Intensive Care Med (1996) 22: 199–207

ORIGINAL

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The automatic selection of ventilation parameters during the initial phase of mechanical ventilation

Received: 22 July 1994
Accepted: 5 April 1995

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Abstract *Objective:* To test a method that allows automatic set-up of the ventilator controls at the onset of ventilation.
Design: Prospective randomized crossover study.
Setting: ICUs in one adult and one children's hospital in Switzerland.
Patients: Thirty intubated stable, critically ill patients (20 adults and 10 children).
Interventions: The patients were ventilated during two 20-min periods using a modified Hamilton AMADEUS ventilator. During the control period the ventilator settings were chosen immediately prior to the study. During the other period individual settings were automatically determined by the ventilator (AutoInit).
Measurements and results: Pressure, flow, and instantaneous CO_2 concentration were measured at the airway opening. From these measurements, series dead space (V_{DS}), expiratory time constant (RC), tidal volume (V_T), total respiratory frequency (f_{tot}), minute ventilation (MV), and maximal and mean airway pressure ($P_{aw,max}$ and $P_{aw,mean}$) were calculated. Arterial blood gases were analyzed at the end of each period. $P_{aw,max}$ was significantly less with the AutoInit ventilator settings while f_{tot} was significantly greater ($P < 0.05$). The other values were not statistically significant.
Conclusions: The AutoInit ventilator settings, which were automatically derived, were acceptable for all patients for a period of 20 min and were not found to be inferior to the control ventilator settings. This makes the AutoInit method potentially useful as an automatic start-up procedure for mechanical ventilation.

Key words Closed-loop controlled ventilation · Human · Initial settings · Computer · Mechanical ventilation

Introduction

Mechanical ventilation of intubated patients in acute respiratory failure can roughly be divided into three phases: initiation, maintenance, and weaning. In the maintenance and weaning phases the ventilator settings are usually guided by decisions based on arterial blood gas analysis, the patient's lung and chest wall mechanics, and other clinical criteria. These determinations are made by the clinician and the ventilator is set accordingly. Alternatively, ventilator settings determined by a computer have been suggested and applied successfully in experimental conditions either using

closed-loop control [1–14] or an expert system [15]. Automatic control of the weaning phase has also been proposed [16]. At the onset of ventilation, the parameters must be pre-set without knowing exactly how much ventilation the patient needs. Physicians and respiratory therapists rely on rough estimates and clinical experience to make these determinations [17].

Automatic determination of the initial ventilation parameters based on measurements using test-breaths has been suggested in a recent study [18]. The drawback of this study is that the authors did not actually apply the derived ventilator setting. The purpose of the present study was to test a modified version (AutoInit) in intubated patients by applying the proposed ventilator settings for 20 min, which is a relatively short period of time, yet longer than the time usually needed from the initiation of mechanical ventilation until the first blood gas results are available at the bedside for readjustments of the ventilator settings.

This paper is the first report to describe a fully automatic method to initiate mechanical ventilation and its result in adults and children. The intention is to demonstrate physiological plausibility of the method.

Patients and methods

Patients

Thirty critically ill patients (20 adults aged 19–75 years and 10 children aged 4–12 years) selected at random from the Cantonal Hospital Chur and the University Children's Hospital Zurich were investigated. A subgroup of nine patients without spontaneous breathing was analyzed separately. The description of the patients is given in Table 1. All patients had been intubated and connected to either a Hamilton VEOLAR or a Siemens 900C ventilator prior to the investigation. Inclusion criteria were intubation with cuffed tubes, no leak between the cuff and the tracheal wall, and hemodynamic and respiratory stability. Cuff tightness was tested with a pressure of 30 cm H_2O. If the pressure did not fall more than approximately 2 cm H_2O after more than 10 s, the absence of a leak was assumed. Patients were considered hemodynamically stable if they were not under circulatory shock and no vasoactive drugs were administered. Patients were considered respiratory-stable if

Table 1 Patient description

No.	Age (years)	Weight (kg)	Size (cm)	PEEP (cmH_2O)	FIO_2	Clinical information
1	22	50	170	5	0.4	Severe head injury, comatose
2	62	92	168	7	0.5	Septic syndrome, acute respiratory insufficiency
3	75	62	168	3	0.4	Postoperative ventilation after brain tumor surgery
4	68	84	176	5	0.4	Tracheotomy because of upper airway obstruction
5	33	64	170	15	0.5	Severe ARDS after bacterial pneumonia and septic shock
6	52	76	164	3	0.3	Colon perforation, bacterial peritonitis, respiratory insufficiency
7	19	73	175	8	0.4	ARDS after polytrauma
8	68	89	170	5	0.4	Colon necrosis, retroperitoneal abscess, respiratory insufficiency
9	40	60	172	3	0.4	Severe head injury, comatose
10	27	100	170	3	0.5	Intracerebral hemorrhage
11	71	70	165	3	0.3	Head injury, hematopneumothorax, serial rib fractures
12	34	100	185	3	0.3	Shoulder trauma, severe head injury, blunt chest trauma
13	65	60	168	10	0.5	Severe ARDS, sepsis
14	43	83	186	3	0.4	Ruptured cerebral aneurysm
15	40	72	170	3	0.4	Severe head injury, multiple maxillofacial fractures
16	73	81	175	8	0.4	Hematopneumothorax, blunt chest trauma
17	64	85	180	5	0.5	Septic shock, intra-abdominal abscess
18	23	60	170	5	0.4	Lung contusion left, hematothorax, blunt abdominal trauma
19	25	55	172	5	0.3	Severe head injury, nosocomial pneumonia, aspiration
20	50	70	165	5	0.4	Myasthenia gravis, thoracotomy, malignant thymoma
21	5	20	110	4	0.3	Severe head injury
22	12	35	153	5	0.35	Severe head injury
23	9	27	120	4	0.3	Severe head injury
24	9	24	145	5	0.3	Severe head injury
25	4	15	97	4	0.4	Severe head injury
26	12	37	150	5	0.3	Severe head injury
27	10	30	130	4	0.3	Severe head injury
28	7	32	130	5	0.25	Severe head injury
29	8	31	121	5	0.21	Severe head injury
30	11	28	140	4	0.21	Severe head injury
Mean	34.7	58.8	158	5.1	0.37	
SD	24.5	25.5	23	2.5	0.08	

no changes in the ventilator settings were made during the 2 h preceding our measurements and if only minor changes in the blood gases had occurred. Patients with therapeutic hyperventilation due to head injuries or permissive hypercapnia were excluded. Additional exclusion criteria were PEEP > 15 cm H_2O, age below 3 years, or refusal of consent. No distinction was made between oral or nasal intubation or patients with tracheotomies. Patients in all ventilatory modes were entered into the study. This included synchronized intermittent mandatory ventilation (SIMV), pressure-controlled, synchronized intermittent mandatory ventilation (PCSIMV), controlled mechanical ventilation (CMV), pressure-controlled ventilation (PCV), pressure-support ventilation (PSV), and intermittent mandatory ventilation (IMV). For the investigation periods the patients were disconnected from their ventilator and connected to a Hamilton AMADEUS (Hamilton Medical Rhäzüns, Switzerland) ventilator. On this machine the patients were ventilated for two periods, each 20 min long; one period used the ventilator settings chosen by the clinician (control) and the other period used the AutoInit ventilator settings. The sequence of the two periods was randomized with equal numbers of patients assigned to both groups. The ventilator settings chosen by the clinician were identical to those used immediately prior to the onset of the study. The AutoInit ventilator settings consisted of a target tidal volume ($V_{T\text{init}}$) and target respiratory frequency (f_{init}) calculated from measurements of series dead space (V_{DS}) and expiratory time constant (RC) during five standard test-breaths at the onset of the AutoInit period [18] (Appendix). The ventilation mode used during application of AutoInit was PCSIMV. This mode is similar to SIMV with the exception that the mandatory breaths are pressure controlled and not volume controlled. In addition, the spontaneous breaths are augmented by pressure support ventilation. Since this mode does not allow for set volumes, the input pressure level was automatically adjusted until the target $V_{T\text{init}}$ was achieved. Similarly, SIMV rate was adjusted to achieve the target f_{init} and the I : E ratio was set so that the exhalation time was always greater 2 RC. For safety reasons, P_{insp} was not allowed to increase beyond a pre-set $P_{\max}$ considered by the therapist to be safe for the patient and f_{init} was increased instead to achieve the same minute ventilation. The control algorithms were implemented on a Macintosh computer, which in turn controlled the ventilator (Fig. 1). FIO_2 and PEEP were left unaltered. Breath pattern and blood gases of the two periods of ventilation were compared. For this purpose the means of f_{tot}, MV, V_T, $P_{\text{aw,max}}$, and $P_{\text{aw,mean}}$ during the final 5 min of each period were calculated. At the end of each period, arterial pH, $PaCO_2$ and PaO_2 were measured. Statistical comparison between the two periods was calculated using a paired 2-tail t-test. Regression analysis was calculated to determine whether the difference of the compared values depended on their mean [19], and an unpaired t-test was used to assess whether or not the changes in the measured variables depended on the sequence of the two periods. Patients who did not breathe spontaneously were additionally analyzed as a subgroup. All statistical analysis was done with StatVeiw 4.0 (Abacus Concepts, Berkeley, Calif). Informed consent from next-of-kin was obtained for all patients. The protocol was approved by the ethics committee of the participating hospitals.

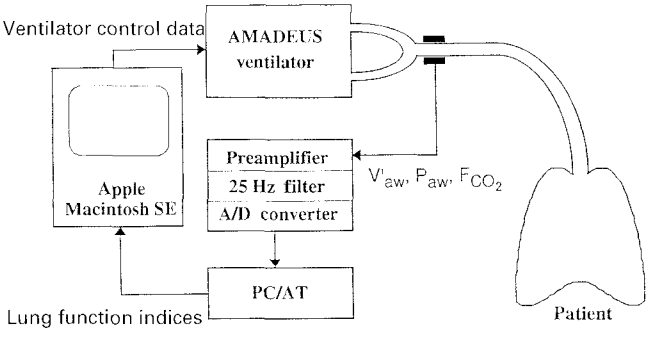

Fig. 1 Apparatus to measure flow (V'_{aw}), pressure (P_{aw}) and instantaneous CO_2 concentration (F_{CO_2}) at airway opening, as well as to calculate and apply AutoInit ventilator settings. Closed-loop controllers were implemented on the Macintosh computer and controlled the ventilator settings in AutoInit phase

Measurement set-up

Measurements included airway flow, airway pressure and instantaneous concentration of CO_2 in the exhaled air. For this purpose a heated screen pneumotachograph (PT–180, Erich Jaeger GmbH & CO. KG, Höchberg, Germany) and a Novametrix 1260 mainstream CO_2 analyzer (Novametrix Medical Systems Inc., Wallingford, Conn.) were placed between the ventilator Y-piece and endotracheal tube. In six cases, a Hamilton variable orifice flow meter instead of the screen pneumotachograph was used for technical reasons. All data were read into an IBM-PC/AT compatible microcomputer using an AD converter. Calibration of the sensors was done prior to each measurement. The signals were corrected for gas viscosity changes and CO_2 analyzer delay [20]. From the flow and CO_2 signals a CO_2 versus volume curve was constructed to determine V_{DS} [21]. End tidal CO_2 was not used as a parameter. The additional lung-function indices calculated were V_T, RC [22], f_{tot}, MV, $P_{\text{aw,max}}$ and $P_{\text{aw,mean}}$. When AutoInit ventilator settings were applied, an Apple Macintosh SE computer controlled the ventilator based on the data calculated by the PC. Figure 1 shows a schematic of the measurements and control set-ups.

Results

A total of 30 patients were investigated, all of whom tolerated the test-breaths as well as the AutoInit ventilator settings. Two patients had to be excluded from final evaluation: patient 10 because protocol was violated (PEEP change), patient 22 because V_T was greater than 10 V_{DS} which was according to the study design, interpreted as a failure of the AutoInit procedure. In the latter case, the breath pattern was calculated by hand, using the AutoInit algorithm and the patient was then ventilated with that breath pattern for 20 min, but the results were not used for the final evaluation. Table 2 shows V_T, f_{tot}, MV, $P_{\text{aw,max}}$, and the arterial blood gas analysis results obtained during ventilation with the control settings as well as during ventilation with the AutoInit settings.

Patient 5 transiently needed an increased FIO_2 in the control period before suctioning. The same occurred with patient 7 during AutoInit. Patient 13 was not given the high V_T suggested by AutoInit;

Table 2 Breath pattern and ABG results for all patients

No.	Control								AutoInit						
	Mode	V_T ml	f_{tot} /min	MV l/min	$P_{aw,max}$ cm H_2O	pH	$PaCO_2$ mmHg	PaO_2 mmHg	V_T ml	f_{tot} /min	MV l/min	$P_{aw,max}$ cmH_2O	pH	$PaCO_2$ mmHg	PaO_2 mmHg
1	PSV	230	24.7	5.7	16.0	7.36	45	139	438	15.5	6.8	21.7	7.45	34	107
2	SIMV	540	10.0	5.4	31.9	7.40	35	85	335	24.7	8.3	16.8	7.39	36	83
3	PSV	501	7.7	3.9	12.8	7.49	33	93	492	12.1	6.0	15.2	7.57	25	76
4	PSV	366	16.7	6.1	14.0	7.42	44	85	595	11.9	7.1	21.4	7.47	39	75
5	PCSIMV	366	28.3	10.4	40.4	7.39	48	78[a]	404	29.0	11.7	38.5	7.46	39	52
6	PSV	350	24.7	8.6	11.4	7.48	35	87	376	22.5	8.5	12.8	7.48	36	101
7	PCSIMV	436	27.0	11.8	28.5	7.42	40	68	493	31.7	15.6	35.4	7.43	42	120[a]
8	PSV	345	21.5	7.4	18.1	7.46	34	67	371	20.8	7.7	24.4	7.47	34	64
9	SIMV	688	10.0	6.9	16.6	7.42	37	143	468	13.0	6.1	9.9	7.39	42	148
10[b]	SIMV	722	12.3	8.9	24.1	7.43	28	130	368	14.6	5.4	16.9	7.36	39	71
11	PSV	539	14.0	7.5	17.0	7.43	38	84	425	17.1	7.3	10.4	7.43	39	72
12	PSV	550	18.9	10.4	13.4	7.39	39	78	511	16.5	8.4	11.6	7.38	42	81
13	PSV	409	22.2	9.1	30.2	7.48	40	62	406[c]	22.5	9.1	30.0	7.49	39	67
14	PSV	685	13.2	9.0	12.2	7.49	40	83	443	16.7	7.4	11.9	7.48	41	78
15	PSV	347	21.7	7.5	11.5	7.44	38	86	318	22.1	7.0	8.9	7.44	38	83
16	PSV	405	20.9	8.5	15.5	7.45	43	71	578	14.2	8.2	21.4	7.45	43	72
17	SIMV	624	16.7	10.4	20.4	7.37	41	102	619	19.2	11.9	19.4	7.39	39	97
18	PSV	425	20.3	8.6	19.0	7.45	38	76	397	23.6	9.4	14.3	7.44	39	75
19	PSV	382	28.4	10.8	14.5	7.50	33	105	422	25.0	10.6	16.1	7.51	33	112
20	PSV	204	22.0	4.5	13.9	7.37	44	73	269	20.1	5.4	18.5	7.37	41	70
21	IMV	159	19.6	3.1	13.4	7.40	39	118	141	20.1	2.8	11.6	7.39	41	115
22[d]	PCV	419	12.1	5.1	23.9	7.34	33	91	168	16.5	2.8	14.0	7.22	50	88
23	PSV	352	11.1	3.9	17.0	7.35	35	141	242	16.6	4.0	14.9	7.34	33	132
24	CMV	337	15.1	5.1	21.8	7.41	35	110	250	20.3	5.1	15.9	7.39	36	108
25	CMV	159	19.0	3.0	22.1	7.27	37	155	159	22.7	3.6	18.5	7.31	33	164
26	CMV	358	12.0	4.3	21.7	7.43	36	118	270	17.9	4.8	15.5	7.45	35	125
27	CMV	462	10.0	4.6	31.6	7.36	34	102	211	19.4	4.1	14.8	7.30	41	96
28	CMV	320	12.0	3.8	32.3	7.36	36	74	210	23.2	4.9	20.3	7.40	33	74
29	IMV	345	10.2	3.5	25.6	7.45	33	78	190	18.7	3.6	17.8	7.44	33	77
30	PCV	415	8.9	3.7	21.2	7.35	33	94	220	17.3	3.8	15.8	7.33	27	97
Mean		415	17.0	6.7	20.4	7.41	37.5	96	366	19.6	7.0	18.0	7.42	37.0	92.8
SD		144	6.2	2.7	7.5	0.05	4.4	25.3	132	4.7	2.9	7.0	0.06	4.4	26.7

[a] Patient was hyperoxygenated for succtioning
[b] Protocol violation (PEEP changed during study); patient was excluded from final evaluation
[c] V_T automatically limited to avoid exceeding P_{max} limit
[d] V_T exceeded 10* V_{DS} during the test breaths; AutoInit breath pattern was calculated by hand; patient was excluded from final evaluation

instead the controller's safety feature automatically reduced V_T and increased the frequency.

Table 3 shows a comparison of the key ventilatory parameters and of the blood gas analysis results. The sequence of the periods had no influence and f_{tot} was significantly larger during the AutoInit period ($P < 0.05$). $P_{aw,mean}$, V_T, and the blood gas values did not differ significantly. The differences were independent of the mean of the parameters measured during both periods.

In a subgroup of patients without apparent spontaneous breathing, the respiratory frequencies were significantly higher, and V_T and $P_{aw,max}$ were significantly lower in AutoInit (Table 4). Minute ventilation was not significantly different.

Table 3 Comparison of ventilatory parameters and blood gases measured during application of the conventional and AutoInit breath patterns ($n = 28$). Values are mean ± SD. Positive difference means larger value in AutoInit

	Control	AutoInit	Difference	P
V_T (ml)	404 ± 137	366 ± 135	− 37 ± 126	0.13
f_{tot}(/min)	17.4 ± 6.3	19.8 ± 4.7	2.4 ± 5.4	0.03
MV (l/min)	6.7 ± 2.7	7.1 ± 3.0	0.4 ± 1.2	0.09
$P_{aw,max}$ (cmH_2O)	20.1 ± 7.7	18.0 ± 7.1	− 2.2 ± 6.3	0.08
$P_{aw,mean}$ (cmH_2O)	9.8 ± 5.2	10.2 ± 4.8	0.5 ± 3.1	0.44
pH	7.41 ± 0.05	7.42 ± 0.06	− 0.01 ± 0.03	0.19
$PaCO_2$ (mmHg)	38.0 ± 4.1	36.9 ± 4.5	− 1.1 ± 4.0	0.66
PaO_2^a (mmHg)	96.5 ± 25.5	94.2 ± 26.1	− 2.3 ± 9.1	0.21

[a] Patients 5 and 7 excluded because of hyperoxygenation before suctioning

Table 4 Comparison of key features and of the conventional and AutoInit breath pattern in passive patients ($n = 9$) . Values are mean ± SD. Positive difference means larger value in AutoInit

	Control	AutoInit	Difference	*P*
V_T (ml)	403 ± 150	257 ± 94	− 146 ± 81[b]	0.0006
f_{tot} (/min)	11.9 ± 3.2	19.7 ± 3.6	7.8 ± 3.8	0.0003
MV (l/min)	4.5 ± 1.2	4.9 ± 1.5	0.4 ± 1.8	0.27
$P_{aw,max}$ (cmH_2O)	25.0 ± 5.7	16.1 ± 2.9	− 8.8 ± 4.7	0.0005
$P_{aw,mean}$ (cmH_2O)	9.4 ± 3.4	9.1 ± 1.9	− 0.4 ± 2.9	0.71
pH	7.38 ± 0.06	7.38 ± 0.06	− 0.01 ± 0.04	0.63
$PaCO_2$ (mmHg)	35.1 ± 1.5	35.1 ± 4.5	0 ± 4.2[b]	–
PaO_2 (mmHg)	106.6 ± 28.1	108.0 ± 31.7	1.4 ± 4.9[b]	0.40

[a] $n = 8$; $n = 6$ for the difference
[b] Difference depended on mean

Discussion

This paper reports a method of automatically finding adequate ventilator settings (AutoInit) for the initial phase of ventilation. When AutoInit settings were applied for 20 min, only the change in respiratory frequency was statistically significant. All other values remained unchanged when compared to control ventilator settings. In the subgroup of patients without spontaneous breathing the changes in V_T, respiratory frequency, and $P_{aw.max}$ were statistically significant.

There was no statistically significant difference in the blood gas analysis results obtained after applying the AutoInit settings. The question remains whether AutoInit caused unacceptable blood gases. $PaCO_2$ ranged from 33 to 48 mmHg after ventilation when the ventilation pattern was chosen by the clinician and from 25 to 43 mmHg after ventilation when the AutoInit breath pattern was used. When values below 35 mmHg were considered hypocapnic and values above 45 mmHg were considered hypercapnic, six patients were hypocapnic and one patient was hypercapnic during the control period, while nine patients were hypocapnic and no patient was hypercapnic with AutoInit. This indicates that 75% and 68% of the patients were normoventilated during the two ventilation periods. However, none of the arterial CO_2 partial pressures posed any danger to the patients. A $PaCO_2$ of 25 mmHg over several hours is used in the treatment of patients with severe head injuries, and a $PaCO_2$ up to 70 mmHg is reported to be tolerated in ARDS patients [23]. The pH ranged from 7.27 to 7.50 for the clinician-chosen breath patterns and from 7.30 to 7.57 for the AutoInit breath patterns. When a pH of 7.35–7.45 is considered normal [24], two patients had a pH below normal and six patients had a pH above normal during the control period. During the AutoInit period three patients had a pH below normal and eight patients had a pH above normal. The number of patients with abnormal pH between the control period and the AutoInit period did not change significantly. However, none of the observed pH values was deleterious to the patients. It has been shown by other investigators [13] that ARDS patients can be adapted to tolerate a pH of 7.22.

A value above 60 mmHg for $PaCO_2$ is considered acceptable for stable patients without ischemic vascular disease [25]. Using the AutoInit breath pattern, the lowest PaO_2 was observed in patient 5 (52 mmHg). This patient had severe ARDS and his PaO_2 was 59 mmHg prior to the study. However, the control-setting results of this patient are difficult to interpret because FIO_2 was transiently increased to 1.0 as part of the endobronchial suctioning procedure. Therefore, none of the patients was put at risk concerning blood gas values during the AutoInit period especially when considering the limited time for which the AutoInit settings are intended to be used.

The patients were ventilated for 20 min with the AutoInit settings, after which an arterial blood gas analysis was performed; this is a relatively short period on a ventilator. The intended use of the AutoInit method is to provide the patient with adequate ventilation until blood gas data are available and not to determine a breath pattern that is better than one the clinician would choose. Twenty minutes are therefore considered appropriate for the purpose of this study.

The average V_T during the AutoInit period was 37 ml lower than during the control period, which is not statistically significant. However, V_T did change by more than 50% in some patients for two reasons: (1) V_T varied between 2.9 and 15.4 ml/kg during the control period while the AutoInit algorithm always chose a target V_T of 12 ml/kg, and (2) V_{DS} is not just dependent upon body weight. Although Radford's formula [26] is still widely used, more recent work has suggested that dead space is anatomically determined by body size [27] and lung volume [28] rather than by body weight. Functionally, V_{DS} is influenced by many other factors such as end-inspiratory pause [29], inspiratory flow [30], and spontaneous activity [31]. Also, V_{DS} depends on the length and diameter of the endotracheal tube. This may lead to some deviations from the true V_{DS}. The principal correlation between V_{DS} and patient size and weight should, however, be preserved because small patients use small endotracheal tubes and large patients use large ones. In our study 11 patients were orally intubated, 13 patients were nasally intubated, and 4 patients were tracheotomised. There was no evidence that

the intubation route influenced the AutoInit breath pattern. V_{DS} can therefore be accepted as a rough indicator of patient and lung size, which lead, in this study, to a slightly decreased V_T.

Two possible problems of low V_T are hypoventilation and alveolar collapse. In the first problem of hypoventilation, it can be suspected that in some patients V_T could become dangerously low, i.e., less than the dead space. This can, however, be prevented by using V_{DS} to calculate V_T. Also, if V_T is larger than 10 times V_{DS} in the test-breaths, a measurement error is assumed, the procedure is aborted and an alarm is activated that indicates the failure of the automatic procedure and a manual entry is suggested. This happened in patient 22 where the endotracheal tube was cut short, which caused V_T to exceed the limit of $10*V_{DS}$. As a result, the test-breaths were judged invalid. In spite of this, and to test the limitations of the AutoInit algorithm, the breath pattern was still calculated and patient 22 was then ventilated with that pattern for a period of 20 min. Although the small V_{DS} measured led to a V_{Tinit} of only 168 ml instead of 419 ml during the control period, the patient was still well oxygenated with a PaO_2 of 88 mmHg. The $PaCO_2$ of 50 mmHg was above normal while the pH of 7.22 was clearly below normal because of hypoventilation. Although these values indicated a ventilation far from optimal, none posed a danger to the patient, given that the breath pattern was only applied for a limited amount of time.

The second problem is that a small V_T could lead to alveolar collapse and hypoxemia. A V_T of 10–15 ml/kg is believed to prevent alveolar collapse and is therefore used to improve arterial oxygenation [32]. This belief found its culmination in the use of "sighs" with, however, controversial results [33]. Our results show that 20 min of ventilation at lower V_T does not impede arterial oxygenation.

The main risk of a large V_T is barotrauma caused by the excessive pressure needed, particularly in patients with stiff lungs. For this reason a safety feature built into the AutoInit procedure limits the pressure to a maximum level, which is pre-set by the clinician. This safety feature was implemented in patient 13, a case of severe ARDS. In this patient V_T was limited to 406 ml instead of 800 ml. To compensate, the frequency was increased.

Generally, respiratory frequency was higher during ventilation with the AutoInit settings. The AutoInit method attempts to minimize the work of breathing imposed on a spontaneously breathing patient by using the Otis formula [34] to calculate the target respiratory frequency. However, minimization of the work of breathing is not the primary goal of the AutoInit method. The purpose of the AutoInit method is to select a breath pattern for the initial 20 min of ventilation.

According to this model, the optimal rate depends on resistance and compliance. For a given set of alveolar ventilation, airway resistance (R_{aw}), and respiratory systems compliance (C_{rs}), the work of breathing changes with respiratory frequency. The resistive component of the load increases with respiratory frequency while the elastic component of the load decreases. These changes are not linear, which leads to a respiratory frequency where the sum of both loads and the total work of breathing becomes minimal. According to the results of this study, this is achieved at a higher respiratory frequency than was used in the control settings and confirms the result of an earlier study [18]. It is particularly evident in the passive patients for whom the average difference was 7.8 breaths/min. In contrast to the spontaneously breathing patients, these patients could not independently increase breathing frequency while being ventilated with the clinician-chosen ventilator settings. High rates can lead to breath-stacking and an increase in peak pressure [35]. The AutoInit method attempts to prevent these problems by taking the RC into account. In particular, the respiratory frequency is tuned in order to always have an exhalation time of larger than twice the RC. In this study, the method was successful and none of the adverse effects occurred in our patients. The overall peak pressure actually decreased.

Our study included 30 patients of different pathologies, ranging from severe ARDS to healthy lungs in adult patients (1–20). In contrast, the children's lungs were all healthy. Although this limits the scope of the study, it reflects the fact that most children between 3 and 15 years of age admitted to the ICU of the children's hospital in Zürich are trauma victims with head injuries. Also, the AutoInit settings were only used on normoventilated patients. For patients who need to be hyperventilated, such as those with severe head injury, the AutoInit breath pattern could yield a $PaCO_2$ that is too high, putting these patients at an unacceptably high risk. For these patients the therapist should apply a correction factor to the AutoInit ventilator settings at the start of mechanical ventilation.

Measurement at the airway opening is crucial to the AutoInit method. Flow, pressure, and CO_2 concentration of the respired gas need to be measured simultaneously. The measuring site poses special handling problems that need to be considered before such a method can become clinically acceptable. Many errors are possible, one of which is leaks around the end

of the endotracheal tube. These occur especially in pediatric patients where the use of uncuffed tubes is common. Leaks can influence the measurement of V_{DS} and RC. For this reason patients with leaks around the end of the endotracheal tube were excluded from our study. To calculate an initial breath pattern for these patients, some method to compensate for the measurement errors caused by leaks has to be devised first.

The method used to measure the RC yields exact values for a one-compartment lung of a completely passive patient with full exhalation [22]. In patients with respiratory muscle activity it is less accurate, and most of our patients were at least partially spontaneously breathing. RC tends to be overestimated at time constants below 1 s and a underestimated at time constants above 1 s, which means that the ventilator is not optimally tuned to the patient's RC. It also indicates that extreme settings are automatically prevented. In the worst case, the RC has no significant influence on the ventilator settings. However, it does appear to be sufficient to avoid excessive breath stacking.

V'_A used in Eq. 3 was based on an estimation of V'_{CO_2}. An alternative to estimating V'_{CO_2} would be to actually measure V'_{CO_2}. For this purpose, a steady-state condition would be needed which means that the breathing pattern and the metabolism must stay constant for a considerable amount of time prior to the measurement. Because the test-breath pattern almost certainly does not coincide with the patient's previous breathing pattern, a steady state cannot be assumed and a V'_{CO_2} measurement is not possible.

Thus far, only one study has explicitly addressed the problem of choosing adequate settings for the initial phase of mechanical ventilation [18]. To human operators it is a simple task to judge the appropriateness of an initial V_T and a respiratory frequency, which does not assume that it is easy to determine optimal values for these parameters. However, it is evident, for example, from the body size and clinical signs that a V_T of 600 ml is not suitable for a small child. This may sound like a trivial argument, but with respect to closed-loop controlled ventilation it is not. A ventilator has only limited knowledge about the attached patient and the V_T and airway pressure alone are insufficient to determine the appropriate parameters. At a given preset pressure level, for example, a low V_T is compatible with stiff lungs, high airway resistance, and/or poor synchronization of patient and ventilator. Alternatively, the patient may be simply a small child without pulmonary pathologies. The first problem, therefore, is to find a breathing pattern that can be used on patients of any size, pathology, and state of spontaneous breathing. Pressure-controlled, synchronized, intermittent mandatory ventilation appears to be suitable for this task. The second problem is to find an algorithm such as V_{DS}, which can distinguish between patients of different size based on measurements at the airway opening. The third problem is to find yet another algorithm to identify the primary mechanical properties of lungs and chest wall, which can be achieved by measuring the RC. The fourth problem is how to select appropriate values for target frequency and V_T to ventilate the patient adequately during the initial phase. For this problem, minimization of the work of breathing seems a sensible solution. The AutoInit method encompasses all of these proposed solutions.

One might object that the parameters relevant for oxygenation, PEEP and FIO_2, still have to be entered manually. The setting of these parameters does not depend on patient morphology and lung mechanics, but on the patient's lung pathology, mainly the ventilation-to-perfusion ratio. It is therefore not possible to decide on these settings by simple measurements made at the airway opening. It is also a completely different set of rules that are used to choose initial PEEP and FIO_2. Therefore, a completely new approach is required to address this topic.

Before AutoInit can be released for practical application, a few technical problems need to be overcome: reliability checks, cost, and unstable patients (poor capnograms). No procedure is 100% reliable, whether it is conducted by a machine or a human being. In this study one patient in 30, i.e., 3.3% failed the plausibility test during the test-breaths. Despite this failure the patient was still ventilated adequately, if not perfectly, for the test period of 20 min with the breath pattern calculated by hand according to the same algorithm used by the AutoInit procedure. The question is: is the acceptance criterion too stringent or is it too loose? In this study only one patient reached the acceptance limit; therefore, more data are needed to answer this particular question.

Automatic procedures like the one described in this paper are of limited value to today's clinician, because the equipment needed to implement these procedures is not yet common in the average ICU and there is no compelling reason for an automatic set-up in the initial phase of ventilation. However, the hardware needed to perform breath-by-breath lung function analysis is becoming less expensive every year. The latest generation of ventilators are microprocessor-controlled, and integrated capnography will become more common in the future. Closed-loop control will be available in future ventilators. For such algorithms AutoInit will provide a method of defining the initial values of frequency and V_T.

Managing difficult and unstable patients is another area in which the AutoInit algorithm could be helpful, e.g., as a part of an expert system built into the ventilator or monitoring equipment [36]. However, measurements at the airway opening may in some cases not provide enough data, especially in hemodynamically unstable patients. Further research is necessary to investigate such applications of the AutoInit algorithm.

The purpose of this study was to demonstrate physiological plausibility of AutoInit in critically ill patients. We conclude that AutoInit is a feasible method of automatically determining the settings for the initial phase of mechanical ventilation. Manual data entry such as height and weight is not needed, and this method is applicable for a wide range of critically ill patients, including children and adults. The use of AutoInit is proposed only for the initial phase of ventilation; careful titration of ventilation based on blood gases and clinical observation is still a necessity.

Appendix:

Description of the AutoInit method

A short description of the AutoInit method follows; for a more detailed description see Laubscher et al. [18]. AutoInit starts with a sequence of five test-breaths. The results of the analysis of flow, pressure, and CO_2 concentration are used to derive the AutoInit ventilator settings. The test-breaths are based on pressure-controlled, synchronized intermittent mandatory ventilation (PCSIMV). The mechanical respiration rate is set to 15 breaths/min and the inspiratory pressure level is set to 15 cmH_2O above PEEP. Under these circumstances it takes a maximum of 20 s to achieve the initial breath pattern from the 5 test-breaths.

To calculate $V_{T\text{init}}$, the patient's weight is estimated from V_{DS} using Radford's formula [26]:

$$\text{weight} = V_{DS} * 0.45$$

where weight is measured in kg and V_{DS} in ml. The $V_{T\text{init}}$ is then set to 12 times the weight:

$$V_{T\text{init}} = 12 * \text{weight}$$

where $V_{T\text{init}}$ is measured in ml and weight in kg. The f_{init} is calculated from RC, V_{DS}, and an estimate of alveolar ventilation V'_A using the minimal work of breathing approach [34]:

$$f_{\text{init}} = 30 \frac{\sqrt{1 + \frac{200}{3}\pi^2 RC \frac{V'_A}{V_{DS}}} - 1}{\pi^2 RC}$$

where f_{init} is calculated in breaths/min, V'_A in l/min, RC is measured in seconds, and V_{DS} in ml. To obtain V'_A, first the CO_2 production (V'_{CO_2}) is estimated from the weight obtained by Eq. 1. V'_A is calculated as $V'_{CO_2}/0.05$, assuming a desired alveolar CO_2 concentration of 5% [18].

A safety feature prevents the use of erroneous test-breath results: V_T generated by the test-breaths needs to be larger than twice V_{DS} and smaller than 10 times V_{DS}. Otherwise, the AutoInit procedure is aborted and an alarm is activated. Thus, test-breaths which contribute mainly to dead-space ventilation as well as erroneous measurements of V_{DS} are excluded.

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