

## Correction for Mechanical Dead Space in the Calculation of Physiological Dead Space

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### Research Article

When physiological dead space ( $V_{d_p}$ ) is calculated for a patient who has alveolar dead space, e.g., after pulmonary vascular occlusion, less than the full volume of attached mechanical dead space ( $V_{d_m}$ ) appears in the measured dead space ( $V_{d_n}$ ). Under these conditions the traditional subtraction of  $V_{d_m}$  from  $V_{d_n}$  leads to underestimation of  $V_{d_p}$  and can give a falsely small ratio of  $V_{d_p}$  to tidal volume ( $V_t$ ) when, in fact, an abnormally large  $V_{d_p}/V_t$  exists. To make the proper correction for  $V_{d_m}$ , two equations have been derived and validated with seven subjects having  $V_{d_p}/V_t$  from 0.29 to 0.87, using  $V_{d_m}$ 's from 120 to 322 ml. With only a small modification, these equations are suitable for routine clinical use and give  $V_{d_p}/V_t$  within 0.02 of that by the validated equations (32 of 33 comparisons). The fraction of  $V_{d_m}$  subtracted from  $V_{d_n}$  is the square of the ratio of effective alveolar to total alveolar ventilation and is never  $> 1$ . This fraction is  $(P_{aCO_2}/P_{aCO_2})^2$ , where  $P_{aCO_2}$  and  $P_{aCO_2}$  are the mean partial pressures of expired alveolar and of arterial  $CO_2$ ; in the other equation this fraction is  $[P_{eCO_2}/P_{aCO_2} (V_t - V_{d_{an}} - V_{d_m})]^2$  where  $P_{eCO_2}$  is mixed expired  $P_{CO_2}$  and  $V_{d_{an}}$  is anatomical dead space. The second equation requires an estimated  $V_{d_{an}}$  and is applicable when  $P_{aCO_2}$  is not measured or does not [...]

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# Correction for Mechanical Dead Space in the Calculation of Physiological Dead Space

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**ABSTRACT** When physiological dead space ( $V_{Dp}$ ) is calculated for a patient who has alveolar dead space, e.g., after pulmonary vascular occlusion, less than the full volume of attached mechanical dead space ( $V_{Dm}$ ) appears in the measured dead space ( $V_{Dn}$ ). Under these conditions the traditional subtraction of  $V_{Dm}$  from  $V_{Dn}$  leads to underestimation of  $V_{Dp}$  and can give a falsely small ratio of  $V_{Dp}$  to tidal volume ( $V_T$ ) when, in fact, an abnormally large  $V_{Dp}/V_T$  exists. To make the proper correction for  $V_{Dm}$ , two equations have been derived and validated with seven subjects having  $V_{Dp}/V_T$  from 0.29 to 0.87, using  $V_{Dm}$ 's from 120 to 322 ml. With only a small modification, these equations are suitable for routine clinical use and give  $V_{Dp}/V_T$  within 0.02 of that by the validated equations (32 of 33 comparisons). The fraction of  $V_{Dm}$  subtracted from  $V_{Dn}$  is the square of the ratio of effective alveolar to total alveolar ventilation and is never  $> 1$ . This fraction is  $(P_{ACO_2}/P_{ACO_2})^2$ , where  $P_{ACO_2}$  and  $P_{ACO_2}$  are the mean partial pressures of expired alveolar and of arterial  $CO_2$ ; in the other equation this fraction is  $[P_{ECO_2}/P_{ACO_2}(V_T - V_{D_{an}} - V_{Dm})]^2$  where  $P_{ECO_2}$  is mixed expired  $PCO_2$  and  $V_{D_{an}}$  is anatomical dead space. The second equation requires an estimated  $V_{D_{an}}$  and is applicable when  $P_{ACO_2}$  is not measured or does not plateau (as in exercise).

## INTRODUCTION

Physiological dead space ( $V_{Dp}$ )<sup>1</sup> is becoming a more useful index of impaired perfusion of pulmonary vessels

A preliminary report of this work has appeared in abstract form. (Singleton, G. J., R. L. Smith, R. L. Trager, and C. R. Olsen. 1969. *Physiologist*. 12: 356.)

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<sup>1</sup> *Abbreviations used in this paper:*  $f_p$ , fraction of ventilation to perfused alveoli;  $F_{ACO_2}$ , mean concentration of  $CO_2$  in expired alveolar gas;  $F_{ECO_2}$ , concentration of  $CO_2$  in mixed expired gas;  $P_{ACO_2}$  mean partial pressure of  $CO_2$  ( $PCO_2$ ) in

as normal values and conditions for  $V_{Dp}$  become more precisely defined (1). When a normal adult breathes spontaneously at a normal tidal volume ( $V_T$ ),  $V_{Dp}/V_T$  is  $< 0.45$  and decreases with increased  $V_T$  (1, 2).  $V_{Dp}/V_T$  may increase with age (1) and with a variety of parenchymal lung diseases. However, a very large ratio (e.g., 0.8 at a normal  $V_T$ ) or an increase of this ratio with the increased  $V_T$  of exercise (2) supports the diagnosis of pulmonary vascular occlusion.

In the traditional calculation of  $V_{Dp}$ , all of the mechanical dead space ( $V_{Dm}$ ) is subtracted from the measured dead space ( $V_{Dn}$ ).<sup>2</sup> As given in Enghoff's modified Bohr equation (3),

$$V_{Dp} = V_{Dn} - V_{Dm} = \frac{P_{ACO_2} - P_{ECO_2}}{P_{ACO_2}} \cdot V_T - V_{Dm}, \quad (1)$$

where  $P_{ACO_2}$  and  $P_{ECO_2}$  are the partial pressures of  $CO_2$  in arterial blood and mixed expired gas, respectively. Suwa and Bendixen have analyzed the change of  $P_{ACO_2}$  with added  $V_{Dm}$  and have shown that total subtraction of  $V_{Dm}$  can lead to underestimation of  $V_{Dp}$  (4). This underestimation occurs whenever gas from  $V_{Dm}$  is inspired into nonperfused alveoli where it has no direct effect on gas exchange with alveolar capillary blood.

We have derived and validated two equivalent equations for making the proper calculation and present evidence that shorter modified forms give, with precision  $V_{Dp}$  at the  $V_T$  of the measurement ( $V_{Tn}$ ).

expired alveolar gas;  $P_{ACO_2}$ , mean  $PCO_2$  in arterial blood;  $P_{ECO_2}$ ,  $PCO_2$  in mixed expired gas;  $r$ , correlation coefficient;  $V_A$ , effective alveolar ventilation per breath;  $V_{CO_2}$ , volume of  $CO_2$  expired per breath;  $V_{D_{alv}}$ , alveolar dead space;  $V_{D_{an}}$ , anatomical dead space;  $V_{Dm}$ , mechanical dead space;  $V_{Dn}$ , total measured dead space;  $V_{Dp}$ , physiological dead space;  $V_T$ , expired tidal volume.

<sup>2</sup> *Subscripts specific for this paper:* n, value measured with  $V_{Dm}$  attached; o, value without  $V_{Dm}$  attached.

## METHODS

**Derivation.** The volume of CO<sub>2</sub> expired in a breath (VCO<sub>2</sub>) is given by

$$V_{CO_2} = F_{ECO_2} V_T = F_{ACO_2} (V_T - V_{D_{an}} - V_{D_m}), \quad (2)$$

where  $F_{ECO_2}$  and  $F_{ACO_2}$  are the mean concentrations of CO<sub>2</sub> in the mixed expired gas and in the expired alveolar gas, respectively, and  $V_{D_{an}}$  is anatomical dead space. Dividing by  $P_{ACO_2} V_T$  and converting concentrations to partial pressures:

$$\frac{V_{A_n}}{V_T} = \frac{P_{ECO_2}}{P_{ACO_2}} = \frac{P_{ACO_2} (V_T - V_{D_{an}} - V_{D_m})}{P_{ACO_2} \cdot V_T}, \quad (3)$$

where  $V_{A_n}$  is measured effective alveolar ventilation per breath.

To derive equations for  $V_{D_p}$ , we have assumed that addition of  $V_{D_m}$  does not change the fraction of ventilation to perfused alveoli ( $f_p$ ). Using the equation for  $f_p$  derived by Julian, Travis, Robin, and Crump (5), and denoting, respectively, the conditions with and without  $V_{D_m}$  by "n" and "o":

$$f_p = \frac{P_{E_o} CO_2}{P_{A_o} CO_2 - P_{A_o} CO_2 + P_{E_o} CO_2} = \frac{P_{E_n} CO_2}{P_{A_n} CO_2 - P_{A_n} CO_2 + P_{E_n} CO_2} \quad (4)$$

Cross multiplying the middle and right sides of equation 4 and dividing by  $P_{A_o} CO_2 P_{A_n} CO_2$ :

$$\frac{P_{E_o} CO_2}{P_{A_o} CO_2} - \frac{P_{E_o} CO_2 P_{A_n} CO_2}{P_{A_o} CO_2 P_{A_n} CO_2} = \frac{P_{E_n} CO_2}{P_{A_n} CO_2} - \frac{P_{E_n} CO_2 P_{A_o} CO_2}{P_{A_n} CO_2 P_{A_o} CO_2}. \quad (5)$$

Substituting the left side of equation 3 (with appropriate subscripts) for the first term on each side of equation 5, and substituting the right side of equation 3 for  $P_{E_o} CO_2 / P_{A_o} CO_2$  in the second term on each side of equation 5:

$$\frac{V_{A_o}}{V_{T_o}} - \frac{P_{A_o} CO_2 P_{A_n} CO_2 (V_{T_o} - V_{D_{an_o}})}{P_{A_o} CO_2 P_{A_n} CO_2 V_{T_o}} = \frac{V_{A_n}}{V_{T_n}} - \frac{P_{A_o} CO_2 P_{A_n} CO_2 (V_{T_n} - V_{D_{an_n}} - V_{D_m})}{P_{A_o} CO_2 P_{A_n} CO_2 V_{T_n}}. \quad (6)$$

Substituting  $(V_{T_n} - V_{D_n})$  for  $V_{A_n}$  and  $(V_{T_o} - V_{D_{p_o}})$  for  $V_{A_o}$ :

$$V_{D_{p_o}} = \frac{V_{T_o}}{V_{T_n}} \left[ V_{D_n} - \frac{P_{A_o} CO_2 P_{A_n} CO_2}{P_{A_o} CO_2 P_{A_n} CO_2} \cdot \left( V_{D_{an_n}} - \frac{V_{T_n}}{V_{T_o}} \cdot V_{D_{an_o}} + V_{D_m} \right) \right]. \quad (7)$$

Substitution for  $P_{A_o} CO_2$  from equation 3 gives an equivalent equation:

$$V_{D_{p_o}} = \frac{V_{T_o}}{V_{T_n}} \left[ V_{D_n} - \frac{P_{E_o} CO_2 V_{T_o}}{P_{A_o} CO_2 (V_{T_o} - V_{D_{an_o}})} \cdot \frac{P_{E_n} CO_2 \cdot V_{T_n}}{P_{A_n} CO_2 (V_{T_n} - V_{D_{an_n}} - V_{D_m})} \cdot \left( V_{D_{an_n}} - \frac{V_{T_n}}{V_{T_o}} \cdot V_{D_{an_o}} + V_{D_m} \right) \right]. \quad (8)$$

The validity of equations 7 and 8 can be tested by calculating  $V_{D_{p_o}}$  for the same subjects with different  $V_{D_m}$ 's. If the assumption holds that  $f_p$  remains constant with added  $V_{D_m}$ , then  $V_{D_{p_o}}$  (and  $V_{D_{p_o}}/V_{T_o}$ ) should remain constant.

In the routine measurement of dead space,  $V_{D_{p_o}}$  is always calculated for  $V_{T_o} = V_{T_n}$ . If  $V_{D_{an_o}} = V_{D_{an_n}}$ , then equations 7 and 8 simplify to

$$V_{D_{p_o}} = V_{D_n} - \left[ \frac{P_{A_o} CO_2 P_{A_n} CO_2}{P_{A_o} CO_2 P_{A_n} CO_2} \right] \cdot V_{D_m} \quad (9)$$

$$V_{D_{p_o}} = V_{D_n} - \left[ \frac{P_{E_o} CO_2 V_T}{P_{A_o} CO_2 (V_T - V_{D_{an}})} \cdot \frac{P_{E_n} CO_2 V_T}{P_{A_n} CO_2 (V_T - V_{D_{an}} - V_{D_m})} \right] \cdot V_{D_m}. \quad (10)$$

Since equations 9 and 10 are equations 7 and 8 at the  $V_T$  and  $V_{D_{an}}$  of the measurement, experimental validation of equations 7 and 8 also validates 9 and 10.

If it can be shown that substitution of  $P_{A_n} CO_2 / P_{A_n} CO_2$  for  $P_{A_o} CO_2 / P_{A_o} CO_2$  (and the equivalent substitution in equation 10) result in very little error, then two good working equations are

$$V_{D_p} = V_{D_n} - \left[ \frac{P_{A_n} CO_2}{P_{A_n} CO_2} \right]^2 \cdot V_{D_m} \quad (11)$$

$$V_{D_p} = V_{D_n} - \left[ \frac{P_{E_n} CO_2 \cdot V_T}{P_{A_n} CO_2 (V_T - V_{D_{an}} - V_{D_m})} \right]^2 \cdot V_{D_m}. \quad (12)$$

These equations, like equations 9 and 10, give  $V_{D_p}$  at  $V_{T_n}$ ; but they require data from only a single collection.

**Measurements.**  $V_{D_n}$  was measured in seven men chosen to represent a wide range of  $V_{D_p}/V_T$ . The men sat upright and breathed spontaneously through a rubber mouth piece and Hans-Rudolph valve with a combined  $V_{D_m}$  of 120 ml. Additional measurements were made with pipes of varying lengths and internal diameter of 2 cm between the mouth piece and valve. Expired gas was collected in a 350 liter gasometer. The subjects breathed through each  $V_{D_m}$  for at least 8 min before each measurement was begun. Arterial blood was collected from an indwelling catheter during the middle minute of a 3 min gas collection. End-tidal CO<sub>2</sub> at the mouth and mixed expired CO<sub>2</sub> from the gasometer were measured with an infrared CO<sub>2</sub> meter. Alveolar CO<sub>2</sub> plateaued for each subject. Correction was made for the volume of gas lost through the CO<sub>2</sub> meter, and the total volume of expired gas was corrected to BTPS (body temperature, pressure, saturated with water).  $P_{CO_2}$ ,  $P_{O_2}$ , and pH were measured with an Instrumentation Laboratory blood gas analyzer (Instrumentation Laboratory Inc., Lexington, Mass.). Both the infrared CO<sub>2</sub> meter and the CO<sub>2</sub> electrode were calibrated with the same gases, previously analyzed with the Scholander 0.5 cm<sup>3</sup> gas analyzer. Duplicate measurements using the same  $V_{D_m}$  were made for six of the men. The reproducibility of  $V_{D_n}/V_T$  was within 0.02 for five men; the sixth (C. W.) had very disparate  $V_T$ 's with the same  $V_{D_m}$ . Of the 41 collections, one deviated inexplicably for C. O. from all the other results (duplicate measurement with 120 ml  $V_{D_m}$ ) and was discarded; however, duplicate measurements with 218 ml  $V_{D_m}$  were made with perfect agreement for  $V_{D_n}/V_T$ .

**Calculations.**  $V_{D_p}$  (and  $V_{D_p}/V_{T_n}$ ) were calculated for each collection using no correction ( $V_{D_n}$ ), the traditional correction (equation 1), and equations 9-12. Equations 7 and 8 were

tested by using the  $V_T$  and  $PCO_2$ 's of the initial condition (with 120 ml  $V_{D_m}$ ) for the "o" condition (without  $V_{D_m}$ ). Equations 8 and 10 include 120 ml  $V_{D_m}$  in the denominator of the ventilation ratio for the "o" condition. The last collection (instead of the first with the same 120 ml  $V_{D_m}$ ) was used to calculate  $V_{D_{po}}/V_{T_o}$  for C. W., because his initial  $V_T$  far exceeded all subsequent  $V_T$ 's. The mean end-tidal  $PCO_2$  was used for  $PA_{CO_2}$ ,

and  $V_{D_{an}}$  was estimated from ideal body weight (6, 7). Where  $[PE_{CO_2}V_T/PA_{CO_2}(V_T - V_{D_{an}} - V_{D_m})]$  was  $>1$  (C. O.), a value of 1 was used.

Regression lines (8) for  $V_{D_p}/V_T$  on  $V_{D_m}/V_T$  were calculated for each method and each subject. Comparisons of  $V_{D_p}/V_{T_n}$  by equations 11 with 9 and by 12 with 10 were made, and correlation coefficients ( $r$ ) were calculated (8). The initial

TABLE I  
 *$V_{D_p}/V_T$  with Added  $V_{D_m}$  Calculated by (a) No Correction for  $V_{D_m}$ , (b) Traditional Correction,  
(c) Equation 7, and (d) Equation 8*

Subject, diagnosis, age, height, estimated $V_{D_{an}}$	Respiration rate per min			$PE_{CO_2}$	$PA_{CO_2}$	$PA_{CO_2}$	$V_{D_n}/V_{T_n}$	$V_{D_p}/V_{T_n}$	$V_{D_{po}}/V_{T_o}$	$V_{D_{po}}/V_{T_o}$
	$V_{D_m}$	$V_T$					(a)	(b)	(c)	(d)
	ml	ml		mm Hg	mm Hg	mm Hg				
C. O.	120	473	19.0	18.0	36.9	38	0.53	0.27	0.29	0.27
Asthma in remission,	170	515	20.7	16.4	36.1	37	0.55	0.22	0.26	0.25
40 yr, 69 inches,	218	538	21.3	14.9	37.8	41	0.64	0.23	0.31	0.27
141 ml	270	591	21.0	13.9	38.7	42	0.67	0.21	0.32	0.27
	322	652	21.3	13.6	39.2	42	0.68	0.18	0.30	0.26
	218	538	22.0	14.7	36.8	41	0.64	0.24	0.33	0.28
C. W.	120	891	10.7	22.4	37.8	40	0.44	0.31	0.42	0.42
Emphysema-bronchitis,	170	696	14.0	20.2	37.3	45	0.55	0.30	0.43	0.43
55 yr, 67 inches,	218	649	16.3	16.8	34.4	45	0.62	0.29	0.45	0.43
130 ml	270	732	14.3	16.8	36.9	45	0.63	0.26	0.44	0.42
	322	689	16.0	14.9	36.9	46	0.67	0.21	0.42	0.35
	120	518	16.7	19.0	34.4	44	0.57	0.33	0.42	0.40
J. R.	120	890	9.7	17.8	33.5	41	0.57	0.43	0.48	0.52
Bronchitis-emphysema,	170	800	13.0	17.3	30.9	42	0.59	0.38	0.45	0.50
70 yr, 66 inches,	218	890	11.7	16.3	32.8	42	0.61	0.37	0.46	0.52
120 ml	270	840	14.0	14.3	33.6	43	0.67	0.35	0.46	0.54
	322	900	14.0	13.0	32.0	43	0.70	0.34	0.48	0.57
	120	730	13.3	18.2	30.4	40	0.55	0.38	0.42	0.47
M. C.	120	692	22.0	19.1	32.0	45	0.58	0.40	0.49	0.50
Emphysema-bronchitis,	170	694	24.0	16.4	29.6	42	0.61	0.37	0.49	0.49
56 yr, 69.5 inches,	218	759	21.0	13.5	27.7	40	0.66	0.37	0.53	0.54
144 ml	270	734	21.0	14.5	31.6	42	0.66	0.29	0.47	0.47
	322	823	21.0	13.4	29.8	43	0.69	0.30	0.51	0.51
	120	727	21.7	15.5	25.9	37	0.58	0.42	0.51	0.51
H. V.	120	1013	21.7	16.3	27.1	40	0.59	0.47	0.53	0.55
Bronchitis-emphysema,	170	910	20.3	16.7	28.1	41	0.59	0.40	0.49	0.51
56 yr, 73 inches,	218	979	18.7	14.9	27.3	40	0.63	0.40	0.52	0.55
165 ml	270	1043	18.3	15.6	28.4	39	0.60	0.35	0.48	0.51
	322	1162	17.3	14.6	28.4	40	0.63	0.35	0.51	0.54
	120	1091	19.0	15.3	24.9	36	0.58	0.47	0.53	0.55
E. B.	120	580	19.0	16.3	32.4	59	0.72	0.52	0.66	0.67
Emphysema-bronchitis,	170	636	19.3	16.7	36.6	61	0.73	0.46	0.65	0.66
56 yr, 69 inches,	218	642	16.7	15.6	41.4	65	0.76	0.42	0.65	0.68
141 ml	270	712	16.0	15.1	38.2	64	0.77	0.39	0.66	0.67
	322	729	16.0	14.0	38.7	64	0.78	0.34	0.65	0.65
	120	556	20.7	16.0	32.3	57	0.72	0.50	0.65	0.66
L. H.	120	478	33.0	7.1	16.8	59	0.88	0.63	0.86	0.87
Embolism-emphysema,	170	470	34.3	6.5	19.6	63	0.90	0.54	0.87	0.88
62 yr, 63.5 inches,	218	501	36.0	5.9	22.0	62	0.90	0.47	0.86	0.88
113 ml	270	507	37.3	5.3	23.0	63	0.92	0.38	0.86	0.87

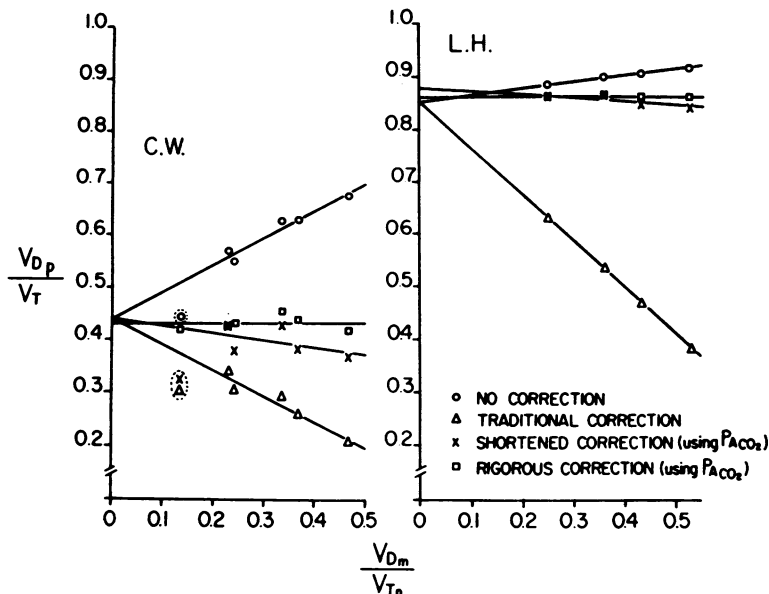


FIGURE 1 The change of  $V_{Dp}/V_T$  with added  $V_{Dm}$  for C. W. and L. H. Values plotted are by (a) no correction for  $V_{Dm}$ , (b) traditional correction (equation 1), (c) shortened equation 11, and (d) rigorous equation 7. Extrapolation of the regression lines to  $V_{Dm} = 0$  indicates the approximate  $V_{Dp}/V_T$  of the subject when breathing without  $V_{Dm}$ . The decrease of  $V_{Dp}/V_T$  by equation 11 represents for C. W. a true decrease as a result of the increased  $V_T$  response to added  $V_{Dm}$  (see text). The three encircled points were calculated for an initial  $V_T$  200 ml greater than any succeeding measurement. These data were not used in the calculation of regression lines because of the unusually large  $V_T$ .

measurements were not included in these correlations, because  $P_{A_nCO_2}/P_{A_nCO_2}$  and  $P_{A_oCO_2}/P_{A_oCO_2}$  (and their equivalents in equations 10 and 12) were identical.

## RESULTS

Fig. 1 shows  $V_{Dp}/V_T$  calculated by four methods for C. W. and L. H. The intercepts of the regression lines at  $V_{Dm} = 0$  indicate the approximate  $V_{Dp}/V_T$  ratios of the patients when breathing without  $V_{Dm}$ . As  $V_{Dm}/V_{Tn}$  increases,  $V_{Dn}/V_{Tn}$  and the traditional correction for C. W. appear to deviate equally from the intercept value of 0.44; neither gives the proper value. For L. H. (pulmonary embolism), the increase in  $V_{Dn}/V_{Tn}$  is only 0.06 with 0.53 added  $V_{Dm}/V_{Tn}$  (270 ml  $V_{Dm}$ ); when the traditional correction is used,  $V_{Dp}/V_T$  is 0.38, a gross underestimation of the 0.85 intercept. Table I (column b) shows for the group that underestimation of  $V_{Dp}/V_T$  by the traditional correction increased as alveolar dead space increased.

Equations 7 and 8 give  $V_{Dp0}$  at a constant  $V_T$  (the assumed value for  $V_{T0}$ ). In Fig. 1 the results from equation 7 (rigorous correction using  $P_{ACO_2}$ ) produce horizontal regression lines for both patients. This constancy in  $V_{Dp0}/V_{T0}$  is shown in Table I for each of the seven subjects and for both equations. For six of the seven men the intercepts of the regression lines for equations

7 and 8 at zero  $V_{Dm}$  are within 0.02 of those for  $V_{Dn}/V_{Tn}$ .

Equations 9 and 10 calculate  $V_{Dp}/V_T$  at the  $V_T$  of the measurement (rather than at a constant  $V_T$  as in equations 7 and 8). With added  $V_{Dm}$  the subjects tended to increase  $V_T$  slightly and  $V_{Dp}/V_T$  by equations 9 and 10 decreases accordingly. The decrease for C. W. in Fig. 1 by equation 11 is essentially the same as by equation 9. This slight decrease represents a true decrease in  $V_{Dp}/V_T$  with spontaneously increasing  $V_T$  (1, 2). The encircled measurement in Fig. 1 ( $V_T$  373 ml greater than the repeat with the same  $V_{Dm}$ ) is further evidence of this true decrease.

Values for  $V_{Dp}/V_T$  by equations 11 and 12 agree within 0.02 of the values by the more rigorous equations 9 and 10 in 32 of 33 comparisons for both pairs of equations. The correlations are extremely high ( $r = 0.998$  for each comparison).

## DISCUSSION

Dead space in the original Bohr equation (9) or measured by Fowler's method (10) is  $V_{D_{an}} + V_{Dm}$ , i.e. mechanical dead space is simply an extension of  $V_{D_{an}}$ . However, physiological dead space includes alveolar dead space ( $V_{D_{alv}}$ ) which is a functional volume (11),

defined as the difference between physiological and anatomical dead space (12).  $V_{D_{alv}}$  is primarily caused by reduced perfusion of alveoli relative to their ventilation (13). If  $V_{D_m}$  were simply an extension of  $V_{D_{an}}$  during measurement of  $V_{D_n}$ ,  $V_{D_{alv}}$  would also equal  $V_{D_n} - V_{D_{an}} - V_{D_m}$ . The fact that  $V_{D_p}$  is underestimated when all of  $V_{D_m}$  is subtracted from  $V_{D_n}$  indicates that this is not so. As  $V_{D_{alv}}$  increases an increasingly smaller fraction of dead space gas from  $V_{D_m}$  is inhaled into the perfused areas of the lung where it decreases effective ventilation (increases dead space). In the non-perfused alveoli  $V_{D_m}$  gas has little effect on dead space, i.e. effective ventilation cannot be decreased below 0. The nonperfused alveoli do contribute indirectly to gas exchange by exhaling part of the  $CO_2$  inhaled from  $V_{D_{an}}$  and  $V_{D_m}$  in the previous breath (12). When  $V_{D_m}$  is added, a smaller volume of this gas escapes to the outside, but its  $CO_2$  concentration is greater. Equations 7 and 8 take all these changes into account.

The nearly horizontal slopes of  $V_{D_{po}}/V_{T_o}$  on  $V_{D_m}/V_T$  and the agreement of the intercepts at  $V_{D_m} = 0$  with those for  $V_{D_n}/V_T$  indicate the validity of equations 7 and 8 and of the assumption used in their derivation (that  $f_p$  does not change significantly with added  $V_{D_m}$ ).

Equations 11 and 12 are good working equations to use with data from a single collection. As with the traditional correction for  $V_{D_m}$ , they apply only to the conditions ( $V_{T_n}$ , posture, spontaneous or assisted ventilation, etc.) of the measurement. The substitutions of  $P_{A_n}CO_2/P_{A_n}CO_2$  for  $P_{A_o}CO_2/P_{A_o}CO_2$ , and the equivalent substitution using  $V_{D_{an}}$  introduce little error as shown by the comparisons of equation 11 with 9 and 12 with 10.

Since the ratio within the brackets of equations 11 and 12 is the ratio of effective to total alveolar ventilation, it can never be  $> 1$ . When the calculated  $P_{A_o}CO_2/P_{A_o}CO_2$  in equation 11, or the equivalent ratio in equation 12 is  $> 1$ , simply subtract  $V_{D_m}$  from  $V_{D_n}$ .

Both equations 11 and 12 can be applied at large tidal volumes. However, if alveolar  $CO_2$  does not plateau, e.g., during the hyperventilation of exercise, then equation 12 using  $V_{D_{an}}$  is preferable. Any of several equations from the literature can be used for estimating  $V_{D_{an}}$  (14, 15). When comparing  $V_{D_p}/V_T$  during exercise with rest, 3 ml should be added to the estimated  $V_{D_{an}}$  for every 100 ml over the subject's resting  $V_T$  (1, 16). When  $V_T$  is very small, e.g.,  $< 300$  ml for normal adults, correction for  $V_{D_m}$  is not dependable because alveolar ventilation begins before washout of  $V_{D_{an}}$  and  $V_{D_m}$  is complete (17).

Clinically,  $V_{D_p}/V_T$  at normal tidal volumes gives a better index of alveolar dead space than do arterial-alveolar  $CO_2$  gradients when there is coexistent uneven ventilation. In addition, hyperventilation of exercise can be used to distinguish the normal decrease of

$V_{D_p}/V_T$  from the increased  $V_{D_p}/V_T$  accompanying pulmonary vascular occlusion (2). Since hyperventilation requires low resistance breathing valves having significant dead space, the proper correction for  $V_{D_m}$  is important.

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