CO_2 Rebreathing of T-Piece System in Patients during Recovery Phase from Acute Respiratory Failure

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Eight respiratory parameters which might affect the amount of carbon dioxide rebreathing were assessed in seven patients who were breathing spontaneously from large-bore T tube system during the recovery phase from acute respiratory failure.

With multivariate regression analysis, the absolute amount of rebreathed CO_2 at the connector of endotracheal tube (VINSPCO2) were approximately estimated by using relatively small number of parameters, including minute volume (VEXP), fresh gas inflow to T piece system (VFGI) and preferably by additional parameters concerning CO_2 output of the patients.

CO_2 rebreathing ratio, VINSPCO2 devided by gross outward flux of CO_2 at the connector (VEXPCO2), was predicted with simple regression equation by using (VEXP/VFGI) as follows,

(VINSPCO2)/(VEXPCO2) = 0.405 + 0.33xln (VEXP/VFGI)

The maximum (VEXP/VFGI) ratio to prevent rebreathing of CO_2 at the connector was 0.30, whereas the ratio to prevent CO_2 accumulation due to rebreathing was 0.45. (Key words: T-piece, CO_2 rebreathing, acute respiratory failure)

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Introduction

In 1937, Ayre[1] introduced a T-piece as an anesthetic system chiefly for children. Recently the simple T tube system has been widely used for patients with respiratory failure who are receiving ventilatoy support, to provide humidified inspiratory gas of a specified F_IO_2[2]. The purpose of the present study is to evaluate the amount of rebreathing of CO_2 as a function of fresh gas inflow and multiple respiratory parameters, and to determine the minimum requirement of fresh gas inflow to avoid rebreathing of CO_2 gas in spontaneously breathing intubated patients who were in recovery phase from acute respiratory failure.

Methods

The study was conducted on seven adult patients (table 1) who were admitted to our institute after trauma or acute neurological disorders. Informed consent for the procedure was obtained from the patients or their families. All the patients had been ventilated mechanically

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Table 1. Profile of the patients studied
Abbreviations, MV: mechanical ventilation, CPAP: continuous positive airway pressure, NT: nasotracheal intubation, OT: orotracheal intubation, TS: Traceostomy

no.	age (yrs)	sex	weight (kg)	diagnosis	duration of MV/CPAP (days)	artificial airway	V_D/V_T (%)
1	77	F	45	burn, CO-intoxication	6	NT	48
2	25	M	62	cerebral contusion facial injury	3	OT	-
3	82	M	55	near drowning post CPR	7	TS	52
4	26	M	68	cerebral contusion extradural hematoma	3	OT	-
5	52	F	66	cerebral contusion pulmonary contusion	18	TS	42
6	69	F	48	cerebellar hemorrhage chronic renal failure	11	TS	37
7	53	F	53	rupture of basilar artery, aspiration pneumonia	15	TS	45

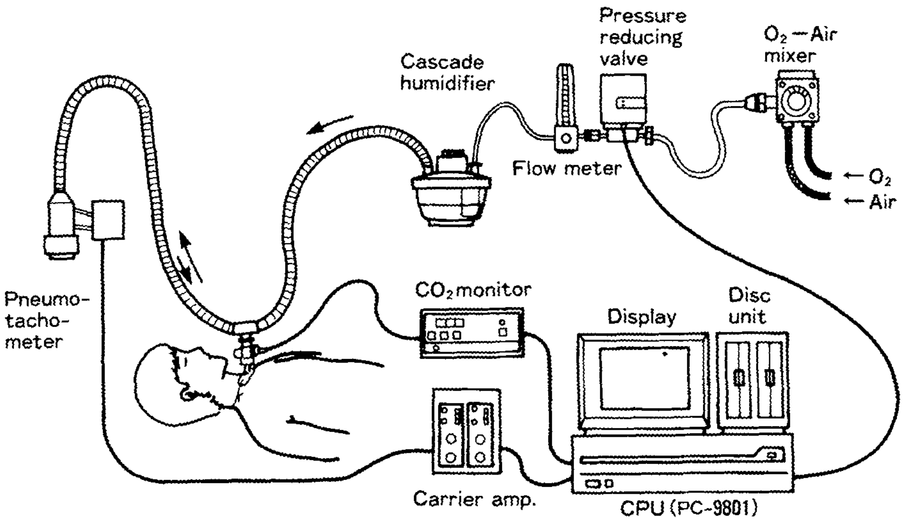
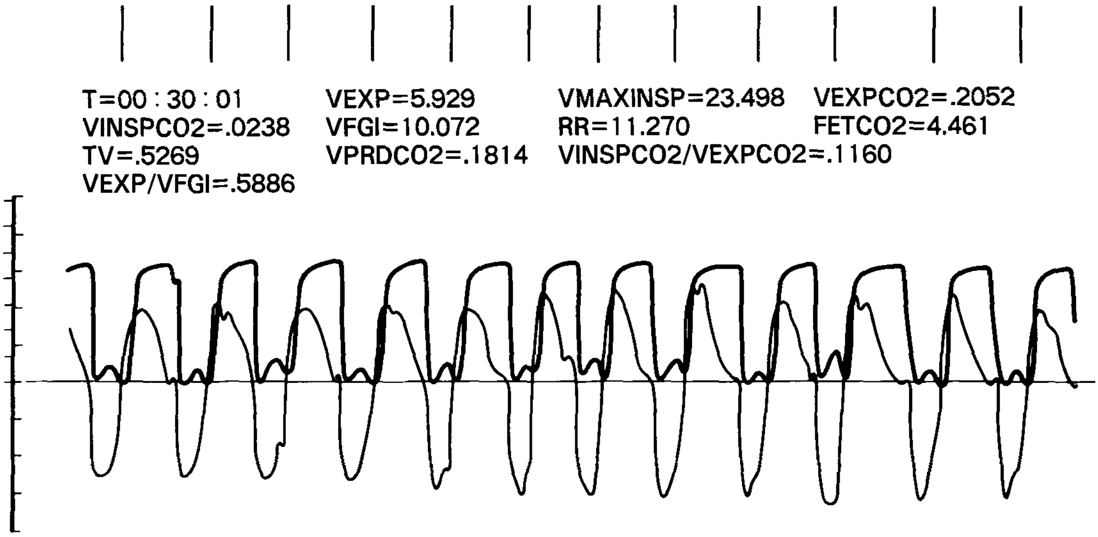


Fig. 1. Schematic diagram of experimental procedures. See text for details.

for various period of time for acute respiratory failure. Weaning from the mechanical ventilation was performed with decreasing the rate of intermittent mandatory ventilation with or without PEEP. All the measurements were done within 6 hours after the successful weaning from mechanical ventilation or CPAP. Four patients had tracheostomy tube and three patients had nasal or oral endotracheal tube.

Schematic diagram of measurement is shown in fig. 1. Standard corrugated tube of polyvinyl chloride (Inspiron Co., I.D. = 22 mm) was used as an inspiratory and an expiratory (reservoir) limb of the system. Both limbs were connected to standard T-piece (Inspiron Co., O.D. = 22mm, I.D. = 15mm). Rapid responding infrared absorption capnograph of flow-through type with no delay time (Nihon Kohden OIR-7101) calibrated with gas mixture of known CO_2 concentration, was interposed between the T-piece and the connector of endotracheal tube. Dead space between the stream line of fresh gas and the infrared beam was 5 ml. Expiratory limb was long enough to prevent the breathing



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T=00:30:01          VEXP=5.929          VMAXINSP=23.498     VEXPCO2=.2052
VINSPCO2=.0238      VFGI=10.072         RR=11.270           FETCO2=4.461
TV=.5269            VPRDCO2=.1814       VINSPCO2/VEXPCO2=.1160
VEXP/VFGI=.5886
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Fig. 2. A picture of computer display (retouched for clarity) showing instantaneous CO$_2$ concentration at the sensor (thick curve), instantaneous gas flow at the sensor (negative in inspiration, thin curve), together with respiratory parameters, each of which was averaged for one minute. Vertical bars on top indicate beginning of each expiration.

Abbreviations, VEXP: minute volume, VMAXINSP: maximum inspiratory flow, VEXPCO2: CO$_2$ exhaled through the sensor, VINSPCO2: CO$_2$ inhaled through the sensor, VFGI: fresh gas inflow, RR: respiratory rate, FETCO2: fraction of end-tidal CO$_2$, TV: tidal volume, VPRDCO2: CO$_2$ production.

Table 2. Means, standard deviations and ranges of measured parameters (n=312)

variable	mean	s.d.	min.	max.
VEXP(l/min)	11.656	5.141	3.182	26.038
VMAXINSP(l/min)	38.040	14.716	11.577	73.559
VEXPCO2(l/min)	0.462	0.271	0.101	1.428
VINSPCO2(l/min)	0.245	0.273	0.001	1.110
VFGI(l/min)	10.675	3.849	2.885	24.359
RR(min-1)	25.674	5.223	11.489	38.603
FETCO2(%)	4.911	0.782	3.080	6.496
TV(l)	0.456	0.184	0.146	1.030
VPRDCO2(l/min)	0.217	0.073	0.098	0.313

of room air (total volume of expiratory limb including a pneumotachometer was 1500 ml). Fleisch type penumotachometer (Nihon Kohden, TP-602T), calibrated on a Collins spirometer was connected to the end of expiratory limb to measure instantaneous flow, which was the numerical sum of fresh gas inflow and ventilatory flow of patients.

Instantaneous values of CO$_2$ concentration at the sensor (FCO2) and the flow at the end of expiratory limb (VEND) were fed to a microcomputer (Nihon Denki, PC-9801) every 25 miliseconds via an analogue to digital converter (12 bits). Fresh gas inflow (VFGI) was calculated as the timed mean of VEND, and the instantaneous gas flow at the CO$_2$ sensor (VSENS) was calculated as VEND-VFGI. These variables, averaged for one minute at every two and half minutes, were displayed on an oscilloscope and stored in magnetic disks. Amount of carbon dioxide exhaled or inhaled through the CO$_2$ sensor (VINSPCO2 and VEXPCO2, respectively) was calculated by integrating instantaneous (VSENS x FCO2) over the time. CO$_2$ production

Table 3. Correlation matrix between each parameter (n = 312, *p<0.01)

	VEXP	VMAXINSP	VEXPCO2	VINSPCO2	VFGI	RR
VEXP	1	0.9332*	0.8998*	0.8854*	-0.3174*	0.4533*
VMAXINSP	0.9332*	1	0.8603*	0.8000*	-0.2625	0.2571
VEXPCO2	0.8998*	0.8603*	1	0.9676*	-0.4561*	0.3354*
VINSPCO2	0.8854*	0.8000*	0.9676*	1	-0.5605*	0.3054
VFGI	-0.3174*	-0.2625	-0.4561*	-0.5605*	1	0.0877
RR	0.4533*	0.2571	0.3354*	0.3054	0.0877	1
FETCO2	0.0935	0.1264	0.4664*	0.4099*	-0.3773*	-0.0514
TV	0.8429*	0.8827*	0.8010*	0.7977*	-0.3891*	-0.0548
VPRDCO2	0.4640*	0.5948*	0.5695*	0.3434*	0.1277	0.2526

(VPRDCO2) was obtained as VEXPCO2 – VINSPCO2. Fresh gas inflow (F_IO_2 0.3 to 0.4) was changed slowly in a linear fashion from approximately 3 l/min to 25 l/min over the first 60 minutes and then from 25 l/min to 3 l/min over the following 60 minutes by automatically driving an electronic pressure reducing valve (Toko Engineering, EP200) by the microcomputer system. The following nine variables were analyzed. Minute volume (VEXP, l/min), maximum inspiratory flow (VMAXINSP, l/min), CO_2 exhaled per minute through the sensor (VEXPCO2, l/min), CO_2 inhaled per minute through the sensor (VINSPCO2, l/min), fresh gas inflow (VFGI, l/min), respiratory rate (RR, min^{-1}), end tidal fraction of CO_2 (FETCO2, %), tidal volume (TV, l) and CO_2 production (VPRDCO2, l/min). All gas volumes were corrected to STPD. The statistical analysis was performed with Student's paired-t test, standard linear, transformed bivariate, and multivariate regression analysis, and $p<0.01$ was taken as the minimal level of significance.

Results

A typical display of instantaneous CO_2 concentration and gas flow at the CO_2 sensor, with a set of derived parameters, was shown in fig. 2.

312 sets of nine parameters were used for statistical analysis. The data while patients coughed or strained was excluded from the analysis. Table 2 shows the means, the standard deviations, and the ranges of measured respiratory parameters at the range of fresh gas inflow tested (3.2–26.0 l/min). The correlation matrix between each parameter is shown in table 3.

1) Amount of rebreathed carbon dioxide at CO_2 sensor

Carbon dioxide rebreathed across the CO_2 sensor (VINSPCO2) showed significant positive correlations with VEXP ($r = 0.885$), VMAXINSP ($r = 0.800$), VEXPCO2 ($r = 0.968$), FETCO2 ($r = 0.410$), VT ($r = 0.798$), and VPRDCO2 ($r = 0.343$). It also showed significant negative correlation with VFGI ($r = -0.560$).

By multivariate regression analysis, VINSPCO2 was most accurately expressed with equations including VEXPCO2 as follows,

$$\begin{aligned}\mathrm{VINSPCO2} = {} & 6.5374 \times 10^{-1} \times (\mathrm{VEXPCO2}) \\ & - 1.042 \times 10^{-2} \times (\mathrm{VFGI}) \\ & + 7.38 \times 10^{-3} \times (\mathrm{VEXP}) \\ & - 3.191 \times 10^{-2} \qquad \text{---}(1) \\ & (R^2 = 0.9587)\end{aligned}$$

Excluding VEXPCO2 which is hard to determine in daily clinical practice from independent variables, VINSPCO2 was expressed satisfactorily with

$$\begin{aligned}\mathrm{VINSPCO2} = {} & 4.262 \times 10^{-2} \times (\mathrm{VEXP}) \\ & + 1.1443 \times 10^{-1} \times (\mathrm{FETCO2}) \\ & - 7.3064 \times 10^{-1} \times (\mathrm{VPRDCO2}) \\ & - 5.92 \times 10^{-3} \times (\mathrm{VFGI}) \\ & - 5.9173 \times 10^{-1} \qquad \text{---}(2) \\ (R^2 = 0.9487) &\end{aligned}$$

or more simply

$$\begin{aligned}\mathrm{VINSPCO2} = {} & 3.630 \times 10^{-2} \times (\mathrm{VEXP}) - 1.914 \\ & \times 10^{-2} \times (\mathrm{VFGI}) + 2.636 \times 10^{-2} \\ & \qquad \text{---}(3) \\ (R^2 = 0.8707) &\end{aligned}$$

In view of high agreement of equation (1) to data, transformed bivariate analysis including four dependent and independent variables in equation (1) was carried out. CO_2 rebreathing

FETCO2	TV	VPRDCO2
0.0935	0.8429*	0.4640*
0.1264	0.8827*	0.5948*
0.4664*	0.8010*	0.5695*
0.4099*	0.7977*	0.3434*
-0.3773*	-0.3891*	0.1277
-0.0514	-0.0548	0.2526
1	0.1452	0.4016*
0.1452	1	0.3818*
0.4016*	0.3818*	1

ratio (VINSPCO2/VEXPCO2) was best expressed as a function of (VEXP/VFGI) as follows (fig. 3). (fig. 3).

$$(\mathrm{VINSPCO2/VEXPCO2}) = 0.405 + 0.331 \times \ln(\mathrm{VEXP/VFGI}) \quad \text{---}(4)$$

2) End-tidal CO_2 concentration

FETCO2 showed significant positive correlation with VEXPCO2 (r = 0.4664), VINSPCO2 (r = 0.4099), VPRDCO2 (r = 0.4016) and significant negative correlation with VFGI (r = -0.3773) (fig. 4).

By multivariate regression analysis, FETCO2 was expressed by

$$\mathrm{FETCO2} = 5.3034 \times (\mathrm{VINSPCO2}) - 2.501 \times 10^{-1} \times (\mathrm{VEXP}) + 6.673 \times (\mathrm{VPRDCO2}) - 1.567 \times 10^{-3} \times (\mathrm{VFGI}) + 5.244 \quad \text{---}(5)$$

$$(R^2 = 0.7842)$$

or, when VINSPCO2 was excluded from independent variables,

$$\mathrm{FETCO2} = 7.1173 \times (\mathrm{VPRDCO2}) - 1.198 \times 10^{-1} \times (\mathrm{VFGI}) - 6.107 \times 10^{-2} \times (\mathrm{VEXP}) + 5.356 \quad \text{---}(6)$$

$$(R^2 = 0.4512)$$

All the regression equations listed above ((1) – (6)) were significant by analysis of variance.

3) Threshold to elicit ventilatory response to CO_2 rebreathing

When minute volume (VEXP) or end-tidal CO_2 (FETCO2) were plotted against minute volume/fresh gas inflow ratio (VEXP/VFGI), a inflexion was clearly seen where VEXP or FETCO2 increases for increasing (VEXP/VFGI) (fig. 4 and fig. 5). This value of VEXP/VFGI was thought to be the threshold where the patient started to rebreath CO_2 down to alveoli causing retention of CO_2 and hyperventilation. This VEXP/VFGI value was obtained for each patient by extrapolating a polynominal curve (fitted to points where VEXP or FETCO2 exceeded resting value by +10%) to resting value of either VEXP or FETCO2 (table 4). The mean VEXP/VFGI of the inflection was 0.449 ± 0.049 (mean ± s.d.) for VEXP and 0.452 ± 0.058 for FETCO2. There was no statistical difference between these values. The VEXP/VFGI of each patient where no rebreathing will take place at the CO_2 sensor, calculated by extrapolating logarithmic functin in the form of equation (4), are also shown in table 4. The mean VEXP/VFGI thus obtained was 0.301 ± 0.048 and significant difference was found between VEXP/VFGI for inflection of either VEXP or FETCO2.

Discussion

T-piece system is commonly used for non-anesthetized intubated patients who are breathing spontaneously during or after weaning from ventilatory support[2,3]. When the capacity of reservoir limb is large enough to prevent dilution of the inspired gases by air, fresh gas inflow must be high enough to avoid the rebreathing of expired CO_2.

The threshold of fresh gas inflow to avoid rebreathing of CO_2 in classical T-tube system or its modification is relatively easy to determine and has been investigated by mathematical analysis[4,5], laboratory mechanical models[6,7], or in human under anesthesia[8,9]. But none of these reportes dealt with the quantification of CO_2 rebreathed when the fresh gas inflow is reduced below the threshold level.

The ratio of fresh gas inflow to minute volume (i.e. fresh gas inflow/minute volume) or its reciprocal (i.e. minute volume/fresh gas inflow), and respiratory flow pattern have been known to be major factors for determining this threshold level.

Using a mathematical model, Onchi et al.[4] suggested that fresh gas flow of over 3 times the minute volume is needed for respiratory flow resembling a sine wave. Mapleson[5], in his mathematical model, assumed a square flow and suggested a fresh gas flow of twice and 3 times the minute volume when the inspiratory/expiratory ratio is 1:1 and 1:2, respectively.

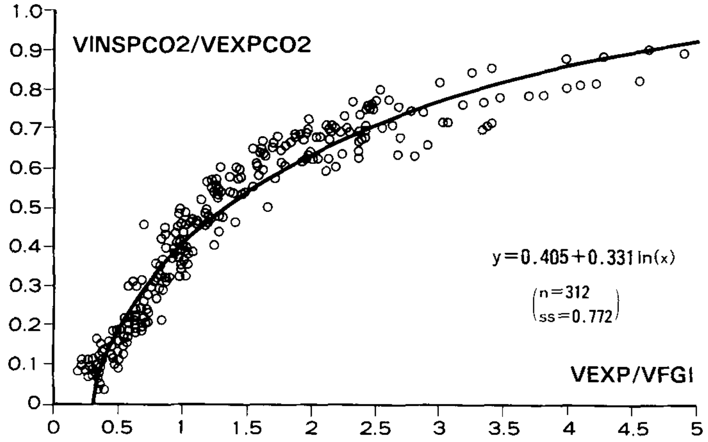

Fig. 3. VINSPCO2/VEXPCO2 (ordinate) plotted against VEXP/VFGI (abscissa), showing good fitting to a logarithmic function

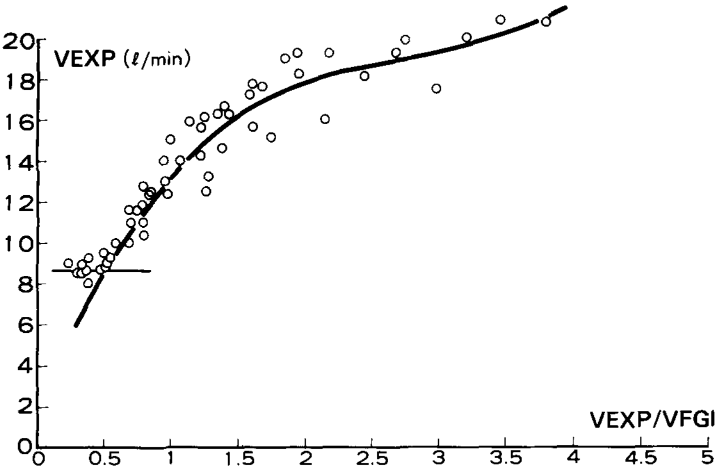

Fig. 4. A typical plot of VEXP against VEXP/VFGI (patient no. 3). VEXP/VFGI for inflection point was calculated as 0.516.

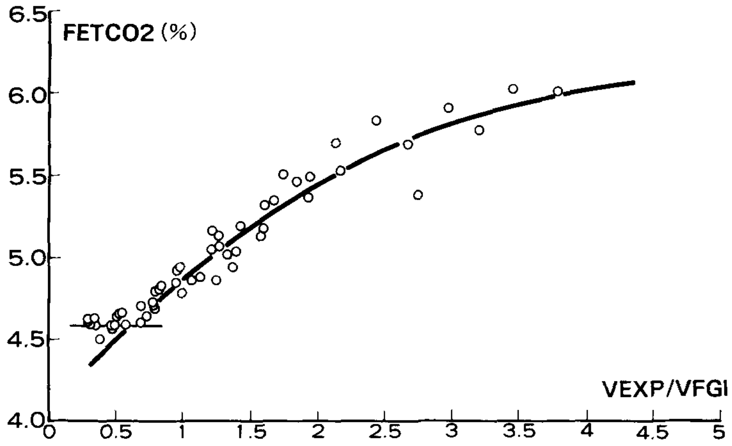

Fig. 5. FETCO2 plotted against VEXP/VFGI of the same patient as fig. 4 .

His results indicated that if, for the same tidal volume, the inspiratory flow rate pattern is "peaky", more rebreathing of CO_2 may occur from the expiratory limb. Inkster[6] used a mechanical "patient" of piston and pump with a mechanical dead space, and suggested a fresh gas flow of 2.5 times of the minute volume may be required to avoid rebreathing for respiratory flow of sine wave. Harrison[7] using a similar laboratory model stated that a fresh gas flow of

Table 4. Threshold values of VEXP/VFGI for VEXP, FETCO2 and elimination of CO_2 rebreathing at the sensor

patient no.	threshold(VEXP)	threshold(FETCO2)	threshold(CO2 sensor)
1	0.418	0.398	0.284
2	0.481	0.510	0.340
3	0.516	0.553	0.376
4	0.501	0.444	0.303
5	0.422	0.430	0.270
6	0.410	0.405	0.310
7	0.395	0.424	0.228
mean±s.d.	0.449±0.049	0.452±0.058	0.301±0.048

slightly less than 2.5 times of the minute volume with a sine wave pattern, and up to 3 times of it with the extreme flow pattern produced by a ventilator, was necessary. He indicated that the shorter the expiratory pause the higher was the fresh gas flow/minute volume ratio required. Using Bain modification of Mapleson D type of T-piece system, Byrick and Janssen[10] examined the amount of CO_2 rebreathed at the distal end of the endotracheal tube by multiplying the instantaneous concentration of inspired CO_2 by the inspired flow in patients under enflurane and halothane anesthesia, and stated that the fresh gas flow to abolish rebreathing of CO_2 is highly variable, and is dependent on the changes of respiratory waveform brought about by each inhalational anesthetics.

The present investigation has been undertaken on patients in their recovery phase from acute respiratory failure and the effects of variation in inspiratory/expiratory ratio or expiratory pause were relatively small compared to those of VMAXINSP, RR or TV.

The amount of CO_2 rebreathed at the sensor does not necessarily represent the CO_2 actually rebreated into the alveoli. But this may give us important informations about the factors which affect the actual rebreathing of CO_2.

VINSPCO2 showed the highest correlation with VEXPCO2. This is not an unexpested result because in a steady state, VINSPCO2 plus VPRDCO2 which is relatively small in variation compared to other parameters, should be equal to VEXPCO2. The high correlation of VMAXINSP with VINSPCO2 supports the previously reported concept that "peaky" inspiration auguments rebreathing of CO_2, but this is partly due to the increase of VEXP as a result of decreasing VFGI. The fact that VINSPCO2 can be expressed satisfactorily with relatively small number of easily measurable independent variables may be due to high correlation coefficients between each variables. The good fitting of equation (4) to pooled data from all patients is probably due to the reason that the ratio (VINSPCO2/VEXPCO2) partly cancel out the variations in VPRODCO2.

End-tidal CO_2 concentration (FETCO2) could be expressed by statistically significant multivariate regression equation, however, the fitting was relatively poor compared to equations to express VINSPCO2. This may be mainly due to the variance of resting FETCO2 and of ventilatory drive to accumulated CO_2 in each patient. This result presented a striking contrast to those of mechanical models, or patients under controlled ventilation with modified T anesthesia circuit, in which minute volume were fixed and were not responding to CO_2 accumulation.

The mean threshold of VEXP/VFGI to cause hyperventilation or elevation of FETCO2 due to rebreathing of CO_2 was 0.45 in our series of patients, with the range of 0.395 to 0.553. On the other hand, the threshold to eliminate CO_2 rebreathing at the connector of endotracheal tube was 0.301, with the range of 0.228 to 0.376.

The difference between these two threshold values may be due to the fact that when the VEXP/VFGI is slightly greater than the threshold to eliminate CO_2 at the connector, CO_2 is rebreathed from T-system mainly at the late phase of inspiration (fig. 2). This part of inspired CO_2 may fill only the deadspace, resulting in no actual load of CO_2 to the body.

Threshold values of VFGI/VEXP, the reciprocal of VEXP/VFGI, are 2.22 (range 1.81–2.53) for actual rebreathing of CO_2. This value is almost same as those of previous reports[4–7]. Our results suggest that in patients with spontaneous breathing on T-piece system in their recovery phase from acute respiratory failure, VEXP and VFGI, or VEXP/VFGI or its reciprocal VFGI/VEXP are major parameters to determine the amount of CO_2 rebreathing. T-tube system works as a non-rebreathing system when VEXP/VFGI is below 0.30, and signs of CO_2 accumulation in patients appears when VEXP/VFGI is below 0.45.

In summary, CO_2 rebreathing characteristics of T-piece system was studied on spontaneously breathing intubated patients in their recovery phase from acute respiratory failure, by slowly changing fresh gas inflow to the system. Amount of CO_2 rebreathed at the connector of endotracheal tube could be approximately estimated by equations including minute volume, fresh gas inflow, and parameters including CO_2 output of patients such as gross CO_2 expired through the connector, or net value of it (i.e. CO_2 production rate of the patients). When the latter informations were not available, the equations to express CO_2 rebreathing ratio by minute volume to fresh gas inflow ratio was thought to be quite beneficial, supporting the previously reported results with mathematical or mechanical models of Ayre's T-piece system. Mean threshold values of minute volume/fresh gas inflow ratio, from the present study, were 0.3 for elimination of CO_2 rebreathing at the connector of endotracheal tube and 0.45 for elimination of CO_2 retention of the patients.

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