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 CO_2 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 CO_2 production measured on the Siemens Model 930 I.R. CO_2 Analyzer. The dead space volume was calculated using the CO_2 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.

$$\dot{V}_E = k\,\dot{V}_A + f\,V_D \quad \text{where} \quad \dot{V}_A = \frac{(P_B - 47)\,\dot{V}_{CO_2}}{P_aCO_2}$$

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

Three manipulations were performed: 1) the CO_2 body stores were increased by inspiring 12% CO_2 for 15 minutes then using the control variables to keep the $PaCO_2$ normal (Table 1), 2) a constant infusion of $NaHCO_3$ increasing production of CO_2 (Table 2) and 3) selecting a new $PaCO_2$ 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 $PaCO_2$ 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 CO_2 production was being used to control the minute ventilation, the end tidal CO_2 should not correlate unless they were in steady state; indeed the R value was -.2519. The correlation coefficient for the $ETCO_2$ versus $PaCO_2$ was .9365.

DISCUSSION: This study was performed in a model with normal lungs. In this model, however, CO_2 removal by ventilation could be controlled well with this non-invasive monitoring system. We have plotted a record of oxygen uptake against CO_2 excretion which were being monitored together by attaching our oxiconsumeter to the Siemen's 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 CO_2. This control system only required 3 channels on the input BUSS - frequency, CO_2 excretion and effective ventilation - when the pre-processed digital signals from the Siemens monitors are used. The CO_2 production does not depend on the recognition of the momentary peak signal accurately as the $ETCO_2$ 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 $PaCO_2$ figure to correct the k. Many variables are needed for accurate feedback loop control of a ventilator (one system uses 32 variables), however, CO_2 production should be a good control variable until production exceeds the ability to excrete. With increasing use of the Siemen's 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
$\dot{V}_{CO_2}$ Control	6.6±1.6	30±2.5	210±62	37.5±3.5
	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