Technical Note

Mechanical Ventilation of Infants:

Significance and Elimination of Ventilator Compression Volume

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Compression volume of the Emerson Postoperative Ventilator was determined at two different ventilator phasing characteristics, both by plugging the apparatus outflow orifice and by ventilation of a model lung-thorax system. The results of the two methods were similar and indicated a compression volume of 2.8 ml./cm. water for this ventilator when the humidifier was 60 per cent filled, as it commonly is used clinically. The presence of such a large compression volume is undesirable when this adult-type ventilator is used for infants and small children or for investigations of certain physiologic respiratory parameters during mechanical ventilation. A modified apparatus was constructed with negligible compression volume.

When any intermittent positive-pressure breathing device is used to ventilate a patient, gas is compressed within the volume of the apparatus to a degree dependent upon the inflation pressure developed within the total system. The larger the volume of the apparatus between the flow generator and the patient's airway, the greater will be the volume of gas compressed within this apparatus for a given inflation pressure. Of the total amount of gas developed by the ventilator during each inflation phase, the fraction compressed within the apparatus is not a part of the patient's tidal ventilation. Okmian[1] emphasized the importance of this fact early in his series of investigations involving the use of the Engstrom ventilator with newborn and small infants.

Most commonly used intermittent positive-pressure ventilators are constructed to expel totally from the system, during the expiratory phase, all gas generated during the inspiratory phase of each cycle. These are basically nonrebreathing devices which require no additional mechanisms for eliminating expired carbon dioxide. Therefore, gas expelled from the exhalation orifice with each breath includes not only the expired tidal volume but also gas compressed within the apparatus distal to the inspiratory check valve.

Critical evaluations are essential when mechanical ventilators designed primarily for adult patients are adapted for use with infants and small children. To determine the effects of mechanical ventilation on the physiologic deadspace and V_D/V_T ratio of the anesthetized, paralyzed infant,[2] using the Emerson Postoperative Ventilator ‡ as a constant-volume, piston-driven, intermittent gas flow generator, we found it necessary to construct a modified apparatus with negligible compression volume in order to collect from the exhalation orifice only the tidal volume from the infant without dilution by compression volume gas from the apparatus.

This report provides data on compression volume for the original and modified designs of the Emerson Ventilator and discusses the implications of ventilator compression volume when positive-pressure devices are used, either clinically for respiratory support or for investigations of certain physiologic respiratory parameters.

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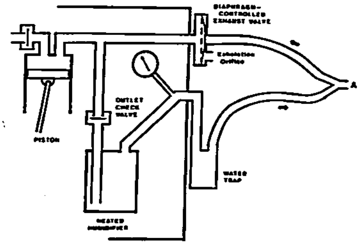

FIG. 1. Emerson Postoperative Ventilator design. Total compression volume space distal to outlet check valve (humidifier empty; Tygon delivery tubings to Y-connector: I.D. ¾ inch, length 4 feet) = 5,500 ml. Volume of components external to cabinet = 1,350 ml.

Methods

Compliance of the lungs plus chest wall (total respiratory compliance) can be simulated in the laboratory by using a rigid container of suitable capactiy. Although elastic forces are not involved, a definite increment of gas volume will enter the container when a definite increment of pressure is applied. For purposes of laboratory studies, the slope of volume increments plotted against pressure increments can be considered as the effective "compliance" of the rigid container; this "compliance" is proportional to the volume of the container.

For this study, a model lung-thorax system with a total capacity of 3,950 ml. was constructed, using a two-way stopcock and a tightly sealed glass bottle container. With a simple Boyle's Law calculation, which assumes that the conditions of gas compression are isothermal, the effective "compliance" of this model lung was 3.8 ml./cm. water. In general, however, when gas is compressed its temperature is raised, unless the compression occurs very slowly, allowing the heat developed to dissipate through the walls of the container. If no heat is lost from the gas during compression, the compression is said to be adiabatic. Hill and Moore[3] have demonstrated that at ventilator rates greater than four per minute, conditions of compression are within five per cent of adiabatic in an artificial lung-thorax similar to that used in this study. Under adiabatic conditions, during intermittent positive-pressure compression within the container at rates greater than four per minute, the effective "compliance" of the model was calculated to be about 2.8 ml./cm. water. This value approximates the total respiratory compliance determined for infants under similar conditions of mechanical ventilation.[4, 5]

Pressure changes within the model lung were measured from a separate orifice by a Statham model PR23 pressure transducer and the output was recorded on a Grass model 5A polygraph.

Room air, as generated by the Emerson Ventilator piston stroke, was used as the ventilating gas (relative humidity = 50 per cent). Expiratory gas was collected directly from the exhalation orifice of the expiratory valve in a low-inertia water spirometer of one-liter capacity. Volume measurements per inflation were determined from the average of five successive ventilator cycles, after each collected volume (ATPS) had been corrected for 50 per cent saturation with water vapor.

Two methods were used for determining the compression volumes of both the original Emerson Ventilator apparatus and the modified apparatus. The first method involved collecting gas expelled from the system during ventilation of the model lung-thorax. Ventilator settings were adjusted for each series of measurements to provide an inspiratory-to-expiratory ratio of 1:1 at 30 cycles per minute, or an I:E ratio of 1.5:1.8 at 18 cycles per minute.

The delivered volume from the piston was regulated for each cycling rate and I:E ratio to achieve a peak inspiratory pressure within the model lung of 26 to 30 cm. water. The tidal volume of the simulated lung-thorax system, *i.e.*, that part of the gas generated per cycle which actually "ventilated" the model, was calculated by the adiabatic gas compression formula,[1]

$$V_T = V_D\left\{\left(1 + \frac{p}{P_B}\right)^{1/H} - 1\right\}$$

where: V_T = gas compressed in model lung ("tidal vol.," ml.).

V_D = capacity of model lung (ml.).

p = peak inflation pressure (cm. H_2O).
P_B = atmospheric pressure (cm. H_2O).
H = 1.4 (the ratio of the specific heats of air at constant pressure and at constant volume).

The compression volume (V_{T_C}) of the apparatus used for mechanical ventilation is the difference between the average gas volume per inflation collected in the spirometer and the V_T calculated for the model lung during each series of measurements.

The second method for determining compression volume involved plugging the Y-connector orifice which connects to the patient's airway (at "A" in figs. 1 and 2), then setting the piston stroke to compress gas within the apparatus volume itself to a pressure of about 27 to 30 cm. water. The gas compressed during five successive cycles was collected in the spirometer from the exhalation orifice, and volume corrections made as before. These values should approximate those obtained during ventilation of the model lung if all the mechanical factors of ventilator function remain nearly the same during complete obstruction to the outflow of inflation gas from the apparatus as during simulated ventilation of a patient.

Results

Original Emerson Ventilator Design

The design of the Emerson ventilator is shown schematically in figure 1. The outlet check valve ("inspiratory valve") is located within the ventilator cabinet proximal to the humidifier, and the diaphragm-controlled exhaust valve ("expiratory valve") is attached to the front of the cabinet. Each of these valves permits the gas generated by the piston stroke to flow in one direction only. The piston-cylinder employed in this study was the smaller of the two available, having a maximum stroke volume of about 400 ml. All of the tubing used in the apparatus was Tygon, which can be considered non-distensible except at high pressures, thereby providing an apparatus volume which remained fixed over the pressure range used in this study.

TABLE 1. Original Emerson Ventilator Design

	Ventilator Characteristics	Inflation Pressure (cm. H_2O)	Avg. Spirom. Vols./Cycle (ml.)	Calc. V_T of Model Lung (ml.)	Compression Vol. (V_{T_c}) of Apparatus (ml.)	Compression Vol. (V_{T_c}) of Apparatus (ml./cm. H_2O)	Piston Stroke Volume Scale (ml.)
Ventilation of model lung-thorax system	Humidifier—Empty I:E = 1:1 Rate = 30/min.	(1) 30	198	83	115	3.8	140
		(2) 30	201	83	118	3.9	140
		(3) 30	201	83	118	3.9	140
	Humidifier—1,700 ml. water I:E = 1:1 Rate = 30/min.	(1) 30	163	83	80	2.7	125–130
		(2) 30	169	83	86	2.9	125–130
	I:E—1.5:1.8 Rate = 18/min.	(1) 26	147	71	76	2.8	125–130
Ventilation of apparatus with patient-connection orifice plugged	Humidifier—Empty I:E = 1:1 Rate = 30/min.	(1) 27	104		104	3.9	105
		(2) 27	105		105	3.9	105
		(3) 27	105		105	3.9	105
	Humidifier—1,700 ml. water I:E = 1.5:1.8 Rate = 18/min.	(1) 26	65		65	2.5	70–75
		(2) 26	69		69	2.7	70–75

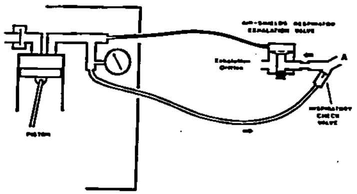

FIG. 2. Modified ventilator design. Compression volume space between inspiratory and expiratory valves = 45 ml. Inspiratory delivery tubing is Tygon, I.D. ¼ inch, length 4 feet.

The results obtained during ventilation of the model lung-thorax system, with the humidifier either empty or about 60 per cent filled and at one or two cycling characteristics of rate and phase, are presented in table 1. A second or third measurement was made for each set of conditions except in one instance. Tidal ventilations of the model lung (V_T) were calculated by the formula for an atmospheric pressure of 1,020 cm. water. Compression volume (V_{T_C}), representing gas compressed within the apparatus which did not ventilate the model lung, is expressed both as the average measured volume per cycle (ml.) and as the volume in ml./cm. water pressure.

The compression volume measurements determined by plugging the patient-connection orifice of the Y-connector are presented in table 1. Here, the average volumes collected per cycle are equivalent to the compression volume of the apparatus. It is apparent from the similarity of these two sets of results for V_{T_C} in ml./cm. water that either method of measurement provides a reasonable estimation of the ventilator apparatus compression volume.

Direct water-displacement measurement of the components external to the cabinet indicated their volume to be 1,350 ml. By using the compression volume values determined in this study, the total apparatus volume distal to the outlet check valve was calculated by the formula to be about 5,500 ml. when the humidifier was empty and about 3,800 ml. after 1,700 ml. of water was added to the humidifier. By subtraction, the apparatus volume within the cabinet, distal to the outlet check valve, was about 4,150 ml. with the humidifier empty and about 2,450 ml. when the humidifier was approximately 60 per cent filled. Gas compressed within this total apparatus volume during inflation is prevented by the outlet check valve from returning to the piston chamber as the piston descends, and this gas must be expelled, together with the patient's tidal volume, out the exhalation orifice.

Modified Ventilator Design

The modified design, developed to reduce the magnitude of the compression volume, is shown schematically in figure 2. The same-sized piston was utilized as in the original. The remaining cabinet components were bypassed. An inspiratory valve was specially constructed within one arm of the patient Y-connector, and an Air Shields Respirator expiration valve was connected to the other arm of the Y-connector. By placing both valves close to the patient's airway, the space available for gas compression between the valves was reduced to 45 ml. Gas compression which occurred in the 400-ml. apparatus volume proximal to the inspiratory check valve returned to the piston chamber as the piston descended.

A humidifier was not incorporated in the modified apparatus because supplemental humidification of respired gases is a poorly controlled variable and is not required for physiologic studies of short duration.

The results obtained during ventilation of the model lung-thorax system, and those obtained when the Y-connector orifice was plugged, are shown in table 2. These data indicate that the compression volume of the modified design was negligible, and the gas expelled from the exhalation orifice represented only the expired tidal ventilation of the model lung without dilution by gas compressed within the apparatus.

Discussion

When adult-type mechanical ventilators are used to provide the small tidal volumes for infants and small children, or when positive-pressure breathing devices are used during certain studies of physiologic respiratory parameters, the significance of the apparatus compression volume is exaggerated and must not be overlooked. Okmian,[7] in studying the applications of the Engstrom Ventilator for newborns and small infants, constructed a nomogram to determine the compression volume of this ventilator at various inflation pressures and total apparatus volumes. By measuring with a spirometer the total gas expelled from the system each minute, he used the nomogram to determine the infant's minute ventilation.

Several problems in the original design of the Emerson Ventilator are similar to those of the Engstrom Ventilator, when used for infants and small children. Because of the large compression volume, the scale which indicates the delivered piston volume is not accurate for determining a desired tidal ventilation; nor does the volume measurement of gas expelled from the exhalation orifice represent a reliable estimation of the patient's tidal or minute ventilation. With the humidifier about 60 per cent filled, as commonly used, the compression volume of the Emerson Ventilator is about 2.8 ml./cm. water. This volume is almost equal to that which ventilates the infant. As water evaporates from the humidifier during use, the compression volume becomes even greater, reaching about 3.9 ml./cm. water when the humidifier is empty. In order to maintain a constant airway pressure and tidal ventilation over prolonged periods, either the piston stroke volume must be increased frequently or the water level of the humidifier must be kept near the starting level.

Furthermore, the addition of a considerable amount of compression volume gas to the patient's exhaled gas makes this arrangement unsuitable for physiologic studies which require the collection of pure tidal-volume gas from the patient.

The primary modification of the original Emerson Ventilator design was the reduction of the intrinsic volume of the apparatus in order to reduce the magnitude of the compression volume. This was accomplished by moving the valves close to the patient's airway and by eliminating the heated humidifier and large-bore delivery tubings from the system.

With this modification, the compression volume distal to the inspiratory check valve is negligible, and the gas expelled from the system after each inflation represents only the expired tidal volume from the model lung or patient. The compression volume gas proximal to the inspiratory valve is drawn back into the cylinder during the downward stroke of the piston.

A second aim of the modified design was to construct a system in which the delivered piston volume, as shown on the indicator scale, closely approximated the actual tidal volume of the model lung. The results indicate that this aim also has been achieved to a reasonable degree.

TABLE 2. Modified Ventilator Design

	Ventilator Characteristics	Inflation Pressure (cm. H_2O)	Avg. Spirom. Vols./Cycle (ml.)	Calc. V_T of Model Lung (ml.)	Compression Vol. (V_{Tc}) of Apparatus		Piston Stroke Volume Scale (ml.)
					(ml.)	(ml./cm. H_2O)	
Ventilation of model lung-thorax system	I:E = 1:1	(1) 30	84	83	Negligible	Negligible	75–80
	Rate = 30/min.	(2) 30	82	83	Negligible	Negligible	
		(3) 30	83	83	Negligible	Negligible	
	I:E = 1.5:1.8	(1) 29	81	80	Negligible	Negligible	80
	Rate = 18/min.	(2) 28	80	78	Negligible	Negligible	80
		(3) 28	79	78	Negligible	Negligible	80
Ventilation of apparatus with patient-connection orifice plugged	I:E = 1:1	(1) 70	0.9		Negligible	Negligible	55
	Rate = 30/min.	(2) 30	Negligible		Negligible	Negligible	25

In conditions where humidification of the inspired gas is desired for prolonged mechanical ventilation, a nebulizer or humidifier must be incorporated into the modified arrangement. Repeat measurements of the compression volume of the apparatus would be necessary if the adaptation were made distal to the inspiratory valve.

Summary

Measurements by two different techniques indicate that the Emerson Postoperative Ventilator, as it is commonly used, has a compression volume of about 3.9 ml./cm. water with the humidifier empty and about 2.8 ml./cm. water with the humidifier 60 per cent filled.

A compression volume of such magnitude makes this ventilator inaccurate for pre-setting a desired tidal volume by the piston stroke-volume scale or for determining tidal volume by spirometric measurement of gas expelled from the exhalation orifice, especially when this ventilator is used with infants or small children. This design also is unsuitable for certain respiratory studies which require the collection of pure exhaled tidal volume gas undiluted by compression volume gas.

A modified apparatus design with negligible compression volume is presented and discussed.

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Drugs

BARBITURATE AND ANTICOAGULANT The effects of pentobarbital and barbital upon pharmacologic activity of dicumarol were evaluated in rats. Groups treated with dicumarol plus barbiturates had shorter mean prothrombin times and lower incidences of hemorrhage than the group treated with dicumarol alone. Barbiturates exerted a protective action against even a toxic dose of dicumarol. The mean sleeping time of groups treated with pentobarbital alone was not significantly different from that of groups treated with pentobarbital plus dicumarol. These findings contrast with those of other authors who have found barbiturates to enhance the hypcprothrombinemic action of a similar indirect-acting anticoagulant, Danilone. (*Lucas, O. N.: Study of the Interaction of Barbiturates and Dicumarol and Their Effect on Prothrombin Activity, Hemorrhage, and Sleeping Time in Rats, Canad. J. Physiol. Pharmacol. 45: 905 (Sept.) 1967.*)