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Use of the oxygen cost of breathing as an index of weaning ability from mechanical ventilation

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Abstract. The oxygen cost of breathing (which is the difference in oxygen consumption measured during controlled ventilation and again during spontaneous ventilation) was measured in 30 patients between the ages of 17 and 96 years at the time of commencement of weaning from mechanical ventilation. There was a significant exponential correlation between the oxygen cost of breathing in ml/m^2/min and the oxygen cost of breathing as a percentage of total oxygen consumption during spontaneous ventilation (OCB/$\dot{V}_{O_2}$ SV%) and the duration of weaning in days.

Key words: Respiration – Artificial – Weaning index

Weaning from mechanical ventilatory support in critically ill patients commences after improvement or resolution of the precipitating insult. The appropriate time to initiate the weaning process is based on subjective as well as objective factors as the traditional weaning criteria can be unreliable [1].

The time course and eventual outcome of the weaning process is difficult to predict. Attempts to do so have lead to complicated scoring systems with both ventilatory and non-ventilatory measurements [2].

The oxygen cost of breathing (OCB) was shown by Nishimura et al. to be significantly greater in postoperative patients who failed extubation, than in those who were successfully extubated [3].

In this study we explore the relationship between the oxygen cost of breathing (OCB) and the derived variable, the oxygen cost of breathing as a percentage of total oxygen consumption during spontaneous ventilation (OCB/$\dot{V}_{O_2}$ SV%) and weaning ability.

Institutional approval for the study was obtained from the Human Subjects Committee of the University of Toronto.

Methods

Thirty patients (14 male and 16 female) ranging in age from 17 to 96 years were consecutively selected for study. All were recovering from a critical illness which had necessitated mechanical ventilation for at least 24 h. Only patients who were awake, haemodynamically stable and well oxygenated with an F_IO_2 of less than 50% were included in the study.

The investigators were not involved in the clinical decision making process. Prior to commencement of weaning forced vital capacity (FVC), peak negative inspiratory force (N.I.F.) and the PaO_2/F_IO_2 ratio were measured. Two OCB measurements were made within 4 h of each other using an indirect calorimetric technique and the results averaged. An indirect calorimetric technique has been described in the past [4, 5]. Expired gas was collected into a 100 l meteorological balloon for 5 min. Expired volume was measured with a calibrated Wright's spirometer which had been previously referenced against a Tissot spirometer. Simultaneously, a sample of inspired gas was collected for analysis. Prior to sampling, the system was checked to ensure against gas leaks. Both inspiratory and expiratory samples were analysed after drying over calcium chloride crystals using the Ergo Oxyscreen Metabolic Analyser (Jaeger Inc., Montreal, Quebec, Canada) which incorporates a polarographic oxygen analyser and an infra-red carbon dioxide analyser. Prior to each measurement the analysers were calibrated using two standard test gases.

Carbon dioxide production ($\dot{V}_{CO_2}$) and oxygen consumption ($\dot{V}_{O_2}$) were calculated using standard formulae and gas volumes were then converted to standard temperature pressure and dry (STPD) [6].

Indirect calorimetry was carried out during controlled ventilation (CV) and then during the last 5 min of a 20 min period of spontaneous ventilation (SV).

During CV, the ventilator frequency was adjusted to inhibit all spontaneous ventilatory efforts as detected by the airway pressure gauge. During SV, continuous positive airway pressure (CPAP) was set at 5 cms, H_2O and equal to positive end expiratory pressure (PEEP) used during CV. Both ventilatory modes were provided by either the Bear II (Bear Medical Systems Inc., Riverside, Ca.) or the Bennett MA II (Puritan, Bennett Corp., California).

As far as possible, steady state was maintained by sampling during periods of minimal movement and stimulation. Arterial blood gases were drawn during each sampling period to ensure stability of PaO_2 and $PaCO_2$.

Table 1. Patient data: diagnosis, ventilation and weaning

Disease	Age	Sex	WT. (ngs)	Duration of IPPV (Days)	OCB ml^2/m^2/min	OCB/$\dot{V}_{O_2}$ SV %	Duration of weaning
1. Multiple sclerosis	21	F	47	10	5.9	3.7	2
2. COPD/CCF	84	M	46	2	4.25	3.4	2
3. Cervical decompression	64	M	70	1	11.8	6.5	1
4. Pulmonary oedema/ cardiomyopathy	52	M	64	3	4.52	3.2	1
5. Small bowel resection	87	F	52	1	7.25	7.3	1
6. Phenobarb overdose	17	F	67	3	12.2	7	1
7. Hypercalcaemia/ pneumonia	70	F	62	5	9	6	5
8. LVF/myocardial infarction	63	F	73	6	3.7	3	1
9. Hemicolectomy	63	F	60	1	6.55	5.8	1
10. CCF/pneumonia/ COPD	96	M	82	2	5.65	5.7	1
11. Carotid endartarectomy	68	F	60	5	0.96	1.3	1
12. Small bowel resect/ renal failure/COPD	57	F	45	2	14.8	11.7	1
13. Cholescystectomy/ ARF	63	M	117	1	13.2	12	1
14. Wound sepsis post ACB	42	F	60	1	16.6	12.1	1
15. Hypercalcaemia/ lymphoma	42	M	80	2	15.3	10.1	1
16. ARDS post ACB	62	M	75	7	7.3	5.1	1
17. Pneumonia/COPD	72	M	71	6	21.6	14.1	3
18. Pancreatitis	50	M	81	3	9.39	5	1
19. COPD	69	M	65	3	63.5	35.4	43
20. Hemicolectomy/ CRF/CCF	70	F	61	6	6.51	3.4	1
21. Pneumonia/quadraplegia	42	M	61	12	20.9	12.2	7
22. Pneumonia/CCF/ dementia	74	F	55	1	14.2	9.7	1
23. MI/CCF/COPD	68	F	55	3	22.8	13.7	2
24. Pulmonary oedema/ MI	52	F	59	1	6.81	4.8	1
25. Lobectomy/COPD	55	M	63	1	24.5	13.7	1
26. COPD	53	M	69	1	22.5	15.3	2
27. Pneumonia/restrictive lung disease/ scleroderma	67	F	35	2	44.6	23	4
28. CRF/COPD	70	F	59	5	21.5	13	14
29. LVF	69	F	67	6	27.8	16	10
30. COPD	52	M	43	8	51.3	27.5	240

CCF = congestive cardiac failure; COPD = chronic obstructive pulmonary disease; LVF = left ventricular failure; ARF = acute renal failure; ACB = aortocoronary by-pass; ARDS = adult respiratory distress syndrome; CRF = chronic renal failure; MI = myocardial infarction; OCB/$\dot{V}_{O_2}$ SV % = oxygen cost of breathing as a percentage of total oxygen consumption during spontaneous ventilation

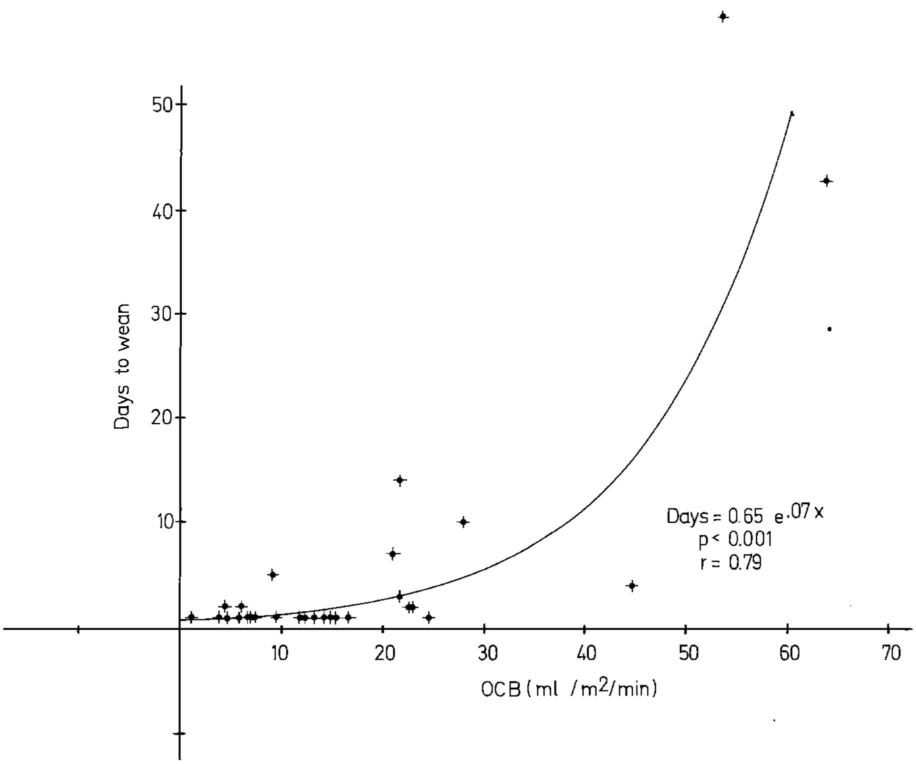

Fig. 1. Exponential correlation of the relationship between duration of weaning in days and the oxygen cost of breathing (OCB). $n = 30$

The difference in oxygen consumption measured during CV ($\dot{V}_{O_2}$ CV) and SV ($\dot{V}_{O_2}$ SV) is the OCB [7]. This is expressed as the OCB per metre of body surface area per min (OCB/m^2/min) and as the oxygen cost of breathing as a percentage of total oxygen consumption during spontaneous ventilation (OCB/$\dot{V}_{O_2}$ SV %).

After the measurements were made, patients were weaned by one of 2 methods as ordered by the clinical staff. Either a conventional wean with gradually increasing periods of time of spontaneous ventilation using the CPAP circuit of the ventilator alternating with periods of controlled ventilation, or an IMV (intermittent mandatory ventilation) wean by gradually reducing the IMV rate until all the inspiratory effort was being provided by the patient breathing on the CPAP circuit of the ventilator. The end point of the weaning process was taken as extubation or for patients with a tracheostomy the discontinuation of CPAP.

Table 2. Patient outcome

		Comment
Number of patients	30	
Failure to wean	2	1 died 43 days after start of weaning, 1 ventilator dependent 240 days later
Required reintubation within 48 h of extubation	2	1 cardiogenic shock 20 h after extubation, 1 congestive cardiac failure 2 days after extubation and died 3 days later
Death within 4 days of weaning	1	1 cardiac arrest 2 days after extubation

The results were analysed by regression analysis of the duration of weaning in days against the OCB in ml/m^2/min and the OCB as a percentage of total oxygen consumption during spontaneous ventilation (OCB/$\dot{V}_{O_2}$ SV %).

Results

Of the 30 patients studied, 10 were post operative (Table 1) and 11 had chronic obstructive pulmonary disease (COPD). A conventional weaning technique was used in 13 patients and an IMV wean in the remaining 17 patients. Two patients failed weaning (Table 2), a 69-year-old COPD man with an OCB of 33.4% died 43 days after the start of weaning from a cardiac arrest. A 52-year-old respiratory cripple with an OCB of 27.5% remains ventilator dependent 390 days after the commencement of weaning. One patient who developed severe cardiogenic shock secondary to a myocardial infarct 20 h after extubation required reintubation and mechanical ventilation.

The $\dot{V}_{O_2}$-SV was greather than the $\dot{V}_{O_2}$ CV in all patients. The mean difference between the 2 measurements of OCB/$\dot{V}_{O_2}$ SV % performed in each patient was 3.69% with a standard deviation of 3.06%.

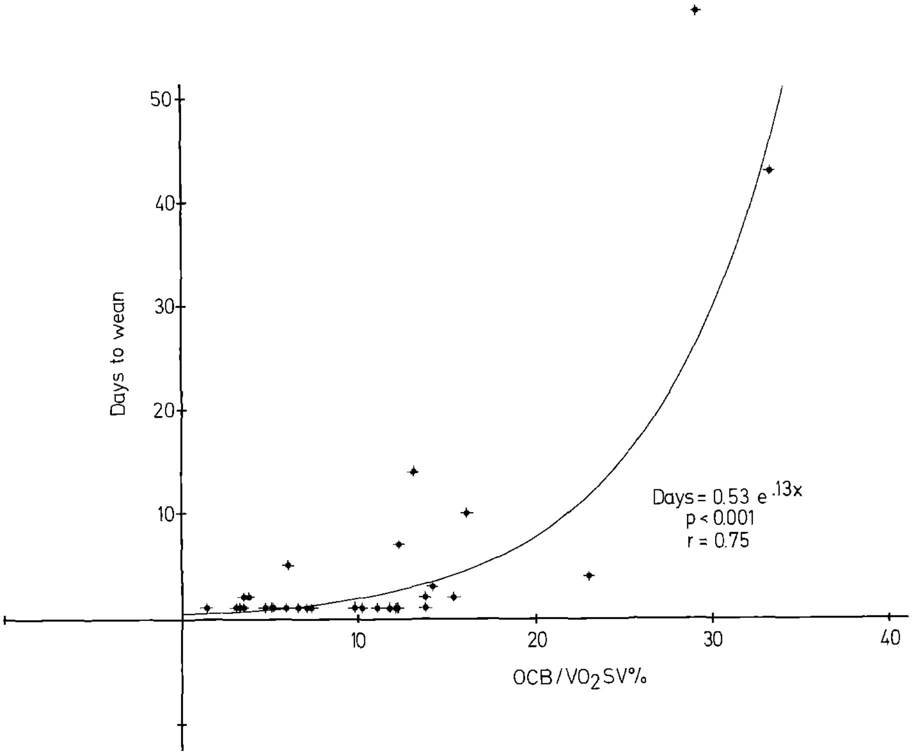

Fig. 2. Exponential correlation of the duration of weaning in days and the oxygen cost of breathing as a percentage of total oxygen consumption during spontaneous ventilation (OCB/V_{O_2} SV %). $n = 30$

There was a significant exponential correlation between the OCB in ml/m^2/min and the duration of weaning in days (Fig. 1): days = 0.65 $e^{0.07x}$, $r = 0.79$, $p < 0.001$. Again there was a significant exponential relationship between the OCB/$\dot{V}_{O_2}$ SV % and the duration of weaning (Fig. 2): days = 0.53 $e^{0.13x}$, $r = 0.75$, $p = <0.001$.

The FVC, NIF and Pa O_2/F_IO_2 ratio were not helpful in predicting the time course of the weaning process.

Discussion

Traditional weaning criteria used to assess the ability of patients to wean from mechanical ventilation include vital capacity greater than 10 ml/kg, the ability to generate a maximal inspiratory force of greater than −20 cm H_2O, an alveolar-arterial oxygen tension gradient breathing 100% oxygen less than 300 mmHg [8, 9] and a dead space to tidal volume ratio (V_D/V_T) of less than 0.58 [10]. The traditional weaning criteria have not been found useful in predicting the ability of patients to wean from prolonged mechanical ventilation and up to 20% of patients who satisfy these criteria may still fail extubation [2, 11].

There are many factors in addition to the mechanical and oxygenation factors discussed above which can delay weaning. Included are respiratory muscle fatigue and discoordination [12, 13, 14], sepsis [7, 15], nutritional deficiency [16, 17], anxiety and decreased level of consciousness [18, 19]. Regimes of parenteral nutrition containing excess glucose increase ventilatory demands because of increased CO_2 production [20]. Energy supplied by intravenous fat emulsions minimise CO_2 production [19, 21].

Due importance is given to nutritional support in critically ill patients in our ICU. Feeding is started early preferably by the enteral route, but if not, tolerated total parenteral nutrition is commenced.

Repeat IV boluses of opioids such as morphine sulphate 2–4 mg and/or benzodiazepines such as diazepam 2 mg are used to facilitate controlled ventilation in our ICU. Muscle relaxants are rarely required. All such drugs are omitted if possible or used in minimal dosage from the midnight before weaning commences.

Many of the inhibitors of weaning have in common the fact that they increase oxygen consumption and/or respiratory muscle work [15, 22] and hence OCB. This can lead to respiratory muscle fatigue and weaning failure [13].

The OCB is increased in patients with emphysema [7, 22, 23]. Chronic lung disease is common amongst patients requiring prolonged artificial ventilation; 3 of 6 patients in this series who required more than 5 days to wean had chronic lung disease. The OCB is increased postoperatively after cardiac surgery [24] and in hypercatabolic states such as sepsis and multiple trauma [25].

The CAP and IMV circuits of the Bear 11 and Bennett MA 11 ventilators used in this study are demand valve operated systems. Demand valve systems have been shown to increase the work of breathing when compared with continuous-flow CPAP and IMV circuits now being incorporated into newer ventilator models [26, 27, 28]. When weaning difficulty is encountered, the facility to change to a ventilator with continuous-flow circuitry would be advantageous.

Critically ill patients requiring mechanical ventilation often have an increased OCB. The OCB measured at the start of weaning correlates with the ease of weaning and duration of weaning.

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