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Experimental and clinical tests of the oxyconsumeter: A new oxygen uptake monitor

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Summary

The prototype of a microprocessor controlled oxygen uptake monitor oxyconsumeter developed by Draegerwerk AG, Luebeck, FRG, has been tested. The measuring accuracy of this device was assessed with laboratory bench experiments utilizing both the nitrogen dilution technique and the hydrogen combustion technique to simulate oxygen uptake ($\dot{V}O2$). The correlation coefficient between the simulated and the measured $\dot{V}O2$ values was 0.9989 ($p < 0.05$, $n = 115$). The average relative error of the $\dot{V}O2$ values was $-3.32\% \pm 3.88\%$ when breathing 21 vol% oxygen and $-5.58\% \pm 4.53\%$ for 70 vol% oxygen (percent of reading). This was within the range given by the manufacturer ($\pm 5\%$ for 21 vol% to < 40 vol%, $\pm 10\%$ for 40 vol% to < 70 vol%) with few exceptions. Furthermore the oxyconsumeter was used in clinical experiments to determine oxygen uptake during general anaesthesia. Oxygen uptake was monitored using a non-rebreathing system with an externally triggered expiratory valve. The difference between preanaesthetic reference values and values determined during anaesthesia averaged -24.8 ± 20.1 ml/min/m2 oxygen. This average relative change of $-16.0 \pm 11.5\%$ was statistically significant in 11 of 15 cases ($p < 0.05$).

Introduction

Knowledge of whole-body oxygen uptake ($\dot{V}O2$) in critically ill patients is important in understanding cardiovascular function, tissue perfusion, tissue metabolism, and caloric expenditure [3, 10, 13, 16, 25, 35]. Significant abnormalities in $\dot{V}O2$ and metabolism often occur in the critically ill patient. Reduced oxygen uptake in patients with severely reduced cardiac index may represent obligatory adjustment at the tissue level to critically reduced oxygen delivery. In hypovolemic shock, the $\dot{V}O2$ decreases as the cardiac output declines, which is due to vascular volume depletion [3, 17, 26, 35]. The change in oxygen uptake with shock is to be seen in connection with the acid-base balance [17]. A decrease in $\dot{V}O2$ indicates deterioration, an increase indicates an improvement of the patient's situation. Therapy monitoring by continuous measurement of $\dot{V}O2$ in hypovolemic shock is more advantageous than monitoring blood pressure [17]. Cellular dysfunction in septic shock causes a decreased $\dot{V}O2$, despite a normal or higher than normal cardiac output [15, 35]. Multiple fractures and major infections such as peritonitis can cause an increase in metabolic rate and in $\dot{V}O2$ by as much as 50%. In extensive third degree burns metabolic rates are often 50% to 110% higher than normal [15].

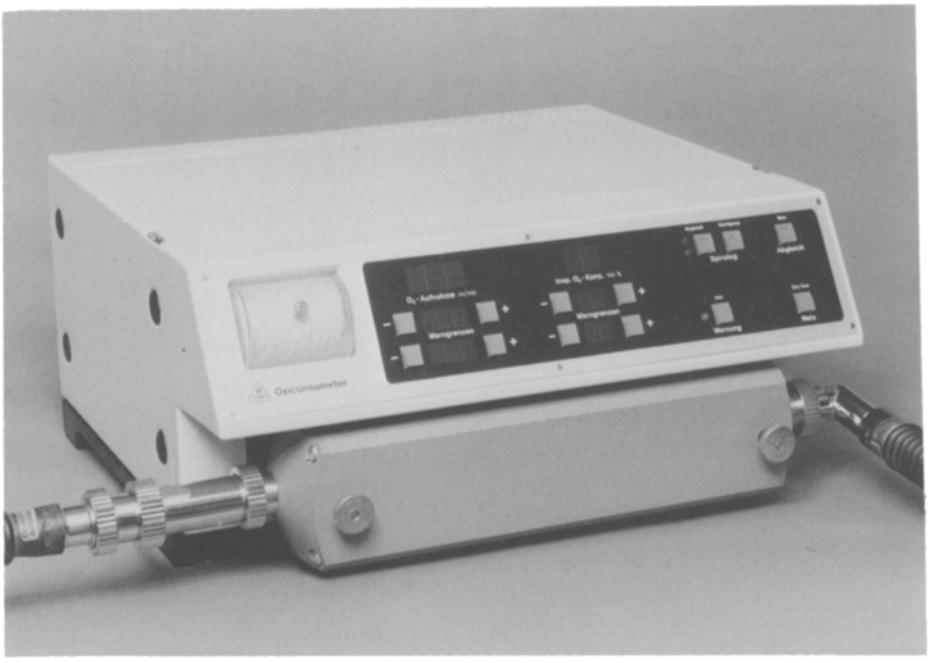

Fig. 1. The oxyconsumeter oxygen uptake monitor, general view.

Indications for the continuous monitoring of $\dot{V}O2$ in critically ill patients are:

- monitoring for several types of shock [3, 17];
- monitoring the time course of diseases with low or high metabolic rate (artificial hypotension, intoxication, major infections, multiple injuries, third degree burns) [7, 15, 31];
- control of cardiopulmonary function, e.g., post-extra-corporeal circulation [18, 31];
- monitoring adult respiratory distress syndrome [6];
- control of parenteral nutrition [10, 15];
- control of weaning from ventilator [31];
- calculation of cardiac output by the Fick principle [1, 3, 17, 19, 33].

The methods for measuring $\dot{V}O2$ can be classified as follows:

- Douglas bag, spirometry [8, 11, 21];
- computer aided inspiratory and expiratory gas analysis [23];
- flow-through technique [14, 17];
- replenishment technique [30, 33, 34, 35].

Several limitations (the expense of instrumentation, the need for frequent manual calibration, patient interface difficulties, and intermittent determination) discourage conventional methods for their clinical routine use [34]. The measurement of $\dot{V}O2$ in critically ill patients using improved measuring methods introduces difficulties too. Some of the problems are: maintenance of a constant inspiratory oxygen concentration, accurate measurement of tidal volume and tightness of the breathing system [9, 13, 24, 32]. Several commercial oxygen uptake monitors have recently been developed for measuring oxygen uptake in critically ill patients [2, 4, 35]. One of these is the oxyconsumeter, developed by Draegerwerk AG, Luebeck, FRG. An earlier prototype was tested both in the laboratory and in the clinic. Although the instrument was designed for application in intensive therapy, we performed clinical tests in anaesthetised patients.

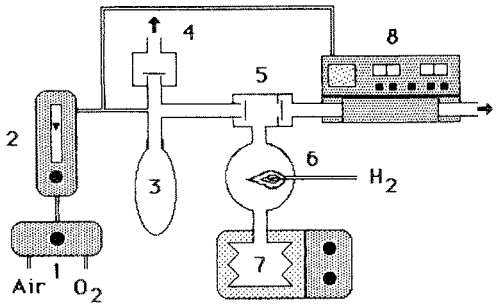

Fig. 2. Experimental arrangements for simulating oxygen uptake: 1. Gas mixing device, 2. Flowmeter, 3. Breathing bag, 4. Overflow valve, 5. Non-rebreathing valve, 6. Combustion chamber (using the nitrogen-dilution technique the combustion chamber was substituted by a T-piece for adding nitrogen), 7. Anaesthesia ventilator, 8. Oxyconsumeter.

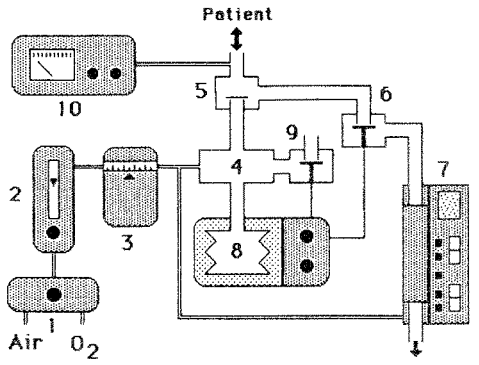

Fig. 3. Experimental arrangement for measuring the oxygen uptake during anaesthesia: 1. Gas mixing device, 2. Flowmeter, 3. Halothane vaporizer, 4. Non-rebreathing anaesthetic system, 5. Inspiratory valve, 6. Externally triggered expiratory valve, 7. Oxyconsumeter, 8. Anaesthesia ventilator, 9. Pressure release valve, 10. Carbon dioxide monitor.

Material and methods

Description of instrumentation

The oxyconsumeter is a microprocessor controlled instrument designed for the continuous monitoring of $\dot{V}O2$ in a non-rebreathing system (Fig. 1). The measuring principle of the oxyconsumeter is based on the replenishment technique. This technique was first described by Westenskow et al. in 1977 [33] for the rebreathing system and in 1978 [34] for the non-rebreathing system.

All expired gas from the patient passes a mixing chamber. Gas samples from the inspiratory limb of the breathing system and from the outlet of the mixing chamber are analysed for their oxygen concentration. After comparing these values, oxygen will be added to the expiratory gas until the mixed-expiratory oxygen concentration equals the inspiratory oxygen concentration (FIO2) [33, 34]. The added oxygen flow, which corresponds in steady state to the patient's oxygen uptake, is measured and displayed in ml/min. The displayed value corresponds to the mean value of 15 breaths. This is realized by the following technique: The values of 15 breaths are stored electronically. After each breath the first of these values will be deleted and the last value stored.

Advantages of this technique are [33]:

- measurement of inspired or expired flow is not required
- the oxygen sensor is a null detector, so a simpler, less expensive sensor can be used at higher inspired oxygen percents
- the system can be applied to many respiratory systems without major modifications

The prototype built by Draeger has a working range for

- minute volume from 5 to 25 l/min
- FIO2 from 20 to 70 vol%
- $\dot{V}O2$ from 100 to 1000 ml/min

(Its accuracy is given as
21 vol% to < 40 vol%: ± 5%,
40 vol% to < 70 vol%: ± 10%)

The accuracy of the oxyconsumeter was assessed using two different methods.

Nitrogen dilution technique

The experimental arrangement is shown in Fig. 2. A breathing bag with a volume of 3 liters was filled with an oxygen/air mixture produced by a gas mixer (Polymed 201, Draegerwerk AG, Luebeck, FRG).

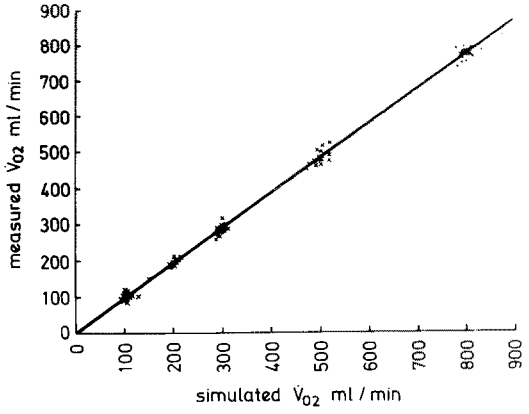

Fig. 4. Regression line showing the linear dependence between the simulated and the measured $\dot{V}O2$ values. ($\dot{V}O2$ meas. = −2.13 + 0.9678 ⋆ $\dot{V}O2$ sim.; r = 0.9989; n = 115)

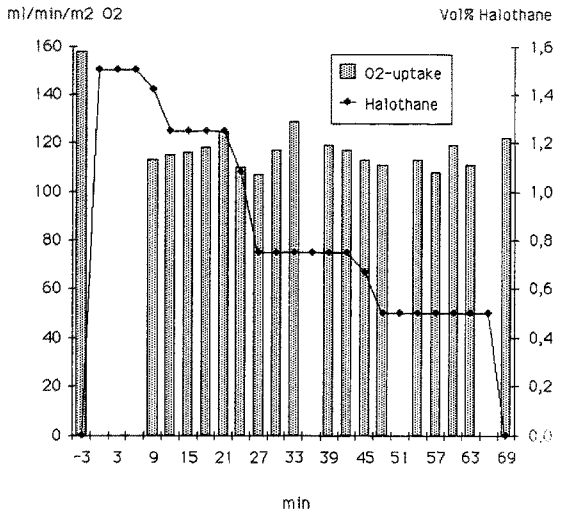

Fig. 5. Oxygen uptake index during anaesthesia in a female patient (age: 43, height: 167 cm, weight: 59 kg) undergoing radical mastectomy. Each column represents mean $\dot{V}O2$ values of 3 measurements. The first column shows oxygen uptake before induction of anaesthesia.

Using a ventilator a distinct gas volume was intermittently taken from the breathing bag via a non-rebreathing valve and directed to the oxyconsumeter. To this 'breathing gas' a defined volume of one hundred percent nitrogen was added to simulate $\dot{V}O2$ by diluent effect [14]. The nitrogen flow was measured with a bubble flowmeter [27]. Flow was measured before and after each trial. Excessive fresh gas could escape through an overflow valve. The added nitrogen ($\dot{V}N2$ add) simulated $\dot{V}O2$ according to the relationship [22]:

$$\dot{V}O2 = \frac{\dot{V}N2 \text{ add} \times FIO2}{(1 - FIO2)}$$

In this study the oxygen concentrations of the fresh gas were determined using the oxygen sensors of the oxyconsumeter. These values checked twice at different days with a magneto-dynamic oxygen analyser (Servomex Oxygen Analyser OA.570, Sybron Taylor, U.K.) yielded a mean value (n = 11) of the relative error of −1.28 ± 1.24%.

Experimental conditions:

- simulated oxygen uptake (ml/min): 100, 200, 300, 500, 800
- tidal volume (ml): 500, 1000
- respiratory frequency (1/min): 10, 15, 20, 25*
- O2-concentration (vol%): 21, 30, 40, 70**

* only with tidal volume 1000 ml

** only with frequencies 10 and 15 /min

Table 1. Measuring accuracy of the oxyconsumeter for simulating oxygen uptake using the nitrogen dilution technique (number of measurements in each condition n = 19).

Sim. O2 uptake (mean values) (ml/min)	Meas. O2 uptake (mean values) (ml/min)	Relative error (mean values ± SD) (%)
104.1	99.1	−4.52 ± 8.36
202.2	195.4	−3.34 ± 3.15
299.1	285.7	−4.48 ± 3.61
497.0	478.0	−3.84 ± 2.48
803.0	774.8	−3.53 ± 1.61

Table 2. Measuring accuracy of the oxyconsumeter for simulating oxygen uptake using the hydrogen combustion technique (number of measurements in each condition n = 4).

Sim. O2 uptake (mean values) (ml/min)	Meas. O2 uptake (mean values) (ml/min)	Relative error (mean values ± SD) (%)
114.8	107.6	−6.35 ± 10.54
209.3	199.9	−4.47 ± 2.08
303.2	287.7	−5.11 ± 3.29
513.9	496.7	−3.29 ± 4.86
825.1	802.7	−2.59 ± 3.42

At each condition during a period of 22 breaths the $\dot{V}O2$ value of every second breath was taken for calculating mean values (n = 11).

Hydrogen combustion technique

This method is based on the combustion of hydrogen. Hydrogen was burned inside a 5 l cylindrical copper container [28]. The container was cooled by a water coil-type radiator. The hydrogen flow was measured with a bubble flowmeter too. To avoid the formation of nitrogen oxides, nitrogen was substituted by argon in the fresh gas mixture.

The oxygen uptake is expressed by the equation:

$$2\ H2 + O2 \rightarrow 2\ H2O$$

It is assumed that both gases are ideal, in this way the molar relation can be transformed to an equation with volume dimensions [28]. The measuring arrangement for testing the oxyconsumeter corresponded essentially to that used by the nitrogen dilution technique (Fig. 2).

Experimental conditions:

- simulated oxygen uptake (ml/min): 100, 200, 300, 500, 800
- tidal volume (ml): 500
- respiratory frequency (1/min): 10, 15, 25
- O2-concentration (vol%): 30, 70*

* only with frequencies 10 and 15 /min

At each condition $\dot{V}O2$ was averaged over 22 breaths and of mean value calculated (n = 11). This value was taken as basic value for all further calculations. The calculation of the relative error is based on the equation:

$$\text{relative error} = \frac{\dot{V}O2\ \text{meas.} - \dot{V}O2\ \text{sim.}}{\dot{V}O2\ \text{sim.}} * 100$$

Table 3. Mean values of the relative errors of the measured oxygen uptake for different inspired oxygen concentrations (FIO2).

FIO2 (vol%)	Mean rel. errors (%) ± SD of the measured $\dot{V}O2$	
	N2 dilution techn.	H2 combustion techn.
21	−3.32 ± 3.88 (n = 25)	–
30	−3.05 ± 5.11 (n = 25)	−5.64 ± 6.79 (n = 10)
40	−4.15 ± 4.01 (n = 25)	–
70	−5.58 ± 4.53 (n = 20)	−3.09 ± 2.84 (n = 10)

Monitoring of oxygen uptake during anaesthesia

$\dot{V}O2$ was measured in 15 female patients, age 40 to 69 years, undergoing mastectomies. In 10 patients the inspired oxygen concentration was 40 vol% and in 5 patients 60 vol%. About 45–60 minutes after premedication (1 mg/kg pethidine and 0.01 mg/kg atropine) $\dot{V}O2$ was measured for about ten minutes and the last three one minute values averaged to find the mean value. The patient breathed room air via a mouthpiece and a non-rebreathing valve directed the expired gas to the oxyconsumeter.

All patients were anaesthetized with hexobarbitone (4.42–8.91 mg/kg), halothane (0.5–1.5 vol%) in oxygen/air and fentanyl if necessary (single dose: 0.1 mg). Following the recommendation of the manufacturer, nitrous oxide was avoided. Endotracheal intubation was facilitated with suxamethonium (1.30 mg/kg), and during anaesthesia muscle relaxation was maintained with a suxamethonium drip (1 mg/ml). All patients were ventilated with IPPV using a volume controlled ventilator. The endexpiratory CO2 was measured using a CO2-Monitor Normocap CD–102 (Datex Instrumentarium Oy, Finland) and maintained between 3.3 vol% and 4.8 vol%.

A non-rebreathing anaesthetic system was used (Fig. 3). An important part of this system is an externally triggered expiratory valve, which ensures a continuous expiratory gas flow without disturbances. The values for oxygen uptake measured by the oxyconsumeter during anaesthesia were recorded every minute, starting 15 min after endotracheal intubation. Depending on the duration of anaesthesia the number of values ranged from 30 and 111. During the study the room temperature averaged 24.5°C (range 24 to 25°C) and the barometric pressure averaged 767 mmHg (range 755–775 mmHg). All oxygen uptake values shown in the text and tables are at ATPD conditions.

Results

Table 1 shows mean $\dot{V}O2$ values and their relative errors using the nitrogen dilution technique. Table 2 gives results for the hydrogen combustion technique. Accuracy was independent of the inspired oxygen concentration and the different breathing parameters. All mean $\dot{V}O2$ values show a negative offset from the simulated values. Table 3 gives mean values for the relative errors for different FIO2. The average relative error determined with the nitrogen dilution technique increases from $-3.32 \pm 3.88\%$ in room air to $-5.58 \pm 4.53\%$ in 70 vol% O2. The average relative error with the hydrogen combustion technique was $-5.64 \pm 6.79\%$ in a fresh gas mixture with 30 vol% O2 and $-3.09 \pm 2.84\%$ in that of 70 vol% O2. The correlation coefficient between measured $\dot{V}O2$ and the values simulated using the nitrogen dilution technique was 0.9991. The regression equation was $\dot{V}O2$ meas. $= -1.50 + 0.9659 \star$ ($\dot{V}O2$ sim). The correlation coefficient for the hydrogen combustion technique was 0.9980, and the regression equation was

$$\dot{V}O2 \text{ meas.} = -5.04 + 0.9764 \star (\dot{V}O2 \text{ sim}).$$

The results of the correlation analysis indicate a strong liner dependence between the simulated $\dot{V}O2$ values and the measured $\dot{V}O2$ values. The very small difference between both regression lines can not be plotted. Therefore all simulated and measured values of both techniques are plotted together (Fig. 4). The relative errors are independent on the inspired oxygen concentration as shown by analysis of variance ($p < 0.05$).

Table 4 shows the results of the clinical experiments. The mean value for oxygen uptake index before anaesthesia breathing air was 148.5 ± 19.7 ml/min/m2. The mean value for oxygen uptake index during anaesthesia was 123.7 ± 19.7 ml/min/m2. Statistically there is a significant difference between the preanaesthetic reference values and the values determined during anaesthesia in 11 of 15 cases (U-test, $p < 0.05$). The decrease in oxygen uptake averaged $16 \pm 11.5\%$ for all 15 patients.

For the studied 15 patients the standard deviation of oxygen uptake index ranged from ± 5.8 ml/min/m2 to ± 27.9 ml/min/m2. The oxygen uptake during anaesthesia showed more or less distinct fluctuations (Fig. 5).

Discussion

The main purpose of this investigation was to mea-

Table 4. Mean values ($\pm$ SD) of oxygen uptake index (ml/min/m2) of each of 15 cases before (A) and during (B) anaesthesia.

Case	A	B	Diff. (%)	Sign.
1	152 ± 14.9	121 ± 9.2	−21	*
2	159 ± 10.7	116 ± 5.8	−27	*
3	178 ± 8.5	117 ± 11.0	−35	*
4	142 ± 1.6	114 ± 9.7	−20	*
5	132 ± 9.5	109 ± 6.7	−17	*
6	131 ± 27.6	112 ± 17.8	−15	
7	126 ± 3.2	105 ± 10.3	−17	*
8	130 ± 2.1	114 ± 6.8	−12	*
9	163 ± 7.9	129 ± 11.0	−21	*
10	128 ± 10.6	127 ± 7.5	− 0.4	
11	133 ± 6.6	123 ± 8.6	− 7	*
12	186 ± 5.5	133 ± 17.1	−29	*
13	156 ± 11.0	117 ± 10.9	−25	*
14	172 ± 12.2	188 ± 27.9	+ 9	
15	140 ± 6.3	131 ± 11.4	− 7	

* Significance of the difference: $p < 0.05$ (U-test).

sure the accuracy of a prototype oxygen monitor (oxyconsumeter) within its working range under simulated clinical conditions typical for adults.

The used nitrogen dilution and hydrogen combustion techniques are established methods for simulating oxygen uptake ($\dot{V}O2$) [5, 14, 22, 28]. The accuracy of these two methods are limited by the accuracy of the flowmeter used for measuring the nitrogen and the hydrogen flow resp. [35]. One of the best suited flowmeters for measuring small gas flows is the bubble flowmeter, which has an accuracy better than 2% [27]. The reproducibility of our bubble flowmeters is characterized by a variation coefficient between 0.19% and 0.79% of reading for nitrogen and 0.22% and 0.62% for hydrogen with respect to the range of the simulated $\dot{V}O2$ values.

Our studies demonstrate the accuracy of the oxyconsumeter as well as its limitations. The errors of the measured $\dot{V}O2$ mean values ascertained in this study are within the range given by the manufacturer. The slight increase of the relative error seen with high oxygen concentration in the fresh gas mixture using the nitrogen dilution technique was not statistically significant, as shown by analysis of variance. The predominant negative measuring errors seem to be a systematic error caused by the calibration of the oxyconsumeter prototype by the manufacturer.

This study demonstrated the use of the oxyconsumeter during anaesthesia. It was not intended to find relations between depth of anaesthesia and $\dot{V}O2$.

For proper function the oxyconsumeter needs an undisturbed expiratory gas flow. Therefore the clinical experiments were performed using a modified non-rebreathing system with an externally triggered expiratory valve. Because of a significant cross-sensitivity of the oxygen sensors of the oxyconsumeter against nitrous oxide the application of nitrous oxide during anaesthesia was strictly avoided.

Comparing the oxygen uptake values during anaesthesia with the preanaesthetic reference values in 11 of 15 cases a significant decrease ($-16\% \pm 11.5\%$) in oxygen uptake was seen. The average oxygen uptake index in our patients was 114 ± 18 ml/min/m2 (STPD) during halothane anaesthesia. The calculated basal oxygen uptake index was 121 ml/min/m2, using the age and sex of the patients in this study and a table adapted from Nunn et al. [20]. Comparing these values the $\dot{V}O2$ index of our patients decreased about 5% below the basal rate. Theye et al. [29] described an average oxygen uptake about 100% of predicted basal values in patients during light halothane anaesthesia without premedication, thiopental induction and muscle relaxants. But with muscle relaxants oxygen uptake averaged 84% of predicted basal values. In the author's opinion the difference is attributed to increased oxygen consumption of skeletal muscle in the unparalysed state. Huang et al. [12] observed a depression of the oxygen uptake during halothane or fentanyl anaesthesia with muscle relaxation of approximately 30% of predicted basal values (130 ml/min/m2). The most relevant factor for decreasing oxygen uptake during anaesthesia seems to be muscle relaxation. In our studies muscle relaxation was maintained with suxamethonium drip infusions which needs frequent adjustments depending on observed spontaneous muscle activities. This could be the reason for the smaller decrease in $\dot{V}O2$ in our investigations (about 5%).

Conclusions

The results confirm the accuracy of the oxyconsumeter within its specified working range. A dependence of the measuring error on the oxygen concentration in the fresh gas mixture was not demonstrable by our measurements.

It is possible to monitor the oxygen uptake during anaesthesia without application of nitrous oxide using the oxyconsumeter in connection to a non-rebreathing system with an externally triggered expiratory valve.

The advantage of the oxyconsumeter for measuring $\dot{V}O2$ of patients in relation to conventional methods and some continuous measuring methods are:

- simple use
- continuous monitoring

- simple connection to various ventilators (only two connections)
- simple cleaning

Acknowledgements

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