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Orr et al.

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(54) **METHODS FOR ACCURATELY, SUBSTANTIALLY NONINVASIVELY DETERMINING PULMONARY CAPILLARY BLOOD FLOW, CARDIAC OUTPUT, AND MIXED VENOUS CARBON DIOXIDE CONTENT**

(75) Inventors: **Joseph A. Orr**, Park City, UT (US); **Kai Kück**, Hamburg (DE)

(73) Assignee: **Ric Investments, Inc.**, Wilmington, DE (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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Related U.S. Application Data

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(51) **Int. Cl.**
A61B 5/00 (2006.01)

(52) **U.S. Cl.** **600/532**; 73/23.3; 422/84

(58) **Field of Classification Search** 600/529–538, 600/504, 525; 73/23.3; 422/84
See application file for complete search history.

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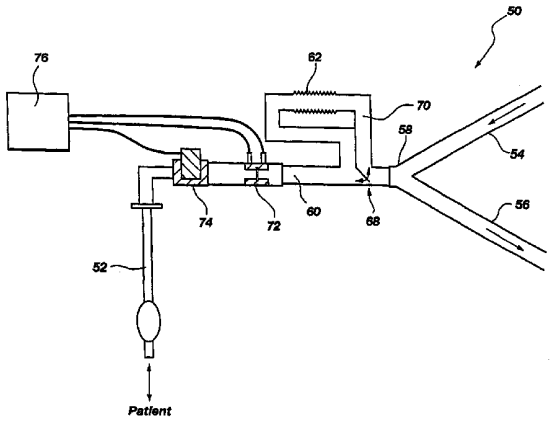
Primary Examiner—Robert L. Nasser
(74) *Attorney, Agent, or Firm*—Trask Britt

(57) **ABSTRACT**

A method for noninvasively determining the pulmonary capillary blood flow or cardiac output of a patient includes measurement of respiratory flow and carbon dioxide pressure of the patient's breathing. These measurements are used to calculate carbon dioxide elimination and an indicator of the carbon dioxide content of the patient's blood. A geometric relationship between the carbon dioxide elimination data and the data of the indicator of carbon dioxide content is determined. At least one set of the data is modified and at least one other determination of a geometric relationship between the data is made to find the most accurate data set. The data may be modified by filtering or clustering. A slope of at least a portion of the geometric relationship is then used to determine the pulmonary capillary blood flow or cardiac output of the patient.

28 Claims, 6 Drawing Sheets



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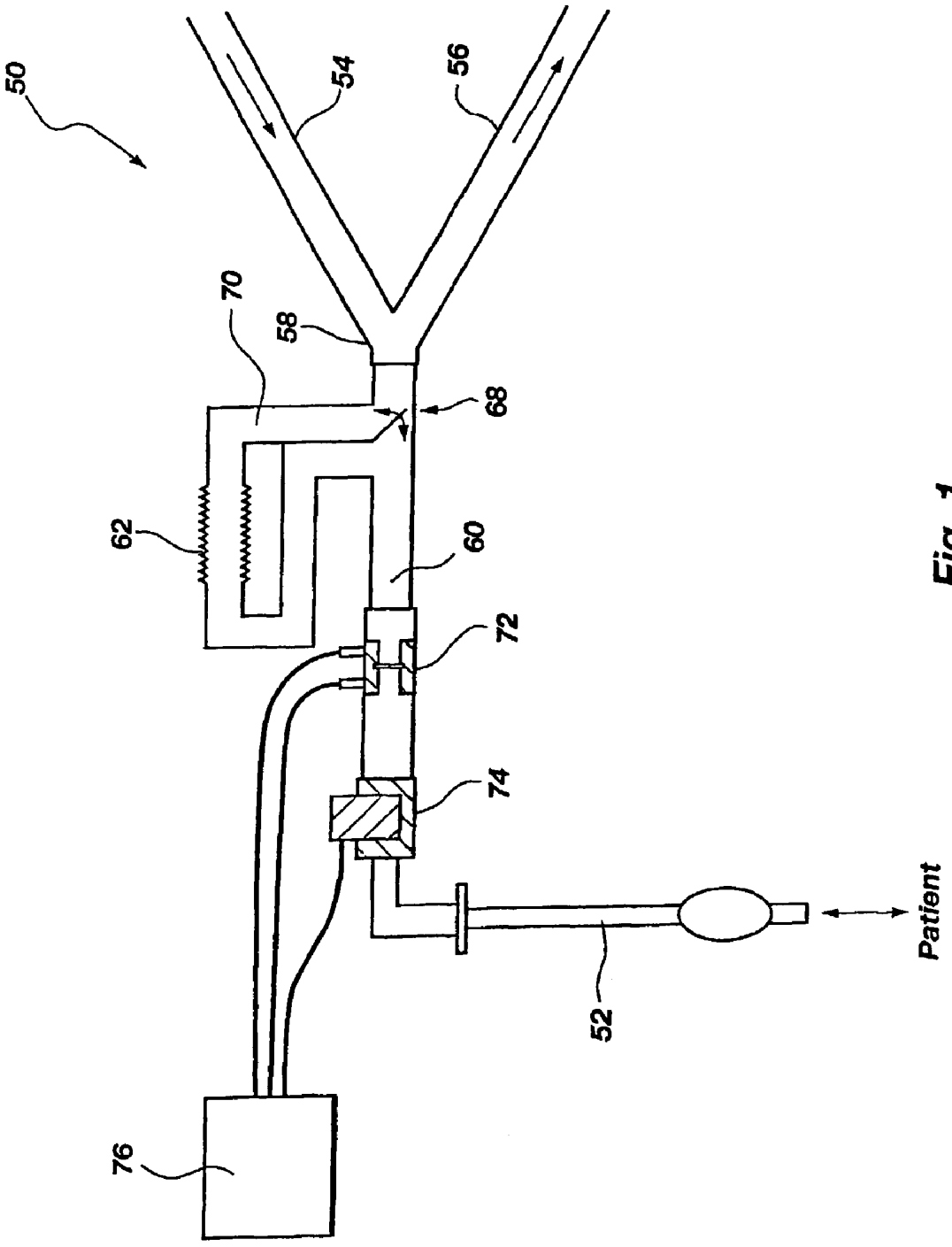

Fig. 1

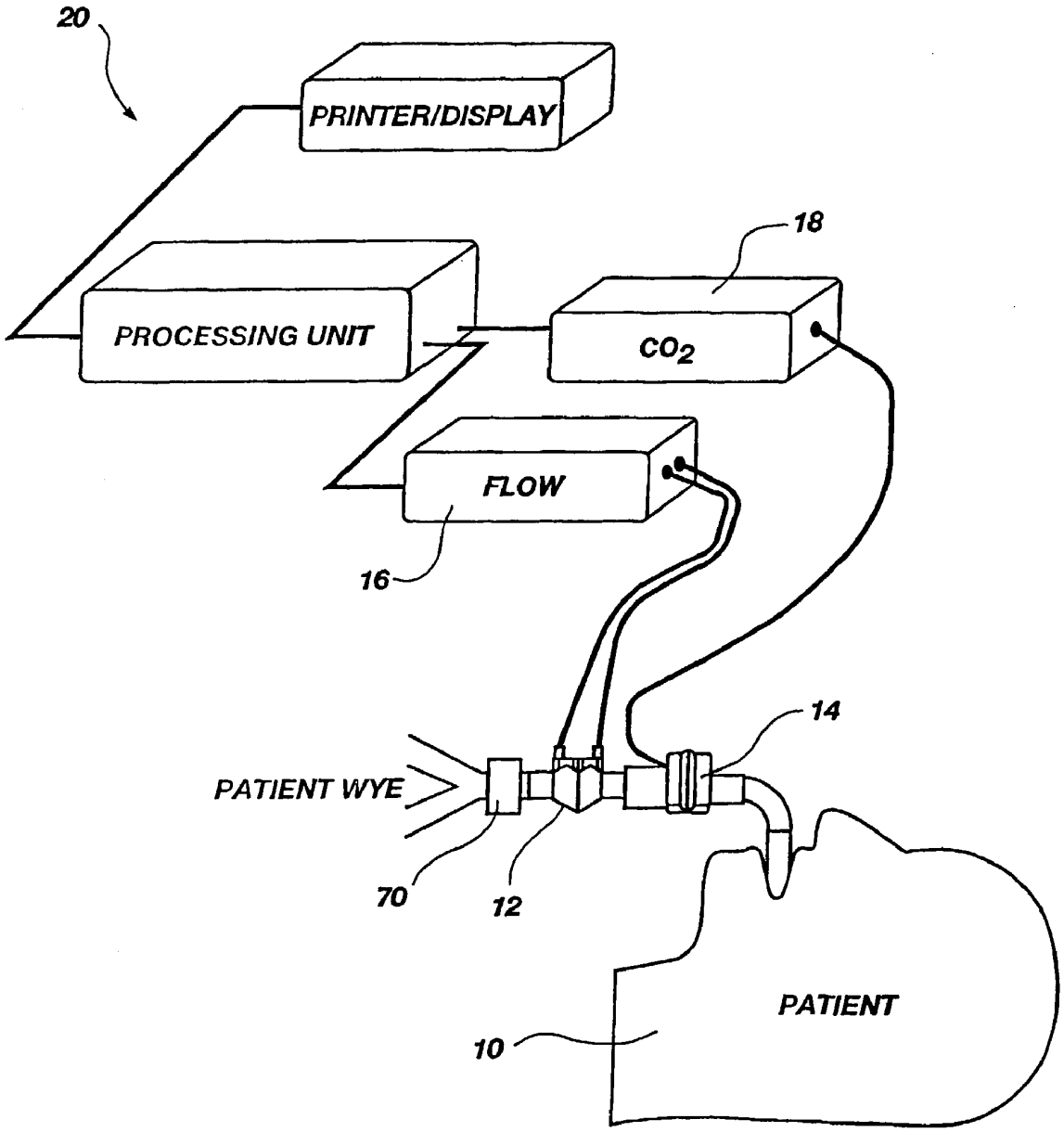
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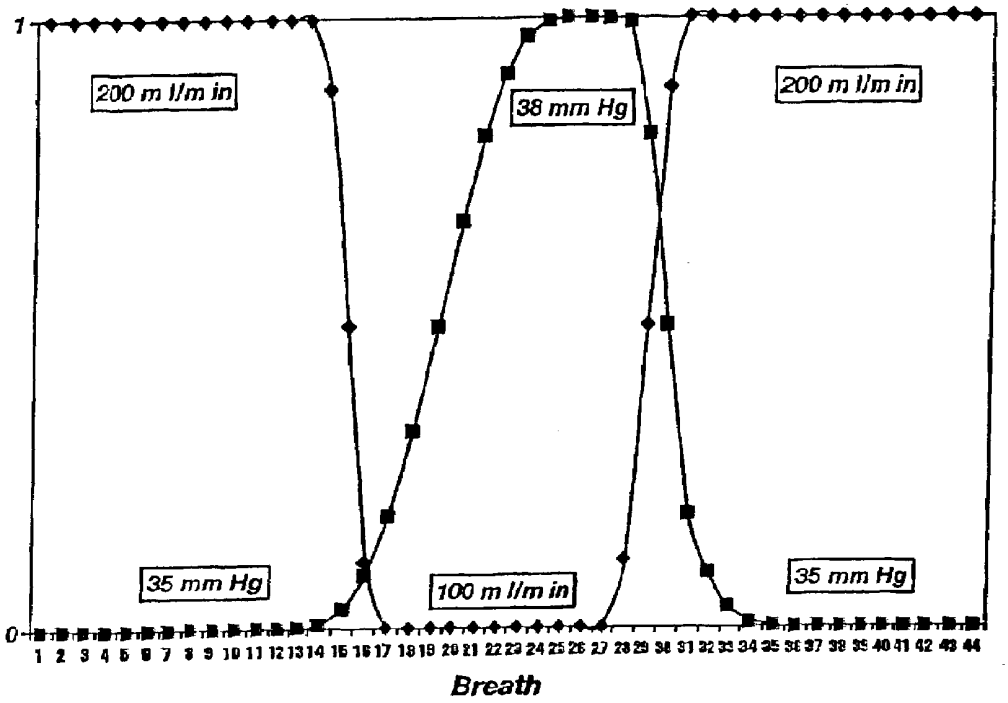
Fig. 2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0
200 m l/m in
38 mm Hg
200 m l/m in
35 mm Hg
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35 mm Hg
Breath

Fig. 3A

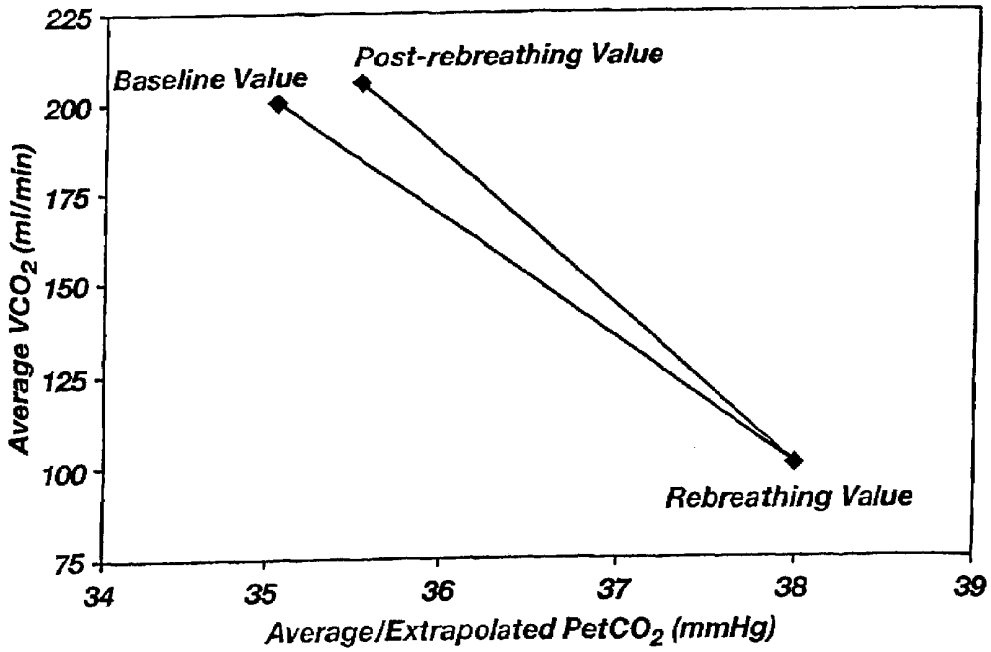
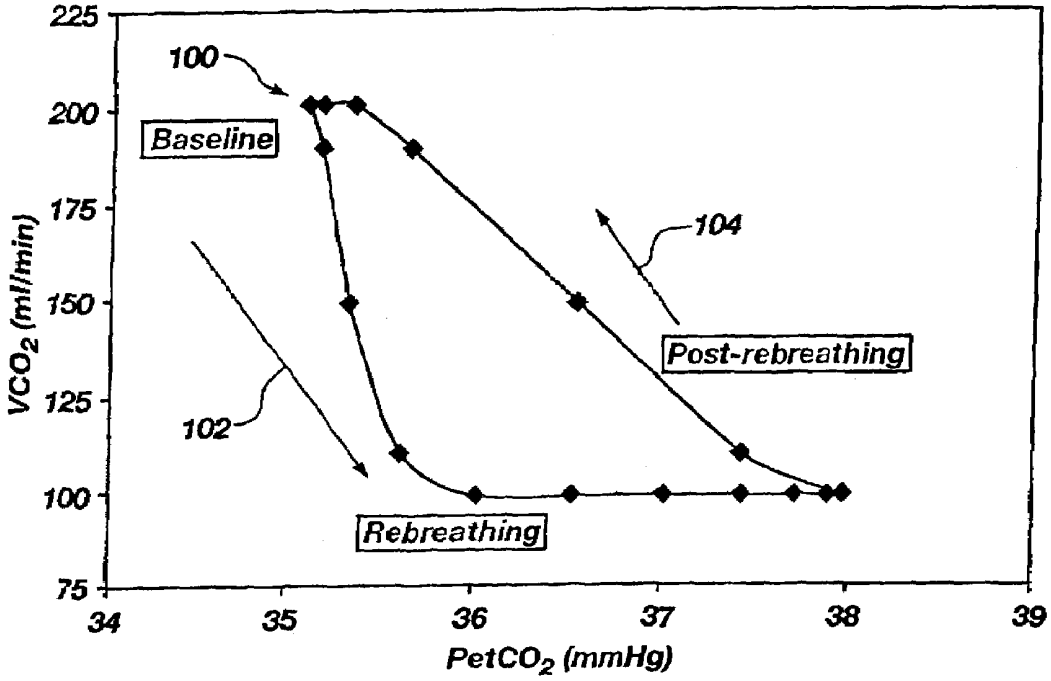

225
200
175
150
125
100
75
Average VCO2 (ml/min)
Baseline Value
Post-rebreathing Value
Rebreathing Value
34
35
36
37
38
39
Average/Extrapolated PetCO2 (mmHg)

Fig. 3B


225
200
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125
100
75
34
35
36
37
38
39
VCO_2 (ml/min)
$PetCO_2$ (mmHg)
100
Baseline
104
Post-rebreathing
102
Rebreathing

Fig. 3C

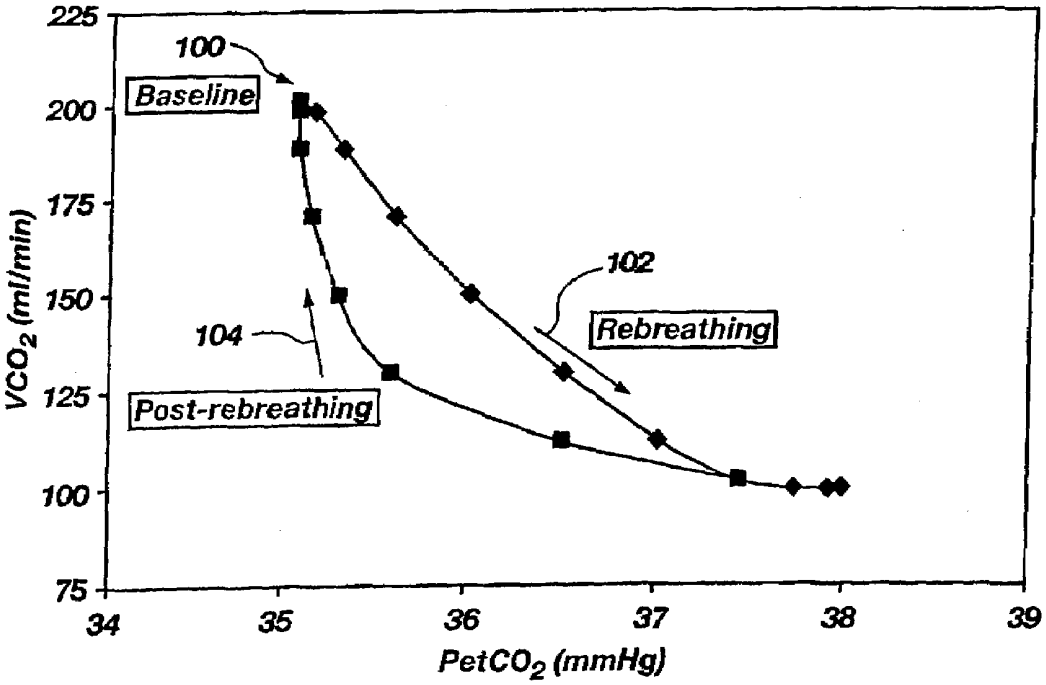
225
200
175
150
125
100
75
34
35
36
37
38
39
VCO_2 (ml/min)
$PetCO_2$ (mmHg)
100
Baseline
102
Rebreathing
104
Post-rebreathing

Fig. 3D

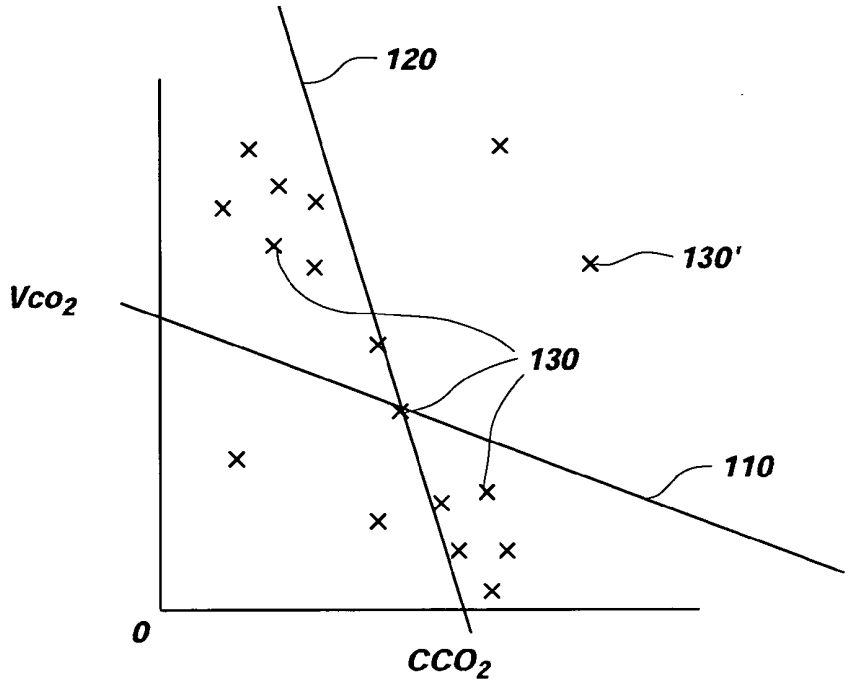

Fig. 4A

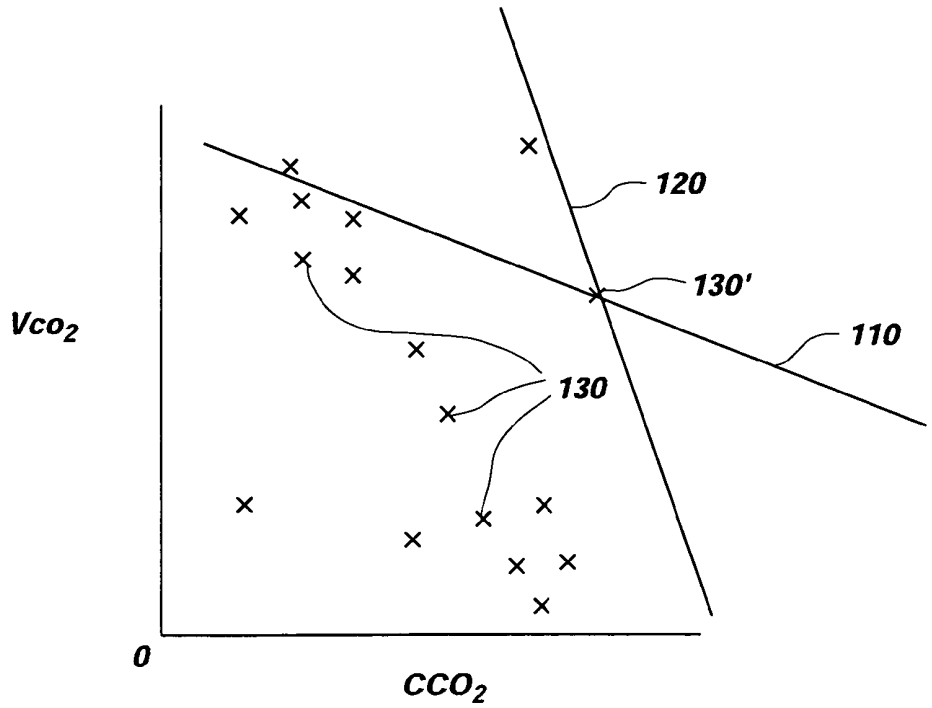

Fig. 4B

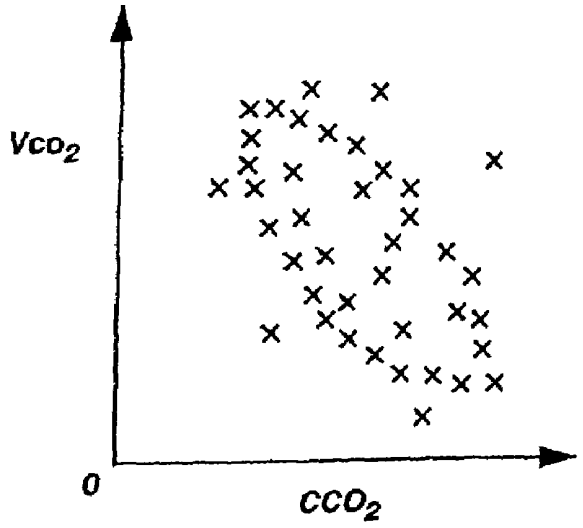

Fig. 5

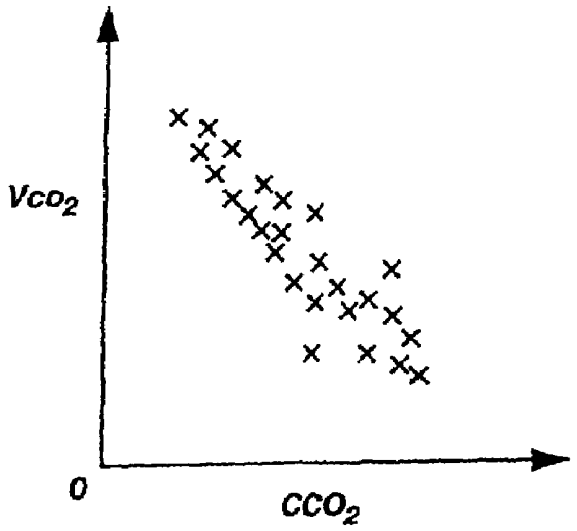

Fig. 6

METHODS FOR ACCURATELY, SUBSTANTIALLY NONINVASIVELY DETERMINING PULMONARY CAPILLARY BLOOD FLOW, CARDIAC OUTPUT, AND MIXED VENOUS CARBON DIOXIDE CONTENT

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of application Ser. No. 09/510,702, filed Feb. 22, 2000 now U.S. Pat. No.6,540,689, issued on Apr. 1, 2003.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to methods for accurately, noninvasively measuring the pulmonary capillary blood flow (PCBF), cardiac output, and mixed venous carbon dioxide content of the blood of a patient. Particularly, the present invention relates to a method for noninvasively measuring pulmonary capillary blood flow or cardiac output that employs an algorithm to increase the accuracy of data upon which the pulmonary capillary blood flow or cardiac output measurement is based.

2. State of the Art

Carbon dioxide elimination (V_{CO_2}) is the volume of carbon dioxide (CO_2) excreted from the body of a patient during respiration. Conventionally, carbon dioxide elimination has been employed as an indicator of metabolic activity. Carbon dioxide elimination has also been used in rebreathing methods of determining pulmonary capillary blood flow and cardiac output.

The carbon dioxide Fick equation:

$$Q=V_{CO_2}/(CvCO_2-CaCO_2), \quad (1)$$

where Q is cardiac output, $CvCO_2$ is carbon dioxide content of the venous blood of the patient, and $CaCO_2$ is the carbon dioxide content of the arterial blood of the patient, has been employed to noninvasively determine the pulmonary capillary blood flow or cardiac output of a patient. The carbon dioxide elimination of the patient may be noninvasively measured as the difference per breath between the volume of carbon dioxide inhaled during inspiration and the volume of carbon dioxide exhaled during expiration, and is typically calculated as the integral of the carbon dioxide signal, or the fraction of respiratory gases that comprises carbon dioxide, or "carbon dioxide fraction," times the rate of flow over an entire breath.

The partial pressure of end-tidal carbon dioxide ($PetCO_2$ or $etCO_2$) is also measured in rebreathing processes. The partial pressure of end-tidal carbon dioxide, after correcting for any deadspace, is typically assumed to be approximately equal to the partial pressure of carbon dioxide in the alveoli (P_ACO_2) of the patient or, if there is no intrapulmonary shunt, the partial pressure of carbon dioxide in the arterial blood of the patient ($PaCO_2$).

Rebreathing is typically employed either to noninvasively estimate the carbon dioxide content of mixed venous blood (as in total rebreathing) or to obviate the need to know the carbon dioxide content of the mixed venous blood (by partial rebreathing). Rebreathing processes typically include the inhalation of a gas mixture that includes carbon dioxide. During rebreathing, the carbon dioxide elimination of the patient decreases to a level less than during normal breathing. Rebreathing during which the carbon dioxide elimination decreases to near zero is typically referred to as total rebreathing. Rebreathing that causes some decrease, but not a total cessation of carbon dioxide elimination, is typically referred to as partial rebreathing.

Rebreathing is typically conducted with a rebreathing circuit, which causes a patient to inhale a gas mixture that includes carbon dioxide. FIG. **1** schematically illustrates an exemplary rebreathing circuit **50** that includes a tubular airway **52** that communicates air flow to and from the lungs of a patient. Tubular airway **52** may be placed in communication with the trachea of the patient by known intubation processes, or by connection to a breathing mask positioned over the nose and/or mouth of the patient. A flow meter **72**, which is typically referred to as a pneumotachometer, and a carbon dioxide sensor **74**, which is typically referred to as a capnometer, are disposed between tubular airway **52** and a length of hose **60** and are exposed to any air that flows through rebreathing circuit **50**. Both ends of another length of hose, which is referred to as deadspace **70**, communicate with hose **60**. The two ends of deadspace **70** are separated from one another by a two-way valve **68**, which may be positioned to direct the flow of air through deadspace **70**. Deadspace **70** may also include an expandable section **62**. A Y-piece **58**, disposed on hose **60** opposite flow meter **72** and carbon dioxide sensor **74**, facilitates the connection of an inspiratory hose **54** and an expiratory hose **56** to rebreathing circuit **50** and the flow communication of the inspiratory hose **54** and expiratory hose **56** with hose **60**. During inhalation, gas flows into inspiratory hose **54** from the atmosphere or a ventilator (not shown). During normal breathing, valve **68** is positioned to prevent inhaled and exhaled air from flowing through deadspace **70**. During rebreathing, valve **68** is positioned to direct the flow of exhaled and inhaled gases through deadspace **70**.

The rebreathed air, which is inhaled from deadspace **70** during rebreathing, includes air that has been exhaled by the patient (i.e., carbon dioxide-rich air).

During total rebreathing, substantially all of the gas inhaled by the patient was expired during the previous breath. Thus, during total rebreathing, the partial pressure of end-tidal carbon dioxide ($PetCO_2$ or $etCO_2$) is typically assumed to be equal to or closely related to the partial pressure of carbon dioxide in the arterial ($PaCO_2$), venous ($PvCO_2$), or alveolar (P_ACO_2) blood of the patient. Total rebreathing processes are based on the assumption that neither pulmonary capillary blood flow nor the content of carbon dioxide in the venous blood of the patient ($CvCO_2$) changes substantially during the rebreathing process. The partial pressure of carbon dioxide in blood may be converted to the content of carbon dioxide in blood by means of a carbon dioxide dissociation curve, where the change in the carbon dioxide content of the blood ($CvCO_2-CaCO_2$) is equal to the slope (s) of the carbon dioxide dissociation curve multiplied by the measured change in end-tidal carbon dioxide ($PetCO_2$) as effected by a change in effective ventilation, such as rebreathing.

In partial rebreathing, the patient inhales a mixture of "fresh" gases and gases exhaled during the previous breath. Thus, the patient does not inhale a volume of carbon dioxide as large as the volume of carbon dioxide that would be inhaled during a total rebreathing process. Conventional partial rebreathing processes typically employ a differential form of the carbon dioxide Fick equation to determine the pulmonary capillary blood flow or cardiac output of the patient, which do not require knowledge of the carbon dioxide content of the mixed venous blood. This differential

form of the carbon dioxide Fick equation considers measurements of carbon dioxide elimination, $CvCO_2$, and the content of carbon dioxide in the alveolar blood of the patient ($CaCO_2$) during both normal breathing and the rebreathing process as follows:

$$Q_{pcbf\ BD} = \frac{V_{CO_{2B}} - V_{CO_{2D}}}{(CvCO_{2B} - CvCO_{2D}) - (CaCO_{2B} - CaCO_{2D})}, \quad (2)$$

where $V_{CO_{2\ B}}$ and $V_{CO_{2\ D}}$ are the carbon dioxide production of the patient before rebreathing and during the rebreathing process, respectively, $CvCO_{2\ B}$ and $CvCO_{2\ D}$ are the content of CO_2 of the venous blood of the patient before rebreathing and during the rebreathing process, respectively, and $CaCO_{2\ B}$ and $CaCO_{2\ D}$ are the content of CO_2 in the arterial blood of the patient before rebreathing and during rebreathing, respectively.

Again, with a carbon dioxide dissociation curve, the measured $PetCO_2$ can be used to determine the change in content of carbon dioxide in the blood before and during the rebreathing process. Accordingly, the following equation can be used to determine pulmonary capillary blood flow or cardiac output when partial rebreathing is conducted:

$$Q = \Delta V_{CO_2} / s\Delta PetCO_2. \quad (3)$$

Alternative differential Fick methods of measuring pulmonary capillary blood flow or cardiac output have also been employed. Such differential Fick methods typically include a brief change of $PetCO_2$ and V_{CO_2} in response to a change in effective ventilation. This brief change can be accomplished by adjusting the respiratory rate, inspiratory and/or expiratory times, or tidal volume. A brief change in effective ventilation may also be effected by adding CO_2, either directly or by rebreathing. An exemplary differential Fick method that has been employed, which is disclosed in Gedeon, A. et al. in 18 *Med. & Biol. Eng. & Comput.* 411–418 (1980), employs a period of increased ventilation followed immediately by a period of decreased ventilation.

The carbon dioxide elimination of a patient is typically measured over the course of a breath by the following, or an equivalent, equation:

$$V_{CO_2} = \int_{breath} V \times f_{CO_2}\, dt, \quad (4)$$

where V is the measured respiratory flow and f_{CO_2} is the substantially simultaneously detected carbon dioxide signal, or fraction of the respiratory gases that comprises carbon dioxide or "carbon dioxide fraction."

Due to the measured respiratory constituents upon which V_{CO_2} and $PetCO_2$ calculations are made, V_{CO_2} typically responds to rebreathing about one breath before $PetCO_2$ for the same breath. Accordingly, a V_{CO_2} signal may lead a $PetCO_2$ signal by about one breath. Thus, at a particular point in time, the V_{CO_2} and $PetCO_2$ signals do not correspond to one another. As these values are often used to noninvasively determine pulmonary capillary blood flow or cardiac output, the lack of correspondence between these values may lead to inaccuracies in the pulmonary capillary blood flow or cardiac output determination.

In addition, measurements that are taken during spurious breaths, or breaths which do not provide information relevant to pulmonary capillary blood flow or cardiac output, may act as noise that introduces inaccuracy into the noninvasive pulmonary capillary blood flow or cardiac output determination.

When equation (4) is employed to calculate the carbon dioxide elimination of the patient from the respiratory flow and carbon dioxide fraction measurements over an entire breath, such miscorrelation or noise-induced inaccuracies in either the expiratory flow, the inspiratory flow, or both may cause inaccuracies in the carbon dioxide elimination determination or inconsistencies between carbon dioxide elimination determinations.

Accordingly, there is a need for a method of accurately, noninvasively calculating pulmonary capillary blood flow and cardiac output.

SUMMARY OF THE INVENTION

The present invention includes a method for noninvasively measuring pulmonary capillary blood flow and cardiac output. The present invention includes the use of known rebreathing techniques to substantially noninvasively obtain carbon dioxide elimination (V_{CO_2}) and partial pressure of end-tidal carbon dioxide ($PetCO_2$) measurements of a patient's breathing. These measurements may then be used to calculate pulmonary capillary blood flow or cardiac output of the patient by employing the following equation:

$$Q = \frac{\Delta V_{CO_2}}{\Delta CaCO_2} = \frac{\Delta V_{CO_2}}{s\Delta PetCO_2}, \quad (5)$$

where s is the slope of a standard carbon dioxide (CO_2) dissociation curve, ΔV_{CO_2} is the change in the carbon dioxide elimination of the patient due to a change in effective ventilation, such as that caused by rebreathing, and $\Delta CaCO_2$ and $\Delta PetCO_2$ are the change in the content of carbon dioxide in the arterial blood of the patient and the change in the end-tidal partial pressure of carbon dioxide of the patient, respectively, due to the same change in effective ventilation. Alternatively, a standard carbon dioxide dissociation curve can be used to determine $\Delta CaCO_2$ on the basis of the measured $\Delta PetCO_2$.

As an alternative to the use of the above equations to determine pulmonary capillary blood flow or cardiac output, the substantially noninvasive V_{CO_2} and $CaCO_2$ measurements can be related to each other in a linear fashion. This can be visually diagramed by plotting the V_{CO_2} and $CaCO_2$ measurements against one another on a two-dimensional (X-Y) line graph. The negative slope (−1×m) of the best-fit line through the data is approximately equal to the pulmonary capillary blood flow. The appropriate location and orientation of such a best-fit line may be calculated by linear regression or least squares. Depending on the correlation between the calculated best-fit line and the measured data, it may also be desirable to modify the data to provide a best-fit line that closely corresponds to the data.

In one embodiment of the method of the present invention, the data can be modified by use of a known filter, such as a low-pass filter or a high-pass filter. Either digital or analog filters may be used. Either linear or nonlinear (e.g., median) filters may be used. By way of example, and not to limit the scope of the present invention, a low-pass filter may be applied to the measured V_{CO_2} signal. As another example, a high-pass filter may be applied to the measured $CaCO_2$ signal. Preferably, the filter and filter coefficient that are selected maximize the correlation between the measured V_{CO_2} and $CaCO_2$ signals.

In another embodiment of the method of the present invention, the data points can be modified by clustering.

That is, the data points that are grouped closest to other data points are assumed to most accurately represent the true V_{CO_2} and $CaCO_2$ of the patient. For example, the measured data with at least a predetermined number of close, or similar (e.g., within a specified threshold), data points is retained, while measured data with less than the predetermined number of close data points is discarded. The retained data points are assumed to be located on or near the best-fit line. In clustering, only these closely grouped sets of data points are considered in recalculating the best-fit line for the data and, thus, the negative slope (i.e., $-1\times$ m) of the best-fit line to determine the pulmonary capillary blood flow or cardiac output of the patient.

Another embodiment of the method of the present invention includes modifying the data points that are most likely to be closest to an accurately placed and oriented best-fit line. Each data point, which has a carbon dioxide elimination component (e.g., a y-ordinate component) and a component based on an indicator of carbon dioxide content (e.g., an x-ordinate component), is evaluated on the basis of a predetermined minimum expected pulmonary capillary blood flow and a predetermined maximum pulmonary capillary blood flow. Lines, or the equations therefor, for both minimum expected and maximum expected pulmonary capillary blood flows are located so as to intersect at each data point. Then, the number of the other data points that are located between the two pulmonary capillary blood flow lines or equations is determined for each data point. Only those data points with a threshold number of other data points between the two intersecting lines are used in the determination of the location and orientation of the best-fit line through the data.

Of course, any combination of methods of modifying data may be used to accurately determine the slope of the best-fit line through the measured V_{CO_2} and $PetCO_2$ data and, thus, to determine the pulmonary capillary blood flow or cardiac output of a patient.

The best-fit line through carbon dioxide elimination and carbon dioxide content data may also be used to determine the mixed venous carbon dioxide content of the patient when partial rebreathing techniques are employed to obtain the data. As the mixed venous carbon dioxide content is assumed to equal the carbon dioxide content of the patient's blood when carbon dioxide elimination ceases (which does not occur during partial rebreathing), a best-fit line obtained by use of partial rebreathing techniques can be used to noninvasively determine carbon dioxide content and, thus, mixed venous carbon dioxide content when carbon dioxide elimination is set at zero.

Other features and advantages of the present invention will become apparent to those of ordinary skill in the art through a consideration of the ensuing description, the accompanying drawings, and the appended claims.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIG. **1** is a schematic representation of an exemplary rebreathing circuit that may be employed with the methods of the present invention;

FIG. **2** is a schematic representation which illustrates the componentry that may be utilized to measure respiratory profile parameters that are employed in the methods of the present invention;

FIG. **3**A illustrates an idealized, bidirectional rebreathing cycle with V_{CO_2} values for different breaths depicted as diamonds and $PetCO_2$ values for various breaths shown as squares;

FIG. **3**B is a two-dimensional plot illustrating the use of a known, bidirectional rebreathing process to obtain three V_{CO_2} values and three values representative of the carbon dioxide content of the blood of a patient before, during, and after rebreathing; these three values have been used to substantially noninvasively determine the pulmonary capillary blood flow or cardiac output of the patient;

FIG. **3**C is a two-dimensional plot of a number of V_{CO_2} values against the same number of carbon dioxide content values obtained over a single bidirectional rebreathing cycle;

FIG. **3**D is an exemplary two-dimensional plot depicting V_{CO_2} and carbon dioxide content values from the same rebreathing cycle as that shown in FIG. **3**C and modified in accordance with the method of the present invention;

FIGS. **4**A and **4**B are two-dimensional plots illustrating an embodiment of a method for modifying data to obtain an accurate best-fit line therethrough in accordance with teachings of the present invention;

FIG. **5** is a two-dimensional line graph illustrating a typical plot of V_{CO_2} on the y-axis and $CaCO_2$ on the x-axis; and

FIG. **6** is a two-dimensional line graph illustrating a plot of V_{CO_2} on the y-axis and $CaCO_2$ on the x-axis after the V_{CO_2} and $CaCO_2$ data have been modified in accordance with teachings of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention includes use of the Fick equation to calculate pulmonary capillary blood flow or cardiac output as the ratio of a change in carbon dioxide elimination, or V_{CO_2}, to a change in the content of carbon dioxide, or $CaCO_2$, in the arterial blood of a patient:

$$Q = \frac{\Delta V_{CO_2}}{\Delta CaCO_2}. \tag{6}$$

$CaCO_2$, or the content of carbon dioxide in the arterial blood of a patient, can be noninvasively estimated by determining the $PetCO_2$, or partial pressure of carbon dioxide in the end-tidal respiration of a patient, and converting $PetCO_2$ to $CaCO_2$ by use of a standard carbon dioxide dissociation curve, as is known in the art, as follows:

$$\Delta CaCO_2 = s\Delta PetCO_2, \tag{7}$$

where s is the slope of the carbon dioxide dissociation curve and $\Delta PetCO_2$ is a change in the end-tidal partial pressure of carbon dioxide of a patient effected by a change in ventilation. Thus, pulmonary capillary blood flow or cardiac output can also be calculated as follows:

$$Q = \Delta V_{CO_2} / s\Delta PetCO_2. \tag{8}$$

Other indicators of the carbon dioxide content in the blood of a patient, such as pCO_2, may be used in place of $PetCO_2$ or $CaCO_2$ to determine the pulmonary capillary blood flow or cardiac output of a patient.

V_{CO_2} and $PetCO_2$, $CaCO_2$, pCO_2, or other indicators of the carbon dioxide content in the blood of a patient can be

calculated or determined on the basis of substantially noninvasively obtained respiratory flow and respiratory carbon dioxide pressure data.

FIG. **2** schematically illustrates an exemplary method of substantially noninvasively monitoring the respiration of a patient and of measuring the flow rates and carbon dioxide concentration of gas mixtures that are inhaled and exhaled by a patient **10** over the course of the patient's breathing, such as during normal respiration or during known rebreathing techniques. A flow sensor **12** of a known type, such as the differential-pressure type respiratory flow sensors manufactured by Novametrix Medical Systems Inc. ("Novametrix") of Wallingford, Conn. (e.g., the Pediatric/Adult Flow Sensor (Catalog No. 6717) or the Neonatal Flow Sensor (Catalog No. 6718)), which may be operatively attached to a ventilation apparatus (not shown), as well as respiratory flow sensors based on other operating principles and manufactured or marketed by others, may be employed to measure the flow rates of the breathing of patient **10**.

A carbon dioxide sensor **14**, such as the CAPNOSTAT® carbon dioxide sensor and a complementary airway adapter (e.g., the Pediatric/Adult Single Patient Use Airway Adapter (Catalog No. 6063), the Pediatric/Adult Reusable Airway Adapter (Catalog No. 7007), or the Neonatal/Pediatric Reusable Airway Adapter (Catalog No. 7053)), which are manufactured by Novametrix, as well as main stream and side stream carbon dioxide sensors manufactured or marketed by others, may be employed to measure the carbon dioxide concentration of gas mixtures that are inhaled and exhaled by patient **10**.

Flow sensor **12** and carbon dioxide sensor **14** are connected to a flow monitor **16** and a carbon dioxide monitor **18**, respectively, each of which may be operatively associated with a computer **20** so that data from the flow and carbon dioxide monitors **16** and **18** representative of the signals from each of flow sensor **12** and carbon dioxide sensor **14** may be detected by computer **20** and processed according to programming (e.g., by software) thereof. Preferably, raw flow and carbon dioxide signals from the flow monitor and carbon dioxide sensor are filtered to remove any significant artifacts. As respiratory flow and carbon dioxide pressure measurements are made, the respiratory flow and carbon dioxide pressure data may be stored by computer **20**.

Each breath, or breathing cycle, of patient **10** may be delineated as known in the art, such as by continuously monitoring the flow rate of the breathing of patient **10**.

As use of the Fick equation to calculate pulmonary capillary blood flow or cardiac output requires that a change in V_{CO_2} and $CaCO_2$, $PetCO_2$, pCO_2 or another indicator of the carbon dioxide content in the blood of a patient be known, a change in effective ventilation is required. By way of example, and not to limit the scope of the present invention, rebreathing techniques, such as by use of a dead space **70** such as that provided by the rebreathing circuit illustrated in FIG. **1**, may be employed to cause a change in effective ventilation. FIG. **3**A illustrates the changes that may occur when a bidirectional rebreathing process, such as that disclosed in U.S. patent application Ser. No. 09/150,136, filed Sep. 9, 1998, and assigned to the same assignee as the present invention, is used to effect a change in effective ventilation. The graph of FIG. **3**A illustrates the typical changes in the V_{CO_2} (shown as diamonds) and carbon dioxide content measurements (e.g., $PetCO_2$, shown as squares) that may occur between the baseline breathing (i.e., before rebreathing), during rebreathing, and the stabilization (i.e., after rebreathing) periods of an idealized (i.e., without noise) bidirectional rebreathing cycle. During rebreathing, V_{CO_2} changes from a baseline value (e.g., about 200 ml/min) to a during rebreathing plateau (e.g., of about 100 ml/min.) within about 3 or 4 breaths, whereas carbon dioxide content may take longer to change from a baseline value (e.g., 38 mmHg) to a plateau (e.g., about 35 mmHg).

FIG. **3**B is a two-dimensional plot illustrating that one value, the plateau value, from each of the before, during, and after rebreathing phases of a bidirectional rebreathing process, such as that illustrated in FIG. **3**A, was used to estimate pulmonary capillary blood flow or cardiac output. By way of contrast, in a method of determining pulmonary capillary blood flow or cardiac output incorporating teachings of the present invention, V_{CO_2} and carbon dioxide content data are continually measured, providing a plot such as that shown in FIG. **3**C, with data at **100** being based on before rebreathing measurements, data along arrow **102** being based on during rebreathing measurements, and data along arrow **104** being based on after rebreathing measurements. These data may be obtained by use of a single rebreathing cycle, over the course of a number of rebreathing cycles, at one or more discrete time intervals, or on a breath-by-breath basis, where data is continually measured, calculated, and analyzed in accordance with the method of the invention so as to continually update or monitor the pulmonary capillary blood flow or cardiac output of a patient.

When rebreathing or other known techniques are used to cause a change in effective ventilation so as to facilitate the substantially noninvasive determination of pulmonary capillary blood flow or cardiac output, respiratory flow and carbon dioxide pressure data are obtained during at least the before, during, and after stages of rebreathing. Total or partial rebreathing processes may be used in the method of the present invention. These respiratory flow and carbon dioxide pressure data are then used, as known in the art, to calculate V_{CO_2} and $PetCO_2$, as well as the changes in V_{CO_2} and $PetCO_2$ that occur with the change in effective ventilation.

The calculated V_{CO_2} and $PetCO_2$ data are then used to determine the pulmonary capillary blood flow or cardiac output of the patient, such as by use of the Fick equations presented above.

As an alternative, the pulmonary capillary blood flow or cardiac output of a patient can be determined over the course of a plurality of breaths by expressing the calculated V_{CO_2} data and $CaCO_2$ data or data of another indicator of the content of carbon dioxide in the blood of a patient, such as $PetCO_2$ or pCO_2, in two dimensions, such as on a two-dimensional (X-Y) line graph, with V_{CO_2} data points being measured on the y-axis and $PetCO_2$ data points being measured on the x-axis, then identifying a line that best fits the data, which is also referred to herein as a best-fit line.

For example, the equation for the best-fit line is:

$$y=mx+b \tag{9}$$

or

$$m=\frac{y-b}{x}, \tag{10}$$

where y is the y-axis coordinate of a data point, x is the x-axis coordinate of the same data point, m is the slope of the line, and b is the offset value for the line. If V_{CO_2} is measured on the y-axis and $CaCO_2$ is measured on the x-axis, then

$$m = \frac{V_{CO_2} - b}{CaCO_2}. \quad (11)$$

The negative slope (i.e., −1×m) of the best-fit line through the V_{CO_2}–$CaCO_2$ data would be equal to the pulmonary capillary blood flow or cardiac output of the patient:

$$-m=Q. \quad (12)$$

The best-fit line for the V_{CO_2} and $CaCO_2$ data is preferably determined by use of known linear regression techniques or any other known methodology for determining the relationship between two variables. The method of linear regression provides an accurate pulmonary capillary blood flow or cardiac output value based on a large number of V_{CO_2} and $CaCO_2$ data obtained over the course of one or more changes in effective ventilation. When linear regression is used, the slope (m) of the best-fit line for the data is calculated as follows:

$$m=Lxy/Lxx \quad (13)$$

and the offset (b) of the line is calculated by the following equation:

$$b=\Sigma y/n-m\times\Sigma x/n, \quad (14)$$

where

$$Lxx=\Sigma x^2-(\Sigma x\times\Sigma x)/n, \quad (15)$$

$$Lyy=\Sigma y^2-(\Sigma y\times\Sigma y)/n, \text{ and} \quad (16)$$

$$Lxy=\Sigma xy-(\Sigma x\times\Sigma y)/n, \quad (17)$$

and where n is the number of data points in the plot, Σx is the sum of all x-coordinate (i.e., $CaCO_2$ content) values, Σy is the sum of all y-coordinate (i.e., V_{CO_2}) values, Σx^2 is the sum of the square of all x-coordinate values, Σy^2 is the sum of the square of all y-coordinate values, and Σxy is the sum all paired x- and y-coordinate values multiplied by each other.

When linear regression is used to determine the location and orientation of a best-fit line, a correlation coefficient (r) that quantifies the accuracy with which the best-fit line correlates to the V_{CO_2} and $CaCO_2$ data can also be calculated as follows:

$$r=(Lxy\times Lxy)/(Lyy\times Lxx). \quad (18)$$

Alternatively, any other measure of the quality of fit that quantifies the accuracy with which the best-fit line correlates to the V_{CO_2} and $CaCO_2$ data may be used.

Correlation coefficients range from 0 to 1.0, where a correlation coefficient of 0 indicates that no linear correlation exists between the x-ordinate and the y-ordinate data and a correlation coefficient of 1.0 indicates that the x-ordinate and y-ordinate data are perfectly linearly correlated (i.e., all of the V_{CO_2}–$CaCO_2$ data points are located on the same straight line).

The V_{CO_2}–$CaCO_2$ data points measured before and during rebreathing, however, are rarely located on the same straight line. One reason for this is that, during rebreathing maneuvers, the V_{CO_2} signal typically leads the $PetCO_2$ signal and, thus, the $CaCO_2$ by about one breath. In addition, V_{CO_2} is calculated on the basis of signal components that have higher frequencies than do the $PetCO_2$ signal. As a result, when the V_{CO_2} and $CaCO_2$ measurements calculated over a period of time are plotted against one another on a two-dimensional (X-Y) line graph, the result typically appears as an arc or a loop, as shown in FIGS. **3**C and **5**, rather than as a straight line, depending on the amount of data calculated and the duration of rebreathing. Moreover, V_{CO_2} and $CaCO_2$ measurements may be calculated on the basis of respiratory flow and carbon dioxide pressure data obtained during spurious breaths. Such data do not relate to the pulmonary capillary blood flow or cardiac output measurement. V_{CO_2} and $CaCO_2$ calculations that are based upon such spurious data act as noise that may result in miscalculation of a best-fit line through the calculated V_{CO_2} and $CaCO_2$ data. As a result, the correlation coefficient of a best-fit line to the data is typically much less than 1.0.

The measured respiratory flow and carbon dioxide pressure data or the calculated V_{CO_2} and $CaCO_2$ data can be modified to increase the correlation coefficient between the V_{CO_2} and $CaCO_2$ data and the best-fit line therefor. Preferably, a linear transform is used to increase the correlation coefficient. A linear transform may be used to delay the calculation of a V_{CO_2} data point to accurately coincide therewith a $CaCO_2$ data point based on measurements taken during the same breath. The measured or calculated data may also be filtered by use of a linear transform.

In one embodiment of a method for increasing the correlation coefficient between the V_{CO_2} and $CaCO_2$ data and the best-fit line therefor, a filter is applied to the calculated V_{CO_2} or $CaCO_2$ data. Known analog or digital low-pass, high-pass, or band pass filters, including adaptive filters, may be employed. Linear or nonlinear filters may be employed. Preferably, a first order (single pole) infinite impulse response (IIR) digital filter is employed to filter the V_{CO_2} calculations in a manner that improves the correlation between the V_{CO_2} calculation and the lagging $PetCO_2$/$CaCO_2$ calculation. The equation for such a filter is:

$$V_{CO_2}[n]=\alpha\times V_{CO_2}[n-1]+(1-\alpha)\times V_{CO_2}[n], \quad (19)$$

where $V_{CO_2}[n]$ is the most recently calculated, unfiltered V_{CO_2} data point, $V_{CO_2}[n-1]$previous, filtered V_{CO_2} data point, $V_{CO_2}[n]$ is the new "filtered" value based on V_{CO_2} [n]obtained by use of the filter, and α, is the filter coefficient. The filter coefficient, α, has a range of 0 to 1.0. The greater the value of α, the more profoundly the most recently calculated data point is filtered and, conversely, the lower α values cause the most recently calculated data points to be filtered to a lesser degree. When α is equal to zero, the most recently calculated data point is not filtered.

Due to anatomical and physiological differences between different patients, different patients have differing optimal filter coefficients, α. In addition, as anatomical and physiological changes may occur in a patient over time, the optimum filter coefficients, α, to be used in filtering the V_{CO_2} or $CaCO_2$ values calculated from the patient's breathing may also vary over time. Accordingly, the selection of an optimal filter coefficient, α, is also within the scope of the present invention. Any known optimization method or search algorithm may be employed to select the optimal filter coefficient, α.

As an example of the way in which an optimal filter coefficient may be selected, α is first set to a default value (e.g., 0.85) and the calculated V_{CO_2} or $CaCO_2$ values are filtered on the basis of the default filter coefficient, α. The linear regression is then performed to obtain a best-fit line. If the correlation coefficient of best-fit line calculated with the just-filtered data is less than the correlation coefficient of the immediately preceding best-fit line, which was calcu-

lated with unfiltered data or with a prior filter coefficient, then a predetermined α adjustment value (e.g., 0.01) is changed by multiplying the α adjustment value by −1 and by modifying the filter coefficient by adding the modified α adjustment value thereto. Otherwise, the filter coefficient, α, is modified by adding the unmodified α adjustment value thereto. The process of filtering the data based on a modified filter coefficient, obtaining a best-fit line for the data, comparing the correlation coefficient of the best-fit line to the correlation coefficient of the previous best-fit line, and adjusting the filter coefficient accordingly is then repeated a predetermined number of times (e.g., 50 times). The best-fit line with the greatest correlation coefficient, based on the unfiltered data and each set of filtered data, is selected to calculate the pulmonary capillary blood flow or cardiac output of the patient. When filtering is used, the V_{CO_2}–$CaCO_2$ plot preferably narrows, as depicted in FIGS. **3**D and **6**, to thereby increase the accuracy with which the location and orientation of a best-fit line can be established and, thus, to increase the accuracy of a pulmonary capillary blood flow or cardiac output determination based on the data.

Another embodiment of a method for increasing the correlation coefficient between the V_{CO_2} and $CaCO_2$ data and the best-fit line therefor, which is referred to herein as "clustering," includes the selection of data points that are grouped closely together. That is, the data points that are selected include those data points having a number of other data points within a predetermined range thereof. Data points that are not clustered are probably inaccurate or based on measurements taken during spurious breaths. As an accurate best-fit line through the data would likely be based on the clustered data, the data points that are not located in a cluster are not used in calculating the location and orientation of a best-fit line for the data.

Clustering of the data points may include normalization or transformation of the data such that ranges of the x-coordinate data (e.g., the $CaCO_2$ data) and the y-coordinate data (e.g., the V_{CO_2} data) are substantially the same. Without such normalization, the data group (e.g., the V_{CO_2} data or the $CaCO_2$ data) with the highest range would dominate; the other data group would be less significant.

An exemplary manner in which the data may be normalized includes use of the following normalization:

$$x=(x-\bar{x})/\sigma_x, \tag{20}$$

where:

x is the raw value, $\bar{x}$ is the mean value of all x-axis (e.g., $CaCO_2$) data in the plot, and σ_x is the standard deviation of all x-axis data in the plot. This normalization is applied to all x-axis values. A similar normalization scheme is applied to all of the y-axis values.

The normalized data may then be clustered by searching for a predetermined number (e.g., 5) of the closest data points (e.g., V_{CO_2} or $CaCO_2$ data points) to each of the data points in a group. The differences between the analyzed data point and each of the predetermined number of closest data points are then added together and compared to a predetermined threshold. If the sum of the differences exceeds the predetermined threshold, the analyzed data point is discarded. Of course, the use of other clustering techniques to identify the most accurate data and to disregard probable inaccurate data is also within the scope of the present invention.

Once clustering has been performed, the inverse of the normalization is calculated, or the normalization is undone, to provide an accurate determination of pulmonary capillary blood flow or cardiac output. An example of the manner in which the inverse of the normalization may be calculated includes use of the following equation:

$$x=x\sigma_x+\bar{x} \tag{21}$$

This inverse of the normalization is applied to all of the clustered x-axis (e.g., $CaCO_2$) values. A similar inverse normalization scheme is applied to all of the clustered y-axis data.

Clustering is one of many known techniques for determining outliers. Other known techniques for determining outliers may also be used in the method of the present invention.

Alternatively, or in addition to disregarding probable inaccurate data points, in order to enhance the accuracy of the data, clustering can be used to add synthetic data points. Synthetic data points may be added to increase the correlation coefficient of the best-fit line to the data points on which the best-fit line is based.

Another embodiment of the method for modifying data that incorporates teachings of the present invention is depicted in FIGS. **4**A and **4**B. As with the filtering and clustering embodiments described previously herein, the present embodiment includes selection of data points that are most likely to facilitate an accurate determination of the location and orientation of a best-fit line and, thus, of the pulmonary capillary blood flow or cardiac output of a patient. This embodiment of the method for modifying data includes iteratively examining data points and the distribution of the remaining data points relative to the two lines representing the range of possible PCBF measurements.

As shown in FIGS. **4**A and **4**B, a line or the equation for a line **110** representing a minimum expected pulmonary capillary blood flow (i.e., $-m_{line\ 120}=PCBF_{max}$) and a line or the equation for a line **120** representing a maximum expected pulmonary capillary blood flow (i.e., $-m_{line\ 120}=PCBF_{max}$) are positioned to intersect at a data point **130**. For example, when the x-ordinate is based on $CaCO_2$, line **110** may have a slope of −0.5, which represents a minimum expected pulmonary capillary blood flow of 0.5 L/min, and line **120** may have a slope of −20, which represents a maximum pulmonary capillary blood flow of 20 L/min. Of course, the use of other pulmonary capillary blood flow values for lines **110** and **120** is also within the scope of the present invention.

Next, the number of other data points **130** located between lines **110** and **120** is determined. If the number of data points **130** between lines **110** and **120** is equal to or exceeds a threshold number, the analyzed data point **130** is retained for a subsequent determination of the location and orientation of a best-fit line through the data. Otherwise, the analyzed data point **130** is discarded. The threshold number of data points that must be located between line **110** and line **120** for an analyzed data point to be retained may be a predetermined value or determined by other means. As an example, the threshold number may be set to the median number of data points that are located between line **110** and line **120** when each data point **130** of a set of data points **130** has been evaluated in accordance with the present embodiment of the method for modifying data. This process is repeated until each data point **130** in a set of data points **130** has been so evaluated. FIG. **4**A depicts use of the present embodiment of the data modification method on a data point **130** that will be retained, while FIG. **4**B illustrates use of the present embodiment of the data modification method on another data point **130'** that will not be retained.

FIGS. **3**C and **3**D and FIGS. **5** and **6** illustrate the effect of modifying data in accordance with teachings of the present invention to increase the accuracy with which the location and orientation of a best-fit line through the data may be determined. FIG. **5** illustrates a typical V_{CO_2} vs. $CaCO_2$ plot without such modification, where the plot appears as a loop. By way of contrast, FIG. **6** illustrates the closeness of the data when one or more of the embodiments of the method of the present invention are used to modify the data. FIGS. **3**C and **3**D illustrate plots of V_{CO_2} and $PetCO_2$ data before and after modification in accordance with the present invention, respectively. The increased closeness of the data points makes it possible to determine the orientation and location of a best-fit line therethrough with increased accuracy.

Once all of the data points have been examined, the location and orientation for the best-fit line through the remaining, clustered data are determined. Again, linear regression is preferably used to determine the location and orientation of the best-fit line. The negative slope (i.e., −1×m) of the best-fit line provides a pulmonary capillary blood flow measurement, which may then be used to determine cardiac output. A correlation coefficient can then be calculated, as previously disclosed herein, to indicate the quality of the data used to determine pulmonary capillary blood flow or cardiac output. The correlation coefficient or a quality measure based thereon may then be communicated to the user (e.g., a doctor, nurse, or respiratory technician) or used to weight the resulting pulmonary capillary blood flow or cardiac output value in an output weighted average value.

One or a combination of the embodiments of the method for modifying data in accordance with the present invention may be performed on the measured or calculated data to increase the accuracy with which a best-fit line through the data or the pulmonary capillary blood flow or cardiac output of a patient can be determined.

As an example of the use of filtering and clustering together, the calculated V_{CO_2} data are grouped together as the y-axis data of a two-dimensional line graph and the calculated $CaCO_2$ data points are grouped together as x-axis data points. The data points in at least one of the groups are filtered to determine a best-fit line for the data having an optimum correlation coefficient. The data are also clustered, either before or after filtering, to further improve the correlation coefficient of the best-fit line to the calculated V_{CO_2} and $CaCO_2$ data. The remaining data is then used to determine (e.g., by linear regression) a best-fit line therefor, as well as a correlation coefficient for the best-fit line. The slope of the best-fit line is then calculated and used to determine pulmonary capillary blood flow or cardiac output. The correlation coefficient may also be used to indicate the reliability of the pulmonary capillary blood flow or cardiac output determination or to impart a specific weight to the pulmonary capillary blood flow or cardiac output determination in a weighted average thereof.

Once the location and orientation of an accurate best-fit line for the data has been determined, as disclosed previously herein, the pulmonary capillary blood flow of the patient can be calculated as the negative of the slope of the best-fit line. In addition, cardiac output can then also be determined by adding the pulmonary capillary blood flow of the patient to the intrapulmonary shunt flow of the patient, which can be determined by known processes.

In addition, the best-fit line can be used to estimate mixed venous carbon dioxide content of the patient. Conventionally, total rebreathing techniques have been required to substantially noninvasively measure mixed venous carbon dioxide content. When carbon dioxide elimination eventually ceases during total rebreathing, the partial pressure of carbon dioxide measured at the mouth of a patient may represent the mixed venous carbon dioxide content of the patient. When partial rebreathing techniques are used, the carbon dioxide elimination of the patient is reduced to levels lower than baseline, but is not reduced to zero. By employing teachings of the present invention to determine the best-fit line through data obtained by use of partial rebreathing techniques, the best-fit line can be extended to a point where carbon dioxide elimination would be equal to zero or effectively zero and thereby to determine the carbon dioxide content, or mixed venous carbon dioxide content, of the patient's blood at that point. Equation (11), which is a derivative of the equation for the best-fit line, can be rearranged in terms of carbon dioxide elimination as follows:

$$V_{CO_2}=m\times CaCO_2+b. \tag{22}$$

When carbon dioxide elimination ceases, V_{CO_2} is equal to zero and equation (22) becomes:

$$0=m\times CvCO_2+b, \tag{23}$$

where $CvCO_2$ is the mixed venous carbon dioxide content, which can be rearranged as follows:

$$CvCO_2=-b/m. \tag{24}$$

Accordingly, the present invention also includes a method for substantially noninvasively determining mixed venous carbon dioxide content when partial rebreathing techniques are employed.

Although the foregoing description contains many specifics, these should not be construed as limiting the scope of the present invention, but merely as providing illustrations of some of the presently preferred embodiments. Similarly, other embodiments of the invention may be devised which do not depart from the spirit or scope of the present invention. Features from different embodiments may be employed in combination. The scope of the invention is, therefore, indicated and limited only by the appended claims and their legal equivalents, rather than by the foregoing description. All additions, deletions and modifications to the invention as disclosed herein which fall within the meaning and scope of the claims are to be embraced thereby.

What is claimed is:

1. A method for determining at least one of a pulmonary capillary blood flow and a cardiac output of a patient, comprising:

determining a plurality of data comprising carbon dioxide elimination data and data of an indicator of carbon dioxide content in blood of the patient;

eliminating outlying data points of the plurality of data that do not comprise noise;

identifying a geometric relationship between remaining data points of the carbon dioxide elimination data and corresponding data points of the data of the indicator of carbon dioxide content; and

calculating the pulmonary capillary blood flow or the carbon dioxide content based at least partially on the geometric relationship.

2. The method of claim **1**, wherein identifying the geometric relationship comprises identifying a substantially linear relationship between the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

3. The method of claim 2, wherein identifying the substantially linear relationship comprises determining a best-fit line through the plurality of data.

4. The method of claim 1, wherein identifying the geometric relationship comprises use of linear regression.

5. The method of claim 1, wherein identifying the geometric relationship includes determining a slope of at least a portion of the geometric relationship.

6. The method of claim 1, wherein identifying the geometric relationship is based on all of the carbon dioxide elimination data and the data of the indicator of carbon dioxide obtained during determining the plurality of data.

7. The method of claim 1, wherein determining the plurality of data comprises measuring a partial pressure of carbon dioxide in end tidal respiration of the patient.

8. The method of claim 1, wherein eliminating comprises determining an accuracy with which the geometric relationship corresponds to the plurality of data.

9. The method of claim 8, wherein determining the accuracy comprises determining a correlation coefficient indicative of a correlation between the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

10. The method of claim 1, further comprising filtering at least one of the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

11. The method of claim 10, wherein filtering comprises employing a low-pass filter, a high-pass filter, or a band pass filter.

12. The method of claim 10, wherein filtering comprises employing a geometric or a nongeometric filter.

13. The method of claim 10, wherein filtering comprises filtering the carbon dioxide elimination data.

14. The method of claim 1, wherein elimininating comprises selecting data points to use in the identifying the geometric relationship.

15. The method of claim 14, wherein selecting comprises clustering the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

16. The method of claim 15, wherein clustering is effected before the identifying the geometric relationship.

17. The method of claim 15, further comprising normalizing the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

18. The method of claim 17, wherein normalizing is effected before the clustering.

19. The method of claim 17, wherein normalizing comprises selecting substantially equal ranges for both the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

20. The method of claim 17, further comprising calculating an inverse of the normalizing following clustering and before identifying the geometric relationship.

21. The method of claim 20, wherein calculating the inverse of the normalizing comprises setting ranges for the carbon dioxide elimination data and the data of the indicator of carbon dioxide content back to original values.

22. The method of claim 15, wherein clustering comprises:

identifying a predetermined number of data points having values closest to an analyzed data point selected from one of the carbon dioxide elimination data and the data of the indicator of carbon dioxide content;

calculating differences between each of the predetermined number of data points and the analyzed data point;

summing the differences to obtain a sum;

comparing the sum to a threshold value; and

disregarding the analyzed data point if the sum exceeds the threshold value.

23. The method of claim 15, further comprising filtering at least one of the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

24. The method of claim 14, wherein selecting comprises:

intersecting a first line representing a minimum expected pulmonary capillary blood flow and a second line representing a maximum pulmonary capillary blood flow at an analyzed data point of the data points;

determining a number of others of the data points located between the first line and the second line;

comparing the number to a threshold number; and

retaining the analyzed data point if the number is equal to or greater than the threshold number.

25. The method of claim 24, further comprising repeating at least the intersecting, determining the number of others of the data points, and comparing on at least one other data point of the data points.

26. The method of claim 24, further comprising repeating at least the intersecting, detemining the number of others of the data points, and comparing on each of the data points.

27. The method of claim 24, further comprising filtering at least one of the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

28. The method of claim 24, further comprising clustering the carbon dioxide elimination data and the data of the indicator of carbon dioxide content.

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专利名称(译)	用于准确，基本上非侵入性地确定肺毛细血管血流量，心输出量和混合静脉二氧化碳含量的方法		
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[标]申请(专利权)人(译)	ORR约瑟夫 库克KAI		
申请(专利权)人(译)	ORR JOSEPH A. 库克KAI		
当前申请(专利权)人(译)	RIC投资有限责任公司.		
[标]发明人	ORR JOSEPH A KUCK KAI		
发明人	ORR, JOSEPH A. KUCK, KAI		
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摘要(译)

用于非侵入性地确定患者的肺毛细血管血流量或心输出量的方法包括测量患者呼吸的呼吸流量和二氧化碳压力。这些测量值用于计算二氧化碳消除量和患者血液中二氧化碳含量的指标。确定二氧化碳消除数据与二氧化碳含量指标数据之间的几何关系。修改至少一组数据，并且进行数据之间的几何关系的至少一个其他确定以找到最准确的数据集。可以通过过滤或聚类来修改数据。然后使用几何关系的至少一部分的斜率来确定患者的肺毛细血管血流量或心输出量。