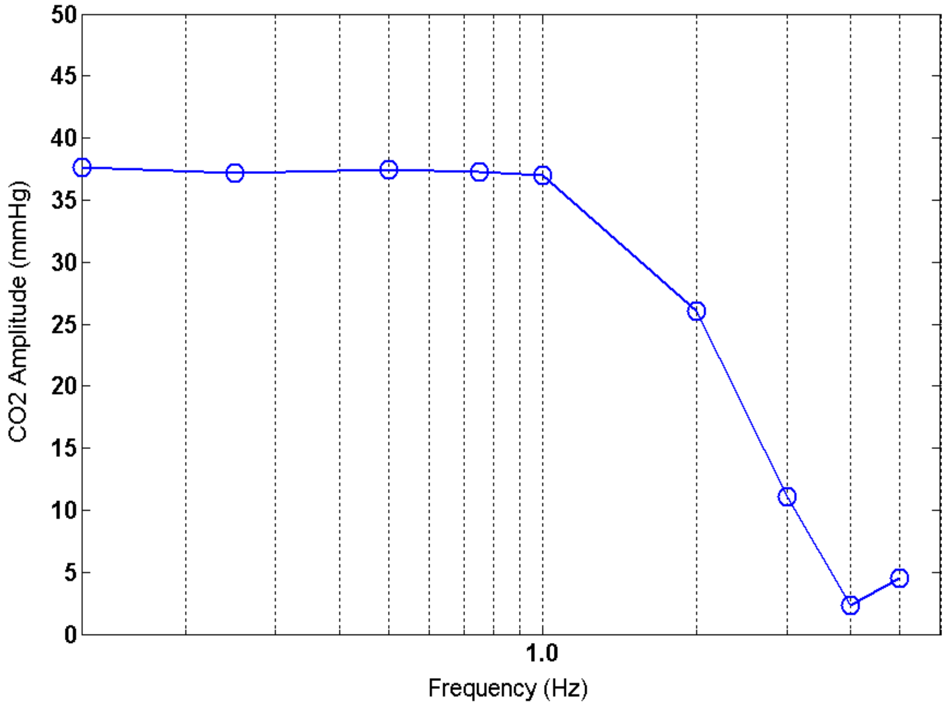

Figure 6 : *Amplitude versus Frequency curve for the Capnolog $EtCO_2$ analyser*

4 Conclusion

The project's aim is to create a method for simulation of human respiratory process sufficient to allow the accurate measurement of the dynamic response of a variety of capnography systems. The simulator mimics the 'patient' in a hospital environment. It allows the production of specific waveforms that may be used to calculate the dynamic response and the frequency response of the $EtCO_2$ analyser. Initial experiments determined the working frequency range of a single $EtCO_2$ analyser.

For the *Drager Capnolog*, the working frequency range is from 0.125 Hertz to 1 Hertz i.e. it can operate for respiratory rates from 7.5 breaths/min to 60 breaths/min. It may not give accurate performance for rates greater than 60 breaths /min.

The total dynamic response has been determined to be 2.6 seconds and is independent of the frequency of the input signal. It is intended in future experiments to determine the effects of different system settings on this key parameter.

Current work for this project involves the design, construction and characterisation of a portable simulation and data collection system so that different capnography systems (mainstream, microstream etc) can then be tested in the field.

5 References

[1] Bhavani Shankar: **Capnography.com** (*http://www.capnography.com/Homepage/HomepageM.htm*)

[2] **Technology overview :Capnography** (Novametrix Products)

Michael A. Frakes, RN, BSN, CFRN, CCRN, and EMT-P, **Measuring end- tidal carbon dioxide: clinical applications and usefulness,** Critical Care Nurse*, Vol 25, no. 5, October 2001.*

[3] **Service Manual and Operators Manual** – Drager Narcomed 3

[4] **Some notes on device calibration**

(http://mechanical-eng.mme.tcd.ie/~clyons/calibrations.pdf)

[5] Breen PH, Masumdar B, Skinner SC :**Capnometer transport delay : measurement and clinical implications.** Anesth Analg. 1994 Mar;78(3):584-6.

[6] **Custom Sensor Solutions, Inc.**

http://www.customsensorsolutions.com/sensterm.htm

[7] Markus R. Owen and Mark A. Lewis : **The mechanics of lung tissue under high –frequency ventilation** *article 2001 society for industrial and applied mathematics*

[8] David N. Proctor and Kenneth C. Beck:

Delay time adjustments to minimize errors in breath-by-breath measurement of VO2 during exercise. Journal of Applied Physiology Vol. 81, No. 6, pp. 2495-2499, December 1996

[9] LaValle TL, Perry AG. Capnography: **Assessing end-tidal CO_2 levels.** Dimensions of Critical Care Nursing. 1995; 14(2): 70–77.