FLOW REQUIREMENTS FOR A MODIFIED MAPLESON D SYSTEM DURING CONTROLLED VENTILATION

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IN THE JULY 1972 ISSUE of this Journal[1] a modified Mapleson D System was described as "A Streamlined Anaesthetic System" (Figure 1). Placing the fresh gas inflow line inside the single breathing tube, a light-weight single tube system was created without valves near the patient's face, bringing the exhaust valve and breathing bag to a convenient place at the anaesthetic machine. In an initial study of the use of this system on unselected patients, it was found that adequate CO_2 elimination was possible during spontaneous breathing and controlled ventilation with a fresh gas inflow as low as 5.5 L/min.

In order to determine the minimum gas flow required for adequate CO_2 elimination and to obtain a useful practical guide for such flow requirements, it was decided to use the Radford Nomogram[2,3] as a guide to the fresh gas inflow requirements of this modified system, during controlled ventilation. This nomogram has been accepted by Anaesthetists as a guide for the adequacy of ventilation.[4]

The Radford nomogram was designed to estimate the tidal volume required to maintain the arterial $PaCO_2$ at 40 mmHg at any given breathing frequency. It was based on the fact that basal carbon dioxide production and respiratory dead space are related to body weight. Radford, *et al.*[3] included several factors which require correction. Such factors are fever, altitude and changes in dead space due to tracheal intubation or tracheostomy. They found that the nomogram predicted tidal volume with sufficient accuracy for clinical use in poliomyelitis patients and in all normal adult patients and infants. Radford[3] stated that there were some conditions under which the nomogram could not be applied, the most important being muscle activity; it obviously cannot be applied without corrections in hyper- and hypo-metabolic states, in conditions where the physiological dead space is increased, or in severe metabolic alkalosis or acidosis, especially in the presence of kidney disease. Except for muscle activity all of these situations are relatively rare and should not interfere seriously with the routine usefulness of the nomogram. The ventilation standards are designed to provide for the removal of carbon dioxide, with the implication that if carbon dioxide is removed the oxygen supply is also adequate. The routine use of high inspired oxygen mixtures in anaesthesia makes this assumption almost invariably correct.

METHOD

A clinical study was carried out on 19 adult patients anaesthetized with the breathing circuit described; there was no patient selection and no standardization

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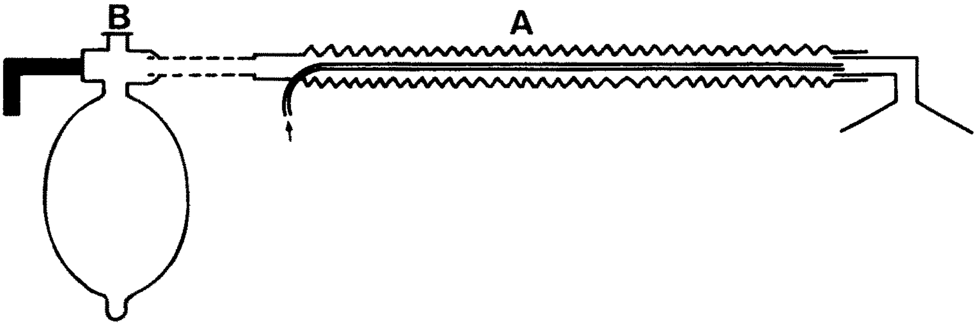

FIGURE 1. Modified Mapleson D System. A = Breathing attachment. B = Bag mouth with pop-off valve. → = Fresh gas inflow from anaesthetic machine.

of premedication or of the anaesthetic agents used. The operations included all types except thoracic procedures. All patients were intubated and maintained on controlled ventilation with a bellows type ventilator (Air-Shields Ventimeter Ventilator), where there is no possibility of air admixture to dilute the inflow of gas from the anaesthetic machine. All patients were ventilated initially with a fresh gas inflow of 7 litres (5L N_2O and 2 L O_2). $PaCO_2$ was determined after thirty minutes. A respiratory rate of 12 to 15 per minute was selected and the tidal volume at the selected rate was derived from the Radford nomogram. The only correction made was for intubation and, accordingly, half the body weight in pounds was substracted. The corrected tidal volume was multiplied by the set rate of the ventilator to determine the fresh gas inflow from the anaesthetic machine (Radford corrected). $PaCO_2$ was determined after 30 minutes ventilation at this inflow. The inflow was then decreased by 25 per cent (Radford corrected – 25 per cent) and the $PaCO_2$ was determined again after 30 minutes. The results are tabulated in Table I. The volume of ventilation in all patients was set at least 50 per cent higher than the inflow volume calculated from the Radford nomogram.

RESULTS

The values in Table I indicate that there is adequate CO_2 removal at an inflow setting at Radford corrected and even at a 25 per cent lower flow the $PaCO_2$ was within an acceptable range in most cases.

In order to determine the average inflow required to achieve a $PaCO_2$ of 40 mmHg, a graph was constructed plotting the mean $PaCO_2$ at Radford corrected and the mean $PaCO_2$ at Radford corrected −25 per cent against the mean inflow (in L/min and ml/kg/min) for each of these values (Figure 2). It is assumed this relationship is approximately linear in the area of these points. We determined a mean inflow of 4.370 L/min was required to achieve a $PaCO_2$ of 40 mmHg, or 54 ml/kg/min. Assuming a $PaCO_2$ of 40 mmHg to be normal, the mean value for the ratio of minimum adequate fresh gas inflow to respiratory minute volume calculated from the Radford nomogram (uncorrected) was 0.67. This ratio is comparable to 0.71 calculated by Kain and Nunn[5] for patients breathing spontaneously with the Magill circuit.

TABLE I

	Name	Age Years	Weight Kg	Sex	7L Inflow ml/Kg/min	7L Inflow $PaCO_2$ mmHg	Radford Calculation Uncorrected ml/min	Radford Calculation Uncorrected ml/Kg/min	Radford Inflow Corrected ml/min	Radford Inflow Corrected ml/Kg/min	Radford Inflow Corrected $PaCO_2$ mmHg	Radford Inflow Corrected - 25% ml/min	Radford Inflow Corrected - 25% ml/Kg/min	Radford Inflow Corrected - 25% $PaCO_2$ mmHg
1	W.P.	77	88.0	M	79.5	32	6960	79.1	5820	66.1	36	4365	49.6	34
2	D.C.	24	100.0	M	70.0	36	7920	79.2	6480	64.8	37	4860	48.6	43
3	H.J.	46	92.8	M	75.4	34	7800	84.1	6474	69.7	34	4855	52.3	41
4	R.B.	63	94.5	M	74.0	37	7260	76.8	6116	64.7	34	4587	48.5	40
5	M.M.	34	59.0	F	109.0	23	5070	85.9	4225	71.6	31	3169	53.7	38
6	M.C.	54	68.9	F	108.0	34	5590	81.1	4680	67.9	42	3510	50.9	52
7	P.C.	36	96.0	M	73.7	39	7700	80.2	6230	64.9	40	4673	48.7	50
8	K.C.	—	84.0	M	83.3	31	6720	80.0	5616	66.9	32	4212	50.1	34
9	M.C.	38	90.3	F	77.5	33	6580	72.9	5194	57.5	35	3896	43.1	42
10	M.M.	79	70.2	F	100.0	31	5590	79.6	4589	65.4	30	3442	49.0	36
11	M.S.	61	63.5	F	105.0	31	5600	88.2	4496	70.8	32	3372	53.1	39
12	M.K.	64	80.7	F	87.0	25	6400	79.3	4992	61.9	32	3744	46.4	37
13	S.O.	64	65.0	F	104.0	27	5400	83.1	4345	66.8	43	3259	50.1	51
14	K.	39	104.5	F	64.0	33	6480	62.0	5112	48.9	34	3834	36.7	—
15	A.W.	43	56.0	F	125.0	29	4800	85.7	4068	72.6	34	3051	54.5	—
16	P.H.	—	74.0	M	94.6	45	6300	85.1	5328	72.0	46	3996	54.0	54
17	M.H.	—	92.0	F	76.2	36	6580	71.5	5166	56.2	39	3875	42.1	42
18	R.E.	26	90.0	M	77.8	29	7800	86.7	6315	70.2	31	4736	52.6	35
19	A.M.	62	79.0	M	88.6	35	7040	89.1	5664	71.7	38	4248	53.8	42
Mean			81.5		88.0	32.6	6504	80.5	5311	65.8	35.8	3983	49.4	41.8
±S.D.			14.1								4.4			6.2

$PaCO_2$ with fresh gas inflow volumes calculated from Radford nomogram.

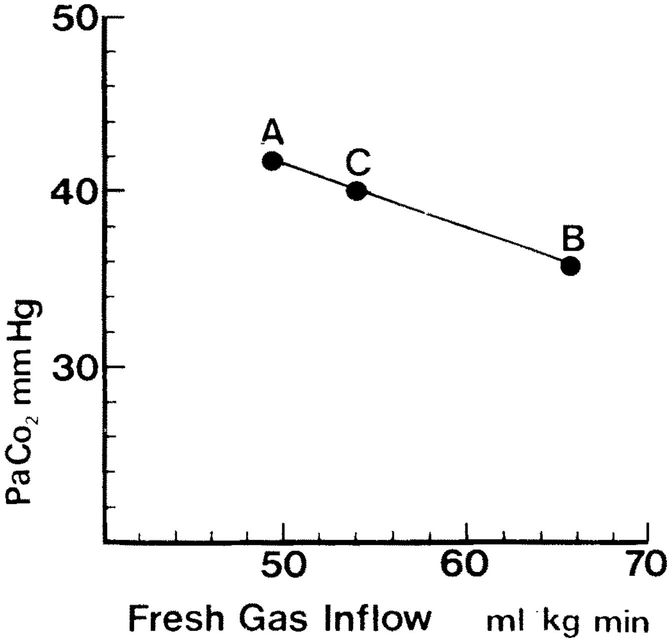

FIGURE 2. Arterial P_{CO_2} levels in relation to fresh gas inflow. B = Fresh gas inflow according to the patient's requirement calculated from Radford Nomogram, corrected for dead space reduction. A = Inflow of fresh gas 25 per cent below value of B. C = Hypothetical mean fresh gas inflow to achieve a $PaCO_2$ of 40 mmHg.

Since the average inflow of 65.8 ml/kg/min produced a mean $PaCO_2$ of 35.8 mmHg it was felt that the inflow calculation could probably be simplified by using a uniform flow of 70 ml/kg/min. This rate of flow was used in 20 unselected patients. All patients were fully paralysed and ventilated with a bellows-type ventilator (Air-Shields Ventilator Ventimeter). The tidal volume delivered by the ventilator was set at 10 ml/kg[6] at a rate of 12 to 14. The volume of ventilation always exceeded the fresh gas inflow of 70 ml/kg/min (using N_2O 50 ml/kg/min and oxygen 20 ml/kg/min). Arterial blood gas determinations were made after at least 30 minutes of ventilation under these conditions.

The results (Table II) indicate that an inflow setting of 70 ml/kg/min is adequate to prevent CO_2 accumulation, using a respirator tidal volume setting of 10 ml/kg and a rate of 12 to 14 per minute. Only one of the 20 patients had a mild respiratory acidosis. This patient had a history of previous pneumonia. Chest x-ray revealed fibrotic changes in both lung bases. The PaO_2 was normal or above normal at a nitrous oxide/oxygen ratio of 5:2 under these conditions.

Discussion

For patients who are being ventilated, Waters and Mapleson[7] have shown that the Mapleson D system involves less rebreathing than the Mapleson A system (Magill attachment). Harrison[8,9] reviewed the modifications of the Ayre's T-piece and concluded that a fresh gas inflow of 2½ to 3 times the minute volume was

TABLE II

	Patient	Age	Wt, Kg	Sex	PO_2	PH	PCO_2	SB	BE
1	C.F.	65	81	M	95	7.33	39	20	−5
2	F.A.	32	63	M	131	7.36	34	20	−5
3	M.P.	55	59.9	M	98	7.33	49	22	−3
4	R.P.	52	73	M	95	7.39	34	22	−3
5	A.T.	68	57	F	158	7.42	30	21	−4
6	K.R.	41	82	M	131	7.40	30	20	−5
7	R.K.	48	75	M	120	7.39	41	24	0
8	R.M.	23	89.5	M	162	7.37	36	21	−4
9	G.P.	62	81.6	M	101	7.37	37	21	−3
10	M.A.	46	54	F	139	7.29	40	18	−7
11	A.L.	71	77.1	F	120	7.38	36	21	−4
12	G.D.	27	78.5	F	103	7.33	32	18	−8
13	J.L.	—	—	M	128	7.37	33	20	−4
14	G.G.	46	56.5	F	132	7.36	35	22	−3
15	E.R.	36	—	F	137	7.38	40	23	−1
16	E.M.	30	48.1	F	142	7.29	39	18	−7
17	A.J.	65	68	M	127	7.39	33	24	−4
18	H.A.	63	82	M	114	7.36	36	20	−5
19	L.	67	70	M	132	7.36	40	22	−3
20	M.G.	69	75	M	102	7.37	37	21	−3
	Mean		70.6		123	7.36	36.6		
	±S.D.		11.4		19	0.03	4.3		

Blood gases in 20 patients ventilated with a fresh gas inflow of 70 ml/kg/min.

required to prevent rebreathing during manual ventilation with a reservoir capacity either more or less than tidal volume. In laboratory models, he reported that fresh gas flows between 1.7 and 3 times minute volume were required to prevent rebreathing, depending upon which of five ventilators was used and upon the respiratory flow pattern. Nightingale, *et al.*[10] pointed out that in most of the reported work pertaining to the T-piece system, emphasis had been placed upon the prevention of rebreathing rather than the avoidance of retention of carbon dioxide by the patient. Their work demonstrated that with manually controlled ventilation this goal is easily achieved despite the occurrence of considerable rebreathing, i.e., the presence of previously exhaled carbon dioxide in the inspired gas mixture. They measured low concentrations of end-expired carbon dioxide occurring in spite of significant rebreathing. They explained that manually controlled ventilation of a paralyzed patient commonly produces a minute volume considerably in excess of his resting ventilation. If, in these circumstances, carbon dioxide were to be eliminated completely from the inspired gas by using a fresh gas inflow of two to three times the actual minute volume, not only would the gas inflow be too great, but body stores of carbon dioxide would be depleted and respiratory water loss would be increased.

In a system which allows complete mixing of the fresh gas inflow with the alveolar gas, the concentration of carbon dioxide in the alveolar gas (FA_{CO_2}) at any one time is determined by the carbon dioxide production ($\dot{V}$) at that time and by the fresh gas inflow (VF), according to the simple relationship.

$$FA_{CO_2} = \frac{\dot{V}_{CO_2}}{VF}$$

On the basis of this assumption it would appear that an inflow volume near the patient's volume of alveolar ventilation would be adequate to maintain a normal CO_2. This has been demonstrated by Kain and Nunn[5] for the Magill system (Mapleson A), who reported a ratio between inflow volume and respiratory minute volume of 0.71 at a normal $PaCO_2$ in spontaneously ventilating patients. From our data an almost identical ratio (0.67) was estimated based on a calculated respiratory minute volume. Keeri-Szantó[11] produced isocapnoeic ventilation using a modified Magill circuit and found an average inflow volume of 4.5 L adequate for this purpose.

Our modified system, the system evaluated by Nightingale[10] and the Magill system provide good mixing of gases. The expired gas and the fresh gas inflow mix in the reservoir tubing and bellows of the ventilator; the excess mixed gas is lost through the expiratory valve of the respirator. Provided that the minute ventilation exceeds the fresh gas inflow, as it did in this investigation and in most of Nightingale's patients, the fresh gas inflow will be the variable of major significance in determining the end-expired carbon dioxide concentration and, thus, the patient's $PaCO_2$. The precise relationship depends upon the degree of mixing that occurs.

Carbon dioxide production may be estimated from body weight. During anaesthesia it is reasonable to assume that carbon dioxide production is influenced also by pre-operative medication, body temperature, the degree of muscular relaxation and the anaesthetic agents used. It must also be assumed that the inflow must be increased under the abnormal conditions described by Radford.[2,3]

Nightingale, *et al.*[10] concluded for paediatric anaesthesia the following guide for selecting a suitable fresh gas inflow when using the T-piece (Mapleson D) with nitrous oxide-oxygen – muscle relaxant anaesthesia. Carbon dioxide retention is prevented by using a minimum total gas inflow of 3 L/min for children under 13.5 kg body weight and by a fresh gas inflow of 220 ml/kg body weight per minute for larger children, with a maximum total flow of 8 L/min. During our study it was noted that an inflow setting of 70 cc/kg/min was difficult to obtain precisely with the rotameters provided on our anaesthetic machines, so in all patients with weights of 50 kg or less an inflow setting of 3.5 L was used (2.5 L of N_2O and 1.0 L of O_2). This flow maintained the same ratio of N_2O to O_2 without dropping the O_2 inflow below 1 L/min. The ventilation in these patients was still maintained at 10 ml/kg or in the very small infants at a ventilating pressure which provided mild hyperventilation. Clinically this provided excellent anaesthetic conditions. Further studies should be carried out with patients weighing less than 50 kg with more precise flowmeters. The use of smaller inflows in these patients would decrease respiratory water loss.

It should be noted that if the fresh gas inflow exceeds the ventilating volume the $PaCO_2$ will depend upon the ventilating volume rather than on the fresh gas inflow. With the inflows of two to three times the actual minute volume suggested by others,[8,9] or the inflows recommended for children,[10] the $PaCO_2$ was undoubtedly dependent on ventilation and not on the inflow of fresh gas.

From the data obtained in this study it is concluded that a fresh gas inflow either determined by the Radford nomogram, or 70 ml/kg/min is adequate to prevent carbon dioxide retention in our modification of the Mapleson D system, providing that the respirator minute volume exceeds the fresh gas inflow and is maintained at 10 ml/kg and a rate of 12 to 14 per minute. The following guide can therefore be used to calculate the inflow of fresh gas required:

1. For patients weighing 50 kg or less
   N_2O inflow 2.5 L/min
   O_2 inflow 1.0 L/min
   Respirator tidal volume = 10 × wt in kg with a rate of 12–14 per minute. In the very small infant the respirator set at a ventilating pressure which provides mild hyperventilation.
2. For patients over 50 kg body weight
   N_2O inflow/min = 50 × wt in kg
   O_2 inflow/min = 20 × wt in kg
   Respirator tidal volume = 10 × wt in kg with a rate of 12 to 14 per minute.

This guide has proven satisfactory for the routine patient presented for anaesthesia. The guide can easily be adjusted in those circumstances where an increased concentration of oxygen might be required. For patients with an elevated body temperature, the corrections suggested by Radford *et al.*[2,3] should be applied, i.e., a 10 per cent increase in flow for each degree centigrade above 37°. The inflow of fresh gas should also be increased in other states of increased metabolism. In obese patients the inflow rate of 70 ml/kg/min is probably somewhat excessive while, in the patient who has had considerable weight loss it would be advisable to base inflow on the patient's normal weight.

Summary

A study was carried out on a modification of the Mapleson D system to determine accurately the patient's inflow requirements during controlled ventilation. This study utilized the Radford Nomogram as a guide. It was concluded that the Radford nomogram calculation corrected only for intubation or an inflow of 70 ml/kg/min was a reliable guide for determining the inflow requirements to maintain mild hyperventilation. This system is dependent upon inflow only if the respirator minute ventilation exceeds the inflow.

Résumé

Nous avons fait une étude sur une modification de système Mapleson D pour déterminer de façon précise les besoins inspiratoires du malade au cours de la ventilation contrôlée. Au cours de cette étude, nous avons utilisé, comme guide, le nomogramme de Radford. Nous en venons à la conclusion que le calcul du nomogramme de Radford corrigé seulement pour l'intubation ou un volume inspiratoire de 70 ml/kg/min constituait un guide fiable pour déterminer les exigences inspiratoires pour maintenir une légère hyperventilation. Ce système dépend sur l'inspiration seulement si le volume minute du respirateur excède le volume inspiratoire.

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