Metabolic monitoring in the intensive care unit: a comparison of the Medgraphics Ultima, Deltatrac II, and Douglas bag collection methods

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Editor’s key points
- Energy requirements are difficult to measure precisely in critically ill intensive care unit patients and are not monitored routinely.
- This small study compared two commercially available metabolic monitors (Medgraphics Ultima and Deltatrac II) with a Douglas bag technique.
- There was poor agreement between readings from the three devices.
- More accurate devices are needed to monitor gas exchange in mechanically ventilated patients.

Background. The accuracy of oxygen consumption measurement by indirect calorimeters is poorly validated in mechanically ventilated intensive care patients where multiple confounders exist. This study sought to compare the Medgraphics Ultima (MGU) and Deltatrac II (DTII) devices, and the Douglas bag (DB) technique in mechanically ventilated patients at rest.

Methods. Prospective comparison of oxygen consumption measurement using three indirect calorimetry techniques in stable, resting mechanically ventilated patients at rest. Oxygen consumption (VO2), carbon dioxide production (VCO2), resting energy expenditure (REE), and respiratory quotient (RQ) were recorded breath-by-breath by the MGU over a 30–75 min period. During this time, simultaneous measurements were taken using the DTII, the DB, or both.

Results. While there was no systematic error (bias) between measurements made by the three techniques (VO2: MGU vs DTII 3.6%, MGU vs DB 3.3%), the limits of agreement were wide (VO2: MGU vs DTII 33%, MGU vs DB 54%).

Conclusions. Resting oxygen consumption values in stable mechanically ventilated patients measured by the three techniques showed acceptable bias but poor precision. There is an important clinical and research need to develop new indirect calorimeters specifically tailored to measure oxygen consumption during mechanical ventilation.

Keywords: indirect calorimetry; mechanical; oxygen consumption; validation studies; ventilators

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Metabolic monitoring is not routinely performed in the intensive care unit (ICU) setting. However, recent studies and reviews have highlighted the likely importance of adequate assessment of energy requirements in mechanically ventilated patients. Hypocaloric feeding will potentially exacerbate poor functional outcomes through significant long-term calorie deficits, while overfeeding is associated with higher mortality rates and an increased length of ICU stay. Furthermore, a more precise estimation of metabolic activity to prevent over- or underfeeding may improve patient outcomes.

An important challenge arises from the difficulty in achieving reliable measurements. Predictive equations used to calculate energy requirements in mechanically ventilated ICU patients show poor agreement against values measured by indirect calorimetry. Whole-body oxygen consumption can be measured directly with the pulmonary artery catheter. However, the use of this invasive device has dwindled markedly over the last few years and has inherent errors, including lung oxygen consumption and mathematical coupling. Even if used, the catheter is unlikely to remain in situ long after the resolution of shock or during the recovery phase of critical illness to avoid infectious and other complications. Thus, the non-invasive technique of indirect calorimetry, using data obtained from inspired and expired gas analysis, is the most readily available means of measuring oxygen consumption and carbon dioxide production.
The Deltatrac II (DTII, Datex Ohmeda, Finland) has been the most widely used and validated device in the ICU, but is no longer manufactured nor supported. Newer devices are currently targeted towards exercise testing in spontaneously breathing patients and little validation data are available in mechanically ventilated patients. While in vitro validation of such devices using lung simulator models is straightforward, in vivo validation techniques are far more challenging as mechanical ventilation introduces significant inconsistencies in temperature, humidity, peak airway pressure, expiratory flow rates, and bias flow. We thus decided to compare readings obtained from a currently available device, the Ultima (MGU) manufactured by Medgraphics (St Paul, Minneapolis, MN, USA), with traditional ‘reference standards’ the DTII, and the Douglas bag (DB) technique, in mechanically ventilated patients at rest.

### Methods

Ethical approval was granted for the study (REC reference number: 09/H1307/107) and informed consent or surrogate approval obtained from all patients or their next-of-kin.

Patients undergoing mechanical lung ventilation with stable settings were recruited from the ICU at University College Hospital, London, UK. Patients were excluded if they had burns, endotracheal or tracheal leaks >10%, open chest drainage, an inspired oxygen ($F_{I O_{2}}$) $\geq$ 0.6, were pregnant, <18 yr of age, or had cardiorespiratory instability requiring frequent changes in ventilator settings, $F_{I O_{2}}$, inotropic, or sedative drug dosages. The measurements were taken simultaneously; therefore, factors such as room temperature and nutritional status were not controlled. The mechanical ventilator used in all studies was the Servo-i (Maquet, Solna, Sweden). Before each test, the DTII and MGU machines were warmed up for 30 min and calibrated in line with the manufacturers’ instructions. Patients were clinically stable for 30 min preceding measurement (<20% variation in heart rate, arterial pressure, or oxygen saturation). Mechanical ventilation settings were kept stable over the hour preceding and during the test period.

Oxygen consumption ($VO_{2}$), carbon dioxide production ($VCO_{2}$), resting energy expenditure (REE), and respiratory quotient (RQ) were recorded breath-by-breath by the MGU over a 30–75 min period. During this time, simultaneous measurements were taken using the DTII, the DB, or both. The tests were repeated, where possible, at different time points over the subsequent month to collect up to three paired measurements per patient using both MGU and DTII, and MGU and DB collection techniques (Fig. 1A and B).

#### DB collection

This method, first described in 1911 by the Oxford physician, Gordon Douglas, has latterly been used to validate measurements made by various metabolic monitors. For the current study, gas was collected over three 5 min periods from the expiratory exhaust of the ventilator, into separate prelabelled 100 litre PVC gas collection bags (Harvard Apparatus Ltd, Edenbridge, UK). Prelabelled 50 ml syringes and three-way taps were purged with 100 ml of expired gas from the respective gas collection bags, before aspiration of 50 ml of gas for analysis from each bag. Twenty millilitres of this gas were then analysed using a blood gas analyser (ABL735 or 825, Radiometer, Brønshøj, Denmark). Two precision gases; 5% CO$_2$/
using a lung simulator.17 The flow sensor was calibrated 
vitro to the flow signal to calculate inspired and expired values.

Within-test coefficients of variation of both VCO2 and VO2 
values obtained over the first 5 min period were calculated 
by flow-by.

As the DTII measures neither flow nor volume, it is not affected 
and that no gases are present other than O2, CO2, and nitrogen.

That nitrogen is neither produced nor retained by the body,
transformation of the Haldane equation with the assumption 
that the volume of CO2 expired by the patient, that is, 
VCO2 = FCO2 × 40 (flow constant). The RQ is derived from a 
transformation of the Haldane equation with the assumption 
that nitrogen is neither produced nor retained by the body, 
and that no gases are present other than O2, CO2, and nitrogen.
As the DTII measures neither flow nor volume, it is not affected 
by flow-by.

Data were collected over 1 min intervals. The mean of the 
values obtained over the first 5 min period where the 
within-test coefficients of variation of both VCO2 and VO2 
were ≤5% was used in the analysis.25-27

**Medgraphics Ultima**
The MGU measures inspiratory and expiratory flows through a 
bi-directional flow sensor and therefore does not require 
the Haldane equation used by most indirect calorimeter devices 
to calculate inspiratory volumes from expiratory volumes.
The oxygen analyser is a fuel cell with a response time <80 ms, 
while the carbon dioxide analyser is a non-dispersive infrared 
sensor with a response time <150 ms. The system samples gas 
continuously and phase aligns O2 and CO2 signals with 
the flow signal to calculate inspired and expired values. In 
vitro validation of the device was carried out jointly by the 
study group and Medical Graphics UK (Gloucester, Glos, UK) 
using a lung simulator.17 The flow sensor was calibrated 
using a 3 litre syringe and the gas analysers were calibrated 
with precision gas before each individual test.

Data points within the MGU tests were excluded if the RQ 
was <0.6 or >1.2, the VT was <150 ml, or the VO2 or VCO2 
were ≤50 ml min−1. Collected data were then averaged as 
the middle five of seven breaths.

**Analysis**
Simultaneous MGU recordings were used for comparison 
against both DTII and DB measurements. Measurements 
were discarded if the mean RQ value obtained from either 
the 5 min DTII or the three DB collections were <0.6 or 
>1.2. Data were to be excluded if the coefficient of vari-
atation (COV) was >10% for individual DB collections, in the 
event, none needed to be excluded or >5% for the DTII 
tests. All coefficients of variation for the MGU tests were 
<14%. The Bland–Altman plots (mean measurements 
made by the two devices vs the difference in measurements 
between the devices) were used to calculate precision 
and bias. We decided a priori that a 30% error was 
acceptable, as recommended by Critchley and Critchley.28
This would give ±600 kcal day−1 error for a patient con-
suming 2000 kcal day−1.

**Results**
Sixteen patients were recruited and tested on 39 occasions. 
Patient characteristics and ventilator settings for each test 
are given in Table 1. Comparisons between techniques, 
number of tests performed, and proportion of excluded tests 
are shown in Table 2, while the reliability of the individual 
techniques is shown in Table 3.

The Bland–Altman plots of VO2, VCO2, REE, and scatter plots 
for RQ are presented in Figure 2, with bias and precision (95% 
limits of agreement) shown in Table 4.

**Medgraphics Ultima vs Douglas bag**
Nineteen valid tests were carried out in nine patients. Although 
bias was good for VO2, VCO2, and REE, precision was weak with 
wide levels of agreement and a maximum random error of 54% 
for VO2, 51% for VCO2, and 43% for REE. If proportionality of 
the measurements is taken into account and the percentage error 
for each individual data set calculated, then the random error is 
42% (−27% to 15%) for VO2, 57% (−17% to 40%) for VCO2, 
and 32% (−9% to 23%) for REE (Supplementary material SB).

**Medgraphics Ultima vs Deltatrac II**
Nineteen valid tests were carried out in 10 patients. Overall bias 
was good for VO2, VCO2, and REE; however, yet again, there 
were wide limits of agreement for all three measures. It was 
superior to the comparison between MGU and the DB techniques 
with random errors of 33%, 27%, and 31% for VO2, VCO2, and 
REE, respectively. If proportionality of measurements is taken 
to account, and the percentage error for each data set calculated, 
then the random error widens to 41% (−13% to 28%) for 
VO2, 31% (2% to 29%) for VCO2, and 37% (−28% to 9%) for REE 
(Supplementary material SB).

**Discussion**
This study describes the unique comparison of a currently avail-
able device the Ultima (MGU) with traditional reference stan-
dards, the DTII and the DB techniques, in mechanically 
ventilated patients at rest.

While the systematic error (bias) between the MGU me-
asurements of VO2, VCO2, and REE, and both those of the DTII 
and the DB, was acceptable, the limits of agreement were 
wide. Comparison between the MGU and the DTII was more
acceptable but at the margins of acceptability for the measurement of metabolic activity, either for research or clinical purposes, albeit assuming the DTII represents an accurate reference standard. There is a remarkable lack of consistency in the criteria deciding comparability between a reference technique and new devices. Using cardiac output measurement techniques as an example, Critchley and Critchley proposed that the accuracy of both devices should be taken into account. Thus, if the reference device, in this case, the DTII, was considered to have an accuracy of $\pm 20\%$ and the test method, in this case, the MGU, a similar accuracy, then the shared limits of agreement would be $\pm 28\%$.

The MGU is predominantly used in exercise testing in spontaneously breathing patients. Validation for this device is relatively scanty, even in spontaneously breathing subjects. Cooper and colleagues compared the MGU and four other devices against the DTII in resting subjects and found all were inferior in terms of within-patient COV for resting metabolic rate, ranging from 4.8% to 10.9% compared with 3% for the DTII. Other studies in healthy self-ventilating individuals using the Medgraphics CCM Express, a device similar to the MGU, have shown acceptable agreement, although lower absolute values compared with the reference technique. VO$_2$ in mechanically ventilated patients at rest is relatively low ($\approx 400$ ml min$^{-1}$), in comparison with the 2–5 litre min$^{-1}$ values seen at peak exercise in ambulant healthy individuals. Therefore, the signal-to-noise ratio is far greater in resting mechanically ventilated patients than that recommended by the exercise testing literature.

Data directly validating indirect calorimetry devices in mechanically ventilated patients are also scarce, despite their promotion as a tool to titrate nutritional input. A recent study in 24 ICU patients...

### Table 1: Patient characteristics. $F_iO_2$, fraction of inspired oxygen

<table>
<thead>
<tr>
<th>Patient</th>
<th>Test</th>
<th>Reason for admission</th>
<th>Age</th>
<th>BMI</th>
<th>Gender</th>
<th>Pressure support</th>
<th>PEEP</th>
<th>$F_iO_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>AAA repair</td>
<td>82</td>
<td>29</td>
<td>M</td>
<td>12</td>
<td>5</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Pneumonia</td>
<td>45</td>
<td>14</td>
<td>F</td>
<td>9</td>
<td>2</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Gastric resection</td>
<td>79</td>
<td>25.7</td>
<td>F</td>
<td>5</td>
<td>5</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Pneumonia</td>
<td>70</td>
<td>30</td>
<td>M</td>
<td>NAVA</td>
<td>5</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Pneumonia</td>
<td>71</td>
<td>20</td>
<td>M</td>
<td>13</td>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Coronary artery bypass graft</td>
<td>78</td>
<td>—</td>
<td>M</td>
<td>12</td>
<td>10</td>
<td>0.50</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Whipple’s procedure</td>
<td>66</td>
<td>—</td>
<td>M</td>
<td>10</td>
<td>5</td>
<td>0.30</td>
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<tr>
<td>8</td>
<td>1</td>
<td>Hemi-colectomy</td>
<td>75</td>
<td>21.7</td>
<td>F</td>
<td>13</td>
<td>5</td>
<td>0.35</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>Pancreatitis</td>
<td>79</td>
<td>27.7</td>
<td>M</td>
<td>10</td>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>Small bowel resection</td>
<td>79</td>
<td>19.7</td>
<td>F</td>
<td>5</td>
<td>5</td>
<td>0.28</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>Thrombotic thrombocyto-penic purpura</td>
<td>58</td>
<td>35</td>
<td>F</td>
<td>10</td>
<td>5</td>
<td>0.30</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>Pleurodesis</td>
<td>76</td>
<td>34</td>
<td>M</td>
<td>8</td>
<td>5</td>
<td>0.30</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>Small bowel ischaemia</td>
<td>69</td>
<td>—</td>
<td>F</td>
<td>14</td>
<td>5</td>
<td>0.35</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>Urosepsis and heart failure</td>
<td>74</td>
<td>—</td>
<td>F</td>
<td>20</td>
<td>5</td>
<td>0.40</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>Femoral artery aneurysm</td>
<td>69</td>
<td>—</td>
<td>M</td>
<td>0</td>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>Pneumonia and heart failure</td>
<td>61</td>
<td>47.3</td>
<td>M</td>
<td>0</td>
<td>5</td>
<td>0.30</td>
</tr>
</tbody>
</table>

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Patients reported the mean REE values as 64% higher for the CCM Express compared against the Deltatrac. Repeated readings from the same instrument gave a COV of 4.1% and 7.9% for Deltatrac and CCM Express, respectively. In the present study, we did not find a systematic bias, although limits of agreement were wide. The coefficients of variation for VO₂ were between 1% and 9%. Other studies also found that VO₂ measured by indirect calorimetry (using a DB and mass spectrometry) was 15% higher than that measured by thermodilution in 29 mechanically ventilated patients. In part, this discrepancy may be related to lung oxygen consumption which is not measured by thermodilution and estimated to be 14 (3)% of whole body VO₂. Other studies also report inconsistent findings regarding the accuracy of newer devices compared against the Deltatrac, for example, the M-COXX device.

Many of these studies were performed using mechanical ventilators that did not use bias flow (flow-by). This is a continuous flow of gas, usually in the order of 2 litre min⁻¹ of the pre-set level of inspired O₂ that is incorporated into most, if not all, modern ventilators. It is delivered through the ventilation circuit and reduces the work of breathing and the sensation of air hunger experienced by the patient during the breath trigger phase of the breathing cycle. Depending on the device being utilized for oxygen consumption, mishandling of this extra volume of oxygen added to the expired volume can significantly impact on the values obtained. Both the MGU and DTII are unaffected by bias flow; the MGU utilizes a flowmeter sited at the tracheal tube within the ventilator circuit, while the DTII measures neither flow nor volume as part of its calculation technique. However, this is a potential source of error for the DB collection or any other device that relies on expiratory volumes. On the other hand, the dead space created by ventilator tubing and heat–moisture exchange systems must be adequately accounted for, so that the MGU correctly phase aligns the flow, oxygen, and carbon dioxide signals.

For reliable measurements, scrupulous attention needs to be paid to the performance of the different techniques, and awareness of the many potential pitfalls. For example, both the DB technique and the indirect calorimetry have multiple potential sources of error (Tables 5 and 6). While every attempt was made to control these errors during this study, the Bland–Altman plots illustrate considerable random rather than systematic error. A 16% measurement error for VO₂ is recognized for the DB technique.

We reduced the potential physiological variability of the tests by performing measurements simultaneously. The possibility that the sampling techniques bias each other was small. The DTII samples inspiratory gas continuously at 150 ml min⁻¹ against a mean minute ventilation (MV) of 12 litre min⁻¹ giving, at worst, a reduction of 1.25% of minute volume. The MGU samples gas continuously, both during inspiration and expiration, at a maximum of 130 ml min⁻¹, potentially creating a 0.36% inspiratory volume error and a 0.72% expiratory volume error.

The MGU consistently reported greater MV than the Servo-i ventilator. This error can be accounted for in the different ways the gases are described by the respective device; MGU
Fig 2 Bland-Altman plots for VO2 and VCO2, and scatter plots for RQ for comparisons between the MGU, DTII, and DB techniques. Each colour represents an individual patient. All plots are MGU-the reference device.
as body temperature and pressure-saturated and Servo-i as atmospherically temperature and pressure-saturated at 21°C. Of interest, the Servo-i delivers a 10–20% larger breath than most clinicians would expect (Supplementary material SC).

As a clinical tool, changes in VO2 may be more relevant and reliable than absolute values, for example, in response to a physiological challenge (e.g. sitting on the edge of bed, change of ventilator settings).

Our study enrolled relatively low numbers of patients with a limited range of VO2, but it serves to highlight some of the issues and pitfalls that must be addressed to develop a metabolic monitoring device that is fit for purpose. Such a device needs to be integrated into a mechanical ventilator, accommodate the challenges of temperature, humidity, dead space, and tidal volume entropy and specifically have precision at low levels of VO2.

**Conclusion**

Although showing low bias when compared with the reference methods of the DB technique and the DTII indirect calorimeter, the MGU lacks precision. This may be due in part to limitations of the reference methods. For this field to move forwards, industry must collaborate with clinicians and researchers to improve the accuracy of devices that monitor gas exchange in mechanically ventilated patients.

**Supplementary material**

Supplementary material is available at *British Journal of Anaesthesia* online.

**Authors’ contributions**

C.B.: study design, patient recruitment, data collection, data analysis, and manuscript preparation. M.S.: study supervision and critical review of the manuscript. M.G.: critical review of the manuscript.

**Declaration of interest**

None declared.

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**References**

18 Douglas C. A method for determining the total respiratory exchange imam. In: *Proceedings of the Physiological Society*, 1911
34 Physicians ATsAcoC. ATS/ACCP Statement on cardiopulmonary exercise testing. *Am J Respir Crit Care Med* 2003; 167: 211 – 77

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