Dynamic Response Measurement of Clinical Gas Analysers

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Abstract

Capnographs are devices that use CO_2 from a patients' expired breath to monitor the cardiopulmonary status during anaesthesia and mechanical ventilation. The waveforms are called capnograms. Capnographs at present are routinely calibrated via a static calibration method only. There is no specific method of dynamically testing capnographs. Since capnograms are time varying, there is a definite requirement to evaluate the dynamic response of these systems.

This paper presents a technique to determine the time and frequency response of capnographs using a custom built $EtCO_2$ simulator system. This system is computer controlled via a C program. A portable version of the simulator system has also been developed using a microprocessor. The waveforms obtained using the simulator system are recorded and image analysis is performed using Matlab to obtain the time and frequency responses of the capnographs. This paper explains the image analysis part of the technique in detail.

Measurements of several types of capnograph systems proved that older capnographs usually do not satisfy the manufacturer quoted specifications for time and frequency response. Monitoring capnographs on a routine basis is thus important and is recommended.

This new technique of time and frequency response measurement can be used as part of a quality control protocol for capnographs; for commissioning and routine monitoring as well as to verify manufacturer quoted specifications in new units.

1. Introduction

Monitoring the concentration of exhaled CO_2 gas enables monitoring of physiological condition of patients during anaesthesia and mechanical ventilation. Normally, the CO_2 concentration of expired breath changes from 0% to 5% at the end of expiration. Capnography is the technique that plots CO_2 concentration against time. Capnographs are devices that produce such traces (capnograms). These devices also calculate an index referred to as the End Tidal CO_2 or $EtCO_2$ which is the maximum concentration of CO_2 at the end of the exhaled breath. This value is taken as an indicator of alveolar CO_2 concentration at the end of gas exchange and by extension the arterial blood CO_2. Capnograms have a standard pattern in a healthy human being and any deviation from this pattern indicates the deterioration in patient condition [1]. To measure the CO_2 concentration accurately, the CO_2 analyser must respond rapidly[3].

This paper presents a new practical method to determine the dynamic behavior of capnographs using a purposely-designed $EtCO_2$ simulator system. This paper is primarily focused on the (image) data acquisition and data analysis parts of the newly developed technique.

1.1. Originality

The only method currently used to check the performance of the capnographs is a static calibration method [1]. There is no definitive method available that would facilitate rapid assessment of the dynamic integrity and efficacy of a capnograph system. Since CO_2 gas waveforms are time varying, there is a definite requirement to evaluate the dynamic response of these systems. It is intended to address this shortfall using this new technique to:

1) Be incorporated into the quality control (QC) procedure and /or be used in the construction of a QC protocol for the evaluation of capnograph systems during the routine monitoring and during commissioning of capnographs.
2) Be utilized as a training /diagnostic system in the clinical engineering environment.

Figure 3 shows a plot of a typical capnogram. This plot is the replica of waveform obtained from the $EtCO_2$ analyser of a sidestream capnograph (a type of capnograph where gas analysis occurs away from the sampling site). The total response time, $t_{response}$, is the total of t_1 (transit time or transport delay time) and t_2 (rise time or sensor response time). Transit time is the time taken for the sample gas to move from the point of sampling to the point of measurement while rise time is the time taken for the analyser output to respond to a sudden step change in carbon dioxide concentration – the time it takes for the analyser output to change from 10% of the final value to 70% of the final value.

Rise time can also be defined as the time taken to change the analyser output from 10 to 90 % of the final value ($t_2 = t_{90}$). The t_{70} value is generally used instead of t_{90} because the 70% point is on a steeper part of the response curve and therefore less susceptible to noise. For all practical purposes, t_{90} is twice the value of t_{70} [3]-[9].

The t_1 value generally accounts for about 89% or more of the $t_{response}$. Generally, t_1 and t_2 are not defined in manufacturers' specifications but these factors should be defined and specified. This is because if t_1 is long, it can prolong t_2 (by subjecting the bolus of gas to dispersal caused by convection and diffusion during transit down the catheter/tube); this can affect the waveform morphology and result in underestimation of $EtCO_2$ during high frequency ventilation. In addition, a long t_1 may introduce an unacceptable delay in the total response time of the analyser [4]. Some findings also suggest that the transit time is more important in attaining a true $EtCO_2$ level [8].

2. Methods

For dynamic and frequency response measurements, an $EtCO_2$ simulator system has been developed so that waveforms of desired frequency can be created. The waveform introduced is a step waveform.

2.1. Description of the $EtCO_2$ simulator system

The $EtCO_2$ simulator system [Figure 1] simulates the human respiration cycle. It is constructed using 5% CO_2 gas and room air as the gas sources that can be switched alternatively. Both supplies are pressure regulated and connected through non-return valves to

electric valves. The valves are fast acting valves with a response time of 3 msec. These are interfaced to a computer using a DAS-08 card and controlled using a C program. The on/off time of valve is user defined allowing a wide range of waveforms to be simulated. The output from the valves is delivered to a 'Y' connector and finally the output from the system is delivered to capnograph [10]. A portable version of the simulator was also developed using a microprocessor (PIC16C57) so that it can be used in clinical environments. This system also uses a small LED circuit to indicate the opening of each valve. The design criteria for the portable system are to ease the application of the system using a keypad configuration and to allow for static calibration as well [11].
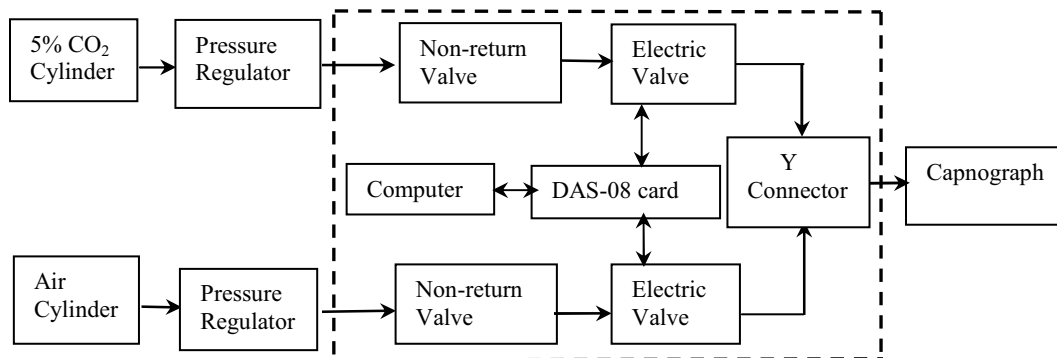
Figure 1. Block diagram of the EtCO$_2$ simulator system

2.2. Data acquisition and analysis

For data acquisition, the capnograms along with the LED states are captured by digital video recording (because most capnographs are standalone units and do not give the user easy access to the raw data). The digital video camera recorder used is a Sony DCR-PC8E with a framerate of 25 fps (frames per second). The image data thus recorded is converted to an uncompressed avi file format using a FireWire card (IEEE1394) and a software (VideoWave5). The '.avi' file is then converted into individual frames (.bmp files) using another software (AVI Quick). These frames are then processed using a program in Matlab so that an exact replica of the original capnogram is obtained in a digital format. An image-processing program described briefly below is designed for bright waveforms on black/dark backgrounds.

The matlab program takes two frames to process at one iteration, so as to obtain a digital value of CO$_2$ magnitude that corresponds to a pixel in the real capnogram.

The former frame is subtracted from the latter. The resultant frame is cropped such that the waveform of interest is captured and the data is finally converted to black and white pixel values. The elements of each column of this matrix are added and the resultant column matrix is stored as a vector 'BW'. This vector will have numerical values in the row; the elements of which had white pixel as their elements and zero (0) values in the row with no white pixel.

The upper leftmost point of cropping (Xmin, Ymin), is considered as the reference point O (0,0) and other points are measured with reference to that point. The lower rightmost point of cropping is (Xmax, Ymax) [Figure 2]. These values are determined from a bmp image and provided to the program before running the program. Using the 'linspace' command in matlab, 'Ymax-Ymin+1' number of equidistant points (in row vector form) are found between Ymin and Ymax, that when transposed and multiplied (array multiplication) with the vector 'BW' (which is also of the same order), gives a column vector (with zero and numerical value

elements). Adding it rowwise gives a value say 'A'. The BW matrix when added rowwise gives a value say 'B'. The value 'A' when is divided by 'B' will give the approx. location of the pixel (position of pixel value) that is desired. This single value is then stored as the position value for that iteration.
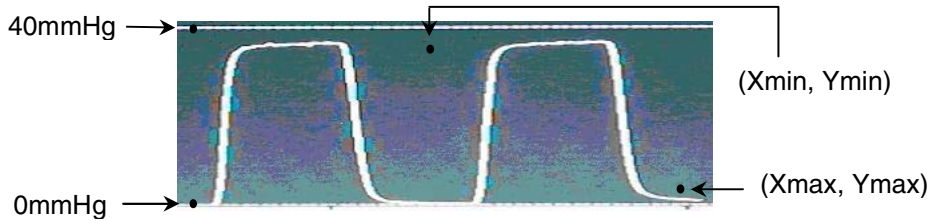
Figure 2. A bmp file of a capnogram trace from Datex Ohmeda, showing the 0mmHg and 40mmg lines, the cropping points, (Xmin, Ymin) and (Xmax, Ymax)

This pixel position (x in equation 1) is then used to calculate the respective CO_2 magnitude value (in mmHg) using the straight-line equation,

$$Y = m x + C; \text{ Where } m = (Y_2 - Y_1) / (X_2 - X_1)...\text{...............}\text{Equation 1}$$

Equation 1 here is used for a plane where the Y-axis has CO_2 magnitude values and the X-axis has the pixel position values. Two required points (ph, 40) and (pl, 0) are known, where, ph and pl are the pixel positions in cropped image of 40mmHg and 0mmHg lines. This process is repeated for all iterations. The separation between frames is taken as 2 so that there is a detectable change between the frames. Therefore, the first frame will be subtracted from the third one, the second from the fourth and so on.

The final result is then a series of points (referred here as the 'CO_2 magnitude vector') that recreates the capnogram plot, if plotted versus the frametime. The frametime value is found out as iteration number divided by frame rate (0.04) and stored as the 'frametime' vector. The LED states captured enables tracing out when the CO_2 valve is open. The 'ON' and 'OFF' state of LED implies the valve 'opening' and 'closing' respectively. The LED state for each iteration is recorded as 'ledstate' vector.

Finally, the program plots the calibrated CO_2 magnitude value (CO_2 magnitude vector) and the LED state (ledstate vector) in the vertical direction versus frame time (the frametime vector) in the horizontal direction that enables the calculation of transit time and time response. A typical capnogram plot is shown in Figure 2 and the capnogram plotted after image analysis is shown in Figure 3.
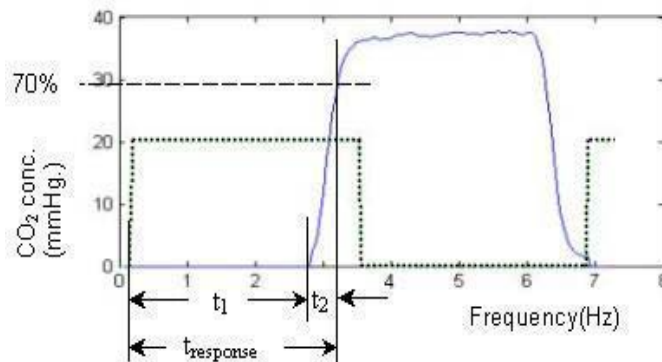
Figure 3. Digital plot labeled showing the transit time (t_1), rise time (t_2) and the total response time ($t_{response}$) of the capnograph.

Transit time (t_1) is calculated as the time difference between when the LED turns ON and the waveform appears. The rise time (t_2) is calculated as the time it takes for the waveform to change from 0% to 70% of the final value. The values t_1, t_2 and $t_{response}$ are shown in Figure 3.

For determining the frequency response, the maximum value of CO_2 ($EtCO_2$) is the amplitude value and the waveform frequency (simulated breaths per minute) is the frequency value [10][11].

3. Results

The experiments performed using the new technique determined the time and frequency responses of several different capnograph systems [10]-[12].

The frequency response curves for the Drager Capnolog (decommissioned and approximately 15 years old unit) and the Datex Ohmeda, M-CAiO (new) units are presented in Figure 4. This plot shows that the frequency response of the Drager Capnolog is 7.5-60BPM (manufacturer specification: 2-99BPM) [13][14] while that for the Datex Ohmeda is 7.5- 80 BPM (manufacturer specification: 4-80BPM)[16]. The dynamic response obtained also is out of manufacturer specification for the Drager Capnolog while is in agreement for the Datex Ohmeda. The complete set of experiments performed and the results obtained is presented in [12].
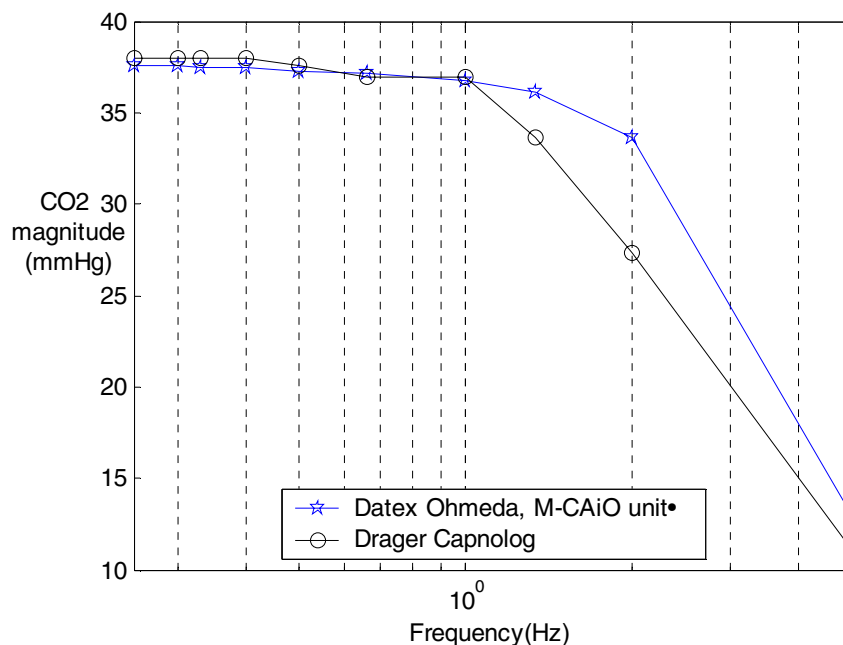
Figure 4. Frequency Response curves for Datex Ohmeda and Drager capnolog

4. Discussion

The image processing technique described in this paper allows the time and frequency response measurement for any capnograph type, irrespective of whether the capnograph has a digital outlet for time and frequency response measurements. This technique also avoids the problem of having to interface with several units for the measurement. This method however is time consuming and requires a large amount of memory space to store and process data.

Further, the frame rate of the camera limits the frequency range. The maximum frequency that can be measured in this experiment is 12.5Hz (because of the Nyquist criteria) as the camera captures at 25fps. The minimum frequency depends upon the capnograph screen. Generally, the width of the screen is around 4000msec; this corresponds to a minimum measurable frequency of 0.25Hz.

5. Conclusions

The results verified that the old capnograph units do show deterioration in performance with their age. It is thus recommended that the time and frequency response should be monitored on a regular basis to ensure safe operation [12]. This new technique is developed to resolve this issue. It can be used as a quality control procedure during the routine monitoring or the commissioning of new capnographs or in the construction of the QC protocol for the evaluation of capnograph systems in the clinical environment. It can also be used to ease the purchase decisions of capnographs in hospitals or to verify the manufacturer quoted specifications.

The time and frequency response determination of capnographs is important as it ensures that the capnograms are free of mechanical error and can be interpreted accordingly. Also, it determines if the capnographs can be used in high frequency ventilation schemes.

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