# United States Patent [19]

**Bell**

[11] **3,729,000**

[45] **Apr. 24, 1973**


[54] **COMPLIANCE COMPENSATED VENTILATION SYSTEM**


[75] Inventor: **Steven A. Bell,** Santa Monica, Calif.

[73] Assignee: **Puritan-Bennett Corporation,** Kansas City, Mo.



[22] Filed: **May 18, 1971**

[21] Appl. No.: **144,521**

[52] **U.S. Cl.**.....**128/145.6,** 417/274

[51] **Int. Cl.**.....**A62b 7/00**

[58] **Field of Search**.....128/145.5, 145.6, 128/145.7, 145.8, 188, 2.08; 417/274, 4, 14, 12, 302; 60/52



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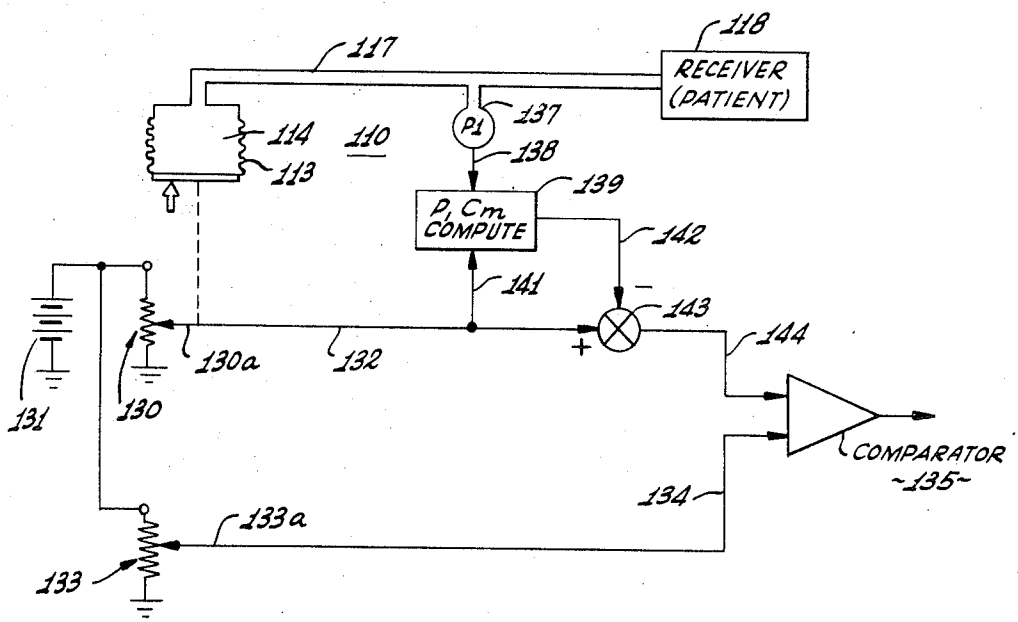
*Primary Examiner*—Richard A. Gaudet
*Assistant Examiner*—G. F. Dunne
*Attorney*—Fulwider, Patton, Rieber, Lee & Utecht



[57] **ABSTRACT**

A method and apparatus for maintaining the volume of gas delivered to a patient by a volume-limited ventilator substantially constant, regardless of changes in the delivery pressure which induce corresponding changes in the compression of the gas and the size of various machine elements in the delivery system such as the delivery tubing and the ventilator bellows. The delivery pressure to the patient is monitored and is used to compute, together with ventilator machine compliance, a compliance compensation volume, i.e., the volume trapped within the machine dead space, which is first subtracted from the measured delivery volume prior to comparison of the latter with a reference proportional to desired delivery volume, to effect ventilator machine control for terminating further volume delivery.


**17 Claims, 4 Drawing Figures**



PATENTED APR 24 1973

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SHEET 1 OF 2

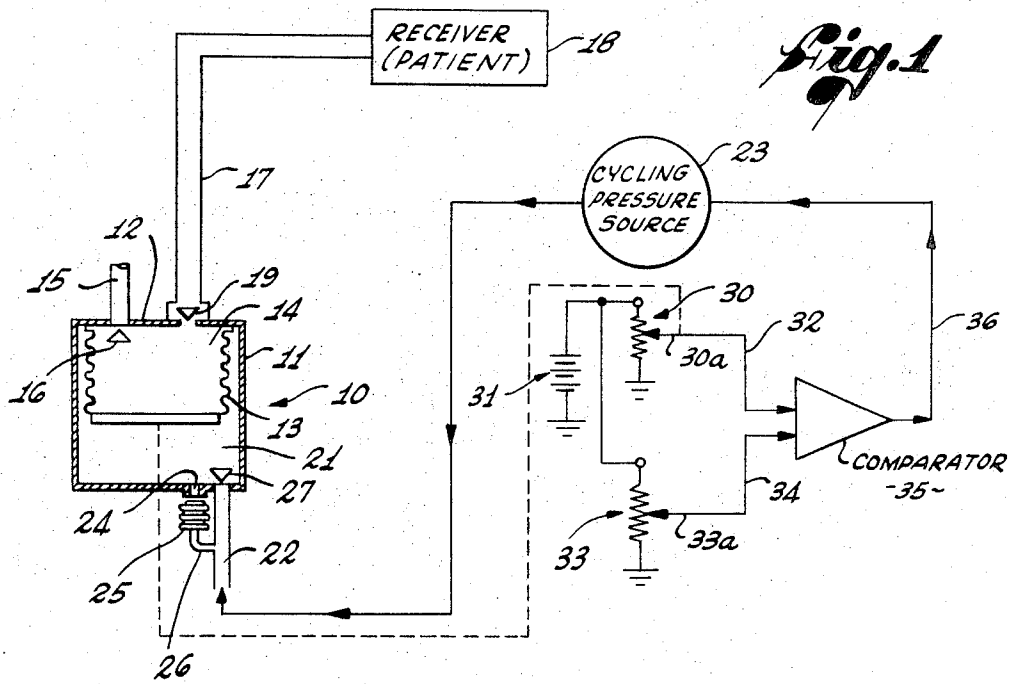



Fig. 1

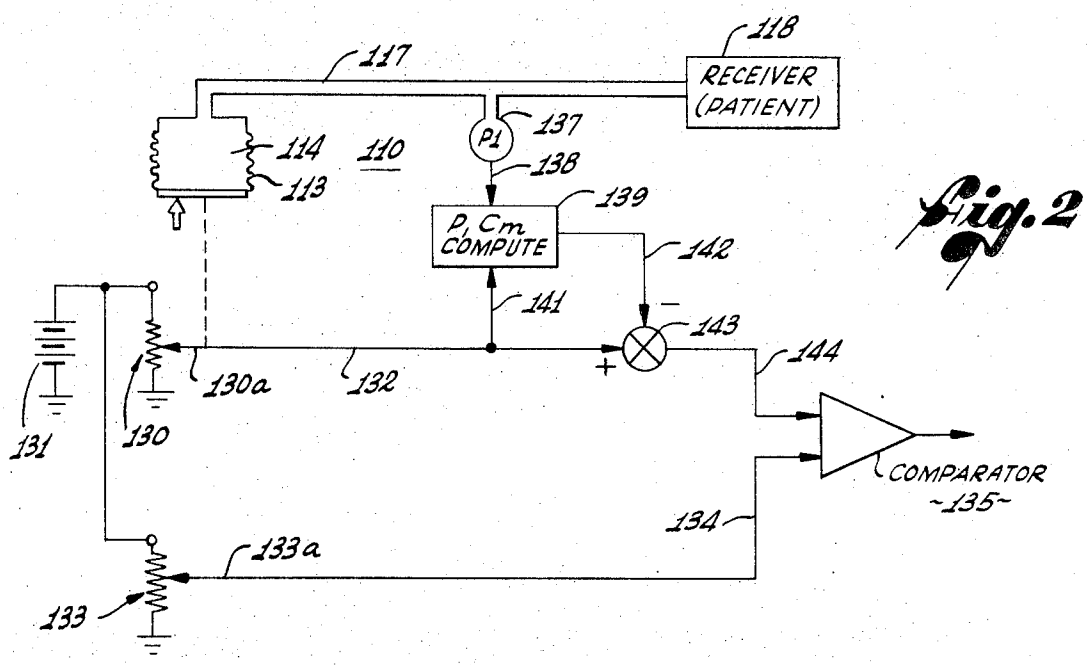



Fig. 2

INVENTOR.
STEVEN A. BELL
BY Fulwider, Patton, Rieber, Lee, and Utecht
ATTORNEYS

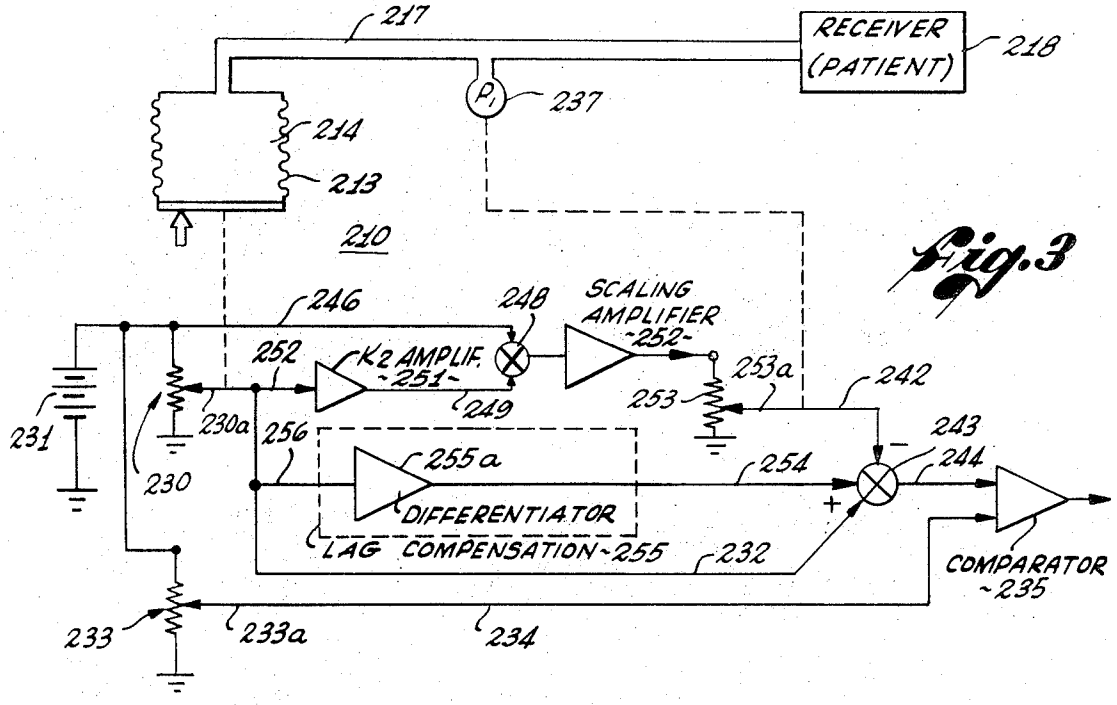



Fig. 3

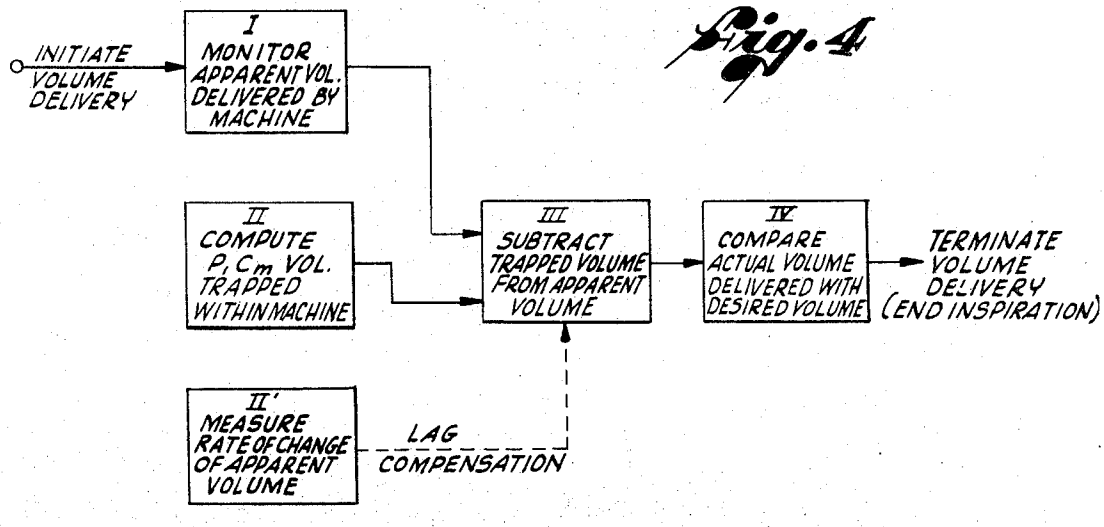



Fig. 4

INVENTOR.
STEVEN A. BELL
BY Fulwider, Patton, Rieber, Lee, and Utecht
ATTORNEYS

# COMPLIANCE COMPENSATED VENTILATION SYSTEM

## BACKGROUND OF THE INVENTION

This invention relates generally to respiration systems and, more particularly, to improvements in volume-limited ventilators wherein a measured volume of gas is delivered to a patient in administering intermittent positive pressure breathing therapy and the like.

Respiration apparatus used in administering intermittent positive pressure breathing therapy and related applications is well known in the art, and it is common practice to measure at the respirator the volume of air or other gas to be delivered to the patient. However, where the delivery pressure changes, due to a change in the patient's condition or an obstruction in the delivery system, the tidal volume delivered to the patient does not remain constant, unless it is adjusted for such pressure changes. This occurs because of compression or expansion of the gas in the delivery system as well as change in the size of the delivery system components. For example, a common value for the tubing compliance of the delivery system is 5 c.c. per centimeter of water change in pressure. Thus, if the ventilator machine is set to deliver 200 c.c. of air or gas to the patient while the pressure in the delivery tubing system is 10 cm $H_2O$, the patient actually receives 200 c.c. less 50 c.c., or only 150 c.c. of gas. Moreover, should the patient's condition change so that 20 cm $H_2O$ pressure are required in the delivery system, the patient would then receive a volume of 200 c.c. less 100 c.c. or only 100 c.c. of gas. Such changes in patient tidal volume can result in relatively rapid and substantial abnormalities in a patient's blood chemistry.

It will be apparent, therefore, that some of the difficult problems confronting medical personnel in administering respiration therapy have been those of accurately and reliably compensating for changes in tidal volume due to ventilator machine compliance and variations in delivery pressure. In this regard, various mechanical expedients have been developed for introducing approximate corrections to offset tidal volume errors caused by changes in delivery pressure. However, such compensation systems have not been entirely satisfactory under all operating conditions.

Hence, those concerned with the development and use of volume-limited ventilator equipment have recognized the need for relatively simple, reliable and accurate machine compliance compensation for such ventilation systems. The present invention fulfills this need.

## SUMMARY OF THE INVENTION

Briefly, and in general terms, the present invention provides a new and improved method and apparatus for compliance compensation in a volume ventilation system, wherein the delivery pressure and apparent volume delivered by the ventilator machine are both monitored, the apparent volume being subsequently modified by the computed value of the volume trapped within the machine dead space, to determine the actual volume delivered to the patient, this actual volume being compared with a preselected desired volume to determine when volume delivery by the machine is to be terminated. Hence, the present invention enables anticipation of and compensation for tidal volume errors due to machine compliance and changes in delivery pressure, and automatically and continuously corrects the output of the volume ventilator so as to maintain constant volume delivery to the patient under all conditions.



In a presently preferred embodiment, by way of example, a volume generator in any suitable form, such as a collapsible bellows or a movable piston, displaces an appropriate gas, such as air, for delivery to a patient. The gas displaced by the volume generator is continuously monitored to provide instantaneous data regarding apparent volume delivered by the ventilator machine. The delivery pressure ($P_1$) is also monitored and is multiplied by a separately computed factor representing total machine compliance ($C_m$) to arrive at a value of the volume at any instant trapped within the dead space of the machine. This trapped volume is subtracted from the previously monitored apparent volume to arrive at the actual volume of gas delivered by the machine to the patient. The latter value of actual volume is compared with a preselected value of desired volume to be delivered and, when the two volume values are equal, volume delivery and the inspiration cycle are terminated, as by generation of an "end inspiration" signal.

The value of machine compliance used in the computation of volume trapped within the machine may be constant or, in the case of a system having components where compliance varies as a function of delivered volume, a more complex function of machine compliance may be specially generated for purposes of providing accurate dead space volume determinations.

In addition, "lag compensation" may be derived from the rate of change of the apparent volume value to modify the actual volume prior to comparison of the latter with the preselected desired volume, so that any errors due to time delay from the initiation of the "end inspiration" signal to the actual cessation of gas flow are corrected.

The new and improved compliance compensated ventilation system of the present invention is extremely accurate and reliable in maintaining constant tidal volume exchange is patients undergoing respiration therapy and satisfies a real need in the art for such a system.

The above and other objects and advantages of the invention will become apparent from the following more detailed description, when taken in conjunction with the accompanying drawings of illustrative embodiments.

## DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a typical volume-limited ventilator without compliance compensation;

FIG. 2 illustrates one embodiment of a volume-limited ventilator apparatus embodying features of the present invention;

FIG. 3 illustrates another embodiment of a volume-limited ventilator apparatus embodying the present invention; and

FIG. 4 is a flow diagram illustrating the steps in the new and improved method of the present invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

One example of a volume ventilator machine of the type to which the present invention may be applied is diagramatically illustrated in FIG. 1 of the drawings. The ventilator machine is shown in its simplest form and, for more detailed descriptions of the overall operation of such systems, reference is made, by way of example, to U.S. Pat. Nos. 3,221,734; 3,368,555 and 3,385,295, which explain in detail the operation of various respirators and ventilators and their physiological effects, and which are incorporated by reference in this application by way of general background, but are not required for an understanding of the present invention.

As shown in FIG. 1, a ventilator **10** comprises a closed, outer housing **11** in which a collapsible bellows **13** has its upper open end sealed to the interior surface of the uppermost wall **12** of the housing. The interior of the bellows **13**, together with the wall **12** of the housing **11**, defines a chamber **14** provided with a gas supply conduit **15** adapted to be selectively closed by an outwardly operating check valve **16**. As pointed out in the aforementioned patents, the conduit **15** may deliver air, air enriched with oxygen, or such gases with vaporized or nebulized medication. The chamber **14** also connects to a delivery system represented schematically by tubing **17** leading to a receiver **18** establishing fluid communication between the ventilator and a patient's respiratory system by any device known in the respiration art including, without limitation, face masks and mouthpieces. Reverse flow from the tubing **17** is prevented by a downwardly operating check valve **19**.

A chamber **21** beneath the bellows **13** is periodically and cylically pressurized through an appropriate operating pressure supply conduit **22** connecting the chamber **21** to a cycling pressure source **23** of well-known construction.

The chamber **21** is provided with a vent **24** to atmosphere under the control of a conventional bellows valve **25** connected by a conduit **26** to the supply conduit **22**, so that the vent **24** closes upon the application of pressure from the source **23** into the conduit **22** and opens when this operating pressure is released. Reverse flow from the chamber **21** into conduit **22** is prevented by a downwardly operating check valve **27**.

Any desired volume-limiting means may be used to control the volume delivered by the ventilator **10**. By way of example, the base of the bellows **13** is mechanically coupled in any suitable manner to the slider arm **30a** of a potentiometer **30** across which a reference voltage from a power supply **31** has been applied. Since the physical travel of the bellows **13** along its axis within the housing **11** is directly proportional to the amount of gas displaced from the chamber **14**, the mechanical position of the slider arm **30*a*** and, hence, the electrical potential on line **32** is likewise proportional to the amount of gas displaced, or apparent volume delivered by the ventilator. The same reference voltage is also applied across a second potentiometer **33** having a slider arm **33a** which is selectively adjusted by the operator in accordance with the desired volume to be delivered, and provides a corresponding output potential proportional to this preselected delivery volume on line **34**. The electrical signals proportional to apparent volume and desired volume are directed over lines **32, 34**, respectively, as a pair of electrical inputs to an electrical comparator **35** of well-known design. When the input voltages to the comparator **35** are equal, the comparator produces an "end inspiration" signal over line **36** to the cycling pressure source **23** which, in turn, causes removal of operating pressure from the ventilator **10** and, therefore, terminates further gas delivery to the patient.

While a bellows **13** is illustrated in FIG. 1 as the volume generator for the ventilator **10**, it will be apparent that any other form of volume generator well-known in the art, such as a moving piston or the like, may be employed to displace gas for purposes of delivery to a patient, without altering the basic operation of the system shown in FIG. 1.

However, the system shown in FIG. 1 depends for its successful operation upon precise correlation between the apparent volume delivered, as measured by the travel of the bellows **13**, and the actual volume delivered to the patient, and no compensation is provided for those errors caused by machine compliance and changes in delivery pressure which may introduce substantial differences between the apparent volume delivered and the actual tidal volume for the patient. Hence, selection of a desired volume, via adjustment of the potentiometer **33** by an operator, is not necessarily an accurate measure of the volume actually delivered by the ventilator to the patient under all conditions of operation.

Referring now more particularly to FIG. 2 of the drawings, there is shown a compliance compensated ventilation system characterized by increased accuracy and reliability in maintaining constant tidal volume for a patient. In the embodiment of the ventilation system illustrated in FIG. 2, reference numerals **110** through **135** designate elements corresponding to those indicated by the reference numerals **10** through **35**, respectively, in the system of FIG. 1. In this regard, it will be understood that the volume generator **113**, while shown for purposes of illustration as a collapsible bellows, may take the form of any suitable volume generating apparatus known in the art.

In the system of FIG. 2, the pressure $P_1$ in the delivery system, between the volume generator **113** and the patient, is monitored by an appropriate pressure transducer **137**, and the output of the transducer is directed over line **138** to any suitable network **139** for computing the dead space volume trapped within the ventilator machine **110**. The dead space volume within the machine is equal to the algebraic product of the delivery pressure $P_1$ multiplied by the total machine compliance $C_m$.

If the ventilation machine **110** is of a type wherein machine compliance can be considered constant, regardless of the delivered volume, then the $P_1C_m$ compute network **139** may be simply a fixed gain amplifier. On the other hand, if the machine compliance varies with the volume displaced by the volume generator, then a more complex function of the machine compliance must first be generated prior to multiplication by the delivery pressure. This is indicated schematically by an electrical input to the compute network **139** over line **141**, the latter being connected to the potentiome-

ter tap **130***a* and, therefore, providing an input proportional to apparent volume delivered.

An electrical signal representing the compliance compensation volume $P_1C_m$ is fed over line **142** as negative input to a summing junction **143** which simultaneously receives as positive input over line **132** an electrical signal representing the apparent volume delivered. The electrical output from the summing junction **143** represents the actual compensated volume delivered and is directed over line **144**, as one input to the comparator **135**, the other input to the comparator over line **134** being the preselected value of desired volume to be delivered to the patient. Hence, the compliance compensated ventilation system of FIG. **2** automatically and continuously corrects the output of the ventilator machine **110** so as to maintain constant volume delivery to the patient under all conditions and avoid the problems of undesired change in tidal volume.

In the embodiment of the invention shown in FIG. **3**, a ventilator compensation system is shown which illustrates one example of typical subsystems for computing compliance compensation volume $P_1C_m$, as well as providing appropriate lag compensation to minimize any errors due to the time delay between the initiation of the "end inspiration" signal and the actual cessation of gas displacement by the volume generator. The reference numerals **210** through **244** in FIG. **3** designate elements corresponding to those designated by the reference numerals **110–144**, respectively, in the embodiment of the invention shown in FIG. **2**.

It can be shown that total machine compliance $C_m$ may be expressed as follows:

$$C_t + C_{vg} = C_m$$

where:

$C_t$ is the compliance of the delivery tubing; and

$C_{vg}$ is the compliance of the volume generator.

It can also be shown that the compliance $C_t$ is, for all practical purposes, substantially constant over the range of operating pressures and volumes encountered by the typical volume ventilator machine, whereas the compliance $C_{vg}$ may vary as a function of volume, as in the case where a bellows or piston is the volume generator. As a result, the total machine compliance $C_m$ may be expressed as:

$$C_m = K_1 - K_2V$$

where:

$K_1$ is a constant representing delivery tubing compliance $C_t$; and

$K_2$ is a constant multiplying apparent volume $V$ to obtain volume generator compliance $C_{vg}$.

Referring again to FIG. **3**, the full reference potential from the supply **231** is directed over line **246** as one input to a summing junction **248**, the latter input being constant and representing the $K_1$ tubing compliance constant. A second input to the summing junction **248** is received over line **249** which is the output of an amplifier **251** having a gain equal to the constant $K_2$ and receiving as electrical input a signal over line **252** representing the apparent volume V delivered by the volume generator **213**. Hence, the output from the summing junction **248** is a voltage proportional to the computed value of total machine compliance $C_m$ in accordance with the previously described mathematical relationships. This latter voltage is directed as input to a conventional scaling amplifier **252**, the output voltage from this amplifier being applied across a potentiometer **253**.

The potentiometer **253** includes a slider arm **253a** having its mechanical position continuously adjusted by the output of pressure transducer **237**, to provide an electrical output over line **242** representing the compliance compensation volume $P_1C_m$. The latter signal representing compensation volume is directed to the negative input of the summing junction **243**. The positive input of the summing junction **243** receives a signal over line **232** representing the apparent volume delivered and also receives at the positive input a signal over line **254** from a lag compensation network **255** responsive to rate of change of volume.

The lag compensation network **255** may take any form well-known in the control systems art and typically includes a differentiator **255***a* receiving as input over line **256** the signal from the potentiometer slider **230***a* representing apparent volume delivered. Hence, the signal to the summing junction **243** over line **254** is a function of the rate of change of the apparent volume delivered and, therefore, provides an output signal over line **244** to the comparator **245** which is already compensated for the anticipated time delay between the initiation of the "end inspiration" signal by the comparator and the actual cessation of gas flow induced by the volume generator **213**.

While the embodiments of the invention shown in FIGS. **2** and **3** illustrate two basic systems for electromechanically compensating a volume ventilation system, it will be appreciated that any equivalent electrical, pneumatic, hydraulic, or other means known in the art may be substituted for the monitoring and computing subsystems shown in FIGS. **2** and **3** without in any way departing from the present invention. In this connection, the method of the present invention embodied by the apparatus of FIGS. **2** and **3** is illustrated by the flow chart shown in FIG. **4** which sets forth the various steps in the compensation process.

After volume delivery has been initiated, step I in FIG. **4** involves the process of monitoring the apparent volume delivered by the ventilator machine. Step II of the compensation method involves the process of computing the dead space volume $P_1C_m$ trapped within the ventilator machine. In step III, the trapped volume is subtracted from the apparent volume delivered by the machine to obtain the actual volume delivered which, in step IV, is continuously compared with the preselected desired volume to be delivered to the patient and, when the two volumes are equal, volume delivery is terminated, typically by generation of an "end inspiration" signal.

If desired, an additional step II′ may be included wherein the rate of change of the apparent volume delivered is measured and is used to compute a lag compensation factor which is added to the computation of actual volume in step III to compensate for anticipated time delay errors.

The method and apparatus of the present invention provides an extremely accurate and reliable means for compensating volume-limited ventilation systems so that constant tidal volume exchange is maintained in patients undergoing respiration therapy, regardless of changes in the patient's condition and in the delivery pressure of the ventilation system.

It will be apparent from the foregoing that, while particular forms of the invention have been illustrated and described, various modifications can be made without departing from the spirit and scope of the invention. Accordingly, it is not intended that the invention be limited except as by the appended claims.

I claim:

1. A method of compliance compensation for a volume-limited ventilator, comprising the steps of:
monitoring the apparent volume delivered by the ventilator;
monitoring the pressure in the delivery system of the ventilator;
electronically computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance of the ventilator; and
electronically subtracting said compensation volume from said apparent volume to determine the actual volume delivered by the ventilator.

2. A method of compliance compensation for a volume-limited ventilator, comprising the steps of:
monitoring the apparent volume delivered by the ventilator;
monitoring the pressure in the delivery system of the ventilator;
computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance of the ventilator;
subtracting said compensation volume from said apparent volume to determine the actual volume delivered by the ventilator;
measuring the rate of change of said apparent volume to determine a lag compensation factor as a function of said rate of change; and
adding said lag compensation factor in the determination of said actual volume.

3. A method of compliance compensation as set forth in claim 2, wherein said step of computing a compensation volume includes determining said machine compliance $C_m$ in accordance with the relationship:

$C_m = K_1 - K_2 V$

where $K_1$ and $K_2$ are selected constants and $V$ is said apparent volume.

4. A method of preserving substantially constant tidal volume exchange using a volume-limited ventilator, comprising the steps of:
initiating volume delivery by the ventilator;
continuously measuring the apparent volume of gas delivered by the ventilator;
continuously measuring the pressure in the delivery system of the ventilator;
continuously computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance of the ventilator;
continuously subtracting said compensation volume from said apparent volume to determine the actual volume delivered by the ventilator;
continuously monitoring said actual volume; and
terminating volume delivery by the ventilator when said actual volume equals a preselected desired volume.

5. A method of compliance compensation for a volume-limited ventilator, comprising the steps of:
monitoring the apparent volume delivered by the ventilator;
monitoring the pressure in the delivery system of the ventilator;
determining total machine compliance $C_m$ of the ventilator in accordance with the relationship:

$C_m = K_1 - K_2 V$

where $K_1$ and $K_2$ are constants and V is said apparent volume;
computing a compensation volume determined by the algebraic product of said pressure and said total machine compliance of the ventilator; and
subtracting said compensation volume from said apparent volume to determine the actual volume delivered by the ventilator.

6. A method of preserving substantially constant tidal volume exchange using a volume-limited ventilator, comprising the steps of:
initiating volume delivery by the ventilator;
continuously measuring the apparent volume of gas delivered by the ventilator;
continuously measuring the pressure in the delivery system of the ventilator;
determining total machine compliance $C_m$ of the ventilator in accordance with the relationship:

$C_m = K_1 - K_2 V$

where $K_1$ and $K_2$ are predetermined constants and $V$ is said apparent volume;
continuously computing a compensation volume determined by the algebraic product of said pressure and said total machine compliance of the ventilator;
continuously subtracting said compensation volume from said apparent volume to determine the actual volume delivered by the ventilator;
continuously monitoring said actual volume; and
terminating volume delivery by the ventilator when said actual volume equals a preselected desired volume.

7. A method of preserving substantially constant tidal volume exchange using a volume-limited ventilator, comprising the steps of:
initiating volume delivery by the ventilator;
continuously measuring the apparent volume of gas delivered by the ventilator;
continuously measuring the pressure in the delivery system of the ventilator;
continuously computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance of the ventilator;
continuously subtracting said compensation volume from said apparent volume to determine the actual volume delivered by the ventilator;
continuously measuring the rate of change of said apparent volume to determine a lag compensation factor as a function of said rate of change;
continuously adding said lag compensation factor in the determination of said actual volume;
continuously monitoring said actual volume; and
terminating volume delivery by the ventilator when said actual volume equals a preselected desired volume.

8. A method as set forth in claim 7, wherein said step of computing a compensation volume includes determining said machine compliance $C_m$ in accordance with the relationship:

$C_m = K_1 - K_2 V$

where $K_1$ and $K_2$ are predetermined constants and $V$ is said apparent volume.

9. A compliance compensated ventilation system for delivering gas to a receiver, comprising:

a volume generator for displacing a gas to be delivered to the receiver;

conduit means for defining a fluid path between said volume generator and the receiver;

means for continuously monitoring the apparent volume delivered by said volume generator;

means for continuously monitoring the delivery pressure in said conduit means;

means for computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance of the ventilation system including said volume generator and said conduit means;

means for subtracting said compensation volume from said apparent volume to determine the actual volume delivered to the receiver;

means for selecting a desired volume to be delivered to the receiver; and

means for terminating further displacement of gas by said volume generator upon said actual volume becoming equal to said desired volume.

10. A compliance compensated ventilation system as set forth in claim 9, wherein said means for terminating displacement of gas includes a comparator for comparing said actual volume with said desired volume.

11. A compliance compensated ventilation system for delivering gas to a receiver, comprising:

a volume generator for displacing a gas to be delivered to the receiver;

conduit means for defining a fluid path between said volume generator and the receiver;

means for continuously monitoring the apparent volume delivered by said volume generator;

means for continuously monitoring the delivery pressure in said conduit means;

means for computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance $C_m$ of the ventilation system including said volume generator and said conduit means, said total machine compliance $C_m$ being determined in accordance with the relationship:

$C_m = K_1 - K_2V$

where $K_1$ and $K_2$ are constants and V is said apparent volume;

means for subtracting said compensation volume from said apparent volume to determine the actual volume delivered to the receiver;

means for selecting a desired volume to be delivered to the receiver; and

means for terminating further displacement of gas by said volume generator upon said actual volume becoming equal to said desired volume.

12. A system as set forth in claim 11, wherein said means for calculating machine compliance $C_m$ includes:

electrical means for providing a constant electrical signal at the value $K_1$;

amplifier means having a gain $K_2$ for receiving as electrical input a signal representing said apparent volume $V$ and providing an output signal representing $K_2V$; and

summing means for combining said $K_1$ signal and said $K_2V$ signal to provide an output signal representing machine compliance $C_m$.

13. A compliance compensated ventilation system for delivering gas to a receiver, comprising:

a volume generator for displacing a gas to be delivered to the receiver;

conduit means for defining a fluid path between said volume generator and the receiver;

means for continuously monitoring the apparent volume delivered by said volume generator;

means for continuously monitoring the delivery pressure in said conduit means;

means for computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance of the ventilation system including said volume generator and said conduit means;

means for subtracting said compensation volume from said apparent volume to determine the actual volume delivered to the receiver;

means for continuously measuring the rate of change of said apparent volume to determine a lag compensation factor as a function of said rate of change;

means for adding said lag compensation factor to said actual volume prior to comparing said actual volume with said desired volume;

means for selecting a desired volume to be delivered to the receiver; and

means for terminating further displacement of gas by said volume generator upon said actual volume becoming equal to said desired volume.

14. A system as set forth in claim 13, wherein said means for continuously measuring the rate of change of said apparent volume includes a differentiator.

15. A compliance compensated ventilation system for delivering gas to a receiver, comprising:

a volume generator for displacing a gas to be delivered to the receiver;

fluid conduit means providing a fluid path between said volume generator and the receiver;

means for continuously monitoring the apparent volume delivered by said volume generator and generating a signal representing said apparent volume V;

means for continuously monitoring the delivery pressure in said conduit means;

means for continuously computing a compensation volume determined by the algebraic product of said pressure and the total machine compliance $C_m$ of the ventilation system including said volume generator and said conduit means, the value of $C_m$ being determined in accordance with the relationship:

$C_m = K_1 - K_2V$

where $K_1$ and $K_2$ are predetermined constants;

means for measuring the rate of change of said apparent volume V to determine a lag compensation factor as a function of said rate of change;

means for subtracting said compensation volume from said apparent volume and adding said lag compensation factor to determine the actual volume delivered to the receiver;

means for selecting a desired volume to be delivered to the receiver; and

comparator means for comparing said actual volume and said desired volume, said comparator means being adapted to terminate further displacement of gas by said volume generator upon said actual volume becoming equal to said desired volume.

**16**. A system as set forth in claim **15**, wherein said means for continuously computing includes:

means for providing a constant signal at the value $K_1$;

amplifier means having a gain $K_2$ for receiving as input said signal representing said apparent volume $V$ and providing an output signal representing $K_2V$; and

summing means for combining said $K_1$ signal and said $K_2V$ signal to provide an output signal representing machine compliance $C_m$.

**17**. A system as set forth in claim **16**, wherein said means for measuring the rate of change of said apparent volume includes differentiation means.

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