

Fuzzy logic control of mechanical ventilation during anaesthesia

J. SCHÄUBLIN, M. DERIGHETTI, P. FEIGENWINTER, S. PETERSEN-FELIX AND A. M. ZBINDEN

Summary

We have examined a new approach, using fuzzy logic, to the closed-loop feedback control of mechanical ventilation during general anaesthesia. This control system automatically adjusts ventilatory frequency (f) and tidal volume (V_T) in order to achieve and maintain the end-tidal carbon dioxide fraction ($F'_{E_{CO_2}}$) at a desired level (set-point). The controller attempts to minimize the deviation of both f and V_T per kg body weight from 10 bpm and 10 ml kg⁻¹, respectively, and to maintain the plateau airway pressure within suitable limits. In 30 patients, undergoing various surgical procedures, the fuzzy control mode was compared with human ventilation control. For a set-point of $F'_{E_{CO_2}} = 4.5$ vol% and during measurement periods of 20 min, accuracy, stability and breathing pattern did not differ significantly between fuzzy logic and manual ventilation control. After step-changes in the set-point of $F'_{E_{CO_2}}$ from 4.5 to 5.5 vol% and *vice versa*, overshoot and rise time did not differ significantly between the two control modes. We conclude that to achieve and maintain a desired $F'_{E_{CO_2}}$ during routine anaesthesia, fuzzy logic feedback control of mechanical ventilation is a reliable and safe mode of control. (*Br. J. Anaesth.* 1996; **77**: 636–641)

Key words

Ventilation, mechanical. Carbon dioxide, partial pressure. Computers. Model, ventilatory mechanics. Model, computer simulation.

During anaesthetic procedures, mechanical ventilation must be controlled continuously and adjusted in order to maintain a suitable arterial carbon dioxide tension (P_{aCO_2}). In anaesthesia for intracranial surgery, for example, hypocapnia is used deliberately to reduce brain volume and intracranial pressure. For this purpose, recommendations have been provided for the initial ventilator settings, particularly for ventilatory frequency (f) and tidal volume (V_T).^{1–3} These settings are corrected according to periodic measurements of arterial blood-gas tensions or by using capnometry, or both.⁴ Monitoring the end-tidal carbon dioxide fraction ($F'_{E_{CO_2}}$) allows indirect, non-invasive, breath-by-breath estimate of P_{aCO_2} and is therefore essential for the control of the patient undergoing mechanical ventilation. As carbon dioxide production per minute (\dot{V}_{CO_2}) and

the relation of alveolar ventilation to pulmonary perfusion (\dot{V}_A/\dot{Q}) may change during anaesthesia and surgery, adjustment of the ventilator settings by the anaesthetist is required. Alternatively, automatic, closed-loop control of mechanical ventilation has been designed and applied to lung models, animals and patients, using feedback control of $F'_{E_{CO_2}}$,^{5–12} of either $F'_{E_{CO_2}}$, inspired ($F_{I_{CO_2}}$) or mixed expired ($F'_{E_{CO_2}}$) carbon dioxide fraction,¹³ of the end-tidal carbon dioxide partial pressure ($P'_{E_{CO_2}}$),^{14 15} P_{aCO_2} ,^{16–21} arterial blood pH (pH_a),²² alveolar pressure over time ($P_A(t)$)²³ and gross alveolar ventilation (\dot{V}_{gA}).^{24 25} The most frequently used output variables of these controllers were the ventilator settings for f , V_T and respiratory minute volume (\dot{V}_E), but other variables such as the ratio of inspiratory to expiratory time (i/E ratio) and the inspiratory pressure support were adjusted, and carbon dioxide, delivered from a rebreathing bag and added to the inspiratory fresh gas mixture, was applied, using proportional–integral–derivative (PID) principles.²⁶

Recently, there has been increasing interest in the use of so-called intelligent control techniques in biomedicine²⁷ and promising modern feedback control systems, based on fuzzy logic,²⁸ have been developed for various applications in industry, for anaesthesia and for other branches of medicine.^{29–32} The software and methodology of a fuzzy controller of artificial ventilation have been developed,²³ but automatic control of $F'_{E_{CO_2}}$ for the respiratory care of patients using fuzzy logic has not yet been performed. It was the aim of this study to compare the performance of this automatic, closed-loop control system to human control.

Patients and methods

We studied 30 patients, 10 females and 20 males, ASA I–III, mean age 47.0 (range 12–84) yr, mean weight 67.2 (41–93) kg, mean height 168.5 (153–192) cm. Written informed consent had been obtained for the study which was approved by the Ethics Committee of the medical faculty of the University of Bern. These patients were undergoing

J. SCHÄUBLIN, PHD, P. FEIGENWINTER, S. PETERSEN-FELIX, MD, DEAA, A.M. ZBINDEN, MD, Institute of Anaesthesiology and Intensive Care, Research Section, University Hospital, Inselspital, 3010 Bern, Switzerland. M. DERIGHETTI, Automatic Control Laboratory, Swiss Federal Institute of Technology, Zürich, Switzerland. Accepted for publication: July 16, 1996.

Correspondence to A. M. Z.

elective general, orthopaedic and ENT surgery. Exclusion criteria were patients of ASA classes >3 , those <10 yr old (or body weight <35 kg), those whose lungs were not ventilated mechanically and where surgery was expected to last less than 2 h, and patients undergoing emergency or intracranial surgery.

Anaesthetic management, except for mechanical ventilation, was selected and performed by the attending anaesthetists according to usual practice. An additional anaesthetist, responsible for the study, was present as a supervisor. We used a modified Cicero ventilator (Drägerwerk AG, Lübeck, Germany), where f and V_T could be adjusted electronically by the control computer.

FE'_{CO_2} was measured at the mouthpiece, using an airway adapter fitted with a gas sampling port and a flow and airway pressure sensor, and a side-stream infrared gas analyser (D-LITE adapter and Capnomac Ultima-SV, respectively, Datex Instrumentarium Corp., Helsinki, Finland). (Medical electrical equipment shall cause no safety hazard in normal and in single fault condition (International Standard 601-1 Clause 3.1 of the International Electrotechnical Commission.)) In the feedback control of mechanical ventilation, any failure of the Datex Capnomac Ultima-SV would be a single fault condition. Therefore, for safety reasons, an auxiliary side-stream anaesthetic gas analyser (M1025B, Hewlett Packard Co, Andover, USA), which was not implemented in the feedback control system, was used. Before the experiment, the gas monitors were calibrated according to the operator's manual. In addition to inspired/expired gas concentrations, peak airway pressure (P_{peak}), plateau airway pressure (P_{plat}), positive end-expiratory airway pressure (PEEP), inspired and expired volumes and pulse oximetry data were measured and displayed by the Datex Capnomac Ultima-SV. According to the manufacturer, accuracy and resolution of this monitor for FE'_{CO_2} measurements were <0.2 and 0.1 vol%, respectively, and for airway

pressure measurements 0.15 and 0.1 kPa (1.5 and 1.0 cm H_2O), respectively. Values of FE'_{CO_2} were displayed breath-by-breath with a response time of less than 360 ms and were transformed, together with the values of the additionally measured variables, to a serial data string and transferred every 10 s to the control computer. Values of the data string output were for FE'_{CO_2} , the mean value of the latest 10 s breath-by-breath values, and for P_{peak} , P_{plat} and PEEP, the momentary values of the previous breath.

AUTOMATIC FEEDBACK CONTROL

With the input of measured (FE'_{CO_2} , P_{plat}) and set variables (f , V_T), the rule-based fuzzy controller determined new ventilator settings for f and V_T with a sample rate of 0.1 Hz, which compensated for the current deviation of FE'_{CO_2} from the set-point (eFE'_{CO_2}) (fig. 1). Details on the fuzzy control algorithm are given in the appendix.

An IBM compatible personal computer was used for feedback control and for acquisition, display and storage of data. Computer programmes for these tasks were written in Modula-2 (Logitech SA, Romanel/Morges, Switzerland).

For human and automatic closed loop control of mechanical ventilation, alarm messages were displayed by the monitoring devices and the control computer if any of the preset limits of various variables were exceeded. The fuzzy control mode could be switched to human control at any time.

CLINICAL INVESTIGATIONS

In 30 patients automatic fuzzy logic feedback control of artificial ventilation was compared with human control, which was performed by five staff members, 15 residents and 10 anaesthesia nurses.

Measurements were started during maintenance of anaesthesia, independent of whether or not surgery had begun. Patients were allocated randomly

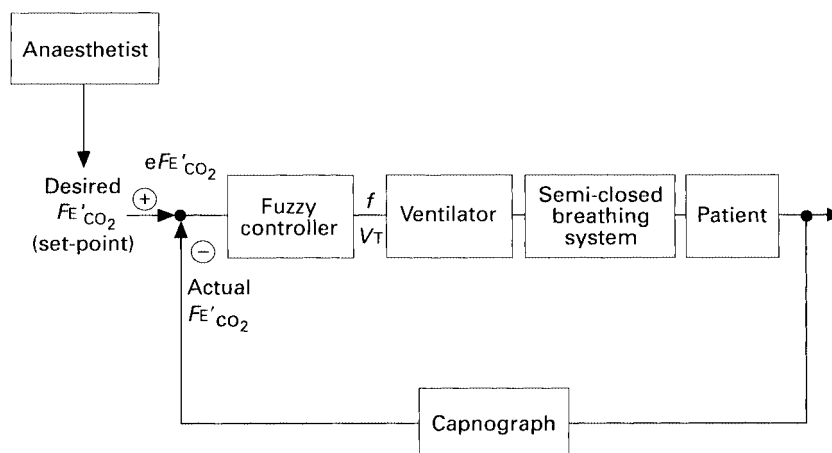


Figure 1 Block diagram of the control loop for mechanical ventilation. From the actual end-tidal carbon dioxide fraction (FE'_{CO_2}), measured by the capnograph (Datex Capnomac Ultima-SV), the deviation from the desired end-tidal carbon dioxide fraction (eFE'_{CO_2}) = desired FE'_{CO_2} (set-point) - actual FE'_{CO_2} was determined and compensated by changes in ventilatory frequency (f) or tidal volume (V_T), or both, computed by the fuzzy controller. Every 10 s, f and V_T were set on the ventilator (Dräger modified Cicero) by the control computer.

Table 1 Sequence of control periods for mechanical ventilation. Set-point of FE'_{CO_2} = desired end-tidal carbon dioxide fraction; f = fuzzy logic control; m = manual control. Thirty investigated patients were allocated randomly to group A or B

	Period No.							
	1	2	3	4	5	6	7	8
Duration (min)	5	20	20	20	5	20	20	20
Set-point of FE'_{CO_2} (vol%)	4.5	4.5	5.5	4.5	4.5	4.5	5.5	4.5
Group A	m	f	f	f	m	m	m	m
Group B	m	m	m	m	m	f	f	f

to the sequence of control periods (table 1). For each control mode and control period f and V_T were set by the anaesthetist (manual control) or the computer (fuzzy logic control) in order to maintain the desired FE'_{CO_2} . Step-changes in the desired FE'_{CO_2} during periods 3, 4, 7 and 8 (table 1) had to be achieved rapidly and smoothly without considerable overshooting and consecutive oscillation of FE'_{CO_2} . I/E ratio, the ratio of end-inspiratory pause time to total inspiratory time ($i_{\text{pause}}/i_{\text{ratio}}$), PEEP and the pressure limitation of the ventilator (P_{max}) were set manually to 1:2, 10%, 5 and 40 mbar, respectively.

Arterial blood was sampled for blood-gas analysis at the end of periods 2 and 6 (set-point of FE'_{CO_2} = 4.5 vol%) for all patients and, as a test, at the end of periods 3 or 7 (set-point of FE'_{CO_2} = 5.5 vol%) for only five randomly selected patients during fuzzy ventilation control.

DATA ANALYSIS

Mean eFE'_{CO_2} , as a measure of accuracy, and the SD of eFE'_{CO_2} , as a measure of the stability of the control, were determined separately for each patient and each period of the trial programme (table 1) and each control mode. For computation of these two variables, data collected during the whole time interval of periods 2 and 6 were used, whereas for periods 3, 4, 7 and 8, only data of the last 10 min of these periods were considered. Step-changes in the set-point of FE'_{CO_2} were judged by the 10–90 rise time (T_{10-90}) and the overshoot. For an increase in the set-point (periods 3 and 7), T_{10-90} was defined as the time required for FE'_{CO_2} to increase from 10% (FE'_{CO_2} = 4.6 vol%) to 90% (FE'_{CO_2} = 5.4 vol%) of the desired change. Because of small fluctuations in measured FE'_{CO_2} , T_{10-90} was determined as the interval between the two events, for which FE'_{CO_2} were ≥ 4.6 and ≥ 5.4 vol% for more than 1 min, respectively. For a decrease in the set-point of FE'_{CO_2} (periods 4 and 8), T_{10-90} was analogously defined. The overshoot was the peak absolute value of eFE'_{CO_2} during the first 5 min after achievement of 90% of the step-change in the set-point.

In addition to the mean eFE'_{CO_2} , the SD of eFE'_{CO_2} , T_{10-90} and the overshoot, mean f , tidal volume per kg body weight (V_T/BW), minute volume per kg body weight (V_E/BW), P_{peak} and P_{plat} were determined for any patient, control period and control mode. Using this reduced sample, means, SD and differences (fuzzy logic minus manual control) of the above mentioned variables were computed. In testing differences between the

control modes the Wilcoxon signed rank test was performed. Statistical software used was SigmaStat (Jandel Scientific GmbH, Erkrath, Germany).

Results

Redundant measurements of FE'_{CO_2} with both side-stream anaesthetic gas analysers revealed differences < 0.4 vol%.

Figure 2 shows the measured FE'_{CO_2} during fuzzy and manual control of mechanical ventilation of the lungs of the patients.

With respect to the accuracy of the control, the mean of the averaged eFE'_{CO_2} for any individual period (table 1) ranged from -0.01 to 0.00 vol% (SD 0.05 vol%) during fuzzy logic control (table 2). The minor increase in both, the corresponding range

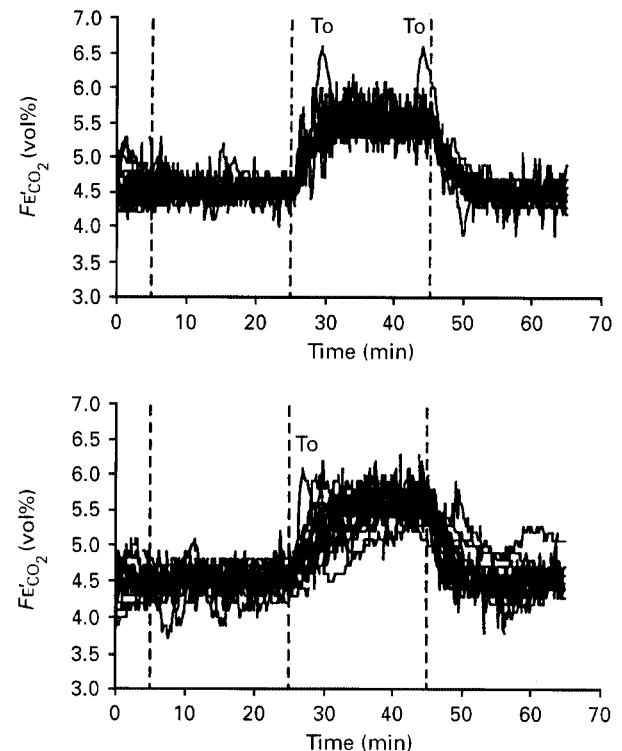


Figure 2 Measured end-tidal carbon dioxide fraction (FE'_{CO_2}) during fuzzy logic control (top) and manual control (bottom) of mechanical ventilation of the lungs of 30 patients according to the sequence of control periods of the trial programme (table 1). T_o = Transient increase in FE'_{CO_2} as a result of limb tourniquet release in two patients; other peaks = inadequate feedback control. The time of initiation of data analysis and of the change in desired end-tidal carbon dioxide fraction (set-point) from 4.5 to 5.5 vol% and from 5.5 to 4.5 vol%, respectively, are indicated by the vertical broken lines.

(from -0.06 to 0.00 vol%) and SD (from 0.07 to 0.14 vol%) during manual control, yielded a statistically significant but irrelevant difference in averaged $eF\dot{E}'_{CO_2}$ values between the control modes ($P < 0.01$) when the set-point of $F\dot{E}'_{CO_2}$ was 5.5 vol%. Values for the SD of $eF\dot{E}'_{CO_2}$, as a measure of the stability of the control, T_{10-90} and the overshoot of any control period, averaged over all patients were approximately, 0.1 (SD 0.05) vol%, 350 (150) s and 0.2 (0.2) vol%, respectively (ns between control modes) (table 2). Comparison of fuzzy *vs* manual control as regards the set (f , V_T/BW) and measured respiratory variables (P_{peak} , P_{plat}) yielded only statistically significant differences for mechanical ventilation during period 3 or 7 (set-point of $F\dot{E}'_{CO_2} = 5.5$ vol%) for these variables (table 2). To achieve and maintain this set-point the fuzzy controller performed, on average, with slightly larger f and smaller V_T/BW , and consequently smaller P_{peak} and P_{plat} compared with human controllers.

Blood-gas analyses revealed that the lungs of the patients were ventilated adequately with a set-point of $F\dot{E}'_{CO_2} = 4.5$ vol% for both control modes (table 3). When the set-point of $F\dot{E}'_{CO_2}$ was 5.5 vol% the five randomly selected patients exhibited, as expected, a moderate respiratory acidosis during fuzzy control of mechanical ventilation.

Discussion

We have demonstrated that during general anaesthesia, fuzzy logic control of mechanical ventilation of the lungs of 30 patients of different ages, with various disease states and surgical procedures, was safe and reliable. Compared with human controllers, the fuzzy controller maintained desired $F\dot{E}'_{CO_2}$ with similar precision and stability and performed with a resembling dynamic response on set-point changes in $F\dot{E}'_{CO_2}$. The breathing pattern, selected by the fuzzy controller, was within clinically acceptable ranges (fig. 2, table 2).

The ventilator settings of the fuzzy controller were based on the recommendations of Kacmarek and Venegas.³ Except for maintaining P_{plat} within suitable limits, the controller did not adapt these settings to the actual state of lung function or lung mechanics of an individual patient, which was the special feature of the lung ventilator controller described by Laubscher and co-workers²⁴ and Weiler, Heinrichs and Kessler.²⁵ It was not within the scope of this study to investigate and qualify various physiological effects as a result of automated ventilation control on respiratory and haemodynamic function. Although the results of blood-gas analyses (table 3) were clinically satisfying for both fuzzy and manual control of ventilation with a set-point of $F\dot{E}'_{CO_2} = 4.5$ vol%, this does not prove that breathing patterns were optimal. Tweed and colleagues,³³ examining the old controversy of the influence of V_T on the well-known impaired pulmonary gas exchange during general anaesthesia, concluded that results from previous investigations had not been consistent. Their own study revealed that patient and surgical factors were more important determinants of pulmonary gas exchange during anaesthesia than V_T or inspired gas composition.

Table 2 Comparison of the quality, and of set and measured ventilatory variables of fuzzy logic *vs* manual control of mechanical ventilation. Values are mean (SD) or mean [SEM] for the 30 investigated patients. For period numbers see table 1. Set-point of $F\dot{E}'_{CO_2}$ = desired end-tidal carbon dioxide fraction; $eF\dot{E}'_{CO_2}$ = desired $F\dot{E}'_{CO_2}$ - actual $F\dot{E}'_{CO_2}$; T_{10-90} = 10 to 90 rise time for step changes in the set-point of $F\dot{E}'_{CO_2}$; f = ventilatory frequency; V_T/BW = tidal volume per kg body weight; $V\dot{E}/BW$ = minute volume per kg body weight; P_{peak} = peak airway pressure; P_{plat} = plateau airway pressure. Sample size = 30; †sample size = 29, size of paired differences = 28. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (Wilcoxon signed rank test)

Set-point of $F\dot{E}'_{CO_2}$ (vol%)	4.5 (period 2 or 6)			5.5 (period 3 or 7)			4.5 (period 4 or 8)		
	Fuzzy control	Manual control	Fuzzy-manual	Fuzzy control	Manual control	Fuzzy-manual	Fuzzy control	Manual control	Fuzzy-manual
Mean $eF\dot{E}'_{CO_2}$ (vol%)	-0.01 (0.05)	0.00 (0.07)	-0.01 [0.02]	0.00 (0.05)	-0.06 (0.10)	0.06 [0.02]**	0.00 (0.05)	-0.02 (0.14)	0.02 [0.02]
SD of $eF\dot{E}'_{CO_2}$ (vol%)	0.09 (0.04)	0.11 (0.04)	-0.02 [0.01]	0.11 (0.05)	0.14 (0.06)	-0.03 [0.02]	0.08 (0.04)	0.10 (0.05)	-0.02 [0.01]
T_{10-90} (s)				313 (90)	392 (179)	-79 [35]	355 (127)†	300 (189)†	45 [39]†
Overshoot (vol%)				0.26 (0.22)	0.33 (0.19)	-0.08 [0.05]	0.15 (0.16)	0.20 (0.17)	-0.05 [0.04]
Mean f (bpm)	9.9 (1.2)	9.6 (1.4)	0.3 [0.2]	8.5 (0.9)	7.6 (1.3)	0.9 [0.3]***	10.2 (1.1)	10.1 (1.4)	0.1 [0.2]
Mean V_T/BW (ml kg ⁻¹)	9.84 (1.00)	9.91 (1.42)	-0.08 [0.16]	8.14 (1.00)	8.82 (1.58)	-0.67 [0.17]***	10.54 (1.10)	10.37 (1.54)	0.18 [0.21]
Mean $V\dot{E}/BW$ (ml min ⁻¹ kg ⁻¹)	98.4 (19.1)	95.7 (20.2)	2.7 [1.9]	69.9 (15.1)	67.0 (13.7)	3.0 [1.6]*	108.3 (21.1)	104.5 (21.1)	3.8 [1.9]*
Mean P_{peak} (kPa)	2.05 (0.31)	2.02 (0.27)	0.03 [0.03]	1.72 (0.22)	1.80 (0.20)	-0.08 [0.02]**	2.14 (0.33)	2.16 (0.31)	-0.02 [0.04]
Mean P_{plat} (kPa)	1.79 (0.24)	1.78 (0.24)	0.01 [0.03]	1.56 (0.19)	1.63 (0.18)	-0.07 [0.02]**	1.87 (0.26)	1.89 (0.27)	-0.03 [0.03]

Table 3 Arterial blood-gas analyses sampled at the end of control periods 2 and 6 of table 1 (desired end-tidal carbon dioxide fraction = 4.5 vol%) of the patients investigated during fuzzy logic and manual control of mechanical ventilation and at the end of control periods 3 or 7 (desired end-tidal carbon dioxide fraction = 5.5 vol%) of five randomly selected patients during fuzzy logic ventilation control (mean (SD) [range]). Set-point of FE'_{CO_2} = Desired end-tidal carbon dioxide fraction; pH_a = arterial blood pH; Pa_{CO_2} = arterial carbon dioxide tension; Pa_{O_2} = arterial oxygen tension; Sa_{O_2} = arterial oxygen saturation Fi_{O_2} = inspired oxygen fraction

Set-point of FE'_{CO_2} (vol%)	4.5	4.5	5.5
Control mode	Fuzzy	Manual	Fuzzy
Sample size	27	29	5
pH_a	7.42 (0.04) [7.35–7.54]	7.42 (0.04) [7.32–7.50]	7.30 (0.06) [7.25–7.41]
Pa_{CO_2} (kPa)	5.03 (0.50) [3.97–5.87]	5.09 (0.45) [4.29–5.93]	6.70 (0.41) [6.03–7.01]
Pa_{O_2} (kPa)	19.9 (3.7) [12.1–25.2]	20.3 (3.8) [11.7–27.5]	18.9 (2.1) [15.5–20.9]
Sa_{O_2} (%)	97.3 (1.3) [92.8–98.8]	97.2 (1.1) [94.7–98.6]	96.6 (1.0) [95.0–97.6]
Fi_{O_2} (vol%)	34.6 (6.1) [29–56]	34.4 (6.2) [29–56]	32.4 (2.1) [29–34]

One of the aims of artificial ventilation control is to maintain Pa_{CO_2} within a small range of a desired value. In this study, however, the automatically and manually controlled variable was FE'_{CO_2} as an expression of PE'_{CO_2} . The arterial to end-tidal PCO_2 difference ($Pa_{CO_2} - PE'_{CO_2}$) is small in healthy individuals, but in anaesthetized patients with altered alveolar ventilation (\dot{V}_A) and pulmonary perfusion (\dot{Q}) (\dot{V}_A/\dot{Q} mismatch) the difference may be considerable.³⁴ An increased and variable end-tidal to arterial gradient may result from pre-existing cardiovascular and respiratory disease states and from the patient's physiological reactions to anaesthesia and surgery, such as variations in arterial pressure, temperature and positioning, prolonged anaesthesia, pulmonary embolism, etc. These situations, but also failing anaesthesia equipment, monitoring devices and control computer, may lead to "erroneous" control. This may be circumvented by changing the set-point of FE'_{CO_2} , for example after control of blood-gas tensions. Safeguards were independent alarm systems implemented on the ventilator, monitoring devices and control computer, in addition to continuous supervision of the feedback control system by the anaesthetist responsible for the study, who had some understanding of the "intelligent" systems built into the research anaesthesia workplace.

Because artificial ventilation of the lungs of a patient represents an ill-defined biological process, fuzzy logic control by its imitation of the anaesthetist's management is promising. In contrast with many studies on computer-controlled ventilation, fuzzy logic ventilation control is feasible in the "uncontrolled" clinical environment and is convenient as it relieves the anaesthetist from routine control work. It is planned to implement the control of mechanical ventilation into the developing control systems for the delivery of inhaled anaesthetics, as reported in this journal by Zbinden and co-workers³¹ and Curatolo and colleagues.³²

Appendix

FUZZY CONTROL ALGORITHM USED FOR AUTOMATIC CONTROL OF MECHANICAL VENTILATION

Basic knowledge on fuzzy logic control, which is necessary for understanding the following, has been given previously.^{29–32}

Input variables of the fuzzy controller were: eFE'_{CO_2} (eFE'_{CO_2} = desired FE'_{CO_2} - actual FE'_{CO_2}) (vol%) and $deFE'_{CO_2}$, which was defined as the difference between actual eFE'_{CO_2} and eFE'_{CO_2} , 60 s

before ($deFE'_{CO_2}(t_0) = eFE'_{CO_2}(t_0) - eFE'_{CO_2}(t_0 - 60s)$) (vol%), f (bpm), tidal volume per kg body weight (\dot{V}_T/BW) ($ml\ kg^{-1}$) and P_{plat} (kPa). The change in minute volume per kg body weight ($d\dot{V}_E/BW$) ($ml\ min^{-1}\ kg^{-1}$) and the change in f (df) (bpm) were the output variables.

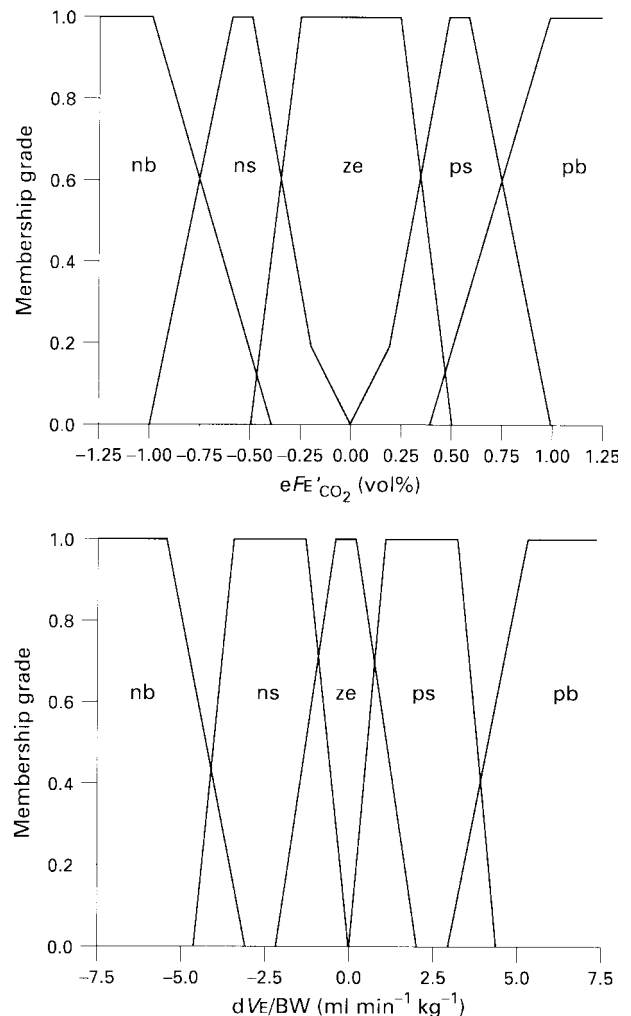


Figure 3 Subdivision of the deviation of actual from desired end-tidal carbon dioxide fraction eFE'_{CO_2} = desired FE'_{CO_2} - actual FE'_{CO_2} and of the change in minute volume per kg body weight ($d\dot{V}_E/BW$) into fuzzy sets nb (negative big), ns (negative small), ze (zero), ps (positive small) and pb (positive big), with graphs of their membership functions. For example, eFE'_{CO_2} = -0.75 vol% belongs simultaneously to both the fuzzy set nb and ns, with an equal membership grade of 0.6.

Twenty-nine linguistic rules were designed, which expressed the intention to achieve and maintain the desired FE_{CO_2} by selection of appropriate ventilator settings and at the same time to minimize the deviation in both f and V_T/BW , from 10 bpm and 10 ml kg^{-1} , respectively, and to maintain P_{plat} within suitable limits ($<3-4$ kPa). By mean of the following examples of rules, the concept of fuzzy logic control of artificial ventilation is explained. In figure 3, typical membership functions of fuzzy sets of the input variable eFE_{CO_2} and of the output variable dVE/BW are presented.

IF $eFE_{CO_2} = ns$ AND $deFE_{CO_2} = pb$ THEN $dVE/BW = ns$

If actual FE_{CO_2} is slightly larger than desired FE_{CO_2} (set-point), which implies eFE_{CO_2} is negative small (ns), and FE_{CO_2} was much larger than the set-point of FE_{CO_2} 60 s before, which implies $deFE_{CO_2}$ is positive big (pb), then reduce VE/BW slightly, which implies dVE/BW is negative small (ns). Performance of this rule acts as a deceleration manoeuvre, which minimizes overshooting or oscillation of FE_{CO_2} , or both, about the set-point.

IF $f = ps$ AND $V_T/BW = pb$ THEN $df = pm$

If actual f is small, which implies f is positive small (ps), and V_T/BW is large, which implies V_T/BW is positive big (pb), then increase f moderately, which implies df is positive medium (pm). By maintaining VE/BW , V_T/BW then decreases.

IF $P_{plat} = pb$ THEN $df = pb$

If actual P_{plat} is large ($P_{plat} = pb$), then increase f considerably ($df = pb$). By maintaining VE/BW , V_T/BW and P_{plat} then decrease.

Rules, sets and membership functions were designed according to clinical experience and modified in pilot studies with 14 anaesthetized patients undergoing mechanical ventilation from whom written informed consent had been obtained.

Maximum–minimum inference was used for determination of fuzzy values of output variables. Applying the centre of gravity method defuzzified, crisp values for the ventilator settings resulted at a rate of 0.1 Hz.

In the computer programme for automatic feedback control of mechanical ventilation various safety restrictions were incorporated to keep the values of input and output variables within reasonable limits. One of these restrictions was that ventilator settings for f were limited to values between 6 and 20 bpm and for V_T/BW to values between 4 and 20 ml kg^{-1} .

Acknowledgements

This study was supported financially by a grant from the Swiss National Science Foundation. We thank B. Neuenschwander, PhD, Department of Social and Preventive Medicine, University of Bern, Bern, Switzerland, for his statistical advice and Mr D. Leibundgut for his assistance in processing the data.

References

- Radford EP jr, Ferris BG jr, Kriete BC. Clinical use of a nomogram to estimate proper ventilation during artificial respiration. *New England Journal of Medicine* 1954; **251**: 877–884.
- Kenny S. The Adelaide ventilation guide. *British Journal of Anaesthesia* 1967; **39**: 21–23.
- Kacmarek RM, Venegas J. Mechanical ventilatory rates and tidal volumes. *Respiratory Care* 1987; **32**: 466–478.
- O'Flaherty D. *Principles and Practice Series, Capnography*. London: BMJ Publishing Group, 1994.
- Saxton GA jr, Myers G. A servomechanism for automatic regulation of pulmonary ventilation. *Journal of Applied Physiology* 1957; **11**: 326–328.
- Frumin MJ, Lee ASJ. A physiologically oriented artificial respirator which produces N_2O-O_2 anaesthesia in man. *Journal of Laboratory and Clinical Medicine* 1957; **49**: 617–622.
- Kamiyama M, Tachibana N, Yamamura H. Automatic controller for artificial ventilation. *Japanese Journal of Anaesthesiology* 1968; **17**: 1047–1048.
- Hilberman M, Schill JP, Peters RM. On-line digital analysis of respiratory mechanics and the automation of respirator control. *Journal of Thoracic and Cardiovascular Surgery* 1969; **58**: 821–828.
- Coles JR, Brown WA, Lampard DG. Computer control of respiration and anaesthesia. *Medical and Biological Engineering* 1973; **11**: 262–267.
- Marsh WI, Smith WD. A flexible system for closed-loop ventilator development. *Journal of Medical Systems* 1982; **6**: 53–59.
- Ohlson KB, Westenskow DR, Jordan WS. A microprocessor based feedback controller for mechanical ventilation. *Annals of Biomedical Engineering* 1982; **10**: 35–48.
- Chapman FW, Newell JC, Roy RJ. A feedback controller for ventilatory therapy. *Annals of Biomedical Engineering* 1985; **13**: 359–372.
- Giard MH, Perrin F, Bouchet P, Robert D, Pernier J. EOLE: un système de contrôle automatique de pO_2 et de pCO_2 en ventilation assistée. *Medical and Biological Engineering and Computing* 1983; **21**: 503–508.
- Ritchie RG, Ernst EA, Pate BL, Pearson JD, Sheppard LC. Closed-loop control of an anaesthesia delivery system: development and animal testing. *IEEE Transactions on Biomedical Engineering* 1987; **34**: 437–443.
- Jantzen JP, Hennes HJ, Kleemann PP. CO_2 -Rückkopplungssteuerung der Narkosebeatmung. Eine experimentelle Studie am Schweinemodell. *Anaesthesist* 1990; **39**: S101.
- Mitamura Y, Mikami T, Sugawara H, Yoshimoto C. An optimally controlled respirator. *IEEE Transactions on Biomedical Engineering* 1971; **18**: 330–338.
- Schulz V, Ulmer HV, Erdmann W, Kunke S, Schnabel KH. Ein Verfahren zur Pa_{CO_2} -geregelten automatischen Ventilation. *Pneumologie* 1974; **150**: 319–325.
- Jordan WS, Westenskow DR. Microprocessor control of ventilation using carbon dioxide production. *Anesthesiology* 1979; **51**: S380.
- East TD, Westenskow DR, Pace NL, Nelson LD. A microcomputer-based differential lung ventilation system. *IEEE Transactions on Biomedical Engineering* 1982; **29**: 736–740.
- Noshiro M. Design of a control system for maintaining a normal arterial pCO_2 by artificial respiration. *Medical and Biological Engineering and Computing* 1984; **22**: 418–425.
- East TD, Andriano KP, Pace NL. Computer-controlled optimization of positive end-expiratory pressure. *Critical Care Medicine* 1986; **14**: 792–797.
- Coon RL, Zuperku EJ, Kampine JP. Systemic arterial blood pH servocontrol of mechanical ventilation. *Anesthesiology* 1978; **49**: 201–204.
- Vasil'eva OI, Ionov IP, Kantor PS, Ul'yanov SV. Dual control of the artificial ventilation process with use of a fuzzy controller in the feedback circuit. *Biomedical Engineering* 1989; **23**: 7–17.
- Laubscher TP, Heinrichs W, Weiler N, Hartmann G, Brunner JX. An adaptive lung ventilation controller. *IEEE Transactions on Biomedical Engineering* 1994; **41**: 51–59.
- Weiler N, Heinrichs W, Kessler W. The ALV-mode: a safe closed loop algorithm for ventilation during total intravenous anaesthesia. *International Journal of Clinical Monitoring and Computing* 1994; **11**: 85–88.
- O'Hara DA, Bogen DK, Noordergraaf A. The use of computers for controlling the delivery of anaesthesia. *Anesthesiology* 1992; **77**: 563–581.
- Linkens DA, ed. *Intelligent Control in Biomedicine*. London: Taylor & Francis, 1994.
- Zadeh LA. Fuzzy sets. *Information and Control* 1965; **8**: 338–353.
- Martin JF. Fuzzy control in anaesthesia. *Journal of Clinical Monitoring* 1994; **10**: 77–80.
- Asbury AJ, Tzabar Y. Fuzzy logic: new ways of thinking for anaesthesia. *British Journal of Anaesthesia* 1995; **75**: 1–2.
- Zbinden AM, Feigenwinter P, Petersen-Felix S, Hacısalihzade S. Arterial pressure control with isoflurane using fuzzy logic. *British Journal of Anaesthesia* 1995; **74**: 66–72.
- Curatolo M, Derighetti M, Petersen-Felix S, Feigenwinter P, Fischer M, Zbinden AM. Fuzzy logic control of inspired isoflurane and oxygen concentrations using minimal flow anaesthesia. *British Journal of Anaesthesia* 1996; **76**: 245–250.
- Tweed WA, Phua WT, Chong KY, Lim E, Lee TL. Tidal volume, lung hyperinflation and arterial oxygenation during general anaesthesia. *Anaesthesia and Intensive Care* 1993; **21**: 806–810.
- Fletcher R. Smoking, age and the arterial-end-tidal PCO_2 difference during anaesthesia and controlled ventilation. *Acta Anaesthesiologica Scandinavica* 1987; **31**: 355–356.