Influence of Various Pressure and Flow Rate Settings of Pressure-Cycled Respirators on Minute Volumes, Expiratory PO_2 and PCO_2 of Normal Men During IPPB

E. Stresemann, M.D.*

The effectiveness of assisted ventilation in conditions of respiratory distress depends on the ability to maintain adequate alveolar ventilation. If the volumes of inspiratory air necessary could be accurately calculated, and no other factors influencing respiration were to be accounted for, it would obviously be simple for efficient assisted breathing to use preselected volumes of air from a respirator to be delivered to the patient. Since the rationale of adequate ventilation is complex, however, particularly in diseases affecting the mechanical properties of the lungs, passive breathing of pre-selected tidal volumes from volume-cycled respirators will not solve the therapeutic problem in many cases. Using pressure-cycled respirators instead, the volumes delivered by the machine might be in question whenever there is no means for such measurements provided by the respirator. In order to assess the influence on minute ventilation of positive pressure and flow rate, this study has been designed to measure the tidal volumes and the composition of expiratory air in normal adults under various settings of a pressure-cycled respirator.

Methods

Expiratory volumes were collected from the exhalation port of a Bird Mark 7 respirator and recorded on a Parkinson-Cowan meter. Inspiratory pressure of the respirator, operating on compressed air, was varied from 5 to 40 cm. of water, most pressure settings being combined with several flow rate settings. The sensitivity to the inspiratory effort-release value was adjusted to the −1 cm. range. No flow rate and pressure setting was considered that interfered with a regular breathing cycle while on IPPB, as occurs when high flow rates are combined with low positive pressure. This leads to a type of ventilation characterized by the machine delivering small "puffs" of air, with inspiratory volumes too inadequate for coordinate breathing.[1]

Minute volumes and breathing rates were recorded over a 2 to 3 minute period for each setting of the respirator with the subjects supine, breathing through a mask (Bird mask no. 3). This was also recorded for unassisted, spontaneous breathing on a spirometer (Godart, Pulmotest), in the same position using the same mask.

In the second part of the study, expiratory air was collected to determine its composition under different settings of pressure and flow rate of the respirator, with simultaneous recording of tidal and minute volumes on a Wright respirometer. Collecting of expiratory air from the exhalation valve of the respirator for determination of mean $F_{E_{O_2}}$ in a Beckman F3 paramagnetic oxygen-analyzer was con-

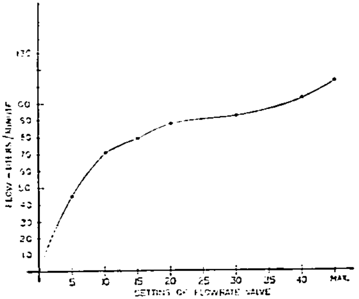

Fig. 1. Determination of flow rates (ordinate) as delivered by selected settings of flow rate valve (abscissa) on bird Mark 7 respirator (Ser. no. 6673786).

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[*] Privatdozent of Internal Medicine. On leave of absence from the Free University of Berlin, Germany. Present address: Cardio-pulmonary Unit, Bird Institute, Palm Springs, California.

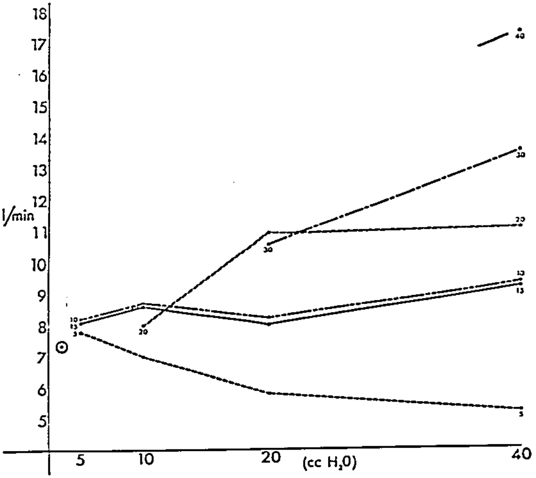

Fig. 2. Minute volumes (mean values) of 4 normal subjects on assisted positive pressure breathing from a Bird respirator at various settings of pressure and flow rate. *Abscissa:* inspiratory pressure. *Ordinate:* minute volumes in liters per minute. Figures next to plotted points indicate flow rate setting of respirator. Encircled point represents the mean minute volume of test subjects at rest as taken on spirometer.

tinued for 4 to 10 minutes with the subject on mask breathing, supine.

$F_{E_{CO_2}}$ was analyzed simultaneously in a Beckman infrared analyzer (Model LB1) by continuous sampling of expiratory air via a small catheter, resting between the front teeth. Recording of O_2 and CO_2 readings was done on a Becknan 10 inch recorder Model 1005 and on a Gilson recorder (Gilson Polygraph, Model M8PM), respectively. End-expiratory CO_2 concentration were read for each breath for determination of mean values.

In order to account for the influence of instrumental dead space on breathing, minute volumes were additionally registered over 10-minute periods in one subject breathing into the spirometer and, in a control measurement, into a Wright respirometer through a respirator mask (Bird respirator mask no. 3), through a Godart spirometer rubber mouthpiece and through a Bird respirator plastic mouthpiece. Instrumental dead space of mask, as well as of rubber and plastic mouthpieces, was determined with measured volumes of water. Allowing for the displacement of mask dead space by protrusion of the face, the mask was sealed at the rim with a plastic foil. This displacement of water in the mask produced by the face was read in mls. from an inter-connected burette.

As the numbers on the Bird respirator pertaining to flow rates do not express litres per minute or other unit, flow rates were measured by connecting the respirator to a Wedge spirometer (Model 370, Medical Science Electronics) and a Gilson 6-channel MSPM recorder. Flow measurements so obtained will inform only about the meaning of the flow rate numbers used in this study in terms of unimpaired flow in liters per minute as delivered by the respirator (fig. 1). Hence, such information will not reflect, for each point of a pressure-volume diagram, the flow rates engaged in passive inflation of the lungs under IPPB in this study.

The subjects selected for this study were 4 normal male adults, ages 24 to 42 years, without clinical evidence of lung disease and without indication of impaired lung function as ascertained by spirometry. They were well acquainted with the mechanism and operation of a respirator. They rested supine for 10 to 30 minutes before the studies.

Table 1. Minute Volumes, Tidal Volumes and Breathing Rates Under Various Pressure and Flow Rate Settings of a Pressure Cycled Respirator

Subject		1			2			3			4		
P_{H_2O} cm.	Flow	MV	f	V_T	MV	f	V_T	MV	f	V_T	MV	f	V_T
5	5	7050	9	783	8970	7.7	1172	7600	8.3	913	7643	11.3	675
10	5	6200	5.8	1061	7591	5.3	1423	7633	8.0	955	6866	10.8	635
20	5	4800	3.0	1600	6774	4.33	1564	6337	3.7	1688	5200	5.7	918
40	5	4900	2.7	1840	7050	2.5	2820	5085	2.7	1914	3716	2.3	1563
5	10	8300	8.4	992	9991	13.2	756	7450	8.8	850	7200	10.2	710
10	10	8300	12.4	672	10596	9.7	1101	7400	9.3	794	8516	13.5	631
20	10	7200	8.5	846	9233	5.2	1786	9075	5.1	1175	7350	8.7	849
40	10	6400	2.5	2559	10125	2.1	5040	9700	4.3	2241	11050	4.5	2455
5	15	7700	6.7	1155	9656	11.4	862	8180	8.1	1010	7000	7.0	1000
10	15	7400	8.7	854	10217	11.7	873	9233	9.0	1025	7450	10.7	700
20	15	7350	8.3	891	8575	4.8	1805	9000	4.7	1930	7200	6.3	1137
40	15	6450	2.5	2580	12466	4.3	2830	9550	3.3	2870	8266	3.2	2612
10	20	6125	8.8	700	10156	12.6	807	8016	9.2	875	7700	9.7	797
20	20	7175	8.3	869	13175	7.5	1757	10597	5.5	1923	12662	6.5	1948
40	20	7475	2.9	2620	15266	4.8	3159	11400	3.5	3255	10116	3.8	2645
20	30	6850	8.8	782	13100	8.1	1613	9084	7.8	1174	13200	13.0	1015
40	30	9275	3.7	2530	17683	5.7	3115	12160	3.3	3650	14633	5.0	2926
40	40	11200	3.8	2987	20862	6.7	3095	17525	6.5	2700	19350	6.0	3225
		6946	11.3	613	6917	9.3	745	7425	10.5	705	7985	14.5	550

P cm. H_2O = inspiratory pressure of respirator; Flow = flow rate setting of Bird respirator flow rate valve; MV = minute volume; f = respiratory rate; V_T = tidal volume. Last row of figure are above data at rest as recorded on spirometer (without IPPB).

Results

For any inspiratory pressure in the range of 5 to 40 cm. of water, lung volumes were primarily a function of the flow rate of the respirator (fig. 2, table 1). Compared with minute volumes at rest, hyperventilation was found in all subjects on IPPB, breathing from the respirator at inspiratory pressures of 20 cm. of water, if flow rate was 20 and above. Hence, with a pressure of 40 cm. of water hyperventilation was pronounced when using flow rates of 20 and above, the highest minute volumes being recorded at a pressure setting of 40 cm. of water and a flow rate of 40. Minute volumes were only slightly elevated at flow rates of 10 and 15 at all inspiratory pressures checked, even at a pressure of 40 cm. of water. Reducing the flow rate further to a setting of 5 at an inspiratory pressure of 40 cm. of water, with one exception, invariably induced a decrease of minute ventilation below the resting level. This tended to cause the sensation of shortness of breath, such that the subjects felt tempted to "fight" the machine (*i.e.*, to prematurely shut off the inspiratory flow from the machine by an expiratory effort), in order to shorten the long inspiratory time at this setting of the respirator.

These findings are reflected in the oxygen and carbon dioxide concentrations in the expiratory air (table 2). There was uniformly a rise in end expiratory P_{CO_2}, reaching 6 mm. of mercury difference from the basal value and a concomitant drop in P_{O_2} with the respirator set at 40 cm. of water inspiratory pressure and a flow rate of 5. Conversely, the inducement of hyperventilation by combining a pressure of 40 with a flow rate of 40 was reflected in a drop in P_{CO_2} and a rise of P_{O_2} in exhaled air.

Regarding the influence on minute volume of mask breathing versus rubber spirometer mouthpiece breathing and versus plastic respirator mouthpiece breathing, it was shown that the additional dead space contributed by these attachments caused a proportional increase in minute ventilation. This increase amounted to more than 1,100 ml. (17–18 per cent) additional minute volume uptake breathing through a mask as compared with minute ventilation breathing through a plastic mouthpiece (table 3).

Discussion

Little systematic study has been done, on the dependence of the efficiency of assisted ventilation on the correct choice of pressure and flow rate setting of pressure cycled respirators, other than the contribution to this subject by Herzog.[2] This author as well as Lyons *et al.*[3] state that higher tidal volumes are obtained with lower flow rates. In confirming this, it was shown, however, in the foregoing studies that the combination of a low flow rate and relatively high inspiratory pressures of 20 cm. of water and above tends to lead to a decrease in minute volumes. This is explained in that the inspiratory pressure setting of the respirator determines the moment of reversal of the inspiratory phase; and that this point will be reached the later, the smaller the air flow to build up pressure to this reversal point and the higher the pressure for this same point is selected. Therefore, although low flow rate versus high inspiratory pressure setting of the respirator will yield highest tidal volumes, this may readily lead to reduction of adequate minute volumes because of the concomitant slowing of respiratory rate. Decrease in minute volumes may be such as to approach alveolar hypoventilation with hypercapnea. On the other hand, high inspiratory pressures, combined with high flow rates, are apt to induce hyperventilation with loss of carbon dioxide. As comparison of tables 1 and 2 shows, on repetition of an experiment on different days the same minute volumes were not always obtained in the same subjects when selecting the high pressure and low flow rate setting of the respirator. This can be explained by the mechanics of the Bird respirator that will permit bypassing the mechanical flow regulation by active acceleration of air flow during inspiration, *i.e.*, by "sucking in" air, in addition to what the respirator is delivering. In some of the experiments, the subjects unintentionally made use of the possibility of averting the breathlessness they ex-

TABLE 2. Influence of Various Flow-Rate and Pressure Settings of a Pressure Cycled Respirator on Minute Volumes and Composition of Expiratory Air

Subject	Pressure (cm. H_2O)	Flow Rate Setting	$\dot{V}$	V_T f	$P_{E_{O_2}}$	$P_{E_{CO_2}}$
1	5	5	6675	534 12.5	113.4	43.5
2	5	5	5375	414 13	114.1	41.5
3	5	5	5800	1288 4.5	113.4	38.0
1	10	10	9000	622 14.5	114.8	38.7
2	10	10	9660	859 11.2	123.3	37.3
3	10	10	7700	1710 4.5	120.5	34.2
1	20	20	9520	1058 9	118.4	38.2
2	20	20	10940	1094 10	127.6	31.3
3	20	20	12075	2683 4.5	124.8	31.1
1	40	40	11750	2798 4.2	129.8	37.5
2	40	40	18240	3483 5.2	131.9	26
3	40	40	13050	4750 2.75	121.2	31.1
1	40	5	5660	2830 2	99.1	49.2
2	40	5	5040	2960 1.7	104.8	43.1
3	40	5	6700	4750 1.6	97.7	44.4

$\dot{V}$ in ml., V_T in ml., f = respiratory rate/minute. $P_{E_{O_2}}$, $P_{E_{CO_2}}$ = O_2 and CO_2 in expiratory air (partial pressures, BTPS).

TABLE 3. Minute and Tidal Volumes on Spontaneous Breathing Through Attachments with Different Instrumental Dead Spaces

	I (plastic mouth piece)		II (rubber mouth piece)		III (mask)	
	A	B	A	B	A	B
$\dot{V}$	6025	6040	6186	6210	7135	7160
f	8.9	11.3	9.3	11.1	10.6	10.7
Vt	680	535	660	560	673	669

Recording on (A) Godart spirometer, (B) Wright respirometer for 10 minute periods in same subject. I = plastic mouthpiece, dead space 15.5 ml. II = rubber mouthpiece, dead space 32.0 ml. III = respirator mask, dead space 150.0 ml. Displacement of mask dead space by subject's face 30.3 ml. $\dot{V}$ = mean minute volume, f = mean respiratory rate, and V_T = mean tidal volume.

perienced when on low flow rate versus high pressure setting of the machine. The variation of some of the results, encountered on repetition of some experiments, does not bear, therefore, on the conclusion that hypoventilation may result when a low flow rate versus a high pressure setting of the respirator is chosen. Consequently, such a setting of the respirator can be safely tolerated only as long as the subject is able to actively counteract an inadequate volume delivery from the machine. This will not hold, of course, for a subject unable to control his respirations, *e.g.*, for the curarized patient or in conditions with depression of the ventilatory drive.

It can be inferred from this study that the combination of a low to medium range pressure with low to medium range flow rate, in a pressure-cycled IPPB machine, leads to minute volumes that closely match the spontaneous minute volume uptake of unassisted breathing at rest. It must be stressed, however, that the study was dealing with normal, nonexercised adults. It is reasonable to conclude that, under altered conditions of acute lung pathology for the same persons, these settings of the respirator would lead to different minute volume uptakes; and that, in such case, the ventilation requirements might be quite different. It is also obvious and has been clearly demonstrated by Herzog,[2] that this conclusion particularly holds good for chronic alterations of mechanical properties of the lungs as in patients with obstructive emphysema. The present study, therefore, merely indicates that breathing from a pressure-cycled respirator without volume control, when operated on an inappropriate setting for volume and flow rate, might induce considerable disturbance of minute volume uptake, leading to hyperventilation as well as contributing to hypoventilation with possible CO_2 retention and hypoxemia.

SUMMARY

Minute volumes, as well as expiratory P_{CO_2} and P_{O_2} were determined in 4 normal male adults on IPPB, breathing room air from a pressure-cycled respirator (Bird Mark 7) under various positive pressures and measured flow rates. In supplement, the influence of instrumental dead space on minute volumes was assessed by breathing through different attachments into a spirometer. It was demonstrated that minute volumes obtained by IPPB are primarily a function of flow rate of the respirator. This fact was the more evident the higher the inspiratory pressure was selected. Inspiratory pressure of 40 cm. of water delivered by low flow rates led to a decrease in minute volumes, eventually bordering hypoventilation in spite of largely increased tidal volumes. Minute volumes closely matching ventilation requirements at rest were met with low to medium range pressure and flow rate setting of the respirator.

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