

[54] COMPLIANCE COMPENSATED
VENTILATION SYSTEM

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128/145.8, 188, 2.08; 417/274, 4, 14, 12,
302; 60/52; 73/194 E

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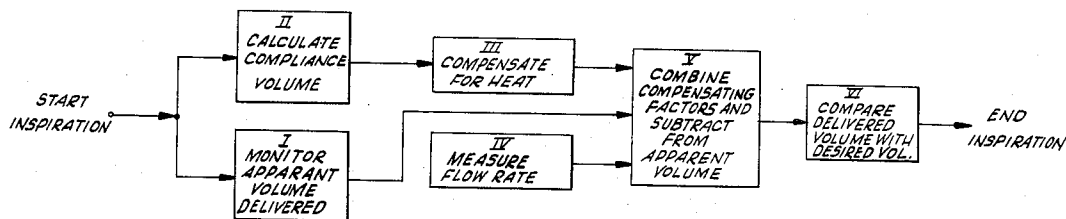
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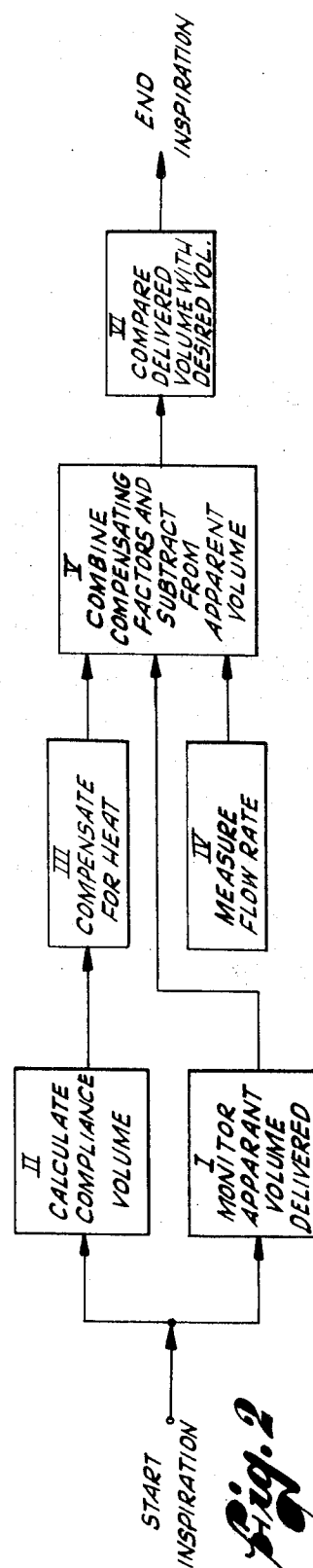
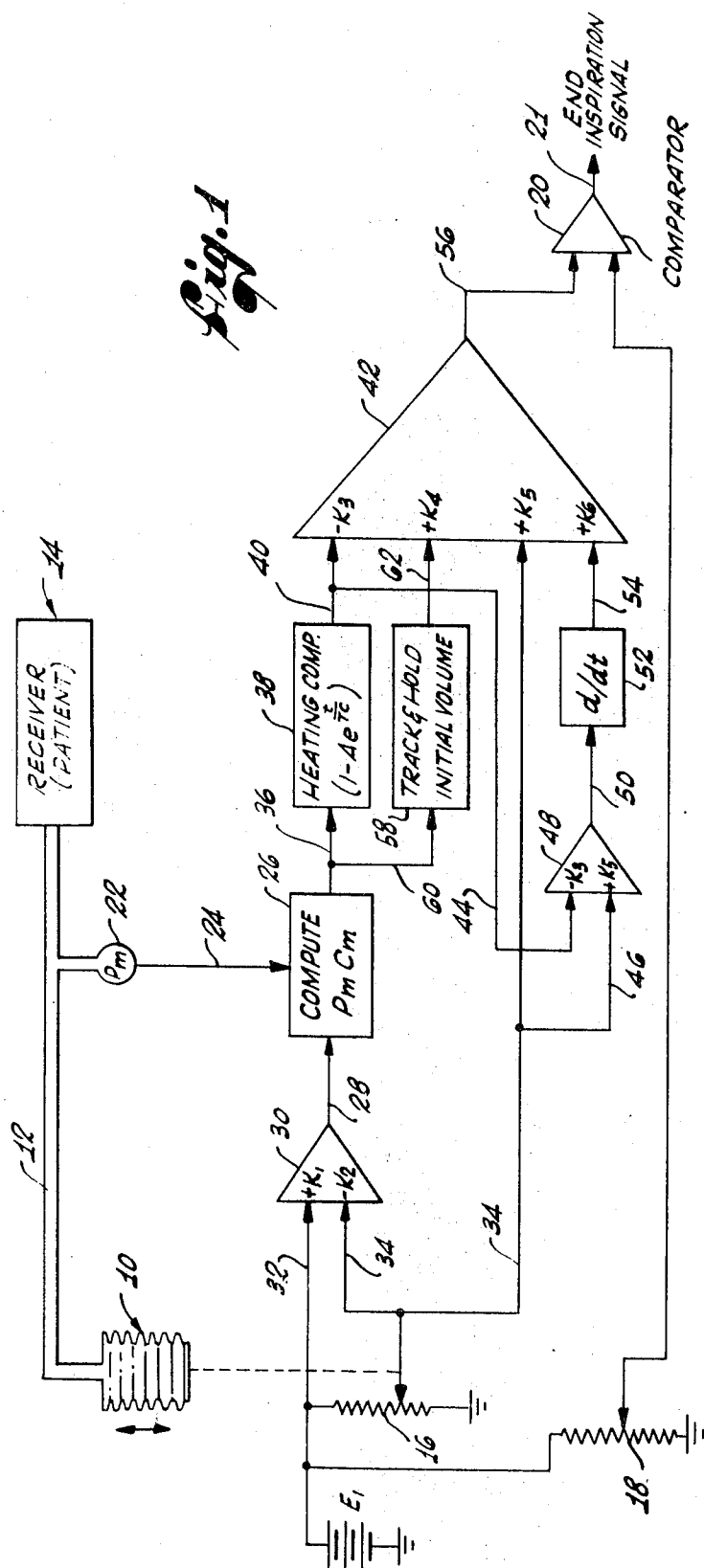
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[57] **ABSTRACT**

Method and apparatus for maintaining a substantially constant volume of gas flow to a patient, particularly an infant, with a volume-limited ventilation system, regardless of changes in the pressure and compliance of the delivery system or patient. The delivery pressure is monitored and combined with corrective factors derived from compliance changes in the system, gas heating under pressure, initial gas pressure, and gas overflow due to inherent system delays. The combined corrections are used to compute a compliance-compensation volume which is the volume of gas trapped within the gas delivery system. The compliance compensation volume is subtracted from the apparent volume of gas delivered to the system to determine the volume of gas actually delivered to a patient. The delivered volume is then compared with a desired reference volume and is terminated when they are equal.

10 Claims, 2 Drawing Figures





COMPLIANCE COMPENSATED VENTILATION SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates generally to respiration systems and, more particularly, to volume-limited ventilators wherein a measured volume of gas is delivered to a patient during each inhalation of a positive pressure breathing system.

Respiration apparatus for positive-pressure breathing therapy and related applications is well known in the art, and it is common practice to determine the volume of gas actually delivered to a patient by making measurements within the respirator. However, when there are changes in the patient's condition or in the system compliance itself, the gas volume reaching the patient does not remain constant. This is due mainly to pressure differences between the patient and the system. As the elimination of carbon dioxide is very dependent on tidal volume, such changes in the volume of gas delivered to the patient can result in rapid abnormalities in a patient's blood chemistry.

Various attempts have been made to introduce corrections to offset such tidal volume changes, and these attempts have proven very satisfactory for ventilators used with adult patients. However, even greater accuracy is desirable in making corrections for infant ventilators. This is because of the relatively low tidal volumes of such infants, compared to the compliance volume of the ventilating machine itself.

Thus, those concerned with the development of volume-limited ventilation equipment, particularly for use with infants, have recognized the need for an improved compliance compensating technique with enhanced reliability and sensitivity, particularly for use on infant ventilators. The present invention fulfills this need.

SUMMARY OF THE INVENTION

The present invention provides a new and improved method and apparatus for compliance compensation in a volume-limited ventilation system, wherein a number of factors influencing changes in tidal volume are monitored and correction signals generated and combined to calculate a compliance compensation volume. The compliance compensation volume is then subtracted from the apparent volume delivered by the ventilator to determine the actual gas volume delivered to a patient. Heretofore unconsidered factors, such as the effects of gas heating during pressurization, are incorporated into the corrections to enable the calculation of actual delivered gas volume to substantially improved accuracy and reliability. Such accuracy permits maintaining the relatively low tidal volume of infants substantially constant.

In a presently preferred embodiment of the invention, the apparent volume of gas from a suitable volume generator is continuously monitored, together with the delivery system pressure. The delivery system pressure is multiplied by a separately computed factor representing total machine compliance, the product representing an intermediate compliance volume. The intermediate compliance volume is further modified to account for the effects of gas heating due to rapid pressurization. The result is the compliance compensation volume representing the volume of gas trapped in the

system, and is subtracted from the apparent volume to arrive at the actual gas volume delivered to a patient. This delivered gas volume is compared to a preselected desired gas volume and, when the two quantities are equal, gas delivery is terminated.

In addition to delivery system pressure changes, the volume of delivered gas is influenced by the positive or negative pressure existing in the system during the expiration phase, e.g. when a "Positive End-Expiratory Pressure" technique is employed. The initial remaining compliance volume is therefore tracked during expiration, and its value at the onset of inspiration is held and added to the correction of the delivered volume.

Further, because the gas shut-off devices normally exhibit a time delay in their operation, gas delivery may not cease immediately when an "end inspiration" signal is generated. Therefore a separate, flow-dependent correction signal is generated to effectively cause the generation of the "end inspiration" signal at an earlier time.

In the presently preferred embodiment of the invention, machine compliance is dependent upon the delivered volume. In the case of an infant respirator, this factor must be included in the calculation of machine compliance.

Thus the method and apparatus of the present invention provide a compensated compliance system of enhanced accuracy and reliability in maintaining substantially constant tidal flows, particularly when, such as in the case of infants, the tidal flow is relatively small compared to the machine compliance.

DESCRIPTION OF THE DRAWING

FIG. 1 is a combined diagrammatic and electrical block diagram illustrating the invention; and

FIG. 2 is a flow diagram illustrating the steps of the new and improved method of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The operation of the invention is illustrated by FIG. 1 of the drawing. The method and apparatus of the invention are basically designed for use with a volume-limited respiration machine which is only briefly and schematically illustrated in FIG. 2. A more detailed description of the operation of such respiration machines is amply described in the literature and particularly in U.S. Pats. Nos. 3,221,734; 3,368,555 and 3,385,295, which are incorporated by reference in this application as background information, but are not required for an understanding of the invention.

As shown in FIG. 1, a volume-limited respirator includes a gas volume generator which may be in the form of a bellows 10, but is not limited to that configuration. The forced collapse of the bellows 10 delivers contained gas to a gas delivery system 12, represented schematically by a tube. The gas is delivered to a receiver 14, such as a patient, by any well known device used in the respiration art, such as face masks, mouth pieces, and the like.

Basically, such respiration systems operate in two phases or cycles, an inspiration phase in which gas is delivered to the patient under positive pressure, and an expiration phase in which gas delivery is terminated and the patient allowed to exhale the gases by the collapse of his lungs. It is basically the inspiration phase with which the present invention is concerned, so the

expiration apparatus is not illustrated. Additionally, it is assumed that the delivery system 12 is equipped with the other necessary equipment of typical respirators, such as check valves and the like, which are not illustrated.

The operation of the system typically proceeds as follows: The bellows 10 is filled with a suitable gas by auxiliary apparatus (not shown), and when the inspiration phase begins, the bellows 10 is forced to collapse to drive the contained gas through the delivery system 12 and into the receiver 14. Mechanically linked to the bellows 10 is a suitable position transducer, such as a potentiometer 16, connected across a voltage source E_1 . A wiper contact 17 of the potentiometer 16 follows the movement of the bellows 10 and, therefore, a voltage-analog of the volume of gas forced out of the bellows appears on the wiper contact. A second potentiometer 18, also connected across the voltage source E_1 , is manually adjustable to set a reference voltage on its wiper contact 19. Heretofore, the bellows volume voltage was simply compared to the reference voltage by some means, such as a conventional comparator 20, and when the voltages were equal, the comparator generated an "end inspiration" signal which was used to terminate the movement of the bellows 10 and start the expiration cycle.

It will be appreciated that the actual volume of gas delivered to a patient can differ radically from the apparent volume delivered to the delivery system 12, as measured by the movement of the bellows 10. Particularly, changes in the compliance of the delivery system 12, i.e., in the capacity of the system 12 to accept the gases delivered by the bellows 10, and the differential pressures between the patient and the delivery system 12, can result in a serious decrease in the actual volume of gas delivered to a patient. Generally, without compensation, the relationship between the desired gas volume as set on reference potentiometer 18 is true only for one set of conditions.

For example, for an adult, the desired gas volume may be 400-600 ml of gas, while the system may retain only 100 ml at the end of the inspiration cycle. Changes in the actual delivered volume for such conditions are relatively easy to detect. For an infant, however, the desired gas volume may be only 10-30 ml, and the changes in the respirator delivery system 12 under such conditions become very difficult to detect.

In the compliance compensation system of the present invention, a number of corrective factors are combined to calculate with greater accuracy the compliance volume, or gas remaining in the delivery system 12, in order to accurately determine the actual gas volume delivered to the patient. Generally, the compliance volume of the delivery system 12 is given by the algebraic product of the delivery system pressure P_m and the total machine compliance C_m . The system pressure P_m is monitored by a suitable pressure transducer 22 in the delivery system 12 and the generated pressure signal is fed over a line 24 to one input of a conventional electrical network 26 which calculates $P_m C_m$, the term C_m being available as a second input to the network on a line 28.

For some operating conditions, such as when an adult is being ventilated, the total machine compliance C_m may be treated as a constant; the error introduced by changing bellows compliance may be considered negligible. But when an infant is being ventilated, the ma-

chine compliance, C_m , must be calculated as accurately as possible, and the bellows compliance is then significant. Thus the total machine compliance is a constant K_1 minus a second term dependent on apparent bellow compliance change $K_2 V_a$ or:

$$C_m = K_1 - K_2 V_a$$

It should be appreciated that the actual constant values are dependent on the type of ventilator being used and are empirically derived.

The total machine compliance (C_m) signal is derived from a summing amplifier 30 with a constant voltage from voltage source E_1 applied to one input line 32 with a multiplication factor of K_1 , and the apparent volume signal V_a from potentiometer 16 applied to a second input line 34 with a multiplication factor of $-K_2$.

It has been found that, for the relatively low volumes of air delivered to an infant, a significant error is introduced when the delivery system 12 is rapidly pressurized, e.g. during high flow. The gas is heated by the pressurization, further increasing the indicated pressure and erroneously increasing the calculated total volume of gas in the delivery system 12. However, following initial heating, the gas cools, and for slow pressurization, e.g. low flow conditions, the heating error is negligible. Therefore, the cooling of the gas, an exponential function, is included in the calculation of the heating error factor.

It is known that the pressure overshoot due to heating follows the exponential function

$$A_0 e^{-\frac{t}{T_0}}$$

where:

A_0 is an empirical constant dependent upon the gas and its container

t is time in seconds, and

T_0 is the thermal time constant of the machine-enclosed gas, and is dependent on the gas and delivery system characteristics.

The intermediate calculated compliance volume $P_m C_m$ available on the line 36 is corrected for the thermal pressure increase by multiplying the term by:

$$1 - A_0 e^{-\frac{t}{T_0}}$$

which lowers the calculated compliance volume by the amount of thermal pressure increase, so that the volume of the delivered, cooled gas will be substantially correct.

In the presently preferred embodiment of the invention, the intermediate compliance volume $P_m C_m$ is on a line 36 which is fed to a suitable conventional network 38 for multiplying $P_m C_m$ by the heating compensation factor. The output of network 38 is then the heat compensated compliance volume and is fed through a line 40 to a first input of a summing amplifier 42 with an empirically derived multiplying factor $-K_3$. The compensated compliance is normally subtracted from the apparent volume signal connected through line 34 to a second input to the summing amplifier 42 with an empirically derived multiplying factor of $+K_5$ to generate a signal indicative of the delivered gas volume.

However, a further error which has to be corrected results when the desired volume is reached and the inspiration cycle is completed. The pneumatic and electrically operated valves on the respirator cannot close instantaneously in response to the "end inspiration" signal on line 21. Therefore, an unwanted additional

volume of gas will be delivered to the patient. The amount of additional gas is dependent upon the rate of flow of the gas out of the system. This additional gas is prevented from reaching the patient by adding to the calculated amount of gas a signal proportional to the calculated rate of flow of gas out of the system. The "end inspiration" signal is then generated slightly earlier in time and the total volume of delivered gas is that desired.

In the illustrated implementation of the invention the compensating factor for flow rate is derived by first independently calculating an approximation to delivered gas volume by subtracting the heat compensated compliance volume signal on line 40 from the apparent volume on line 34 from the bellows potentiometer 16. These two signals are fed on lines 44 and 46, respectively, to the inputs of a summing amplifier 48 which have multiplication factors $-K_3$ and K_5 , respectively.

The resulting approximate-delivered-volume signal is connected through a line 50 to a conventional differentiator 52, and the generated flow rate signal is connected through a line 54 to a third input to the summing amplifier 42 with a derived multiplying factor of $+K_6$.

Under some conditions the system pressure P_m may remain above atmospheric pressure at the end of the expiration phase, and an erroneous compliance volume signal will be fed to the summing amplifier 42. As an example, in some respirator applications, a technique known as "Positive End-Expiratory Pressure" or "PEEP" is used. In this technique, the patient's expiration is intentionally stopped at above atmospheric pressure. To correct this error, a conventional track-and-hold network 58 is connected through a line 60 to the intermediate compliance volume signal on line 24. The network 58 tracks the intermediate compliance volume during the expiration phase and then holds that value as an initial compliance volume error during the inspiration phase. The held compliance signal is connected through a line 62 to a fourth input to the summing amplifier 42 with a multiplication factor of K_4 to correct the generated delivered volume signal. Thus, the delivered volume will be correctly calculated from an initial compliance volume starting point of zero, independent of initial pressure at the onset of the inspiration phase.

The summation of the heat- and compliance-compensated volume signal on line 40, the apparent volume signal on line 34, the flow rate signal on line 54 and the held compliance signal on line 62 in summing amplifier 42 results in an output signal on line 56 indicative of the delivered gas volume to the patient. This signal serves as a first input to the comparator 20, the second input being the desired volume signal. When the two are equal, the comparator 20 generates the "end inspiration" signal on line 21 to end the inspiration phase and begin the expiration phase.

FIG. 2 illustrates the method of the invention. Following the start of inspiration, a first step is to monitor the apparent volume delivered by the bellows. The second step is to calculate the intermediate compliance volume, followed by the third step of compensating the intermediate compliance volume for heat. Concurrently, the fourth step of measuring the flow rate can be performed.

In the fifth step, the compensating factors are combined into a compensated compliance volume, and the

result subtracted from the apparent volume to obtain the actual delivered volume to the patient. In the sixth step, the delivered volume is compared with a pre-selected desired volume, and when the two are equal, and "end inspiration" signal is generated to terminate the inspiration phase and begin the expiration phase.

Thus, the method and apparatus of the present invention provide a substantially reliable and accurate means for compensating volume-limited ventilation systems, particularly such systems designed for ventilating infants. The invention compensates for changes in patient and system changes to deliver a substantially constant volume of gas to a patient.

It will be appreciated that while a specific, presently preferred embodiment of the invention has been described in detail, 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 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 delivery system pressure of the ventilator;
 - computing an intermediate compliance volume determined by the algebraic product of said system pressure and a total machine compliance of the ventilator;
 - deriving a time-decreasing compensation factor dependent upon the substantially transient heating of said gas due to rapid system pressurization;
 - multiplying said intermediate compliance volume by said time-decreasing compensation factor to produce a compensated compliance volume; and
 - subtracting said compensated compliance volume from said apparent volume to determine the actual delivered volume of said ventilator.
2. A method of compliance compensation as defined in claim 1, and further including the steps of
 - independently subtracting said compensated compliance volume from said apparent volume to determine independently an approximation to said actual delivered volume;
 - differentiating said independently determined approximate delivered volume to determine the flow rate of said approximate delivered volume; and
 - using said flow rate to correct said actual delivered volume.
3. A method of compliance compensation as defined in claim 1, including the steps of:
 - comparing said actual delivered volume with a predetermined desired volume; and
 - terminating volume delivery when said delivered volume equal said desired volume.
4. The compliance compensation system of claim 1, including:
 - means for comparing said actual delivered volume with a predetermined desired volume; and
 - terminating volume delivery when said delivered volume equals said 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 delivery system pressure of the ventilator;
 computing an intermediate compliance volume determined by the algebraic product of said system pressure and a total machine compliance of the ventilator;
 compensating said intermediate compliance volume for the heating of said gas under said system pressure by multiplying said intermediate compliance volume by the factor

$$1 - A_e \frac{t}{T_c}$$

where

A is an empirically derived constant for each ventilator,

t is the time, and

T_c is the thermal cooling time constant of the gas in the ventilator

the result being a compensated compliance volume; and

subtracting said compensated compliance volume from said apparent volume to determine the actual delivered volume of said ventilator.

6. A method of compliance compensation as defined in claim 5, and further including the steps of:

independently subtracting said compensated compliance volume from said apparent volume to determine independently an approximation to said actual delivered volume;

differentiating said independently determined approximately delivered volume to determine the flow rate of said approximate delivered volume; and

using said flow rate to correct said actual delivered volume.

7. A compliance compensation system for a volume-limited ventilator comprising:

means for monitoring an apparent volume delivered by the ventilator;

means for monitoring delivery system pressure of the ventilator;

means for computing an intermediate compliance volume determined by the algebraic product of said system pressure and a total machine compliance of the ventilator;

means for deriving a time-decreasing compensation factor dependent upon the substantially transient heating of said gas due to rapid system pressurization;

means for multiplying said intermediate compliance volume by said time-decreasing compensation factor to produce a compensated compliance volume; and

means for subtracting said compensated compliance volume from said apparent volume to determine the actual delivered volume of said ventilator.

8. The compliance compensation system of claim 7 including:

means for independently subtracting said compensated compliance volume from said apparent volume to independently determine an approximation to said actual delivered volume;

means for differentiating said independently determined approximate delivered volume to determine the flow rate of said approximate delivered volume; and

means for using said flow rate to correct said actual delivered volume.

9. A compliance compensation system for a volume limited ventilator comprising:

means for monitoring an apparent volume delivered by the ventilator;

means for monitoring delivery system pressure of the ventilator;

means for computing an intermediate compliance volume determined by the algebraic product of said system pressure and a total machine compliance of the ventilator;

means for compensating said intermediate compliance volume for the heating of said gas under said system pressure by multiplying said intermediate compliance volume by the factor

$$1 - A_e \frac{t}{T_c}$$

where

A is an empirically derived constant for each ventilator,

t is the time, and

T_c is the thermal cooling time constant of the gas in the ventilator

the result being a compensated compliance volume;

means for subtracting said compensated compliance volume from said apparent volume to determine the actual delivered volume of said ventilator;

means for independently subtracting said compensated compliance volume from said apparent volume to independently determine an approximation to said actual delivered volume;

means for independently subtracting said compensated compliance volume from said apparent volume to independently determine an approximation to said actual delivered volume;

means for differentiating said independently determined approximate delivered volume to determine the flow rate of said approximate delivered volume; and

means for using said flow rate to correct said actual delivered volume;

10. The compliance compensation system of claim 9 including:

means for comparing said actual delivered volume with a predetermined desired volume; and terminating volume delivery when said delivery volume equals said desired volume.

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