Intensive Care Med (1989) 15:196–202

Intensive Care Medicine

Methods and devices

Evaluation of methods for indirect calorimetry with a ventilated lung model*

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Received: 5 October 1988; accepted: 20 November 1988

Abstract. A combined lung and ventilator model was built, validated and used to test commercial systems for indirect calorimetry. It simulates O_2 uptake and CO_2 excretion under ventilator treatment conditions. In the model inspiratory gases are diluted with N_2 and CO_2 to give the desired expiratory concentrations. Minute volume, F_IO_2, ventilatory pressure, $\dot{V}O_2$, $\dot{V}CO_2$ and consequently RQ can be altered to simulate the adult clinical situation. A selected respiratory pattern is maintained by the lung model. Equipment for indirect calorimetry can then be connected to it and the results compared. Reference values are derived from measurements with a mass spectrometer and a Godart spirometer. Three commercially available instruments (Beckman MMC, Horizon MMC and Engström MC) were evaluated with this system. The limits of agreement with the reference values under different conditions (F_IO_2 0.4–0.7, ventilatory pressure 0–50 cmH_2O) were determined. Differences as high as 15% from the true values of $\dot{V}O_2$ and $\dot{V}CO_2$ were observed. The pattern of mechanical ventilation and the intrinsic properties of the analyzers in the equipment used for indirect calorimetry influence measurements to a significant extent.

Key words: Indirect calorimetry – O_2 uptake – CO_2 excretion – Lung model – Ventilatory pressure – Volume and flow measurement

Indirect calorimetry in critically ill patients is a complex procedure requiring gas analysis for O_2 and CO_2 concentrations and volume measurement. Oxygen uptake (O_2 consumption, $\dot{V}O_2$) and carbon dioxide excretion (CO_2 production, $\dot{V}CO_2$) offer useful experimental and clinical information under steady state conditions concerning metabolism and gas exchange [1, 3, 5, 7, 10, 13, 15–17]. In the open system gas analysis and volume determination are easily performed with spontaneously breathing patients and with subjects for exercise measurements but they are difficult to achieve in critically ill patients during mechanical ventilation. Elevated O_2 concentrations, temperature, humidity, ventilatory pressure, ineffective separation of inspired from expired gases and leaks may influence the measurements. Recently a number of commercial instruments have been developed for these measurements. Three examples are the Beckman and the Horizon Metabolic Measurement Carts (MMC) and the Engström Metabolic Computer (EMC). Calibration of the single analyzers does not guarantee correct results. Systematic testing is needed for the evaluation of such complex instruments.

This approach has been applied by Damask et al. [9]. The authors used a simple lung model. They found that commercial instruments (Siemens-Elema Servo ventilator 900 B with Carbon Dioxide analyzer 930, Beckman MMC) measure $\dot{V}O_2$ and $\dot{V}CO_2$ within 5% to 13% of reference values. F_IO_2 did not significantly affect this accuracy but at tidal volumes below 350 ml the difference between measured and control data increased. We are concerned that commercial instruments used for indirect calorimetry in the intensive care unit may produce systematic errors due to the characteristics of the analyzers and the breathing pattern of the ventilator. We have designed a combined ventilator and lung model in order to assess the influence of changing ventilatory variables on the accuracy of the instruments. In this paper our lung model is validated and the effect of altered F_IO_2 and

* This publication includes part of the thesis of J. Zundel and preliminary data were presented at the Workshop Salzburg 1986: Methodische Fragen zur indirekten Kalorimetrie.

Supported in part by the Deutsche Forschungsgemeinschaft "SFB 330 Organprotektion", Göttingen

ventilatory pressure on derived values, such as $\dot{V}O_2$ and respiratory quotient (RQ), is tested in three commercial instruments.

Material and methods

Model description

Our lung model shown in Fig. 1 is designed to simulate a patient on a ventilator. The lung is represented in the model as a bag in the box unit. CO_2 and N_2 are added to the inspiratory gases in order to obtain expiratory gas concentrations and volumes.

The pressure of all gases (anesthetic O_2 and air supply, 99.99% pure N_2 and CO_2) entering the system is reduced and kept constant at 3 atmospheres (gauge). They pass through high precision rotameters (triflat tubes, Fischer and Porter, Göttingen, FRG), which are calibrated for the specific gases and appropriate for the flow range. Gas flow is adjusted with the rotameters using previously established calibration curves according to the ventilatory requirements and then kept constant. The ventilator component of this model has a constant flow characteristic. During inspiration O_2 and air flow through the solenoid valve A into the rubber dilution bag. Moisture is added with a Bennett cascade humidifier (not shown in the diagram) set at 35 °C before the gases reach valve G. N_2 and CO_2 are added to the Air/O_2 mixture via solenoid valve B during inspiration. During expiration all inflowing gases are vented to the atmosphere at valves A and B in order to maintain constant flows through the rotameters.

The time for dilution and mixing can be adjusted according to the shape of the capnogram at the sampling port H as measured by the mass spectrometer. The dilution bag is emptied during expiration by opening valve C and pressurizing the chamber. The expiratory gases are directed from the bag past the sampling port H, via valve G and the vent I with a connecting piece to the Godart spirometer (not shown).

The manometer measures ventilatory pressure during the respiratory cycle. At zero pressure valve F is open during the whole respiratory cycle. The pressure in the pressure chamber does not rise above atmospheric level. Higher inspiratory peak pressures are obtained by valve F preventing the air from leaving the chamber during inspiration. Solenoid valve D is open and the pressure regulator E sets the resistance of valve F for the required pressure.

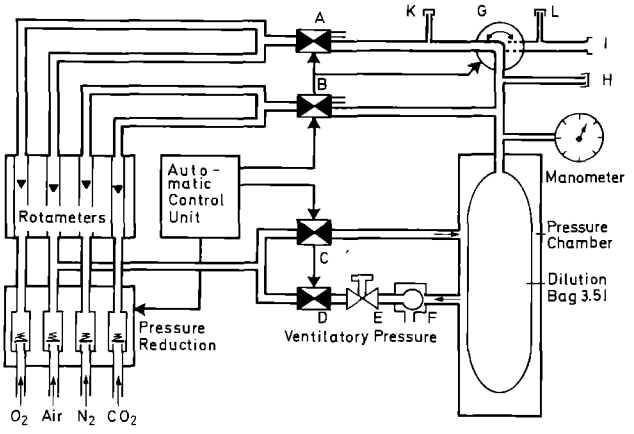

Fig. 1. Schematic presentation of the lung model. A, B, C, D solenoid valves: A, B – for inspiratory gas flow; C – for emptying the dilution bag during expiration; D – determines ventilatory peak pressure via regulator E and valve F; G – mechanical inspiratory/expiratory valve; H, K, L – sampling ports for mass spectrometer; I – connector for the Godart spirometer and the commercial instruments

The rotameter flows are not altered during any series of ventilatory pressure changes. They are not used to calculate the reference values because precise readings can be taken only with difficulty. Instead, the reference values for the model are derived from inspiratory and expiratory gas concentrations sampled at port K and L respectively (mass spectrometer Perkin Elmer MGA 1100) and from expiratory volume measurements at I (Godart wet gas spirometer). This permits the evaluation of the lung model and the assessment of the influence of ventilatory pressure on the reference values. O_2 and CO_2 concentrations and volume are determined by taking single readings at steady state conditions after 3–4 minutes of ventilation. The lung model produces a defined expiratory volume. It does not have a real "biological" inspiratory volume since it does not consume oxygen; it reduces the expiratory oxygen concentration by adding nitrogen and carbon dioxide. This differs from models burning methanol [9] which give a constant respiratory quotient. In our model the RQ can be set to any desired level by adjusting the N_2 flow and leaving the CO_2 flow constant.

Test program

The test program consisted of a constant ventilation with approximately 9.5 l/min. A rate of 10 breaths per minute was chosen with an inspiration/expiration ratio of 1:1. The model was set to vent 350–375 ml CO_2/min STPD with an RQ of 1.0. F_IO_2 was varied from 0.4 to 0.8 and ventilatory peak pressure (P) from 0 to 70 cmH_2O. The systems under investigation were connected to the simulator at vent I and to sampling ports K and H if required.

Calculations

$$\dot{V}_{IATPS} = \dot{V}_IO_2 + \dot{V}_IAir \quad \text{(I)}$$

$$\dot{V}_{EATPS} = \dot{V}_IO_2 + \dot{V}_IAir + \dot{V}N_2 + \dot{V}CO_2 \quad \text{(II)}$$

$$\dot{V}O_{2STPD} = \dot{V}_{E\,STPD} \cdot (F_IO_2 - F_EO_2) \quad \text{(III)}$$

$$\dot{V}CO_{2STPD} = \dot{V}_{E\,STPD} \cdot F_ECO_2 \quad \text{(IV)}$$

Calculations with equations III and IV were made with the volumes corrected for temperature, pressure and saturation for the model and the tested systems. The temperatures were measured in the Godart spirometer and at the commercial volume meters.

Statistical methods

Due to the small number of measurements for variation of pressure ($n = 4$) and of F_IO_2 ($n = 5$) with single readings for each setting and some deviation from the Gaussian distribution, a non-parametric test was selected for all data. The mean differences in percent plus/minus two standard deviations are given for convenience but will be disproportionately large [4]. When a significant difference between tested groups was found with the Friedman test, the Wilcoxon and Wilcox test [19], a rank test for two-way analysis of variance with multiple comparisons, was applied. Data were subjected to tests for pressure and F_IO_2 dependency in the commercial instruments and pressure dependency in the lung model. The instruments were tested against the reference. The Bonferroni method [11] was used to allow for multiple testing at an error level of $\alpha = 0.05$ ($k = 5$). Significant differences are given under results or are indicated in Tables 1 and 2.

Description of the tested instruments

Beckman MMC. The Beckman MMC (MMC B, Beckman instruments, Schiller Park, Illinois, USA) is an automated system designed for exercise testing, which can also be used at the bedside. It measures the expired volume, the mixed expired O_2 and CO_2 con-

Table 1. Differences in measured O_2 uptake and CO_2 elimination between each of three commercial systems and the reference system for varied inspiratory oxygen concentration and ventilatory pressure

F_IO_2	P (cmH_2O)	MMC B			MMC H		EMC	
		$d\dot{V}O_2$ (ml/min)	$d\dot{V}_{corr}O_2$ (ml/min)	$d\dot{V}CO_2$ (ml/min)	$d\dot{V}O_2$ (ml/min)	$d\dot{V}CO_2$ (ml/min)	$d\dot{V}O_2$ (ml/min)	$d\dot{V}CO_2$ (ml/min)
0.4	0	17	8	8	12	3[b]	−15	−15]
0.4	30	−1[a]	−1	15	29	25	−22	−19
0.4	50	69	−19	20	39	35	−33	−31
0.4	70	137[a]	−24	20	23	34[b]	−47	−44]
0.5	0	29	10	2	−10	−28[b]	2	−4
0.5	30	−7[a]	−16	−2	16	5	−12	−19
0.5	50	94	−4	2	20	23	−19	−29
0.5	70	143[a]	−55	2	29	28[b]	−40	−39
0.6	0	8	8	9	−5	−28[b]	4	−9]
0.6	30	−13[a]	−13	12	27	17	−5	−18
0.6	50	111	−20	11	27	20	−13	−26
0.6	70	222[a]	29	10	29	24[b]	−35	−44]
0.7	0	5	−1	2	4	−30[b]	18)	4
0.7	30	−2[a]	−12	8	22	7	9	−5
0.7	50	25	−10	−1	41	19	−6	−20
0.7	70	268[a]	−22	2	54	23[b]	−21)	−35
0.8	0	22	12	−10	−8	−29[b]	−6)	16]
0.8	30	20[a]	−5	19	28	−5	−18	2
0.8	50	145	−15	13	45	21	−25	−15
0.8	70	330[a]	−50	6	47	22[b]	−34)	−37]

Volumes given for STPD conditions
[a, b] Significant differences for pressure (Wilcoxon and Wilcox, $\alpha = 0.05$)
],) Significant differences for F_IO_2 (Wilcoxon and Wilcox, $\alpha = 0.05$)

Table 2. Expiratory volume measured with three commercial systems in comparison with the reference system for varied inspiratory oxygen concentration and ventilatory pressure

F_IO_2	P (cmH_2O)	Ref	MMC B	Ref	MMC H	Ref	EMC
		$\dot{V}_E$ (l/min)	$\dot{V}_E$ (l/min)	$\dot{V}_E$ (l/min)	$\dot{V}_E$ (l/min)	$\dot{V}_E$ (l/min)	$\dot{V}_E$ (l/min)
0.4	0	9.00	9.68	9.07	9.00[b]	9.87	8.70[a]]
0.4	30	9.00	9.71	8.95	9.42	9.77	8.34
0.4	50	9.00	9.72	8.95	9.66	9.80	8.06
0.4	70	8.96	9.77	8.94	9.58[b]	9.79	7.69[a]]
0.5	0	8.98	9.26	9.19	9.00[b]	9.84	8.89[a]]
0.5	30	8.88	9.26	9.09	9.17	9.82	8.61
0.5	50	8.95	9.31	9.13	9.58	9.82	8.34
0.5	70	8.93	9.43	9.05	9.58[b]	9.80	7.97[a]]
0.6	0	8.91	9.64	9.00	8.67[b]	9.82	8.98[a]]
0.6	30	8.95	9.61	8.99	9.33	9.79	8.70
0.6	50	8.96	9.69	8.99	9.42	9.79	8.52
0.6	70	8.91	9.66	8.98	9.42[b]	9.78	8.15[a]]
0.7	0	8.92	9.66	9.14	8.92[b]	9.94	9.34[a]]
0.7	30	8.92	9.72	9.14	9.25	9.89	9.07
0.7	50	8.91	9.78	9.14	9.50	9.94	8.70
0.7	70	8.91	9.68	9.10	9.58[b]	9.88	8.24[a]]
0.8	0	9.22	9.58	9.22	9.00[b]	10.04	9.80[a]]
0.8	30	9.20	10.00	9.22	9.25	10.03	9.48
0.8	50	9.18	9.65	9.19	9.58	10.01	8.98
0.8	70	9.18	9.61	9.21	9.66[b]	10.02	8.52[a]]

Volumes given for STPD conditions
[a, b] Significant differences for pressure (Wilcoxon and Wilcox, $\alpha = 0.05$)
] Significant differences for F_IO_2 (Wilcoxon and Wilcox, $\alpha = 0.05$)

centrations and the inspired O_2 concentration of a patient on a ventilator. It contains an expiratory volume meter using a turbine with a bias flow, an infrared CO_2 analyzer (Beckman LB2) and a polarographic O_2 electrode (Beckman OM-11). In the clinical situation inspiratory O_2 is sampled at the Y-piece of the ventilator tubings. Expiratory gases are drawn from the mixing chamber where they have to be returned for volume determination. Inspiratory O_2 is measured wet; expiratory gases are first dried. The effect of moisture has to be corrected for [6]. The system is linked to the model via vent I and sampling line H (Fig. 1). The latter corresponds to sampling at the Y-piece. In our department we have modified the instruments to compensate for the effect of pressure on the O_2 sensor by an added differential amplifier. We tested the commercial and our modified Beckman MMC (Table 1, $d\dot{V}$ and $d\dot{V}_{corr}$ for O_2).

Horizon MMC. This instrument (MMC H, Sensor Medics, Anaheim, California, USA) is the successor of the Beckman MMC and was also designed for exercise testing. Facilities are incorporated for the calibration of gas analyzers and the volume meter. The turbine in the volume meter has a better resolution than in the Beckman MMC (2.5 ml instead of 10 ml). No bias flow is applied; the turbine is set in motion with every expiration. The gas analyzers are improved versions of Beckman OM-11 and LB-2. The inspiratory gas samples for O_2 are taken from the inspiratory line and not from the Y-piece. The effect of ventilatory pressure on the O_2 electrode is compensated for. All gas samples are dried before being measured. The Horizon MMC is connected with the model via vent I and sampling line K.

Engström MC. The EMC (Gambro Engström AB, Bromma, Sweden) was designed as an integrated part of the Engström Erica ventilator [8]. Volume is measured in the inspiratory line with a venturi flowmeter. A self-calibrating O_2 fuel cell and an infrared CO_2 analyzer (Engström-Eliza) are utilized for gas analysis. Gas samples are taken from inspiratory and expiratory mixing bags. The EMC uses Aridus gas tubes which equilibrate temperature and moisture of the samples with room air. The venturi flowmeter in the ventilator and measurement system has a dual function. It measures volume and controls volume delivery of the ventilator. For evaluation the EMC had to be separated from the Erica ventilator to connect it to our lung model[1]. The model was modified to allow the combination of N_2 and CO_2 from valve B with the gases from valve A between K and G (Fig. 1). The venturi flowmeter was then also positioned between K and G so that it would measure the combined gas flows from valves A and B as inspiratory volume. The inspiratory mixing bag was connected to sampling port K and the expiratory mixing chamber to vent I.

Results

Once set for a ventilatory pressure the lung model will maintain its gas exchange pattern even if there is some degree of pressure variation (Table 2). However, with large increases in ventilatory pressure a statistically significant decrease (Wilcoxon and Wilcox, $\alpha = 0.05$) in delivered volume was noted at 70 cmH_2O (vs 0 cmH_2O). The actual mean difference was -0.51% (-1.39 to $+0.36$). The difference between $F_I O_2$ and $F_E O_2$ remained unaffected by pressure variation. $F_E CO_2$ was significantly different at 0 cmH_2O vs 50 and 70 cmH_2O as well as at 30 cmH_2O vs 50 cmH_2O ventilatory pressure ($\alpha = 0.05$). It was 2.56% (-5.15 to $+0.03$) lower at 70 cmH_2O compared to 0 cmH_2O. The following results for the commercial systems are not affected as the corresponding measurements by the mass spectrometer and Godart spirometer are used as reference values.

There were significant deviations between volumes and oxygen concentration differences measured by the Engström MC (EMC) and by the modified Beckman MMC. Both the MMC Beckman and Horizon MMC differed from the EMC in the determination of $F_E CO_2$ ($\alpha = 0.05$).

Deviation from the reference values generally is larger for ventilatory pressure above 30 cmH_2O (Fig. 2). $\dot{V}O_2$ measurement is affected most in the original Beckman MMC (Table 1, $d\dot{V}O_2$ $\alpha = 0.05$). After installing the differential amplifier, the differences for $\dot{V}O_2$ are no longer statistically significant (Table 1, $d\dot{V}_{corr}$ O_2).

At zero ventilatory pressure all instruments respond within 10% (d±2s) for $\dot{V}O_2$ and $\dot{V}CO_2$ (Table 1), except for the MMC Horizon which has a mean difference of -6.3% for $\dot{V}CO_2$ (-14.9 to $+2.7$). Figure 2 shows increasing $\dot{V}O_2$ and $\dot{V}CO_2$ measurements for higher ventilatory pressure with the Horizon MMC. Both volume and $F_E CO_2$ measurements are

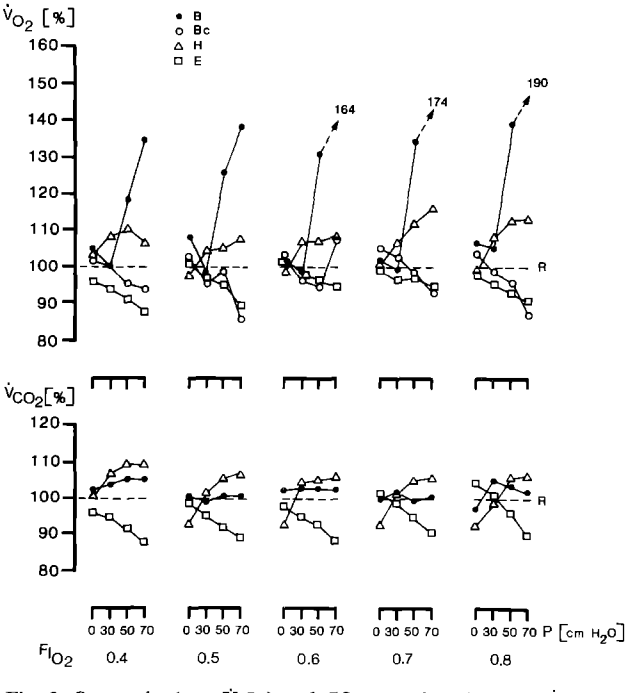

Fig. 2. O_2 uptake (top, $\dot{V}O_2$) and CO_2 excretion (bottom, $\dot{V}CO_2$), measured with three commercial instruments for indirect calorimetry; all data are given in percent of the reference values for the lung model; B – Beckman MMC; Bc – Beckman MMC $F_I O_2$ corrected; H – Horizon MMC; E – Engström MC

[1] We gratefully acknowledge the manufacturer's permission and advice when adapting the Engström MC to our model

significantly affected ($\alpha = 0.05$) but $\dot{V}CO_2$ agrees best with the reference values at 30 cmH_2O ventilatory pressure (F_IO_2 0.5–0.7).

In the EMC increasing F_IO_2 significantly alters F_ECO_2 and F_EO_2 ($\alpha = 0.05$). Increasing pressure reduces volume measurement ($\alpha = 0.05$, Table 1). Increasing F_IO_2 tends to counteract it by augmenting the flow signal ($\alpha = 0.05$, Table 2). Figure 2 shows that $\dot{V}CO_2$ (bottom) and $\dot{V}O_2$ (top) are affected in a similar manner so that the resulting RQ remains valid.

The mean differences for $\dot{V}O_2$ and $\dot{V}CO_2$ of the tested instruments and the reference system, with all ventilatory pressures and O_2 concentrations tested, are given below as difference (d) and range (d−2s to d+2s) in %:

Beckman MMC	$d\dot{V}O_2$ = 20.5% (−29.7% to +70.4%)
F_IO_2 corrected	$d\dot{V}O_2$ = −2.9% (−14.4% to +8.5%)
	$d\dot{V}CO_2$ = −2.1% (−2.4% to +6.5%)
Horizon MMC	$d\dot{V}O_2$ = +6.5% (−3.5% to +16.5%)
	$d\dot{V}CO_2$ = −2.5% (−14.5% to +9.4%)
Engström MC	$d\dot{V}O_2$ = +4.7% (−5.4% to +14.8%)
	$d\dot{V}CO_2$ = −5.6% (−15.2% to +4.0%)

The following limits of agreement (d−2s to d+2s) cover the more common settings used in the clinical situation, F_IO_2 0.4–0.7 and 0–50 cmH_2O ventilatory pressure:

Beckman MMC	$d\dot{V}O_2$ = +7.6% (−14.8% to +30.0%)
F_IO_2 corrected	$d\dot{V}O_2$ = −1.6% (−7.8% to +4.5%)
	$d\dot{V}CO_2$ = −2.0% (−1.8% to 5.7%)
Horizon MMC	$d\dot{V}O_2$ = +5.2% (−3.8% to +14.1%)
	$d\dot{V}CO_2$ = −1.6% (−13.9% to +10.8%)
Engström MC	$d\dot{V}O_2$ = +2.2% (−6.1% to +10.6%)
	$d\dot{V}CO_2$ = −4.6% (−10.7% to +1.5%)

In conclusion the polarographic O_2 electrode in the Beckman MMC is extremely sensitive to increased ventilatory pressure. Volume measurement with the Beckman "turbine" is not affected by ventilatory pressure or oxygen concentration of the gas mixture. Gas composition influences the performance of the flow sensor and the CO_2 electrode to a small but measurable degree in the EMC. The effect of pressure is evident in both the EMC and Horizon MMC. It is possible to use all tested systems for indirect calorimetry within a limited F_IO_2 and pressure range. The pattern of mechanical ventilation and the intrinsic properties of the analyzers in the equipment influence the results to a significant extent.

Discussion

$\dot{V}O_2$ and $\dot{V}CO_2$ are not assessed directly but are calculated from measured values [14]. The rate of exchange of oxygen in a patient is:

$$\dot{V}O_2 = F_IO_2 \cdot \dot{V}_I - F_EO_2 \cdot \dot{V}_E \ . \quad \text{(V)}$$

The rate of exchange of nitrogen is:

$$\dot{V}N_2 = F_IN_2 \cdot \dot{V}_I - F_EN_2 \cdot \dot{V}_E \ . \quad \text{(VI)}$$

Since, in a steady state, the body neither produces nor consumes nitrogen, the rate of exchange of nitrogen is zero:

$$F_IN_2 \cdot \dot{V}_I = F_EN_2 \cdot \dot{V}_E \quad \text{or} \quad \text{(VII)}$$

$$\dot{V}_I = F_EN_2/F_IN_2 \cdot \dot{V}_E \ . \quad \text{(VIII)}$$

Equations V and VIII may be combined to give:

$$\dot{V}O_2 = [(F_IO_2 \cdot F_EN_2/F_IN_2) - F_EO_2] \cdot \dot{V}_E \ . \quad \text{(IX)}$$

Generally the nitrogen concentrations are determined by subtraction from one. Equation IX may thus be written as:

$$\dot{V}O_2 = [(1 - F_EO_2 - F_ECO_2/1 - F_IO_2 \cdot F_IO_2) - F_EO_2] \cdot \dot{V}_E \quad \text{(X)}$$

which is the Haldane transformation.

The Beckman and Horizon MMC apply equation X for the calculation of $\dot{V}O_2$. The EMC determines $\dot{V}O_2$ by calculating $\dot{V}_E$ from $\dot{V}_I$ instead. Enormous errors of $\dot{V}O_2$ may arise with the use of these equations because errors in measurement of the individual gas concentrations multiply. This is especially true for large F_IO_2 and low F_ECO_2 values. It has been shown that measurement of exhaled and inhaled concentra-

tions of nitrogen (equation IX) decreases the error in oxygen uptake determination substantially at high inspired oxygen concentrations [2]. We used equations III and IV for our model and the tested commercial systems to avoid these problems. This requires that in RQ = 1.0 and $\dot{V}_I = \dot{V}_E$. Both conditions were met in our experiments. Thus we analyzed the functions and accuracy of the commercial systems and the influence of ventilatory patterns irrespective of errors introduced by the Haldane transformation.

Delivered volume and $F_E CO_2$ in the model are also influenced by ventilatory pressure to some extent. However our results are not affected since the reference values are obtained independently. The precision and linearity of the gas analyzers were without problems in our investigations except that mechanical ventilation has an effect on some electrodes, which cannot be anticipated by the calibration procedure (ventilatory pressure on $F_I O_2$ in the Beckman MMC [6] and $F_I O_2$ on $F_E CO_2$ in the Engström MC). Stability of the devices and their reaction to step changes was not under investigation.

Volume measurement is crucial. The increase in apparatus dead space with high ventilatory pressures (compression volume) does not produce an error as long as all delivered volume is registered in the volume meters. This is the case in all the tested systems. The error of tidal volume measurement is then compensated for by a corresponding change in gas analysis. The Beckman MMC "turbine" with a bias flow of 12 l/min is an accurate instrument under all tested conditions. It functions as a true volume measuring device and is not affected by ventilatory pressure and gas viscosity [20]. Its drawback was the tedious procedure of adjusting the bias flow to indicate zero. Therefore the bias flow was eliminated in the next "turbine" generation (Horizon MMC). It is our conclusion from the presented experimental data that the recoil of the lung influences the performance of the new volume meter, which shows an inertia effect. This is evident at lower pressures. Stable but erroneously high readings are obtained at higher pressures. The "turbine" worked accurately in a model simulation of spontaneous breathing (i.e. exercise testing conditions [12]).

Elevated ventilatory pressure and high $F_I O_2$ have an adverse effect of about the same magnitude on the venturi flowmeter in the EMC. Since both parameters are measured in the EMC, the errors could be eliminated easily. It is important to realize that the flowmeter in the EMC measures not only volume but also controls volume delivery. At high ventilatory pressures volume measurement is misleading. With our lung model we get low values for $\dot{V}O_2$ and $\dot{V}CO_2$. In the clinical situation the EMC will adjust volume delivery to attain the set volume. Thus volume delivery will be higher than desired. $\dot{V}O_2$ and $\dot{V}CO_2$ are, however, calculated with the set volume, whilst expired gas concentrations are lower due to dilution. Nevertheless RQ is correct. Thus our measurements also apply to the complete Engström system. In it the effects of gas composition on $\dot{V}_I$, and of $F_I O_2$ on $F_E CO_2$ are compensated for, but the effect of ventilatory pressure is not taken into account.

A ventilated lung model for the evaluation of the complex methods of indirect calorimetry offers the advantages of testing devices without having to attain a biological steady state, interfering with nursing care or making animal experiments. The accuracy of commercial instruments (Horizon MMC, Engström MC) is sufficient for gas exchange measurements during controlled mechanical ventilation. The Beckman MC is no longer commercially available but is also suitable if modified by the addition of a differential amplifier. Ventilation patterns and the intrinsic properties of the analyzers do influence the results. Future developments in equipment for indirect calorimetry which can be applied clinically should aim at avoiding the difficulties in volume measurement. These can be overcome for oxygen uptake determination by using methods such as the replenishment technique [18]. The possibilities for measuring oxygen and carbon dioxide with a constant flow generator should be investigated.

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