

TITLE: MICROPROCESSOR CONTROL OF VENTILATION USING CARBON DIOXIDE PRODUCTION

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INTRODUCTION: With the introduction of the Siemens 900B ventilator and its companion low-dead space infrared CO₂ analyzer, the control of ventilation through a convenient electro-mechanical interface utilizing real-time feedback data has become more easily attainable. The problem of multiple variable input correlated with short-time constants and displayed in a meaningful fashion lends itself well to solution utilizing microprocessor digital computer techniques. In pediatric anesthesia and intensive care problems the variables are even wider in range. We have interfaced the Siemens ventilator with the Intel 8085 microcomputer with 16 input channels. This present study is performed utilizing the small dog model and evaluating carbon dioxide excretion as the control variable in the ventilator system.

METHODS: The dog model utilized 10-25 kg dogs anesthetized with thiopental (10 mg/kg), pancuronium (1 mg/kg) and fentanyl (.01 mg/kg). The animals were intubated after the thiopental and placed on the ventilator. Anesthesia was continued by fentanyl .01 mg/kg/hr. An EKG, arterial pressure transducer (femoral) and venous infusion line were inserted. The ventilation was adjusted by the CO₂ production measured on the Siemens Model 930 I.R. CO₂ Analyzer. The dead space volume was calculated using the CO₂ excretion curve. The minute volume was varied following the read out from the printer on a Hewlett-Packard Model 9815A microcomputer. The following computation was performed every 30 seconds to update the ventilator control.

$$\dot{V}_E = k \dot{V}_A + f V_D \text{ where } \dot{V}_A = \frac{(P_B - 47) \dot{V}_{CO_2}}{P_a CO_2}$$

f = frequency, \dot{V}_E = minute ventilation, k = proportional physiological dead space, \dot{V}_{CO_2} = CO₂ excretion, \dot{V}_A = alveolar ventilation.

Three manipulations were performed: 1) the CO₂ body stores were increased by inspiring 12% CO₂ for 15 minutes then using the control variables to keep the PaCO₂ normal (Table 1), 2) a constant infusion of NaHCO₃ increasing production of CO₂ (Table 2) and 3) selecting a new PaCO₂ value desired and evaluating the ability of the program to achieve this (Table 3).

RESULTS: The overall results for 6 experiments is presented in Table 2. Since many data points are gathered in each experiment and averaging this data for all experiments obscures the extremes which are of great interest, I have presented data points from 2 experiments in another manner (space won't permit tables of raw data) in Tables 1 and 3. It is readily apparent that the PaCO₂ was held within narrow ranges although the \dot{V}_{CO_2} varied widely. If the program is working correctly, the correlation coefficient between \dot{V}_{CO_2} and \dot{V}_E should be unity. The actual R value was .9996. Since the CO₂ production was being used to control the minute ventilation, the end tidal CO₂ should not correlate unless they were in steady state;

indeed the R value was -.2519. The correlation coefficient for the ETCO₂ versus PaCO₂ was .9365. **DISCUSSION:** This study was performed in a model with normal lungs. In this model, however, CO₂ removal by ventilation could be controlled well with this non-invasive monitoring system. We have plotted a record of oxygen uptake against CO₂ excretion which were being monitored together by attaching our oxygen consumer to the Siemens system. It illustrates how rapidly and constantly these variables were shifting under anesthesia. $\dot{V}O_2$ changed from 170 to 114 in 6 minutes with the \dot{V}_{CO_2} dropping from 137 to 65. The model required the 30 second time base for control. The dead space in this model was generally fairly constant. The data had to be corrected for dead space change only an average of 3 times for each 6 hour experiment. Correcting for anatomic dead space change is no problem with the monitoring system. Physiologic dead space changes, however, required blood gases to correct the constant k in the formula. Their significant change was signaled by shifting end tidal CO₂. This control system only required 3 channels on the input BUSS - frequency, CO₂ excretion and effective ventilation - when the pre-processed digital signals from the Siemens monitors are used. The CO₂ production does not depend on the recognition of the momentary peak signal accurately as the ETCO₂ signal does; therefore, it is easier to follow with higher frequency ventilation and when the signal is very irregular such as in IMV. When PEEP and CPAP are used, the physiologic dead space shift requires a PaCO₂ figure to correct the k. Many variables are needed for accurate feedback loop control of a ventilator (one system uses 32 variables), however, CO₂ production should be a good control variable until production exceeds the ability to excrete. With increasing use of the Siemens ventilator in pediatric units in the U.S., it is a logical step to use its monitoring capabilities with control logic.

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TABLE 1: N = 16

	V_D	\dot{V}_{CO_2}	ETCO ₂	\dot{V}_E	PaCO ₂
Range	70-118	138-288	4.3-6.5	4.8-9.9	28-31.5
Δ %	68%	108%	51%	106%	12.5%
X ± SD	119±5	228±52	4.8±.6	8.0±1.7	29.8±1.3

TABLE 2: N = 6

	\dot{V}_E L/min	ETCO ₂ torr	\dot{V}_{CO_2} ml/min	PaCO ₂ torr
Control	4.6±1.2	31±1.5	130±25	36±2.5
\dot{V}_{CO_2}	6.6±1.6	30±2.5	210±62	37.5±3.5
Control	4.8±.8	30.5±1	130±22	35±3.4

TABLE 3: N = 20

	V_D	\dot{V}_{CO_2}	ETCO ₂	\dot{V}_E	PaCO ₂
Range	118-134	163-263	3.0-4.9	6.0-11.9	30-23.6
Δ %	14%	61%	63%	98%	27%
X ± SD	119±5	213±35	3.5±.6	9.9±1.4	25±2