A REAL-TIME ALGORITHM TO IMPROVE THE RESPONSE TIME OF A CLINICAL MULTIGAS ANALYSER

Lawdy Wong, MSc,[1] Ruth Hamilton, MB, ChB,[1] Eileen Palayiwa, PhD,[2] and Clive Hahn, D Phil[1]

Wong L, Hamilton R, Palayiwa E, Hahn C. A real time algorithm to improve the response time of a clinical multigas analyser.
J Clin Monit 1998; 14: 441–446

ABSTRACT. Objective. An algorithm to improve the response time of a clinical respiratory multigas analyser is presented. **Methods.** The algorithm involves the application of a second order differential equation to the analyser gas output signals in real-time. The adjusted analyser output signals are compared with those of a quadrupole respiratory mass spectrometer sampling and analysing simultaneously. **Results.** Our results show a close correlation between the adjusted clinical gas analyser and the mass spectrometer signals. Lung volumes derived from a non-invasive sinusoidal inert gas forcing technique, in a model test lung, using the adjusted clinical gas analyser and the mass spectrometer signals demonstrated comparable results. **Conclusions.** The algorithm provides an improvement on the relatively slow response times of the clinical gas analyser for breath-by-breath time-dependent applications. The same algorithm can also be applied to other instruments which have slow response times.

KEY WORDS. Response time, signal processing, differential equation, multigas analyser, mass spectrometer.

INTRODUCTION

One conventional and standard multigas instrument used for the analysis of respiratory gas exchange is the mass spectrometer. The 10–90% response time of a typical mass spectrometer is $\leq$200 ms and the sampling flow rate in the order of $\leq$20 ml/min [1]. These values are acceptable for breath-by-breath respiratory physiology studies. For the non-invasive sinusoidal inert gas forcing technique, developed to measure cardio-respiratory function, we use a quadrupole mass spectrometer (Vacuum Gauge Limited, Cheshire) to measure the inspired and expired gas concentrations of N_2, N_2O, O_2 and CO_2 [2–5]. However, with the bulky size and the high cost of mass spectrometry, it is not practical for the sinusoid technique is to be exploited widely in the clinical environment. It has been our aim to replace the mass spectrometer with a reliable, accurate, small and more portable clinical multigas analyser.

The recent availability of portable multigas analysers using photoacoustic, infra-red and magnetoacoustic spectroscopy techniques has made this replacement a possibility. However, all the clinical multigas analysers currently available suffer from a common shortcoming of having relatively long response times compared to that of the mass spectrometer. The response times quoted from the manufacturer for the respective full scale step changes for the Datex Ultima analyser (Datex Instrumentation, Helsinki) are $\leq$360 ms for CO_2 (0–

From the [1]Nuffield Department of Anaesthetics, University of Oxford, Radcliffe Infirmary, Oxford, OX2 6HE, and [2]Clinical Measurement SDU, John Radcliffe Hospital, Oxford Radcliffe Hospital NHS Trust, Oxford, OX3 9DU, U.K.

Received Dec 17, 1997, and in revised form Aug 12, 1998. Accepted for publication Aug 27, 1998.

Address correspondence to Prof C. E. W. Hahn, Nuffield Department of Anaesthetics, University of Oxford, Radcliffe Infirmary, Oxford, OX2 6HE, U.K.

Journal of Clinical Monitoring and Computing **14**: 441–446, 1998.

10%); ≤480 ms for O_2 (0–100%); ≤360 ms for N_2O (0–100%) and ≤520 ms for anaesthetic agents such as Halothane (0–5%), isoflurane (0–5%), enflurane (0–5%), sevoflurane (0–8%) and desflurane (0–18%).

Datex Ultima response times are short enough for breath-by-breath monitoring in a clinical environment. The forced inspired sinusoid technique requires multiplication of airway flow and gas concentration for calculation of breath-by-breath mixed-expired concentrations. The difference between flow and gas concentration response times causes unacceptable measurement errors. The algorithm presented here reduces gas analyser response time, resulting in satisfactory mix-expired gas concentration measurements.

Simultaneous gas measurements were carried out on the mass spectrometer and the Ultima and direct comparisons were made on the unadjusted and adjusted Ultima signals with that of the mass spectrometer. Lung volumes derived from the signals using sinusoid technique experiments performed on a model test lung were also compared, using both gas analysis systems [6].

A variety of delay and response time correction methods have been developed by other researchers. Both Mitchell and Noguchi et al. modelled the mass spectrometer dynamic response as a first order system [7, 8]. Ariel and Van Liew found that a first order system was unsatisfactory and used a second order exponential response model [9]. Bates et al. used a sophisticated approach based on Wiener filtering and Fourier transform [10]. Tavener et al. modelled the delay and response as a ramp plus two successive exponential processes [11]. The alternative algorithm discussed here uses a second order system with an assumption on the shape of the analyser response to a step concentration change. It can be implemented in real-time and provides a good trade-off between simplicity and correctness.

MATERIALS AND METHODS

Instrumentation

The instrumentation for the sinusoid technique included a respiratory mass spectrometer (VG Quadrupole, Cheshire) to measure the airway gas concentrations; a clinical multi gas analyser (Datex Instrumentation, Helsinki); a variable orifice pneumotachcograph (Flow Sensor, Hamilton Medical, USA) connected to a differential pressure transducer (Validyne, Northridge, CA) where the flow signal is amplified using a flow amplifier (Morgan, Gillingham, Kent); a mechanical ventilator (Servo 900B, Siemens-Elema, Sweden) and a modified version of the microprocessor-controlled dynamic sinusoidal gas delivery unit developed in our department [12]. The output of the gas delivery unit was connected to the input of the ventilator. The ventilator output was connected to the model test lung, which had a geometrical anatomical dead space of 135 ml and a preset alveolar volume of 2385 ml. The hardware block diagram is shown in Figure 1. The mass spectrometer was controlled by an IBM PC-compatible microcomputer (100 MHz, Intel Pentium, 8 MB RAM, 1 GB HD) which also provided the display and data storage facilities. The mass spectrometer sampling probe was placed about 5 cm apart in parallel with the Ultima's probe on the down stream end of the ventilator tubing to avoid excessive gas disturbance inside the tubing caused by different sample flow rates of the two instruments. The response time correction algorithm was connected to the analogue-to-digital converted gas output signals of the Ultima. The 12-bit conversion was carried by the DT2814 data acquisition board (Data Translation, Marlboro, MA) in the microcomputer. The N_2, N_2O, O_2, CO_2 and airway flow signals were recorded at a sampling rate of 25ms.

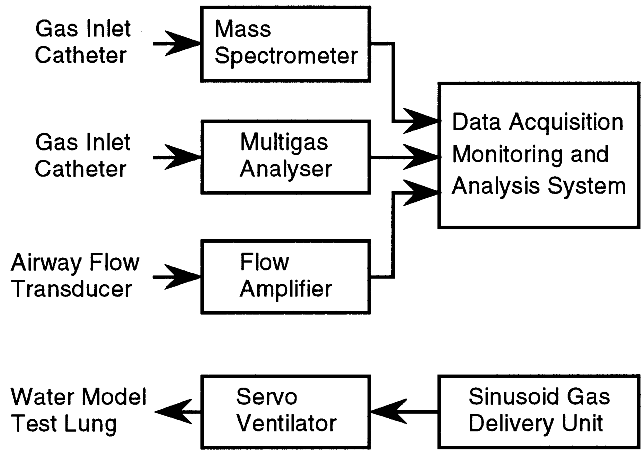

Fig. 1. The block diagram of the system hardware.

The response time of the Ultima is chiefly a function of the time required to wash out the analysis cell, but additional delays may be imposed by the mechanism used to detect the change in gas concentration. The overall instrumental response to a square wave step change in gas concentration is widely accepted to be sigmoidal in shape. The software for the sinusoid technique was designed to take account of the different instrumental delay times of the gas flow, mass spectrometer and clinical gas analyser output signals, so that all the signals could be analysed with correct time-alignments.

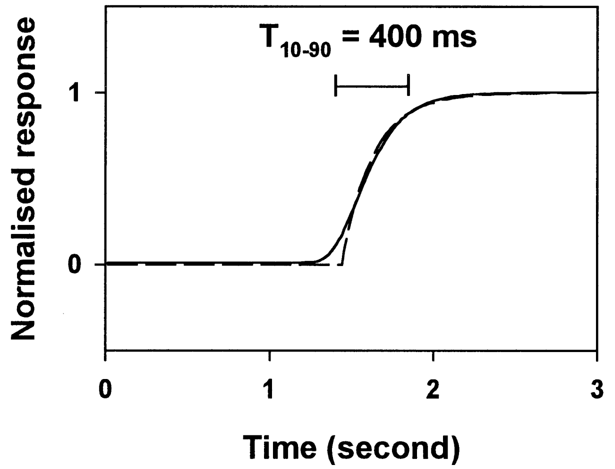

Fig. 2. The response to a step concentration change: a true sigmoidal (solid line) and the assumed exponential (dotted line). The measured T_{10-90} of the sigmoidal response is 400 ms.

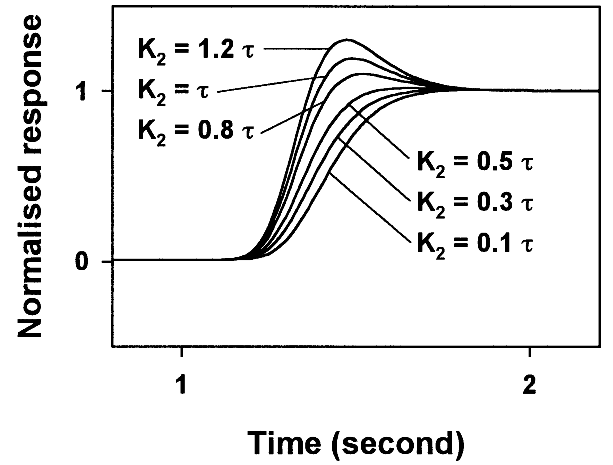

Fig. 3. Diagram showing the effects of the adjusted sigmoidal response in Figure 2 with respect to different K_2 values. $K_1 = \tau = 0.4/(\ln(0.9)-\ln(0.1)) = 0.182$. The adjusted response is critically damped when $K_2 = 0.5\,K_1$. The signals are under-damped when K_2 is above $0.5\,K_1$ and over-damped when K_2 is below $0.5\,K_1$.

Algorithm

The algorithm used to improve the response time of the Ultima gas analyser required prior knowledge of the overall instrumental response time, and the analyser gas output signal was corrected in real-time by applying a second order differential equation. In this correction, the instrumental response to a step change on the gas concentration is assumed to be exponential rather than sigmoidal (see Figure 2). We found that an adjustment (to be discussed later) was needed to be applied to correct the signal in order to remedy this assumption. The gas output signal, $y(t)$, can be represented by:

$$y(t) = y_f(1 - e^{-kt}) \tag{1}$$

where y_f is the final steady state value of the signal and $1/k$, or τ, is the time constant of the exponential response. Its first and second derivatives will therefore be:

$$\frac{dy}{dt} = k y_f e^{-kt} \tag{2}$$

and

$$\frac{d^2y}{dt^2} = -k^2\, y_f\, e^{-kt} \tag{3}$$

Now, taking the second order differential equation described by Arieli and Van Liew [9]:

$$Z(t) = K_1 K_2 \frac{d^2y}{dt^2} + (K_1 + K_2)\frac{dy}{dt} + y \tag{4}$$

where $Z(t)$ is the adjusted signal, K_1 and K_2 are constants.

Substituting Equations (1)–(3) into (4) gives:

$$Z(t) = -K_1 K_2 k^2\, y_f\, e^{-kt} + (K_1 + K_2)k\, y_f\, e^{-kt} + y_f - y_f\, e^{-kt} \tag{5}$$

Equation (5) can be simplified to:

$$Z(t) = -(kK_1 - 1)(kK_2 - 1)\, y_f\, e^{-kt} + y_f \tag{6}$$

In Equation (6), if either:

$$kK_1 - 1 = 0 \quad \text{or} \quad kK_2 - 1 = 0$$

i.e. if either K_1 or $K_2 = k^{-1}$, and $y = 0$ at $t = 0$ then:

$Z(t) = 0$ at $t = 0$ and
$Z(t) = y_f$ at $t > 0$, which is the ideal step response.

The mathematical derivation is based on the assumption that the signal's shape is exponential rather than sigmoidal. By fixing $K_1 = k^{-1} = \tau$, it is found that adjustment on K_2 around k^{-1} is necessary to obtain a critically damped step response. The adjusted response with different values of K_2 is shown in Figure 3.

To apply the above correction and assuming the section between 10% and 90% of the steady state gas concentration of a sigmoidal response is analogous to the same section of an exponential response, we first calculated the time constant, τ, of the Ultima instrument step response from the analyser sigmoidal 10–90% time response to a step change in gas concentration, T_{10-90}, using Equation (7).

$$\tau = \frac{T_{10-90}}{\ln(0.9) - \ln(0.1)} \tag{7}$$

The gas analyser signal was then differentiated twice. The value of the first derivative was the slope between two successive points and the resulting derivative point had the same time value as the first data point. The same procedure was used to obtain the second-derivative and the resulting point had the same time value as the first of the two first-derivative points. The adjusted signal was than calculated by substituting the parameters derived above into Equation (4).

The values of K_1 were assigned as the corresponding time constants of the exponential curves using the response time quoted from the manufacturer and Equation (7). A step response was then applied to individual gases and their K_2 values were then adjusted until the critically damped signals were obtained.

Forcing sinusoids

The forcing sinusoid gas employed was O_2 with a mean of 35% vol/vol and an amplitude of 4% vol/vol. The sinusoid periods administered were 2, 3, and 4 minutes at a respiratory rate of 12 breaths per minute. The mass spectrometer, together with the unadjusted and adjusted Ultima analyser, gas signals and the calibrated flow signals were recorded for the duration of the respective sinusoid period. The same data collection procedure was repeated six times with the same test lung volumes. The lung volumes were calculated for both the mass spectrometer and the Ultima analyser using the tidal ventilation mathematical model of the sinusoid technique developed and then compared to the known volume [13].

RESULTS

Figure 4 shows the O_2 gas concentration signals recorded for a typical breath during the course of an O_2 sinusoid. The rising and trailing edges of the mass spectrometer and adjusted Ultima gas analyser signals show close correlation. Since the presented correction algorithm carried out first and second order differentiations on the raw data, extra signal noise was inevitably generated on the adjusted signal as a consequence. This can be seen on Figure 4B. This noise could have been

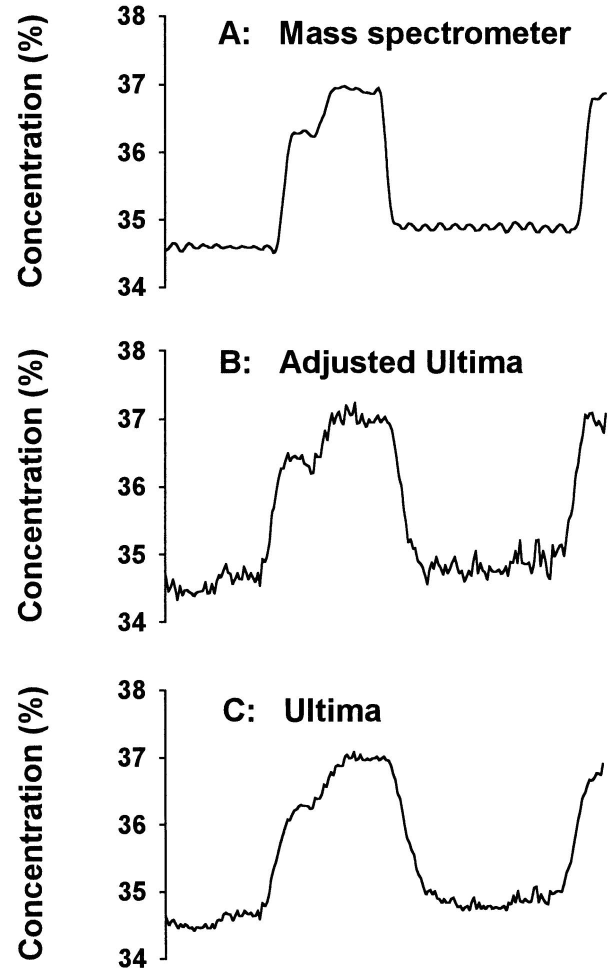

Fig. 4. A typical time-aligned O_2 sinusoid breath acquired by: (A) the mass spectrometer; (B) the adjusted Ultima gas analyser; (C) the non-adjusted Ultima gas analyser.

further conditioned by suitable digital filtering if necessary. Judging from our experimental results, the noise level generated was acceptable for the sinusoid technique and no extra filtering was used. The 10–90% response times of the mass spectrometer, and unadjusted and adjusted Ultima signals, taken from an average of 30 breaths (10 for each sinusoid period) and selected in random from the recorded data, were measured and are shown in Table 1. Again the response times of the mass spectrometer and the adjusted Ultima signals are comparable, and the Ultima 10–90% response time was reduced from 310 ms to 238 ms by the algorithm.

The averaged dead space and alveolar volumes, derived from the recorded data using the sinusoid technique and the tidal mathematical model are shown in Figures 5 and 6, respectively for the two gas analysis systems. Again, comparable results on both dead space

Table 1. The average 10–90% rise-times of the mass spectrometer, the non-adjusted and adjusted Ultima gas analyser

Instrument	Average 10–90% rise-time (ms)
Mass spectrometer	200.0 ± 10.3
Ultima gas analyser	310.1 ± 13.0
Adjusted Ultima gas analyser	238.1 ± 0.9

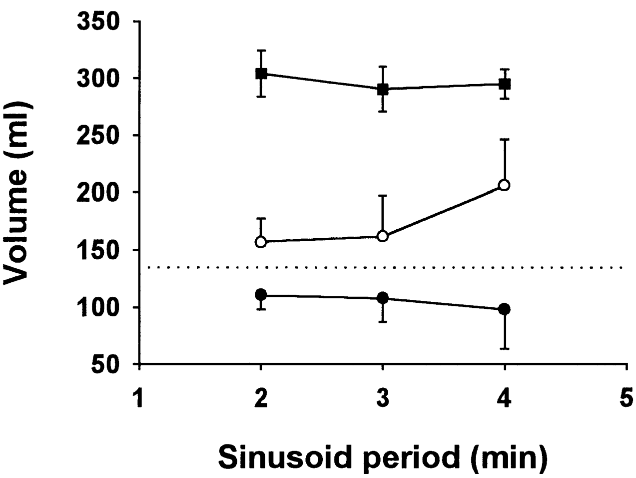

Fig. 5. Calculated dead space volume vs. sinusoid period. ● Mass spectrometer; ○ Adjusted Ultima; ■ Ultima; and the dotted line represents the true dead space.

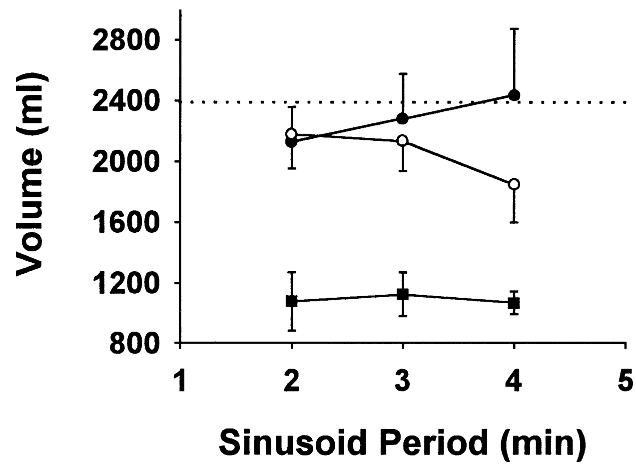

Fig. 6. Calculated alveolar volume vs. sinusoid period. ● Mass spectrometer; ○ Adjusted Ultima; ■ Ultima; and the dotted line represents the true alveolar volume.

and alveolar volume values are shown across the sinusoid periods using the data derived from the mass spectrometer and the adjusted Ultima data sets. From Figures 5 and 6, it is clear that large discrepancies exist between the calculated volumes, derived from the unadjusted Ultima gas concentration output signals, and the true geometrical lung model volumes. This confirms the suspicion that a clinical gas analyser, such as the Ultima, will not be able to replace a respiratory mass spectrometer directly as the gas concentration measuring instrument in the forced inspired sinusoid technique, unless its response time is enhanced considerably by a method such as that demonstrated in this present work.

DISCUSSION

One of the key applications of the forced inspired sinusoid technique is to monitor cardio-respiratory function in patients in the intensive care unit. We have attempted to reduce the complexity and the size of the equipment, by replacing the complex mass spectrometer with a conventional clinical gas analyser, in order to aid the practical application of the technique. From the results derived from our study, the unadjusted Ultima with its existing relatively slow response time cannot act as a straight replacement for a respiratory mass spectrometer. However, the differences between the mass spectrometer and the algorithm adjusted Ultima output signals were small. The algorithm adjusted clinical gas analyser signals were acceptable as the input signals for the forced sinusoid technique, and the calculated lung volumes were essentially indistinguishable from those derived from the much more complicated and expensive mass spectrometer apparatus. The portability of the Ultima gas analyser, with on-line response time correction, provides an excellent alternative to the bulky and expensive mass spectrometer. The assumption that the shape of the instrumental response to a concentration step change was exponential rather than sigmoid did not give a perceptible error to the adjusted signal. The algorithm technique presented here is generic and could also be applied to other instruments whose response times need to be improved.

Ruth Hamilton was in receipt of a Medical Research Council DPhil Research Studentship.

REFERENCES

1. Sykes MK. Gas and vapour analysis. In: Sykes MK, Vickers MD, Hull CJ, eds. Principles of Measurement

and Monitoring in Anaesthesia and Intensive Care. Oxford: Blackwell Scientific Publications 1985; 237–240.
2. Williams EM, Gavaghan DJ, Oakley PA, Sainsbury MC, Xiong L, Black AM, Hahn CEW. Measurement of deadspace in a model lung using an oscillating argon signal. Acta Anaesthesiol Scand 1994; 38: 126–129.
3. Williams EM, Aspel JB, Burrough SM, Ryder WA, Sainsbury MC, Sutton L, Xiong L, Black AM, Hahn CEW. Assessment of cardiorespiratory function using oscillating inert gas forcing signals. J Appl Physiol 1994; 76: 2130–2139.
4. Williams EM, Hahn CEW. Measurement of cardio-respiratory function using single frequency inspiratory gas concentration forcing signals. Adv Exp Med Biol 1994; 361: 187–195.
5. Gavaghan DJ, Hahn CEW. A mathematical evaluation of the alveolar amplitude response technique. Resp Physiol 1995; 102: 105–120.
6. Williams EM, Gale LB, Oakley PA, Sainsbury MC, Hahn CEW. Development of a concentric water-displacement model lung. J Biomed Eng 1993; 15: 420–424.
7. Mitchell RR. Incorporating the gas analyser response time in gas exchange computations. J Appl Physiol 1979; 47: 1118–1122.
8. Noguchi H, Ogushi Y, Yoshiya I, Itakura N, Yamabayashi H. Breath-by-breath VCO_2 and VO_2 require compensation for transport delay and dynamic response. J Appl Physiol 1982; 52: 79–84.
9. Arieli R, Van Liew HD. Corrections for the response time and delay of mass spectrometers. J Appl Physiol 1981; 51: 1417–1422.
10. Bates JHT, Prisk GK, Tanner TE, McKinnon AE. Correcting for the dynamic response of a respiratory mass spectrometer. J Appl Physiol 1983; 55: 1015–1022.
11. Tavener SJ, Withy SJ, Harris EA. Response characteristics of a mass spectrometer. Med Biol Eng Comp 1984; 22: 493–498.
12. Barton SA, Sutton L, Hahn CEW, Black A. A digital system for generating dynamic sinusoidal gas concentration signals. J Appl Physiol 1988; 65: 945–949.
13. Gavaghan DJ, Hahn CEW. A tidal breathing model of the forced inspired inert gas sinewave technique. Respir Physiol 1996; 106: 209–221.