

ENVIRONMENTAL FACTORS AFFECTING THE PERFORMANCE OF INFRARED CO<sub>2</sub>  
ANALYZER AND THE ESTIMATION OF ALVEOLAR CO<sub>2</sub> TENSION

Pei Chin Tang



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13. ABSTRACT Theoretical equations were derived from known physico-chemical laws to determine the effects of room temperature and barometric pressure on the performance of the infrared type of CO <sub>2</sub> analyzer. They were first tested experimentally and then against empirical equations derived from the Godart nomogram. These equations were found to be valid and useful in the estimation of the fractional concentration of CO <sub>2</sub> of gas mixtures under various environmental conditions.  Minimal gas temperature recorded with a thermistor probe at the inlet of the analyzer was used to estimate the water vapor pressure of gas samples in the analyzer chamber. This method was experimentally tested to be valid in estimating CO <sub>2</sub> fractional concentrations of heated wet gas mixtures. It was used to estimate the alveolar CO <sub>2</sub> tension of human subjects with various end-tidal sampling methods. Methods used by others with this type of analyzer were discussed.		

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Pei Chin Tang

Bureau of Medicine and Surgery  
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U. S. Army Medical Research Unit

Approved by

Ashton Graybiel, M.D.  
Head, Research Department

Released by

Captain J. W. Weaver, MC USN  
Commanding Officer

21 March 1968

NAVAL AEROSPACE MEDICAL INSTITUTE  
NAVAL AEROSPACE MEDICAL CENTER  
PENSACOLA, FLORIDA 32512

## INTRODUCTION

Since the introduction of the capacitance pressure transducer in 1946, the infrared absorption type of carbon dioxide analyzer has often been used to estimate the carbon dioxide tension of the respiratory gas (11). It appears, however, that there has never been a generally accepted method of converting the analyzer meter reading to the CO<sub>2</sub> tension in the respiratory gases (3,5-7,9,11-14).

Among the American and European makers of this type of CO<sub>2</sub> analyzer, the Godart Company introduced a built-in mechanical calibrator to eliminate the use of calibrating gas mixtures. For the user of this make of analyzer, a nomogram (4) was provided to describe the effect of the barometric pressure and the room temperature on the calibration of the analyzer. As the nomogram was constructed from empirical data, the question naturally arises as to its theoretical basis. Since room temperature can affect the analyzer reading, another question also arises as to the effect of temperature of the gas sample passing through the analyzer.

In the present report theoretical equations were derived from known physico-chemical laws to relate the fractional concentration of carbon dioxide of the gas mixture, sampled under one environmental condition, to that read from the meter of the analyzer, calibrated under another environmental condition. The validity of the theoretical equations was tested first experimentally and then against the empirical equation derived from the Godart nomogram. An attempt was also made to determine the best approach to convert the meter reading of the infrared analyzer to the carbon dioxide tension in the expired gas.

## PROCEDURE

The infrared carbon dioxide analyzer employed in the present experiments was a Capnograph, made by the Godart Company in the Netherlands, and constructed on the same basic principles as others manufactured in the United States and in Europe (11). It was provided with a built-in mechanical calibrator to give a calibration of the analyzer equivalent to a calibration with dry gas samples under a standard environmental condition of a barometric pressure of 760 mm Hg and a room temperature of 20° C (4). An additional feature of the Capnograph, not available in some other makes, was that the amplifier was adjusted to make the output voltage as well as the meter reading linearly proportional to the carbon dioxide fraction of the gas sample. By connecting the analyzer output to a polygraph, a continuous recording of the meter reading could be made with good accuracy. The analyzer output calibrated in percentage of CO<sub>2</sub> was routinely displayed on one channel of a polygraph.

The analysis chamber inlet was connected to the common limb of a small plastic Y tube (Abbott Venotube). A thermistor needle probe (time constant, 0.6 sec) was inserted through the rubber diaphragm of the injection site which formed one converging limb of the Y tube. The tip of the thermistor probe was placed at the intersection of

the three limbs of the Y tube. A 5-cm length of vinyl tubing, originally provided with the Venotube, was left intact at the end of the other converging limb, thus forming an extension of the analysis chamber inlet.

The thermistor probe was placed about 1.5 cm from the analysis chamber inlet. This distance was experimentally determined in an attempt to record the minimal temperature and consequently the water vapor pressure of the respiratory gas entering the analyzer. At a sample flow rate of 0.6 liter/min, room air was sampled through the Y tube into the analyzer. As the thermistor probe was moved very close to the analysis chamber inlet, the air temperature, as recorded by the thermistor, began to rise, presumably as a result of heat conduction and radiation from the analysis chamber which operates at above 40° C (11). By moving the Y tube containing the thermistor probe back and forth, a point was found where the thermistor was closest to the analyzer inlet and yet recorded no rise of air temperature. This point was assumed to record the minimal gas temperature when respiratory gas was sampled. As the temperature of respiratory gas is ordinarily higher than the room temperature, it loses its heat along the length of the inlet tube. Therefore, the lowest gas temperature would be recorded at a point that is closest to the analyzer inlet just before the gas temperature is again raised by the chamber heat. However, the point of minimal gas temperature tends to move toward the analyzer inlet if the gas temperature is much higher than the room temperature. In practice, a precise point cannot be found unless a series of thermistors can be placed along the inside of the inlet tube. Thus the recorded minimal temperature can be slightly higher than the true minimal temperature, if the gas sample temperature is much higher than the room temperature. Consequently, the calculated value of the water vapor pressure of the gas sample can also be slightly higher than its true value. The minimal gas temperature as recorded by the thermistor probe was displayed on one channel of a polygraph recorder, calibrated in degrees centigrade. The temperature range used was from 25° to 35° C. The recorded temperature was accurate to about 0.2° C.

Two cylinders of dry gas mixtures of CO<sub>2</sub> in air were used. The CO<sub>2</sub> fractional concentration was determined to be 6.60 per cent in one cylinder and 4.82 per cent in another with the Scholander method (10) and verified with the Lloyd method (8).

To vary the temperature of a dry gas mixture, the gas mixture was passed through a copper coil immersed in a water bath into which warm or ice water was introduced. To vary the temperature of a gas mixture saturated with water vapor, the gas mixture was bubbled through about 5 ml of distilled water contained in a 60-ml test tube which was immersed in a water bath, the temperature of which was varied by introducing warm or cold water. The test tube was sealed with a rubber stopper fitted with two glass tubings; the longer tubing served as the bubbling tube and the shorter as the collecting tube that was connected to a 5-ml syringe barrel. In the dry gas sampling experiment, the outlet end of the copper coil was similarly connected. The vinyl tubing forming the extended analyzer inlet was placed in the syringe barrel so that the gas sample pressure was equilibrated with the atmospheric pressure before entering the analyzer.

Substitution of the value of  $T_{ch}$  of equation (4) into equation (3) gives the following equation:

$$F_{mCO_2} = K_c \frac{P_{CO_2}}{RK_t T_r} \quad (5)$$

The constants  $K_c$ ,  $R$ , and  $K_t$  of equation (5) may be consolidated to give the following equation:

$$F_{mCO_2} = K_m \frac{P_{CO_2}}{T_r} \quad (6)$$

where

$$K_m = \frac{K_c}{RK_t} \quad (7)$$

According to Dalton's law of partial pressure, the partial pressure of carbon dioxide ( $P_{CO_2}$ ) may be expressed in terms of the barometric pressure ( $B$ ) and the fractional concentration of the carbon dioxide ( $F_{CO_2}$ ) of the chamber gas as follows:

$$P_{CO_2} = BF_{CO_2} \quad (8)$$

Substitution of the value of  $P_{CO_2}$  of equation (8) into equation (6) gives the following equation:

$$F_{mCO_2} = K_m \left( \frac{B}{T_r} \right) F_{CO_2} \quad (9)$$

During the calibration of the analyzer under a given environmental condition, the variables,  $B$  and  $T_r$ , of equation (9) become the calibration barometric pressure ( $B_c$ ) and room temperature ( $T_c$ ), respectively, and the value of  $F_{CO_2}$  is the  $CO_2$  fractional concentration contained in the calibration gas mixture ( $F_{cCO_2}$ ). Thus, under

the calibration condition, the general equation (9) becomes a specific calibration equation as follows:

$$F_{mCO_2} = K_m \left( \frac{B_c}{T_c} \right) F_{cCO_2} \quad (10)$$

During calibration, the sensitivity of the analyzer is always adjusted to make the meter reading ( $F_{mCO_2}$ ) equal to the fractional concentration of the  $CO_2$  in the calibration gas mixture ( $F_{cCO_2}$ ), as represented by

$$F_{mCO_2} = F_{cCO_2} \quad (11)$$

After the analyzer is calibrated, the value of the constant  $K_m$  can be found by substituting the value of  $F_{mCO_2}$  of equation (11) into equation (10) as follows:

$$K_m = \frac{T_c}{B_c} \quad (12)$$

When a gas mixture containing a carbon dioxide fraction of  $F_{sCO_2}$  is sampled under a barometric pressure of  $B_s$  and at a room temperature of  $T_s$ , the general equation (9) becomes a specific sampling equation as follows:

$$F_{mCO_2} = K_m \left( \frac{B_s}{T_s} \right) F_{sCO_2} \quad (13)$$

Table I

Comparison of the CO<sub>2</sub> Fractional Concentrations of Gas Samples Determined by  
Chemical Analysis and Those Determined by the Infrared Analyzer

$F_c\text{CO}_2$	Dry or Wet	$F_m\text{CO}_2$ (%)	$F_m^*\text{CO}_2$ (%)	$T_s$ (°C)	$B_s$ (mm H <sub>g</sub> )	$f_s$	$F_s\text{CO}_2(\text{D})$ (%)	$T_g$ (°C)	$f_w$	$F_s\text{CO}_2(\text{W})$ (%)
4.82	D	4.80		24.0	769	1.002	4.81			
6.60	D	6.62		20.5	765	0.995	6.59			
6.60	D	6.60		24.0	769	1.002	6.61			
6.60	D	6.59		24.0	769	1.002	6.60			
6.60	D	6.61		24.0	771	0.999	6.60			
6.60	D	6.48		25.0	758	1.020	6.61			
6.60	D	6.48		25.0	760	1.017	6.59			
4.82	W	4.69	4.68	24.0	769	1.002	4.69	25	1.032	4.84
4.82	W	4.63	4.61	24.0	769	1.002	4.62	30	1.043	4.82
4.82	W	4.60	4.57	24.0	769	1.002	4.58	35	1.058	4.85
6.60	W	6.40	6.39	24.0	769	1.002	6.40	25	1.032	6.60
6.60	W	6.36	6.34	24.0	769	1.002	6.35	30	1.043	6.62
6.60	W	6.29	6.26	24.0	769	1.002	6.27	35	1.058	6.63

$F_m^*\text{CO}_2$  is the meter reading ( $F_m\text{CO}_2$ ) corrected for the meter increase  
due to water vapor saturated at the gas temperature ( $T_g$ ).

Based on the standard calibration condition and the correction coefficients, empirical equations for the conversion of CO<sub>2</sub> fractions in the gas sample ( $F_{sCO_2}$ ) to that registered by the analyzer meter ( $F_{mCO_2}$ ), or vice versa, under a sampling barometric of  $B_s$  and at a sampling room temperature of  $T_s$  may be derived.

When the room temperature ( $T_s$ ) is the standard temperature of 20° C, the effect of the barometric pressure ( $B_s$ ) on the performance of the Capnograph may be written as

$$\begin{aligned} F_{mCO_2} &= \left(1 + \frac{B_s - 760}{760}\right) F_{sCO_2} \\ &= \left(\frac{B_s}{760}\right) F_{sCO_2} \end{aligned} \quad (G1)$$

When the barometric pressure ( $B_s$ ) is the standard barometric pressure of 760 mm Hg, the effect of the room temperature ( $T_s$ ) on the performance of the Capnograph may be written as

$$F_{mCO_2} = \left(1 - \frac{T_s - 293}{273}\right) F_{sCO_2} \quad (G2)$$

Equations (G1) and (G2) can be combined into one general equation that relates  $F_{mCO_2}$  and  $F_{sCO_2}$  under any barometric pressure and at any room temperature within the given ranges as follows:

$$F_{mCO_2} = \left(\frac{B_s}{760}\right) \left(1 - \frac{T_s - 293}{273}\right) F_{sCO_2} \quad (G3)$$

This equation is an empirical equation based on the data from the Godart nomogram.

#### COMPARISON OF THE THEORETICAL AND EMPIRICAL EQUATIONS

As stated above, the standard calibration environment of the Capnograph was specified at a room temperature of 20° C, or 293° K, and a barometric pressure of

760 mm Hg. Equation (14) may be made specific for the calibration of the Capnograph by substituting 293 for  $T_c$  and 760 for  $B_c$ . This specific equation after rearrangement becomes

$$F_{mCO_2} = \left(\frac{B_s}{760}\right) \left(\frac{293}{T_s}\right) F_{sCO_2} \quad (17)$$

The correction factors for the barometric pressure ( $B_s/760$ ) are identical in equations (17) and (G3). But the temperature correction factors differ. For ease of comparison, the temperature correction factor of equation (17) may be written as

$$\frac{293}{T_s} = 1 - \frac{T_s - 293}{T_s} \quad (18)$$

When the temperature correction factor of equation (17), as shown in the form of equation (18), is compared with that in the parenthesis of equation (G3), it is apparent that the difference is in the denominators. The denominator of the temperature correction factor in equation (G3) is a constant while that in equation (18) is a variable, the room temperature ( $T_s$ ). As the constant, 273, is equivalent to a room temperature of 0° C, the values of the correction factors in the two equations are identical at a room temperature of 0° C. The temperature correction factors in both equations become one at a room temperature of 20° C, or 293° K. At room temperatures above 20° C, the higher the room temperature, the larger will be the difference between the values of these temperature correction factors. The values of the temperature correction factors of equations (17) and (G3) are shown in Table II. The highest difference of 0.004 occurs at a room temperature of 30° C. The meter reading and the output voltage of the Capnograph are linear and accurate only up to 8% CO<sub>2</sub>. At a room temperature of 30° C and a CO<sub>2</sub> level of 8%, the difference in the meter reading, as calculated from the highest difference of 0.004 between the temperature correction factors of these two equations, amounts to 0.032% CO<sub>2</sub>. Although it appears feasible to use this maximum difference in meter reading to compare experimentally the accuracies of these two equations, it is unlikely that any conclusive result can be found since even this maximum difference is still too small to read accurately from the meter.

## ESTIMATION OF ALVEOLAR CO<sub>2</sub> TENSION

### Effect of the Temperature and the Water Vapor Pressure of the Gas Sample

As the temperature of the expired air is higher than the room temperature, the effect of the temperature of the dry gas sample on the performance of the analyzer was tested. It was found that the meter reading remained constant when the temperature

Table II

The Values of the Temperature Correction Factors of Equations (17) and (G3), in Room Temperature Range of from 15° to 30° C

Equation	Room Temperature (°C)			
	15	20	25	30
(17)	1.017	1.000	0.983	0.967
(G3)	1.018	1.000	0.982	0.963

of the dry gas sample was varied from 20° C to 35° C, at room temperatures ranging from 20.5° to 25.0° C. Therefore, the temperature of the dry gas sample within this temperature range does not affect the analyzer performance.

As the expired air is saturated with water vapor, the effect of the water vapor present in the CO<sub>2</sub>-free air was tested. The effect was too small to read from the analyzer meter. By increasing the gain of the preamplifier of the polygraph, the effect of water vapor on the analyzer meter reading was estimated. As compared with the dry CO<sub>2</sub>-free air, CO<sub>2</sub>-free air saturated with water vapor gave readings of 0.01%, 0.02%, and 0.03% CO<sub>2</sub> at sample temperatures of 25, 30, and 35° C, respectively. Thus, this increase in meter reading due to the presence of water vapor ought to be deducted from the meter reading when the CO<sub>2</sub> fractions of gas samples saturated with water vapor at these temperatures are estimated. However, as these values are exceedingly small, whether or not they are deducted from the meter reading should not significantly affect the experimental results.

The main effect of the presence of water vapor in a gas sample containing CO<sub>2</sub> is, of course, the dilution or reduction of the CO<sub>2</sub> molecules in the analysis chamber. Consequently, the meter reading of a wet gas sample tends to be lower than that of a dry sample with the same fractional concentration of CO<sub>2</sub>. The critical problem is to determine the exact value of the water vapor pressure of the wet gas sample while it is in the analysis chamber. Once this is obtained, the meter reading can be corrected to give the true value of the fractional concentration of CO<sub>2</sub> in the sample.

The method used for the estimation of the water vapor pressure of the wet gas mixture and that of the expired gas in the analysis chamber is illustrated in Figure 1. When a wet gas mixture at room temperature is passed through the analyzer, the water vapor pressure is the saturated vapor pressure at room temperature. It remains unchanged in the analysis chamber. Although the chamber's temperature is much higher than the room temperature and the water vapor pressure is no longer the saturated pressure at this temperature, there can be no increase of vapor pressure because water vapor is not available in the dry analysis chamber.

As far as the infrared analyzer is concerned, expired gases are no different from heated wet gas mixtures since the expired gases are saturated with water vapor at the body temperature. When the expired gas or a heated wet gas mixture is continuously sampled through the inlet tube to the analysis chamber, it loses its heat along the tube, as illustrated by the dotted line in the upper part of Figure 1, and also loses its water vapor as condensations along the tube, as illustrated by the dotted line in the lower part of Figure 1. The expired gas temperature may or may not be lowered to the room temperature, depending on the length of the connecting tube. As the tube is generally made as short as possible in the estimation of alveolar CO<sub>2</sub> tension with an infrared analyzer, the expired gas temperature entering the analysis chamber is usually higher than the room temperature, as illustrated by the large dot in the upper part of Figure 1. Consequently, its water vapor pressure is the saturated vapor pressure at this temperature, as illustrated by the large dot in the lower part of Figure 1. For the same reason

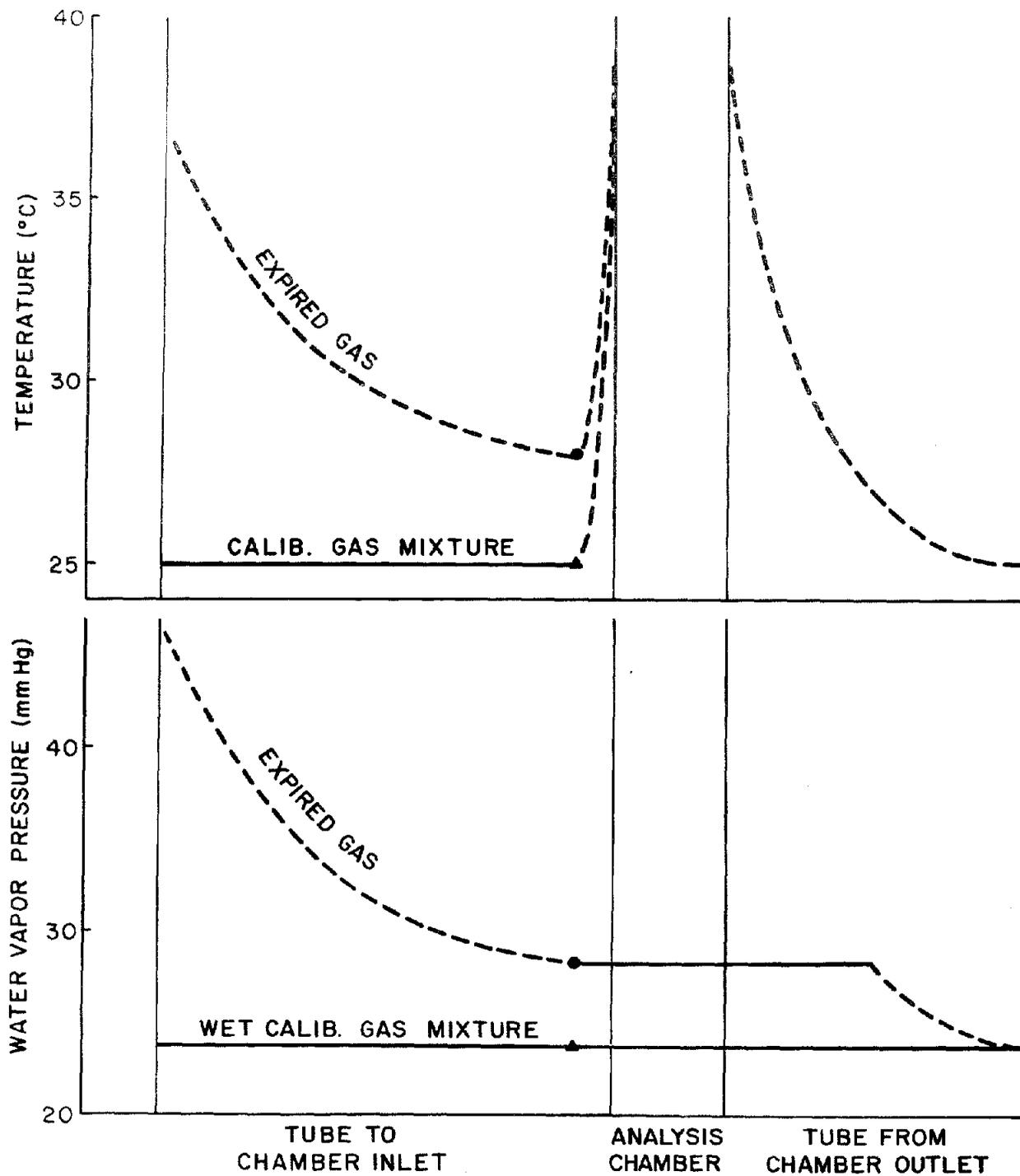


Figure 1

Diagram illustrating the method used for the estimation of the water vapor pressure of the expired gas and that of the wet calibration gas mixture in the analysis chamber of an infrared  $\text{CO}_2$  analyzer. The temperature of the wet calibration gas mixture is assumed to be the same as the room temperature of  $25^\circ \text{C}$ .

as stated above, the water vapor pressure of the expired gas remains at this level in the analysis chamber. Its vapor pressure starts to decrease only when its temperature begins to fall below its minimal entering temperature along the outlet tube, as illustrated in Figure 1. Therefore, the water vapor pressure of the expired gas in the analysis chamber can be estimated by its minimal temperature just before it enters the chamber.

To test this method, gas mixtures saturated with water vapor were analyzed. The minimal gas temperature entering the analysis chamber was recorded with a thermistor probe, as described in PROCEDURE. The results, labeled as wet (W), are shown in the lower half of Table I. The CO<sub>2</sub> fractions of the gas samples determined by chemical analyses are shown as F<sub>c</sub>CO<sub>2</sub>. Equation (16) was used again to calculate the CO<sub>2</sub>

fractions of the gas samples from the meter readings. As equation (16) was derived to analyze dry gases, it was modified to estimate the CO<sub>2</sub> fractions in the wet gases as follows:

$$F_{sCO_2}(D) = f_c F_{mCO_2}^* \quad (19)$$

$$f_c = \left(\frac{760}{293}\right) \left(\frac{T_s}{B_s}\right) \quad (20)$$

$$= 2.59386 \frac{T_s}{B_s}$$

F<sub>s</sub>CO<sub>2</sub>(D) in equation (19) is the same as the F<sub>s</sub>CO<sub>2</sub> in equation (16), and the symbol (D) is added merely to distinguish it from the CO<sub>2</sub> content of wet samples (F<sub>s</sub>CO<sub>2</sub>(W)).

The meter reading (F<sub>m</sub>CO<sub>2</sub>) in equation (16) is replaced with (F<sub>m</sub>CO<sub>2</sub><sup>\*</sup>) which is the meter reading corrected for the increase due to water vapor as described in the preceding paragraph.

The fractional concentration of CO<sub>2</sub> of the wet gas (F<sub>s</sub>CO<sub>2</sub>(W)) was calculated according to the following equations:

$$F_{sCO_2}(W) = f_w F_{sCO_2}(D) \quad (21)$$

$$f_w = \frac{B_s}{B_s - P_{H_2O} \text{ at } T_g} \quad (22)$$

where  $f_w$  = water vapor correction factor  
 $T_g$  = minimal gas temperature entering the analysis chamber, recorded with a thermistor probe, in degrees centigrade  
 $P_{H_2O}$  at  $T_g$  = the pressure of saturated water vapor in mm Hg at  $T_g$

The values of the saturated water vapor pressure at various gas temperatures were obtained from a published table (1).

It is evident from Table I that the estimated values,  $F_{sCO_2(W)}$ , agreed well with the real values,  $F_{cCO_2}$ , of the CO<sub>2</sub> fractions of the gas samples. If the increases in meter reading due to water vapor were not deducted, the error would still be no greater than 0.06% CO<sub>2</sub>. Therefore, our method of using the minimal entering temperature to estimate the water vapor pressure of the heated wet gas mixture in the analysis chamber is valid, and the water vapor correction factor ( $f_w$ ) thus derived may be used to accurately estimate the fractional concentration of CO<sub>2</sub> of a heated wet gas mixture. Since the infrared analyzer does not distinguish an expired gas from a heated wet gas mixture, this method may also be used to estimate the fractional concentration of CO<sub>2</sub> of the expired gas.

#### Estimation of Alveolar Carbon Dioxide Tension

As stated in PROCEDURE, various sampling methods were used in the estimation of the alveolar CO<sub>2</sub> tension. Table III shows the results from two human subjects. Equations (19) and (20) were used for the calculation of  $F_{sCO_2(D)}$  from the meter reading ( $F_{mCO_2}$ ) except that no correction was made for the meter increase due to water vapor as the gas temperatures ( $T_g$ ) never exceeded 30° C. For the calculation of the alveolar fractional concentration of CO<sub>2</sub> ( $F_{ACO_2}$ ), equations (21) and (22) were used by substituting  $F_{ACO_2}$  for  $F_{sCO_2(W)}$  since the analyzer analyzed the respiratory gases as if they were heated wet gas samples.

The alveolar partial pressure of carbon dioxide ( $P_{ACO_2}$ ) was calculated according to the generally accepted equation of

$$P_{ACO_2} = (B_s - 47) F_{ACO_2} \quad (23)^*$$

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\*In equation (23) the alveolar fractional concentration of CO<sub>2</sub> ( $F_{ACO_2}$ ) must be expressed in true fractions. If per cent CO<sub>2</sub> is used, the CO<sub>2</sub> percentage must be divided by 100 to obtain the true fractions.

Table III

Estimation of Alveolar CO<sub>2</sub> Tension with Various Sampling Methods

Sampling Method	Subject	F <sub>m</sub> CO <sub>2</sub> (%)		T <sub>s</sub> (°C)	B <sub>s</sub> (mm Hg)	f <sub>c</sub>	F <sub>s</sub> CO <sub>2</sub> (D) (%)		T <sub>g</sub> (°C)	f <sub>w</sub>	FACO <sub>2</sub> (%)		PACO <sub>2</sub> (mm Hg)		Group Mean	Standard Error
		Mean	S. D.				Mean	S. D.			Mean	S. D.	Mean	S. D.		
1. P-306 Exp. Air	A	4.88 ± 0.04		24	757	1.021	4.98 ± 0.04	26.7	1.036	5.16 ± 0.04	36.6 ± 0.28					
	T	4.77 ± 0.04		24	757	1.021	4.87 ± 0.04	27.0	1.037	5.05 ± 0.04	36.0 ± 0.28					
2. P-306 Ins. Exp. Air	A	4.94 ± 0.05		24	757	1.021	5.04 ± 0.05	26.6	1.036	5.22 ± 0.05	37.1 ± 0.36					
	A	5.07 ± 0.06		25	764	1.012	5.13 ± 0.06	27.5	1.037	5.32 ± 0.06	38.1 ± 0.43	37.78	.0469			
	T	5.06 ± 0.06		24	757	1.021	5.17 ± 0.06	26.2	1.035	5.35 ± 0.06	38.0 ± 0.43					
3. P-311 Exp. Air	A	5.16 ± 0.04		24	761	1.012	5.22 ± 0.04	28.4	1.040	5.43 ± 0.04	38.8 ± 0.29					
	A	4.95 ± 0.04		25	756	1.022	5.06 ± 0.04	28.0	1.039	5.26 ± 0.04	37.3 ± 0.28	38.01	.0615			
	T	5.04 ± 0.10		24	761	1.012	5.10 ± 0.10	28.4	1.040	5.30 ± 0.04	37.9 ± 0.29					
4. T-Tube	A	4.89 ± 0.05		24	757	1.021	4.99 ± 0.05	27.3	1.037	5.18 ± 0.05	36.8 ± 0.36					
	A	5.24 ± 0.05		24	757	1.021	5.35 ± 0.05	28.0	1.039	5.56 ± 0.05	39.5 ± 0.36	38.16	.1157			
	T	5.05 ± 0.06		24	757	1.021	5.16 ± 0.06	27.4	1.038	5.35 ± 0.06	38.0 ± 0.43					
5. Nostril	A	5.10 ± 0.11		24	757	1.021	5.21 ± 0.11	30.0	1.044	5.44 ± 0.11	38.6 ± 0.78					
	T	4.92 ± 0.07		24	757	1.021	5.02 ± 0.07	29.4	1.042	5.23 ± 0.07	37.2 ± 0.50	37.93	.0794			
	T	5.08 ± 0.09		25	764	1.012	5.14 ± 0.09	29.4	1.042	5.36 ± 0.09	38.4 ± 0.65					

Each of the values of the alveolar  $\text{CO}_2$  tension in Table III was estimated from a continuous record of at least 200 sec. Figure 2 shows one of these records which was obtained from sampling the inspired and expired gases inside the nostril. The gas temperature ( $T_g$ ) shows a cyclic pattern with the peak values corresponding to the temperatures of the expired gases. The amplitudes of these temperature cycles were much smaller when sampling from the T-tube and almost nil when sampling from the respiratory valves. In Figure 2, there is a very short delay (20 sec) before the gas temperatures reached a steady level. This delay was much longer (2-3 min) when the gas sample was collected from the respiratory valves which required time to warm up. From a 200-sec segment of the record, as indicated by the arrows in Figure 2, the mean value of the peak gas temperatures ( $T_g$ ) and that of the peak meter readings ( $F_{m\text{CO}_2}$ ) were obtained and entered in Table III. As shown in Figure 2, before and after the sampling, when room air was drawn through the inlet tube, the recorded temperature ( $T_g$ ) was below that of the room air ( $T_s$ ) which was  $25^\circ\text{C}$  during the experiment. This was due to the fact that when room air was drawn through the inlet tube, the water condensation along the tube wall started to evaporate and the air temperature was lowered to its dew point temperature.

The alveolar  $\text{CO}_2$  tensions ( $P_{A\text{CO}_2}$ ) estimated with various methods, as shown in Table III, were all in a narrow range of from 35.9 to 39.5 mm Hg. However, the values obtained with the large respiratory valve, especially when the samples were taken from the expiratory chamber, appear to be slightly lower than those obtained with other sampling methods. Thus, a group mean for each method was calculated by assuming that individual differences between the two subjects were negligible. The group means and their standard errors are shown in the last two columns of Table III. By means of the Fisher's  $\perp$  test, it was determined that method 1 resulted in significantly (at 0.01 level) lower values of alveolar  $\text{CO}_2$  tensions than all other methods. Method 2 resulted in significantly (at 0.01 level) lower values than methods 3 and 4 but not very significantly (at 0.10 level) lower values than method 5. It thus appears that mixing of the dead space gas and the end-tidal expired gas must have occurred when the large respiratory valve was used. Use of this type of respiratory valve for estimation of alveolar  $\text{CO}_2$  tension under resting conditions is therefore not recommended. No significant difference was found among the values obtained by sampling methods 3, 4, and 5. It thus appears that all three methods are suitable for the estimation of the alveolar  $\text{CO}_2$  tension at rest.

Among the users of the infrared  $\text{CO}_2$  analyzer, many (3, 5, 6, 9, 13, 14) did not describe clearly their methods of converting the analyzer meter reading to the alveolar fractional concentration of carbon dioxide. Although they used dry gas mixtures for calibration, none of them mentioned any correction for the water vapor pressure present in the expired gas sample. Lenfant (7) used "warm humidified standard gases" for calibration but did not describe his method in detail. Water vapor correction factor ( $f_w$ ) was mentioned in two publications; a value of 1.03 was used in one (12) and a value of 1.02 was suggested in another (11). According to the authors, these values were arbitrarily chosen, based on the assumption that the respiratory gas temperature would be

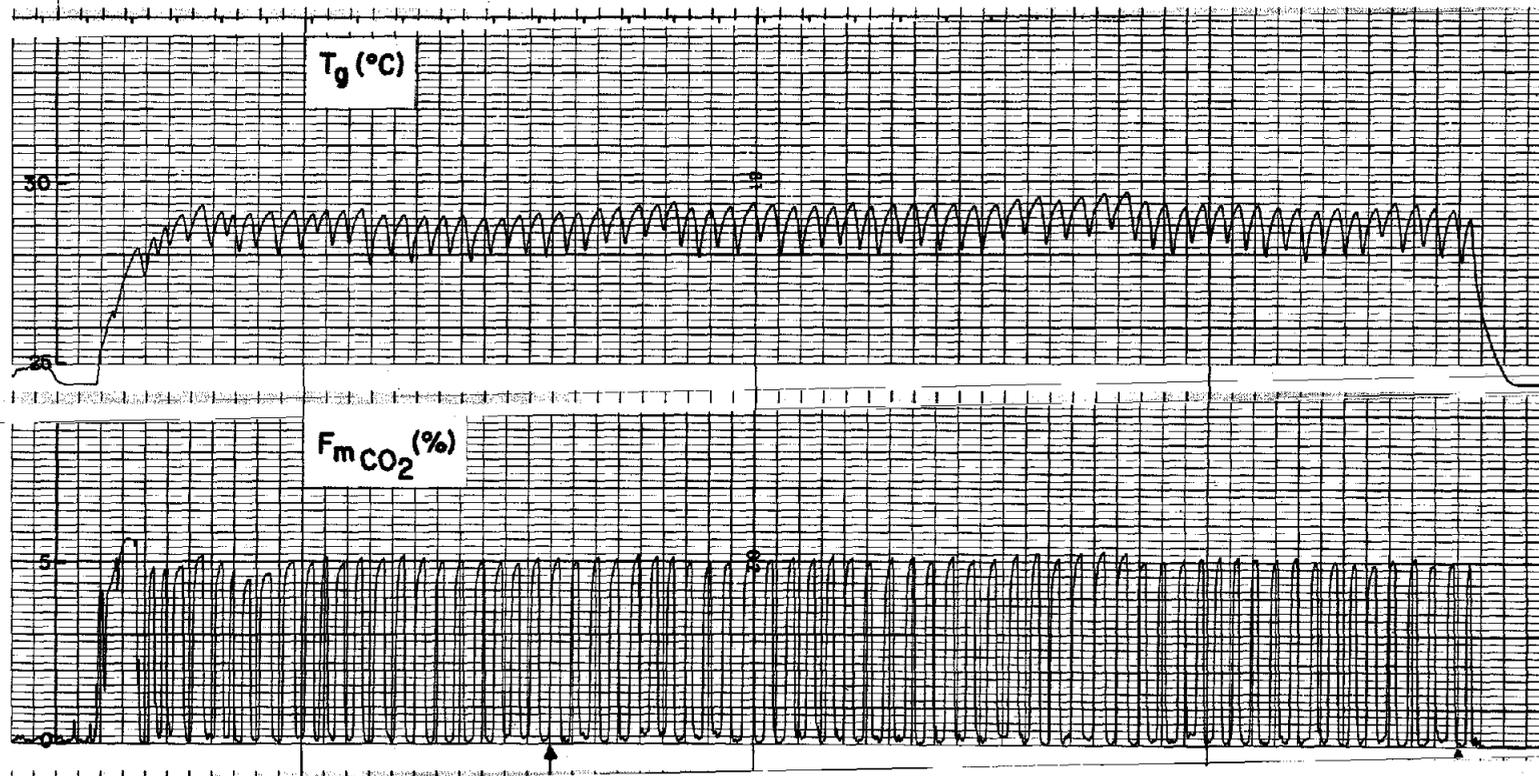


Figure 2

Polygraph record showing simultaneous tracings of the temperature ( $T_g$ ) and the analyzer meter reading of the  $\text{CO}_2$  fractions ( $F_{m\text{CO}_2}$ ) of the respiratory gas sampled from inside of the nostril of one subject. Time marks shown at top of record are in 10-sec intervals. Arrows indicate the part of the record that was used for the computation of the mean values of  $T_g$  and  $F_{m\text{CO}_2}$ .

lowered to the average room temperature before entering the analysis chamber. However, the  $f_w$  values in our experiments, as shown in Table III, were all higher than 1.03. They were about 1.036 when the large respiratory valve was used, corresponding to gas temperatures ( $T_g$ ) of approximately 2° to 3° C higher than the room temperatures ( $T_s$ ). The  $f_w$  values were close to 1.04 when other sampling methods were used, corresponding to gas temperatures 3° to 6° C higher than the room temperatures. As the large respiratory valve is not reliable, we are confined to the use of the small respiratory valve, the T-tube, and direct sampling from the nostril. Therefore, a value of 1.04 for the water vapor correction factor is suggested in the estimation of alveolar CO<sub>2</sub> tension with the end-tidal sampling methods when the minimal entering temperature of the gas sample is not available. A higher value may be required if the sampling is from an endotracheal tube and the inlet tube is very short. However, the level of the minimal gas temperature is dependent on many factors such as the room temperature, the length of the inlet tube, the gas flow rate, and whether there is a heat sink along the pathway of the gas sample. Thus, for a precise estimation of alveolar CO<sub>2</sub> tension with the infrared analyzer, a continuous recording of the minimal gas temperature at the analyzer inlet is recommended.

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