Breath-by-breath analysis of oxygen uptake using the Datex Ultima

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Summary
The Datex Capnomac Ultima monitor combines a sidestream rapid gas analyser with a spirometer. In theory the integral of simultaneous flow and oxygen concentration during inspiration is the inspired and expired volume of oxygen. From the difference between these two amounts, oxygen consumption (\(\dot{V}O_2\)) can be estimated. \(\dot{V}O_2\) was measured in patients under general anaesthesia and compared with that obtained simultaneously using a Datex Deltatrac metabolic monitor. Two techniques to compensate for the delay in rise time of the oxygen sensor were evaluated. The first method steepened the oxygen curve exponentially, and the second used a linear statistical correction. The linear correlation coefficients for \(\dot{V}O_2\) between the Ultima and the Deltatrac were 0.87 and 0.78 for the two methods. The 10th to 90th centile range for error was \(-67.4\text{ to }-59.8\text{ ml min}^{-1}\) for the exponential method and \(-53.2\text{ to }-56.1\text{ ml min}^{-1}\) for the statistical method. The Ultima may be used with moderate accuracy to measure oxygen uptake during anaesthesia. (Br. J. Anaesth. 1995; 74: 155-158)

Key words

Oxygen consumption (\(\dot{V}O_2\)) is an indicator of metabolism and may be used to assess the severity of a disease process, or the success of a therapeutic manoeuvre [1,2]. To be useful in the operating theatre and intensive care, \(\dot{V}O_2\) measurements must be repeatable.

Several systems are available to continuously measure \(\dot{V}O_2\) by integrating the simultaneous values of respiratory gas flow and oxygen concentration [3,4], or by analysis of mixed expired gas [5-8]. These studies showed linear correlations between cardiac output obtained by the continuous Fick methods and those obtained by thermodilution in the range 0.94-0.96, with small biases. However, in a recent study [9] in critically ill patients, the correlation between Fick methods for \(\dot{V}O_2\) and indirect calorimetry was only 0.64.

The main barriers to the widespread clinical use of these techniques are the size of the apparatus and interference from humidity and inhaled anaesthetic agents. The Datex Ultima anaesthetic monitor displays both flow and oxygen content waveforms by sidestream sampling. It has a paramagnetic oxygen sensor and a robust flow sensor that uses the Pitot principle and electronic linearization to obtain flow measurements.

There are two principal problems with the accurate calculation of \(\dot{V}O_2\) from a monitor such as the Ultima [10]. First, the rise time of the oxygen analyser causes a delay in the measured oxygen concentration. Second, the transport delay, inherent in sidestream monitors, causes the oxygen concentration waveform to be out of phase with the flow waveform (fig. 1). We have been investigating methods to overcome these problems and comparing the measurements obtained by the Ultima with those obtained concurrently using the Datex Deltatrac metabolic monitor. The Deltatrac measures \(\dot{V}O_2\) over each minute by diluting mixed expired gas into a known flow of air. By accurately measuring oxygen and carbon dioxide concentrations before and after dilution, it is possible to derive the volume of expired gas. Using the Haldane correction, \(\dot{V}O_2\) may be calculated from the respiratory exchange ratio.

Patients and methods
We studied 22 adult patients without lung disease undergoing prolonged vascular procedures under general anaesthesia. Measurements were obtained during periods when patients were clinically in a relatively steady state. They received a balanced anaesthetic, without nitrous oxide, an inspired oxygen fraction \((FiO_2)\) of less than 0.6, and their lungs were ventilated with a Manley ventilator at a frequency of 8 to 12 b.p.m. and a tidal volume of 600-800 ml in order to maintain an end-expired carbon dioxide concentration of 4.5-5.5%. \(\dot{V}O_2\) was measured during the procedure simultaneously in two ways. First, the expired gas from the Manley ventilator was directed to a Datex Deltatrac metabolic monitor. Second, the flow and oxygen concentration waveforms from the Datex Ultima were analysed. The waveforms were collected from the analogue output using a two-channel, 14-bit data acquisition unit, sampling every 20 ms (Strobes APC, Wellington), and stored on a personal computer. The product of oxygen concentration and flow obtained by the Ultima with those obtained concurrently using a Datex Deltatrac metabolic monitor.
change in oxygen concentration over that time and
the change caused by the difference between the
measured value of oxygen concentration and the
actual value at the start of the 20-ms interval.

The second (statistical) method made no attempt
to directly manipulate the oxygen waveforms, but
instead used a statistically derived correction. The
data were divided randomly into two groups, a
"derivation" group and a "validation" group. Using
the derivation group, the value of $V_{O_2}$
calculated from the Ultima using the "raw"
unaltered waveforms was plotted against the cor-
responding values of $V_{O_2}$ obtained from the
Deltatrac (fig. 2). A linear regression equation was
derived using standard least squares:

$$\text{corrected } V_{O_2} (\text{ml min}^{-1}) = 139.04 + (0.85 \times \text{Ultima } V_{O_2})$$

The standard errors for the intercept and slope were
21.52 ml min$^{-1}$ and 0.10 ml min$^{-1}$, respectively. This
transformation was then applied to each Ultima
value in the validation group to derive a statistically
corrected estimate of $V_{O_2}$.

Statistical analysis was performed on a personal
computer using the NCSS (NCSS Kaysville UT,
USA) statistical package. Data from the two instru-
ments were compared using the linear correlation
coefficient ($r$). In addition, the bias and precision of
the measurements were assessed using the method
of Bland and Altman [11], with their method of
correction to the SD for repeated measures.

Results

Ninety-two pairs of data points were obtained. The
values of $V_{O_2}$ ranged from 190 to 483 ml min$^{-1}$
using the Deltatrac. When the Ultima values were corrected
using the exponential transformation, values ranged
from 112 to 504 ml min$^{-1}$ and when the regression
based transformation was used a range of 191–
442 ml min$^{-1}$ was obtained. The linear correlations
between these corrected Ultima values and the
Deltatrac values were 0.87 and 0.78, respectively.
The scatter plots are shown in figure 3.

The 10th to 90th centile of the differences between

The first (exponential) method steepened the
oxygen concentration waveform during the periods
of rapid increase and decrease by assuming that the
sensor approached the true oxygen concentration in
an exponential manner, and that the measured value
was equal to the real value at the start of inspiration
and during the plateau phases of oxygen concen-
tration. The change in concentration seen over a 20-
ms period was the sum of the fraction of the real

![Figure 1](image1.png)

**Figure 1** Gas flow rate and oxygen ($O_2$) concentration vs time
for the Datex Ultima. The arrow indicates the estimated point
on the oxygen concentration trace that corresponded to the
start of inspiration, and indicates the sampling delay. Negative
flow values indicate inspiration and zero time is the start of
inspiration.

![Figure 2](image2.png)

**Figure 2** Scatterplot of uncorrected values of $V_{O_2}$ for the
Ultima (using the "derivation" group) vs those obtained for the
Deltatrac. The linear regression line from this plot was
used for the statistical method of correction.

breath. The data acquisition system sampled every
second breath, so that approximately five breaths
were analysed per minute. From each breath analysed,
an estimate of $V_{O_2}$ was made and the mean
of five breaths taken. This value was compared with
that obtained by the Deltatrac over the same minute.

The transport delay was estimated by measuring
the time between the onset of inspiration seen on the
flow waveform and the corresponding rapid increase
in oxygen concentration (fig. 1). The paramagnetic
oxygen sensor of the Ultima has a rise time of
approximately 420 ms. During periods of rapid
change in oxygen concentration, early in inspiration
and expiration, the gradient generated by the sensor
would not be as steep as the true gradient. Two
methods were used to correct for this error.

The first (exponential) method steepened the
oxygen concentration waveform during the periods
of rapid increase and decrease by assuming that the
sensor approached the true oxygen concentration in
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![Figure 3](image3.png)

**Figure 3** Scatterplot of $V_{O_2}$ values obtained for the Ultima vs
those obtained for the Deltatrac using the exponential method
of correction (△) and the statistical method (×).
Figure 4 Modified Bland and Altman plot comparing the difference in \( V_O_2 \) between the Deltatrac and the Ultima vs mean \( V_O_2 \) using the exponential method of correction (\( \Delta \)) and the statistical method (\( \times \)).

The corrected Ultima and the Deltatrac values were -67.4-59.8 ml min\(^{-1}\) and -53.2-56.1 ml min\(^{-1}\), respectively. Overall there was little bias with each method of correction of the values derived from the Ultima. The mean difference for the exponential method was 4.2 (95% confidence intervals (CI) -5.7-13) ml min\(^{-1}\) (sd 47.2 ml min\(^{-1}\)). The corresponding values for the statistical method were a bias of 7.3 (95% CI -5.4-19.2) ml min\(^{-1}\) (sd 43.0 ml min\(^{-1}\)). The paired data sets were also compared using a plot of the difference between each paired estimate of \( V_O_2 \) and the mean (fig. 4). Both transformations resulted in a weak trend for the Ultima value being greater than the mean at low \( V_O_2 \) and less at high \( V_O_2 \) values. The regression lines were:

\[
\text{difference (exponential method)} = 84.6 - 0.25 \text{ (mean)}
\]

\[
\text{difference (statistical method)} = 45.8 - 0.12 \text{ (mean)}
\]

The standard errors for the two methods for the intercepts were 17.2 and 23.1 ml min\(^{-1}\), and for the gradients 0.05 and 0.11 ml min\(^{-1}\).

**Discussion**

The Ultima is a purpose-built anaesthetic monitor which, by combining a spirometer and a rapid oxygen analyser, has the potential to measure \( V_O_2 \) but allowances have to be made for the transport delay and the rise time of the oxygen analyser. In this study a Deltatrac metabolic monitor was used as a standard. Although there was a clear association between the two methods, the correlation was not as good as that in some earlier studies where continuously measured \( V_O_2 \) was used to calculate cardiac output and compared with that obtained by thermodilution [3,4]. However, a recent statistical reappraisal [9] has suggested that the accuracy in clinical practice may be much less. In this study, the differences in \( V_O_2 \) derived from the Deltatrac and those obtained from the Ultima were up to 55 ml min\(^{-1}\) and the correlation coefficient was only 0.64.

Two *in vitro* studies have assessed the accuracy of the Deltatrac. Using a gas injection method of validation, the Deltatrac gave 95% CI of error of -12% to +5% [12]. Using a combustion method, a relative error in \( V_O_2 \) of 4% was found [13], which corresponds to 95% CI of about -20 to +20 ml min\(^{-1}\). In *in vivo*, comparisons with a reverse Fick method showed a sd of 19.6 ml min\(^{-1}\) in neurosurgical patients, and of 29.5 ml min\(^{-1}\) in patients with pneumonia [12]. Of interest is that the Deltatrac tended to underestimate at higher values of \( V_O_2 \). The Deltatrac is difficult to use in the theatre setting, it cannot be used with a circle breathing system, is inaccurate when \( F_I O_2 \) > 0.6, and it cannot compensate for nitrous oxide. It calculates \( V_O_2 \) every minute, but as analysis is on mixed expired gas, and both the mixing chamber and the collecting tubing have a significant volume, the value displayed may not accurately represent the actual \( V_O_2 \) over the previous minute. It is better regarded as giving a moving average of the previous 5 min. This is in contrast with values obtained using the Ultima which had a greater variability and presumably more closely reflects instantaneous oxygen uptake. It is difficult to know how much of the variation with the Ultima is caused by measurement error and how much is true physiological variation.

We estimated the transport delay by measuring the time between the onset of inspiration seen on the flow waveform and the sharp rise on the oxygen concentration waveform for each breath. The mean value for this was 2.74 s. The likely effect of small errors in estimating this delay was assessed by varying it from 2.60 to 2.90 s while analysing the same sequence of breaths. The slope of the resulting regression line suggested a 15-ml min\(^{-1}\) change in \( V_O_2 \) for each 20-ms change in estimated delay.

The rise time of the oxygen sensor was compensated for in two ways. One method used a simple linear regression of the unprocessed Ultima measures of \( V_O_2 \) against those of the Deltatrac. This transformation resulted in a reasonable correlation and accuracy, but a large intercept value. The exponential transformation of the original oxygen concentration data is more sensitive to changing patterns of ventilation and so should be more widely applicable.

It might have been expected that a guide to oxygen uptake would be found in the inspired to expired oxygen concentration difference which is displayed on the Ultima. However, the correlation with the reference values for \( V_O_2 \) was only 0.41.

Oxygen consumption is a fundamental indicator of metabolism and if measured continuously and reliably aids the management of the critically ill. This study has demonstrated that it was feasible to use the Datex Ultima to obtain estimates of \( V_O_2 \) on a minute-by-minute basis. However, the degree of accuracy of the method was such that detection of changes in \( V_O_2 \) of less than about 50–100 ml min\(^{-1}\) was unreliable. This degree of accuracy may be comparable with that obtained using pulmonary
artery catheterization and the reverse Fick principle [9].

Acknowledgement
The Deltatrac was loaned by Datex Corp.

References