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Artifacts in the assessment of metabolic gas exchange

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Abstract. In mechanically ventilated patients metabolic gas exchange recordings are frequently influenced by routine patient therapy. In this study the influence of such artifacts is investigated and a method for automatic detection and suppression proposed. This method reduced the influence of artifacts on diurnal oxygen and carbon dioxide exchange from up to 10% to a maximum of 1%.

Key words: Oxygen consumption – Carbon dioxide production – Physiological monitoring – Indirect calorimetry – Energy expenditure – Computers

During the last decade critical care physicians expressed an increasing interest in the bedside measurement of metabolic gas exchange, i.e. oxygen uptake ($\dot{V}_{O_2}$) and carbon dioxide output ($\dot{V}_{CO_2}$). This has led to the construction and validation of a variety of instruments [7, 16, 23, 24], some of which are commercially available. At present this equipment has been widely used for two main clinical problems.

The concern for achieving a daily balance between total energy expenditure (TEE) and nutritional caloric supply revived the application of indirect calorimetry as a tool to assess TEE from metabolic gas exchange. It was known that underfeeding could induce protein loss and deterioration of wound healing [9]. However, it became apparent from indirect calorimetric studies that hyperalimentation with carbohydrate may lead to excess hepatic fat and glycogen deposition [13, 18] with increased carbon dioxide production [1]. It has been advocated, therefore, that indirect calorimetry may guide caloric replacement in the individual critically ill patient, receiving enteral or parenteral nutrition [15]. The metabolic rate of the severely ill patient is subject to large fluctuations especially related to patient activities [4, 22]. Therefore, accurate determination of daily TEE requires the continuous recording of oxygen uptake and carbon dioxide output. However, the established sampling method, using a Douglas bag for the collection of expired gas, allows only for short-term gas sampling and thus merely yields an instantaneous energy expenditure which cannot simply be extrapolated to diurnal TEE [11, 12]. Due to the technical limitations of the old collection methods, resting energy expenditure (REE) was conventionally measured for nutritional purposes under standardized conditions. However, REE is more suitable to compare the metabolic rate of different patient categories rather than to design a nutritional regimen for the individual patient. REE is usually lower than TEE [22]. Therefore, if caloric supply would be based upon REE, in some patients hypoalimentation may occur.

The second clinical problem relates to the critical issue of survival and the short-term balance between supply and demands for oxygen. Since the total buffering capacity of the body for oxygen is relatively small, a variation in the oxygen exchange minute value is directly related to the oxygen extraction by the tissues. $\dot{V}_{O_2}$ can therefore yield significant extra information besides hemodynamic and blood gas data in patients with impaired oxygen extraction, such as in ARDS [3, 10] or in sepsis [14], in which satisfactory arterial blood gas values alone do not imply adequate tissue oxygenation. In this type of application a continuous monitoring of metabolic gas exchange seems to be important and may be used to evaluate the actual effect of therapeutic $\dot{V}_{O_2}$ reduction on gas exchange [6, 17], in the case of an impending O_2 deficit.

Furthermore, it has been postulated that $\dot{V}_{O_2}$ has a highly predictive value in the ultimate outcome of the patient [19]. For these reasons, the recording of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ should be on a continuous basis, and ob-

Table 1. Survey of the clinical data

		No.	%
Sex:	Male	19	76
	Female	6	24
Condition:	respiratory distress syndrome	8	32
	Trauma	4	16
	Recent operation[a]	9	36
	Infection	15	60
Average age:		56 [15 – 83]	

[a] Between 1 and 5 days before recording date

viously the influence of all kinds of artifacts should be minimized. Our strategy is that artifacts if possible should be *prevented* in the first place, as in all monitoring of vital physiological signals. This may either depend upon proper design of the machinery [2, 7, 23], or upon the measurement protocol [5]. Artifacts which cannot be prevented should be *detected* and their influence on the measured values suppressed if possible. This paper describes some artifacts in metabolic gas exchange recordings due to common patient care in the ICU. Furthermore, a method for automatic detection and suppression is demonstrated.

Material and methods

Patient selection

In a surgical intensive care unit 25 mechanically ventilated adult patients were selected between October 1983 and December 1984 on the following basis: *inclusion criteria:* (1) a prediction, based on clinical judgement, of at least 24 h mechanical ventilation; (2) patient at least 6 h post anesthesia (to prevent interaction of N_2O with the O_2 sensor in the metabolic cart); (3) inspiratory oxygen fraction of 60% or less. *Exclusion criteria:* (4) active bleeding; (5) dialysis; (6) air leakage (e.g. thoracic or cuff leakage); (7) unavailability of the equipment (not more than one patient at a time in the trial). After application of the above criteria no other (arbitrary) selection of the patients was performed. This resulted in the study population sample of Table 1.

Patient care

All necessary therapy was administered to the patient as usual, by physicians and nurses who were unaware of the specific purpose of this study. Therapy affecting the recordings included broncho-pulmonary toilet, replacement of ventilator parts and bronchoscopy. During these time intervals the direct connection between patient, ventilator and metabolic monitor was temporarily impossible, causing artifacts in the gas exchange values $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$, but also in the expiratory minute volume ($\dot{V}_E$). All therapeutic interventions were documented on a case report form (CRF).

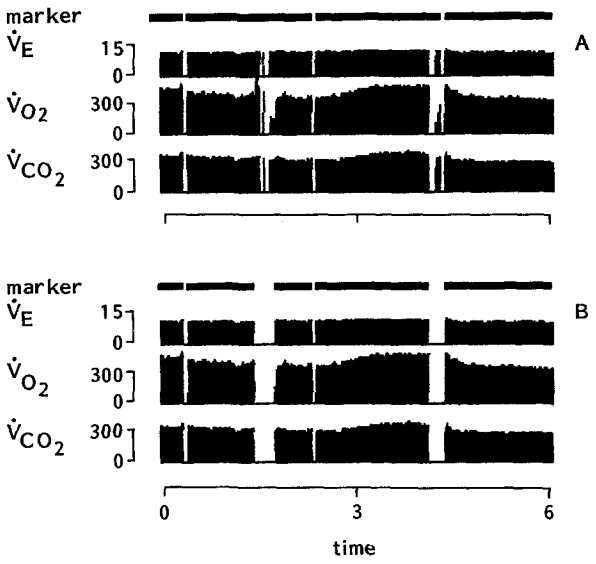

Fig. 1. A Record of $\dot{V}_E$ [l/min], $\dot{V}_{O_2}$ [ml/min] and $\dot{V}_{CO_2}$ [ml/min] without artifact suppression. Marker interruptions indicate time [h] intervals where no data are available due to calibration of the metabolic cart. **B** Same data after application of automatic artifact suppression. Marker interruptions indicate time intervals where no data are available due to calibration or artifacts

Recordings and analyses

The gas exchange values and $\dot{V}_E$ were determined each minute by an automatic metabolic monitor [7]. The obtained minute values were transmitted to a remote computer (DEC, pdp 11/23+) and stored for later analyses.

Diurnal $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ were determinated by summating the recorded minute values, which were previously processed by artifact suppression algorithms. Three different artifact suppression methods were applied to the same data for comparison. (1) A complete exclusion of artifacts guided by the CRF in combination with visual inspection of the data. (2) An automatic algorithm, detecting ventilator disconnection by a $\dot{V}_E$ value below a certain threshold (minute value less than 2 l/min), and suppressing all detected periods plus the next 5 min and the last minute just before the detected artifact from the summation procedure. This period was chosen and tested empirically serving as a compromise between recovery of gas concentrations in lungs, blood and tissues to the previously existing values on the one hand and not loosing too many data on the other. (3) No suppres-

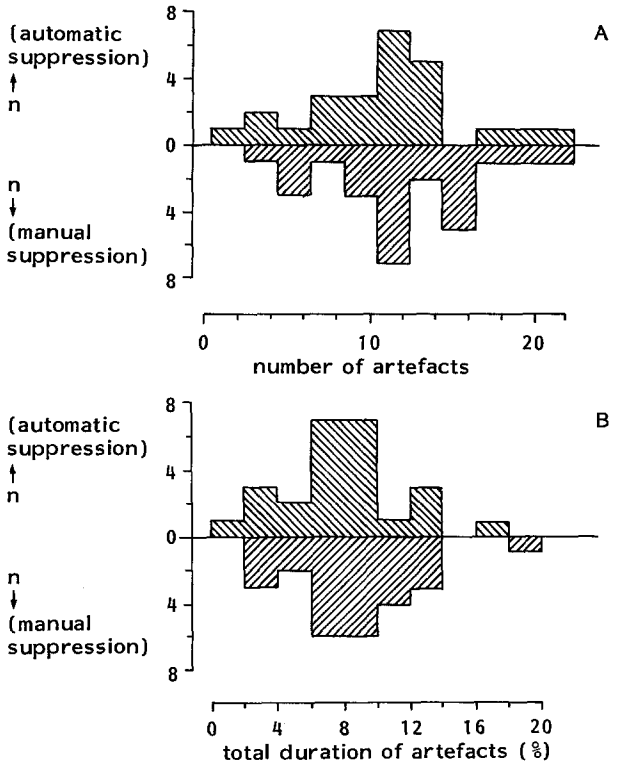

Fig. 2. **A** Distribution of number of artifacts per patient in 24 hours, for automatic (upwards) and manual (downwards) detection. **B** Distribution of total fraction [%] of recording time lost by artifacts per patient, for automatic (upwards) and manual (downwards) detection

sion at all. In the first and second algorithm the missing minute values were replaced by average values to obtain a 24-h total.

The first method is the most accurate technique and is considered as our standard by which the second method, an algorithm which can easily be automated, and the third method, can be judged. A small difference between the first and the second method might be expected since the manual suppression method allows for individual choice of the duration of suppressed periods, depending upon the actual recovery of the gas exchange values. This could also influence the number of artifacts, since two succeeding artifacts with a short interval between them may be classified as a single one of longer duration depending upon the recovery time chosen in the first method.

Results

A typical record of $\dot{V}_E$, $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ is depicted in Figure 1A, which shows the signals without artifact suppression. Apart from the interruptions in the signals every 2 h due to automatic calibration of the metabolic cart (indicated by the marker trace) two artifacts are visible at 1 h 42 min and at 4 h 18 min respectively, both caused by disconnecting the ventilator in order to perform broncho-pulmonary toilet. The same data are included in Figure 1B, however, after automatic artifact suppression. Both artifacts are recognized correctly and excluded from the diurnal gas exchange calculation. In this way exclusion of the artifacts increased diurnal $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ with 5.1% and 4.1% respectively for this patient.

In order to get an impression of the impact of artifacts due to therapy induced ventilator/patient disconnection, the total number of artifacts per patient over 24 h found by (1) manual and (2) automatic detection is depicted in histogram form in Figure 2A. Similarly the total duration of these artifacts, expressed in percentage of total recording-time, is presented in Figure 2B. The manual artifact suppression method detected between 4 and 21 artifacts per patient, resulting in a suppression of 2.5 – 18% of all recorded minute values. The automatic method found between 2 and 22 artifact periods, and excluded 2 – 18% of the total recording time (24 h) per patient. Differences between both methods in number and total duration of artifacts were small, even for the individual cases studied.

The influence of these artifacts on diurnal $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$ and RQ were evaluated by means of relative errors ($\Delta\dot{V}_{O_2}$, $\Delta\dot{V}_{CO_2}$) and the absolute error ΔRQ.

Without artifact processing diurnal $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ were underestimated up to 11% and 10% respectively, compared to our standard (data with manual artifact suppression), as shown for all patients in histogram form in Figure 3A, B. This is dramatically improved ($p<0.001$, Wilcoxon rank test) by application of the automatic artifact suppression method, which gave errors between −1% and +1% for both $\Delta\dot{V}_{O_2}$ and $\Delta\dot{V}_{CO_2}$.

RQ was only slightly overestimated without artifact suppression (up to 2%), which improved by the application of automatic artifact algorithm (Fig. 3C).

Discussion

Gas exchange measurements have been demonstrated to be useful in clinical research and practice. Their accuracy will depend not only on the design of the available instruments, but also on a number of factors dependent upon the purpose of the measurements and the clinical therapy of the patient population.

Implications for short-term monitoring

For applications requiring instantaneous or minute-values of the gas exchange, such as in case of cardiac

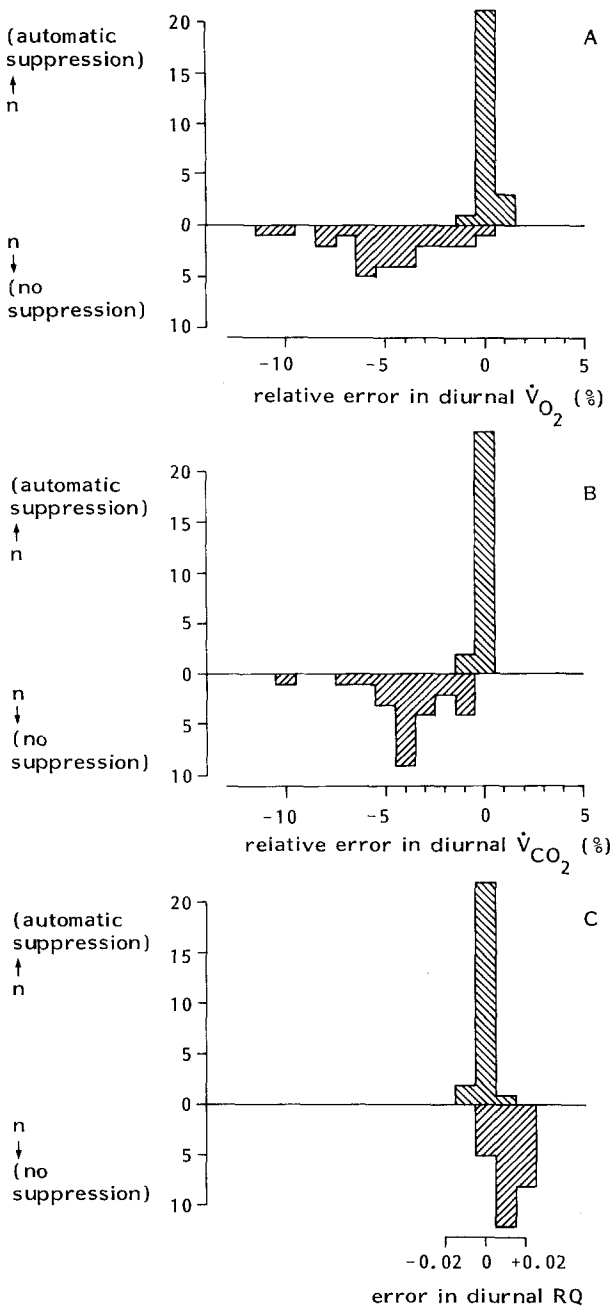

Fig. 3. **A** Distribution of relative error in $\dot{V}_{O_2}$ with automatic artifact suppression (upwards) and without artifact suppression (downwards). **B** Distribution of relative error in $\dot{V}_{CO_2}$ with automatic artifact suppression (upwards) and without artifact suppression (downwards). **C** Distribution of error in RQ with automatic artifact suppression (upwards) and without artifact suppression (downwards)

output monitoring by the Fick principle, it is essential that a steady state is achieved concerning the gas exchange in the patient and the connected gas collecting instruments. Therapeutic interventions such as changes in inspiratory oxygen concentration, breathing pattern, tidal volume, or changes in mental and physical effort may bring the patient from a steady state to a new situation with new blood gas values and associated changes in body gas stores. The impact of such a disturbance was demonstrated by Damask et al. [5], who found an almost twofold increase in $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ suddenly after percutaneous muscle biopsies were performed under local anesthesia. Besides these fluctuations induced by therapeutic changes and patient activities, we have shown that artifacts in gas exchange values are caused by normal ventilatory therapy and nursing care during a considerable period of measurement (up to 18% of total time). It is beyond question that this would reduce the value of gas exchange data for vital physiological monitoring unless certain artifact processing is performed.

The classical approach for individual energy replacement is based on the measurement of REE by means of indirect calorimetry [8]. However, this is a complex and exacting task that requires an astute observer and much patience, because several factors such as patient activities may increase the actual energy expenditure considerably compared to REE [22]. Since the basic objective of individualized caloric replacement is to obtain a balance between expenditure and nutritional intake, and since REE is usually lower than TEE, we prefer to measure gas exchange continuously over the day to calculate diurnal TEE as the basis for energy intake. We have shown that using such recordings, underestimations of TEE by up to 10% can be prevented by simple artifact suppression. This is even more important in monitoring the effects of therapeutic decrease in metabolic rate [6, 17], which can be indicated in case of an impending O_2-delivery deficit.

Conclusion

Clinical employment of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ measurements is severely hampered by instrumentation related errors. This study demonstrates that routine therapy for critically ill, ventilated patients frequently causes artifacts in gas exchange measurements. An adequate detection of these artifacts and suppression of their influence on derived values seems to be indispensible. Routine implementation in a clinical setting is only practical when this is realized without manual operation. The automated artifact suppression mechanism presented here, can easily be incorporated into a microprocessor, that forms a part of most metabolic recording instruments for control purposes.

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