US009414769B2

(12) **United States Patent**
Karst et al.

(10) **Patent No.: US 9,414,769 B2**
(45) **Date of Patent: Aug. 16, 2016**

(54) **METHOD FOR DETERMINING HEMODYNAMIC EFFECTS**

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

(21) Appl. No.: **13/971,478**

(22) Filed: **Aug. 20, 2013**

(65) **Prior Publication Data**

US 2013/0338514 A1 Dec. 19, 2013

Related U.S. Application Data

(63) Continuation of application No. 12/561,960, filed on Sep. 17, 2009, now Pat. No. 8,551,006.

(60) Provisional application No. 61/097,763, filed on Sep. 17, 2008.

(51) **Int. Cl.**
A61B 5/08 (2006.01)
A61B 5/029 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***A61B 5/0806*** (2013.01); ***A61B 5/0205*** (2013.01); ***A61B 5/029*** (2013.01); ***A61B 5/14551*** (2013.01); *A61B 5/4035* (2013.01)

(58) **Field of Classification Search**
CPC A61B 5/0806; A61B 5/0205; A61B 5/029; A61B 5/14551; A61B 5/022; A61B 5/026
USPC 600/507, 504, 481, 483, 484
See application file for complete search history.

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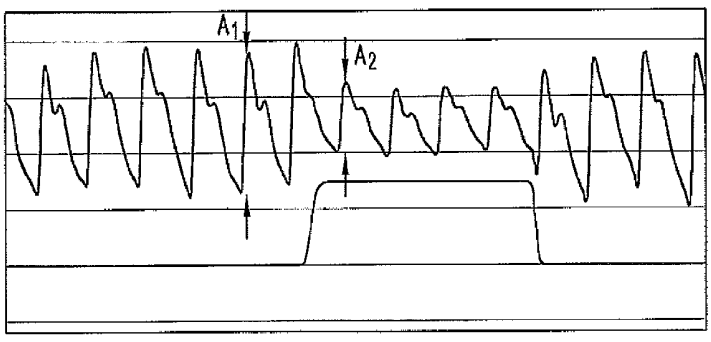
(57) **ABSTRACT**

The present disclosure relates, in some embodiments, to devices, systems, and/or methods for collecting, processing, and/or displaying stroke volume and/or cardiac output data. For example, a device for assessing changes in cardiac output and/or stroke volume of a subject receiving airway support may comprise a processor; an airway sensor in communication with the processor, wherein the airway sensor is configured and arranged to sense pressure in the subject's airway, lungs, and/or intrapleural space over time; a blood volume sensor in communication with the processor, wherein the blood volume sensor is configured and arranged to sense pulsatile volume of blood in a tissue of the subject over time; and a display configured and arranged to display a representative of an airway pressure, a pulsatile blood volume, a photoplethysmogram, a photoplethysmogram ratio, the determined cardiac output and/or stroke volume, or combinations thereof. A method of assessing changes in cardiac output or stroke volume of a subject receiving airway support from a breathing assistance system may comprise sensing pressure in the subject's airway as a function of time, sensing pulsatile volume of blood in a tissue of the subject as a function of time, producing a photoplethysmogram from the sensed pulsatile volume, determining the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation, and determining the change in cardiac output or stroke volume of the subject using the determined ratio.

20 Claims, 2 Drawing Sheets



(51) **Int. Cl.**

A61B 5/1455	(2006.01)
A61B 5/0205	(2006.01)
A61B 5/00	(2006.01)

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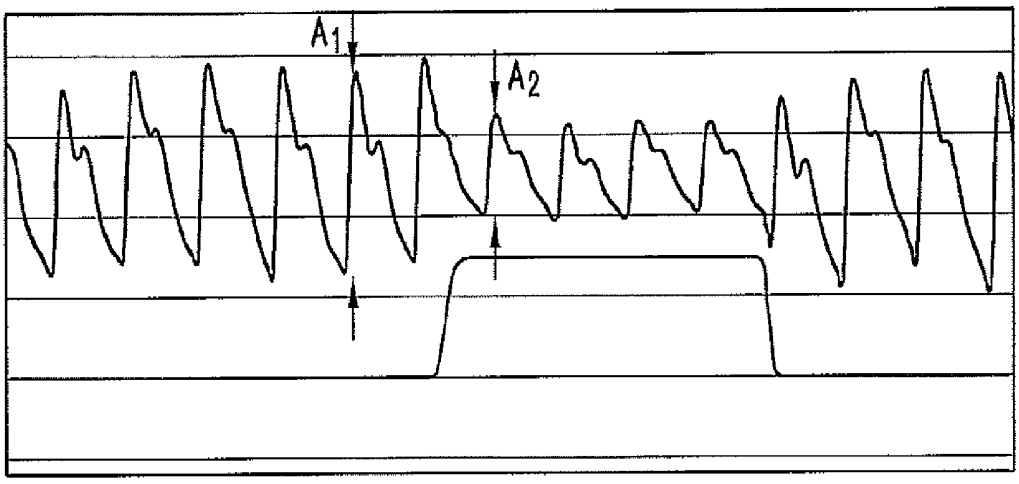
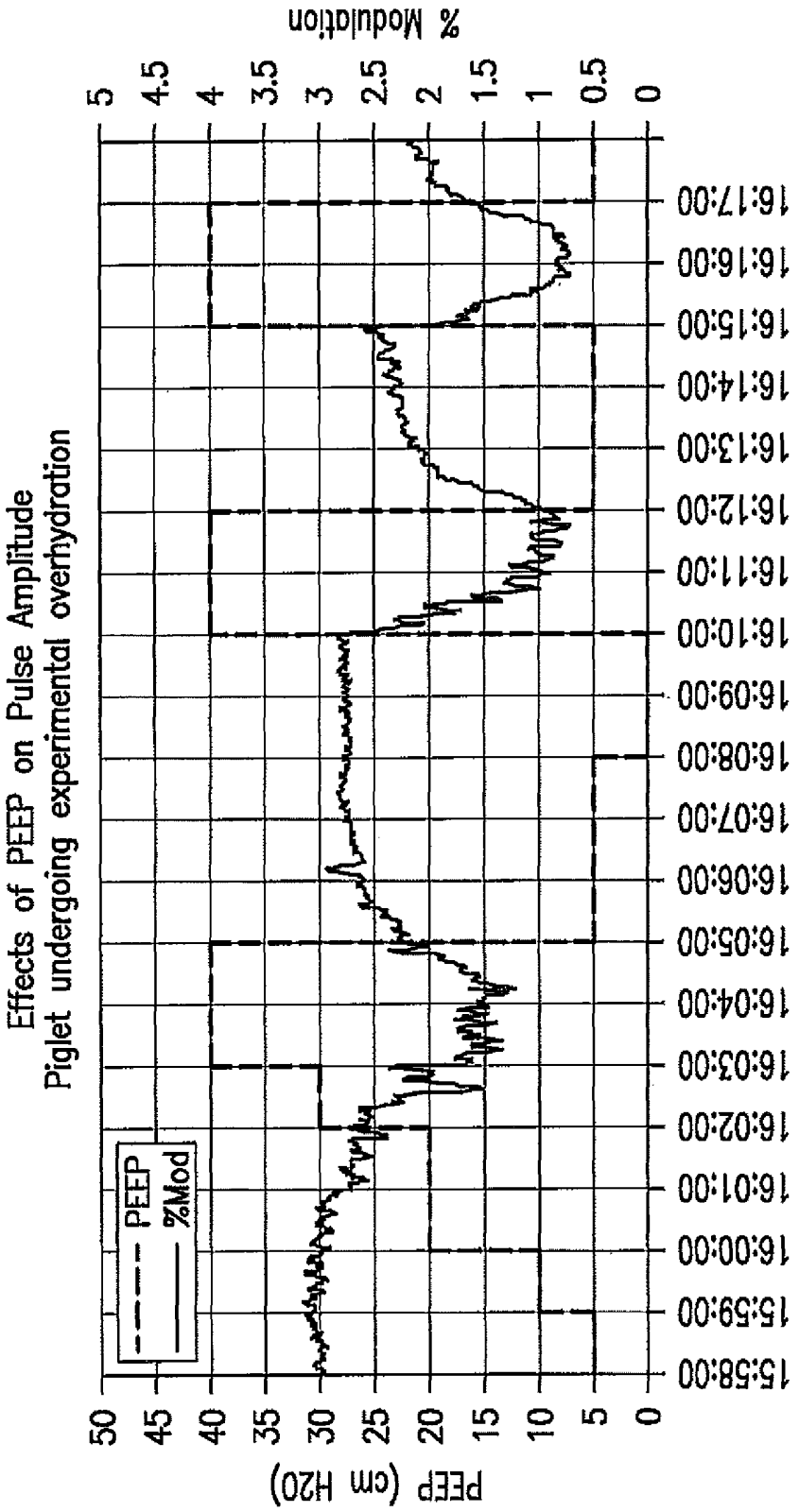


FIG. 1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PEEP (cm H2O)
% Modulation
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10
15
20
25
30
35
40
45
50
0
0.5
1
1.5
2
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16:09:00
16:10:00
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FIG. 2

METHOD FOR DETERMINING HEMODYNAMIC EFFECTS

RELATED APPLICATIONS

This application is a continuation application of and claims the benefit of priority from U.S. patent application Ser. No. 12/561,960, filed on Sep. 17, 2009, now issued U.S. Pat. No. 8,551,006 which claims priority to U.S. Patent Application Ser. No. 61/097,763, filed on Sep. 17, 2008, the entire disclosures of which are hereby incorporated herein by reference.

FIELD OF THE DISCLOSURE

The present disclosure relates, in some embodiments, to devices, systems, and/or methods for collecting, processing, and/or displaying stroke volume and/or cardiac output data.

BACKGROUND OF THE DISCLOSURE

Most oxygen delivered to tissue is carried by hemoglobin. The proportion of oxygen delivered by hemoglobin may drop somewhat for a patient breathing very high levels of oxygen, however. A pulse oximeter may use the time-varying optical response of different wavelengths of light traveling through tissue to estimate pulse rate and the fraction of hemoglobin that carries oxygen molecules in the pulsatile portion. Each data point in the pulse oximeter's time series of optical response measurements represents the quantity of those photons of light that travel on a path from light emitter to light detector and are successfully measured by the detector. The signal level may be reduced by, for example, optical attenuation and scattering of tissue along the path from emitter to detector.

A pulse oximeter may measure changes in the amount of hemoglobin in a local area, along with the spectral response of the changes, over a cardiac cycle, without the need for an absolute reference. A photoplethysmogram (PPG) is an inverted, bandpass filtered graph of the optical response at one wavelength or a combination of wavelengths with respect to time. The ratio of pulse-synchronous change in absorption (PPG modulation) to average signal level is sometimes referred to as percent modulation, although this number depends on the relative quantities of different types of hemoglobin and other absorbers.

An optical sensor may be positioned at a tissue site on a subject that includes a concentration of smaller blood vessels. The light transmitted through these smaller blood vessels may decrease during the pressure wave of systole because of an attending greater volume of absorbers in the distended vessels of the vascular tree. The optical signal may rebound (e.g., increase) during diastole when lower pressure allows the amount of absorbers to decrease. Although the flow of fresh blood may take many seconds to travel to a peripheral site, the pressure waveform traverses the pressurized arterial tree within a much shorter time span. Vascular resistance and compliance of the small arteries, arterioles and capillaries reduces pressure and largely damps out any pulse-synchronous volume changes distal to these vessels.

Empirical calibrations of pulse oximeters using blood-gas measurements may include one or more assumptions that impact accuracy. For example, while tissue sites where pulse oximeters may be used may include arteries and arterioles as the primary conduit for delivering oxygen-rich blood from the left heart to tissue, these tissue sites generally comprise several other tissues and/or structures.

A number of factors may affect average optical response and pulse-synchronous modulation, particularly at peripheral sensor sites such as the finger, ear or foot. The body's control of circulation to the periphery is particularly used for temperature regulation, with vasodilation increasing peripheral blood flow to disperse heat and vasoconstriction acting to minimize the body's loss of heat. Local blood perfusion adapts based on tissue needs and metabolic activity. Drugs, therapies and shifts in fluid or electrolyte content may lead to changes in the distribution of systemic blood flow to the various organs, including the skin. This may also lead to changes in optical response and modulation. Shock, trauma or infection may cause adjustments in blood distribution. Changes in cerebral, muscular, renal or splanchnic circulation, hormonal activity and disease states also may have a significant influence on peripheral blood flow.

These factors may make it difficult to estimate the heart's total stroke volume based on the measurement of blood volume changes at a single sensor site. A "perfusion index" may be used on some occasions, but such a parameter may not adequately account for the myriad influences on distribution of blood flow to different parts of the body. Thus, a perfusion index at a peripheral sensor location may not provide a direct indication of stroke volume and cardiac output, nor even the adequacy of tissue perfusion at the sensor site.

SUMMARY

Accordingly, a need has arisen for improved devices, systems, and methods for determining stroke volume and/or cardiac output of a subject.

The present disclosure relates, in some embodiments, to devices, systems, and/or methods for collecting, processing, and/or displaying stroke volume and/or cardiac output data. According to some embodiments, a device for assessing changes in cardiac output and/or stroke volume of a subject receiving airway support from a breathing assistance system may comprise a processor; an airway sensor in communication with the processor, wherein the airway sensor is configured and arranged to sense pressure in the subject's airway, lungs, and/or intrapleural space over time; a blood volume sensor in communication with the processor, wherein the blood volume sensor is configured and arranged to sense pulsatile volume of blood in a tissue of the subject over time; and a display configured and arranged to display a representative of an airway pressure, a pulsatile blood volume, a photoplethysmogram, a photoplethysmogram ratio, the determined cardiac output and/or stroke volume, or combinations thereof. A processor of a device may be configured and arranged, in some embodiments, to (a) produce a photoplethysmogram, (b) determine a photoplethysmogram ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation, and (c) determine the change in cardiac output and/or stroke volume of the subject using the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation.

In some embodiments, a device for assessing changes in cardiac output or stroke volume of a subject receiving airway support from a breathing assistance system may comprise an airway sensor configured and arranged to sense pressure in the subject's airway, lungs, and/or intrapleural space over time; a blood volume sensor configured and arranged to sense pulsatile volume of blood in a tissue of the subject over time; a processor configured and arranged (a) to receive input from the airway sensor and the blood volume sensor, (b) to produce a photoplethysmogram; (c) to determine a photoplethysmo-

gram ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation, and (d) to determine the change in cardiac output and/or stroke volume of the subject using the determined ratio; and a display configured and arranged to display a representative of a parameter selected from the group consisting of the sensed airway pressure, the sensed pulsatile blood volume, the photoplethysmogram, the determined ratio, the determined cardiac output and/or stroke volume, combinations thereof. The airway sensor of a device for assessing changes in cardiac output or stroke volume of a subject, according to some embodiments, may be configured and arranged to sense pressure in the subject's airway intermittently and/or continuously. The blood volume sensor of a device for assessing changes in cardiac output or stroke volume of a subject may be configured and arranged to sense pulsatile volume of blood in a tissue of the subject intermittently and/or continuously in some embodiments. The blood volume sensor of a device for assessing changes in cardiac output or stroke volume of a subject, according to some embodiments, may be comprised in a pulse oximeter. In some embodiments, the representative of a parameter may be the actual parameter value. The representative of a parameter may be a graphical representation of the actual parameter value according to some embodiments. The breathing assistance system of a device for assessing changes in cardiac output or stroke volume of a subject, in some embodiments, may be selected from the group consisting of a ventilator, a respirator, a CPAP device, a BiPAP device, and combinations thereof. According to some embodiments, a device for assessing changes in cardiac output or stroke volume of a subject may further comprise a pulse rate sensor in communication with the processor. The processor of a device for assessing changes in cardiac output or stroke volume of a subject may be configured and arranged to calculate cardiac output by multiplying the stroke volume by the pulse rate in some embodiments.

A system for assessing changes in cardiac output or stroke volume of a subject may comprise, according to some embodiments, (a) a breathing assistance system, (b) a pulse oximeter comprising a blood volume sensor, (c) a display system, and (d) a processor in communication with the breathing assistance system, the display system, and the pulse oximeter, wherein the processor is configured and arranged to (a) produce a photoplethysmogram, (b) determine the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation, and (c) determine the change in cardiac output or stroke volume of the subject using the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation. In some embodiments, (a) a breathing assistance system may comprise (1) a ventilation system, (2) an airway connection system configured and arranged to link the ventilation system and the subject's airway, and/or (3) an airway pressure sensor configured and arranged to detect pressure in the ventilation system and/or the subject's airway. The airway sensor of a system for assessing changes in cardiac output or stroke volume of a subject may be configured and arranged to sense pressure in the subject's airway (e.g., airway, lungs, and/or intrapleural space) intermittently and/or continuously according to some embodiments. The blood volume sensor of a system for assessing changes in cardiac output or stroke volume of a subject, in some embodiments, may be configured and arranged to sense pulsatile volume of blood in a tissue of the subject intermittently and/or continuously. According to some embodiments, the breathing assistance system of a system for assessing changes in cardiac output or stroke volume of a subject may be selected from the group consisting of a ventilator, a respirator, a CPAP device, a BiPAP device, and combinations thereof. The processor of a system for assessing changes in cardiac output or stroke volume of a subject may be configured and arranged to calculate cardiac output by multiplying the stroke volume by the pulse rate in some embodiments.

A method of assessing changes in cardiac output or stroke volume of a subject receiving airway support from a breathing assistance system, in some embodiments, may comprise sensing pressure in the subject's airway as a function of time, sensing pulsatile volume of blood in a tissue of the subject as a function of time, producing a photoplethysmogram from the sensed pulsatile volume, determining the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation, and determining the change in cardiac output or stroke volume of the subject using the determined ratio. According to some embodiments, a method of assessing changes in cardiac output or stroke volume of a subject receiving airway support from a breathing assistance system may further comprise displaying a representative of the sensed pressure, the sensed pulsatile blood volume, the photoplethysmogram, the determined ratio, the determined cardiac output or stroke volume, or combinations thereof. A method of assessing changes in cardiac output or stroke volume of a subject receiving airway support from a breathing assistance system may further comprise sensing the subject's pulse in some embodiments. A method may further comprise, according to some embodiments, calculating the change in cardiac output by multiplying the change in cardiac output or stroke volume by the sensed pulse. In some embodiments, sensing pulsatile volume of blood in a tissue of the subject may comprise sensing pulsatile volume of blood in a subject's finger, ear, forehead or foot. A method of assessing changes in cardiac output or stroke volume of a subject receiving airway support from a breathing assistance system may further comprise referencing the stroke volume to a parameter selected from the group consisting of zero end-expiratory pressure, current active breathing assistance system control settings, and combinations thereof according to some embodiments.

According to some embodiments, a method of predicting the effect of changes in ventilation settings on stroke volume of a ventilated subject may comprise sensing pressure in the subject's airway during at least one breathing cycle comprising an inhalation and an exhalation, producing a photoplethysmogram spanning the at least one breathing cycle, determining the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation, determining the change in cardiac output or stroke volume of the subject using the determined ratio, referencing the stroke volume to current active ventilation settings of the breathing assistance system, and combinations thereof, and comparing the change in changes in ventilation settings to the current active ventilation settings. The change in ventilation settings, in some embodiments, may comprise a change in a setting selected from the group consisting of positive end-expiratory pressure (PEEP), continuous positive airway pressure, inspiratory pressure target, inspiratory volume target, LE ratio, and combinations thereof.

In some embodiments, a method of assessing the relative strength of an autonomic neural response of a subject connected to a breathing assistance system may comprise determining the cardiac output of the subject at a first airway pressure, changing the subject's airway pressure to a second

airway pressure, monitoring the cardiac output of the subject at the second airway pressure, comparing the cardiac output of the subject at the second airway pressure with the cardiac output of the subject at the first airway pressure, measuring the time required for the cardiac output of the subject at the second airway pressure to return to the cardiac output of the subject at a first airway pressure, and comparing the required time to a reference time to determine the relative strength of an autonomic neural response of the subject.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the disclosure may be understood by referring, in part, to the present disclosure and the accompanying drawings, wherein:

FIG. **1** illustrates a photoplethysmogram (top) and airway pressure (bottom) according to a specific example embodiment of the disclosure, wherein PPG amplitude is reduced during an inspiratory pressure plateau; and

FIG. **2** illustrates changes in percent modulation (measured by a NELLCOR N-600 pulse oximeter) as a function of PEEP in an experimental animal model (e.g., an anesthetized piglet with healthy lungs undergoing fluid volume expansion by 30% of body weight).

DETAILED DESCRIPTION

For a subject (e.g., a patient) undergoing positive pressure ventilation or CPAP, a potential complication is the possibility of hemodynamic compromise. Depending on lung compliance and airway resistance, positive airway pressure exerted by a mechanical ventilator or a CPAP may device result in increased intrapleural pressure. There may exist a transfer function between airway pressure measured by a ventilator and intrapleural pressure exerted by the volume of gas in the lungs. A transfer function may vary (e.g., significantly) across a population and may change within an individual subject. To evaluate the effect of ventilation on hemodynamics, it may be desirable to sense (e.g., measure and/or estimate) pressure in the ventilator circuit, at the airway, in the lungs, and/or in the intrapleural space. The transmural pressure exerted on the vena cavae and other large veins, which may be at the lowest pressure of any part of the systemic circulation, may tend to inhibit venous return for some individuals. The immediate response to the resulting reduction in cardiac preload may be a lower stroke volume.

However, the intrapleural pressure also may act to reduce the effect of cardiac afterload, potentially adding to stroke volume. For individuals with high vascular volume and those with congestive heart failure (CHF), the increased intrapleural pressure may improve stroke volume by minimizing volume overload in the heart and great vessels. Balancing the need for respiratory support and hemodynamic stability often results in tradeoffs in clinical decision-making, such as adjustment of ventilator settings, fluid administration, and/or use of vasoactive drugs.

Because the respiratory cycle usually takes place over a matter of several seconds, it is both longer than the typical cardiac cycle and shorter than the time scale of shifts in blood distribution (e.g., the shifts described in the Background section). Resistances and elastances of the blood vessels may respond to the altered stroke volume over a course of time. Cardiovascular effects brought about by changes in thoracic pressure appear as modulation of the PPG waveform measured by a pulse oximetry sensor within the transit time of the pressure wave to the sensor site. Thus the breath-synchronous modulation of absorbers in the tissue probed by the pulse oximeter is a reflection of the short-term changes in stroke volume. In the simplest example of a pressure-targeted breath, as shown in FIG. **1**, the envelope of the PPG waveform provides a direct indicator of the changes in stroke volume over the respiratory cycle. The amplitude ratio correlates with the stroke volume:

$$\frac{A_2}{A_1} \propto \frac{\text{Stroke volume during inspiration}}{\text{Stroke volume during exhalation}}$$

Expressed another way, the reduction in stroke volume during inspiration compared to a baseline stroke volume during exhalation is a function of the PPG modulation:

$$\frac{A_2}{A_1} - 1 \propto \Delta SV$$

Modulation of the PPG decreases during the inspiratory period, when there is a higher airway pressure plateau, and increases again to its previous level during exhalation.

The present disclosure relates to the use of the change in the PPG amplitude and/or or perfusion index to quantify the effect of airway pressure delivered by a positive pressure ventilator or CPAP device on stroke volume. Changes in cardiac output may be calculated from the product of stroke volume and heart rate (e.g., instantaneous heart rate). For individuals with pressure-targeted modes of ventilation, there may be two distinct pressure levels at which the relative cardiac output may be measured (e.g., the inspired pressure target (PIP) and exhalation pressure target (PEEP)). Calculations over multiple breaths provide increasing accuracy of the computations. For bi-level ventilation, there may be likewise multiple stable pressure plateaus (e.g., high and low PEEP settings). If an ascending (e.g., slowly ascending) ramp in pressure (i.e., the time for the ventilator to reach the inspired pressure target is longer than one or two pulse periods) is used to deliver gas to the patient, these intermediate pressures may also be used to detect relative changes in cardiac output, and/or pressure thresholds at which they occur, by analyzing the relationship of the pulse-to-pulse PPG amplitude with a time-synchronous measurement or estimate of airway, lung, or intrapleural pressure. While a gradual ascending pressure ramp may be explicitly set in pressure-target ventilation, similar ramps in pressure will typically occur in volume-targeted and spontaneous breathing modes (e.g., pressure support and proportional assist ventilation). When the relationship between a gradually ramping airway pressure and the PPG amplitude is being evaluated, it may be desirable to adjust the airway pressure for the pressure drop due to the resistance and/or compliance of the airway, endotracheal tube, and lungs, for example, where these factors may create significant time delays in transferring changes in airway pressure to the lungs. Some methods for assessing these aspects of respiratory mechanics are known to those skilled in the art of mechanical ventilation.

The ventilator or CPAP may also deliver deliberate modulations in airway pressure at moments of minimal airflow or spontaneous respiratory effort as a means of calculating the relative change in cardiac output. Such maneuvers include delivering breaths of known or above-target inspiratory pressure, delivering an exhalation pressure above the PEEP setting, and delivering brief end-inspiratory pauses prior to permitting exhalation.

The technique may include referencing some or all modulations in stroke volume and cardiac output to a baseline measurement at zero end-expiratory pressure (ZEEP) (e.g., atmospheric pressure), at a nominally low PEEP level (i.e., under 5 cm H_2O), and/or to the current active ventilator settings. The dependence of stroke volume or cardiac output on airway pressure may be plotted as a graph showing the percent reduction, or increase, compared to a measured or extrapolated reference level such as ZEEP.

Using the established relationship between airway pressure and cardiac output, the ventilator may be configured and arranged to predict the change in cardiac output arising from any adjustment in ventilator settings. Predicted hemodynamic effects of settings may be based on interpolated values or extrapolated from the shape of the relationship between airway pressure and cardiac output. For example, if the operator desired to increase PEEP, the ventilator may interpolate (e.g., via a processor) the change in cardiac output at the desired PEEP setting and the overall change in cardiac output across the respiratory cycle. For patients with CHF or volume overload, this technique may be especially useful, for example, where the ventilator displays the amount of PEEP that should be added to optimize cardiac output. Other ventilatory parameters that may be adjusted to improve cardiac output include, without limitation, ratio of inspiratory to expiratory time (I:E ratio), peak inspiratory pressure, volume delivered, and percent support, depending on the ventilatory mode.

A reduced envelope of the PPG at the inspiratory pressure plateau may not occur for all individuals. For example, if external pressure reduces cardiac output, a subject's autonomic nervous system may attempt to compensate by increasing ventricular inotropy and/or heart rate. This compensation (or lack thereof) may serve as an indicator of the degree to which mechanical ventilation compromises hemodynamic stability. For example, hemodynamic stability may not be compromised in a subject who experiences rapid and complete compensation for pressure-induced stroke volume modulation. Individuals with reduced autonomic response, on the other hand, may display a sharp change in PPG envelope at the beginning of the inspiratory pressure plateau, followed by a gradual return to the previous amplitude as the balance of sympathetic and parasympathetic effects adjusts. In some embodiments, this indicator may also correlate with depth of sedation, or with level of neural or medullary center activity.

According to some embodiments, the present disclosure relates to devices, systems, and methods for (1) detecting the vitality and sensitivity of the autonomic response, (2) detecting the depth of sedation, and/or (3) detecting neural and/or medullary center activity, comprising detecting a time-varying response of the PPG waveform to a pressure change and determining whether the response exceeds a preselected threshold.

According to some embodiments, the present disclosure relates to devices, methods, and/or systems for measuring modulation of stroke volume and cardiac output as a function of airway pressure provided by a breathing assistance system. For example, methods for assessing changes in stroke volume and/or cardiac output in a subject receiving respiratory support (e.g., with a ventilator and/or CPAP device), may include (a) detecting the subject's airway pressure, (b) detecting a photoplethysmogram signal having an amplitude, and (c) processing the airway pressure and the detected photoplethysmogram signal to produce a relative indication of changes in stroke volume and/or cardiac output of the subject. According to some embodiments, a photoplethysmogram signal may be detected with a pulse oximeter. Computing the indication of stroke volume and/or cardiac output may include processing the airway pressure to detect a respiratory cycle consisting of an inhalation and an exhalation. Computing the indication of stroke volume and/or cardiac output may include producing a PPG and determining the ratio of the PPG amplitude during an inspiration to the PPG amplitude during exhalation.

A breathing assistance system may be configured to provide breathing assistance (e.g., providing ventilation and/or treating an apnea or other breathing condition) to a subject (e.g., a patient). A breathing assistance system may include a ventilation system, a connection system for linking the breathing assistance system to at least a portions subject's airway, and optionally a display system and/or a display connection port. A display connection port may be configured and arranged to communicate (e.g., wired or wirelessly) with a display (e.g., a touch screen, an LCD, a projector, and/or a printer).

A ventilation system may comprise any device, apparatus, and/or system for delivering breathing gas to a patient. For example, a ventilation system may include a ventilator, a respirator, a CPAP device, or a BiPAP device. A ventilation system may include a gas delivery system, a control system, and one or more sensors. In addition, in some embodiments, a ventilation system may include a display system, while in other embodiments, a display system may be distinct form the ventilation system.

A connection system may be configured to deliver gas from a ventilation system to a subject (e.g., a patient) and/or to remove exhaust gas away from the subject. For example, a connection system may comprise any suitable type of breathing circuit (e.g., a single-limb or dual-limb circuit) and/or a patient connection apparatus. The patient connection apparatus may include any device or devices configured to connect the breathing circuit to one or more breathing passageways of the subject. For example, the patient connection apparatus may include a patient connection tube directly connected to the subject's trachea, an artificial airway (e.g., an endotracheal tube or other device) inserted in the subject's trachea, and/or a mask, cushion or nasal pillows positioned over the subject's nose and/or mouth. In embodiments including a patient connection tube, the patient connection tube may include a Wye (or "Y") connector.

A display may be operable to display various data regarding a subject, the operation of a ventilation system, the ventilation of a subject, and/or any other relevant data. A display system may be fully or partially integrated with a ventilation system. In some embodiments, a display system may be part of or otherwise associated with, a graphic user interface, which may be configured to display various information and/or provide an interface (e.g., a touch screen) for accepting input from human operators (e.g., to set or modify ventilation settings, to access data, to change or configure the display, to select and/or modify 3-D waveform representations, etc.). A display device may comprise any type of printer, screen or other visual display for displaying information regarding the patient's breathing patterns and/or the operation of a breathing assistance system. Information displayed may include actual data and/or representations thereof.

A device (e.g., a breathing assistance system, a display system, and/or a device for determining stroke volume and/or cardiac output) may include, according to some embodiments, a processor. A processor may include any system or device for executing code or logic instructions (e.g., software or firmware) for controlling display device, such as a microcontroller, a digital signal processor (DSP), an application

specific integrated controller (ASIC), electrically-programmable read-only memory (EPROM), or a field-programmable gate array (FPGA), for example.

The present disclosure, according to some embodiments, relates to devices, methods, and/or systems for predicting the effect of proposed changes in ventilation settings (e.g., positive end-expiratory pressure (PEEP) and/or CPAP, inspiratory pressure target or I:E ratio (i.e., the ratio of total inspiration time to total exhalation time in a single ventilation cycle)) on stroke volume and/or cardiac output, wherein the proposed changes would alter mean intrapleural pressure. For example, methods for predicting the effect of a ventilator setting change on stroke volume and/or cardiac output may include (a) sensing pressure in the subject's airway, lung, or intrapleural space during at least one breathing cycle comprising an inhalation and an exhalation, (b) producing a photoplethysmogram spanning the at least one breathing cycle, (c) determining the ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation (d) determining the relative change in cardiac output and/or stroke volume of the subject using the determined ratio, (e) referencing the stroke volume to current active ventilation settings of the breathing assistance system, and combinations thereof, and (f) comparing the proposed changes in ventilation settings to the current active ventilation settings.

In some embodiments, the disclosure relates to devices, methods, and/or systems for evaluating the strength of an autonomic neural response based on timing of cardiovascular changes in reaction to ventilatory artifact. For example, a method of assessing the relative strength of an autonomic neural response of a subject connected to a breathing assistance system may comprise (a) determining an indication of the cardiac output and/or stroke volume of the subject at a first airway pressure, (b) changing the subject's airway pressure to a second airway pressure, (c) monitoring the indication of the cardiac output and/or stroke volume of the subject at the second airway pressure, (d) comparing the indication of cardiac output or stroke volume of the subject at the second airway pressure with the cardiac output and/or stroke volume of the subject at the first airway pressure, (e) measuring the time required for the indication of cardiac output and/or stroke volume of the subject at the second airway pressure to return to the level of cardiac output and/or stroke volume of the subject at the first airway pressure, and (f) comparing the required time to a reference time to determine the relative strength of an autonomic neural response of the subject.

As will be understood by those skilled in the art who have the benefit of the instant disclosure, other equivalent or alternative compositions, devices, methods, and systems for determining cardiac output and/or stroke volume can be envisioned without departing from the description contained herein. Accordingly, the manner of carrying out the disclosure as shown and described is to be construed as illustrative only.

Persons skilled in the art may make various changes in the shape, size, number, and/or arrangement of parts without departing from the scope of the instant disclosure. For example, the position and number of airway and blood plethysmographic sensors may be varied. In addition, the size of a device and/or system may be scaled up (e.g., to be used for adult subjects) or down (e.g., to be used for neonatal subjects) to suit the needs and/or desires of a practitioner. Also, where ranges have been provided, the disclosed endpoints may be treated as exact and/or approximations as desired or demanded by the particular embodiment. In addition, it may be desirable in some embodiments to mix and match range endpoints. All or a portion of a device and/or system for determining relative changes in cardiac output and/or stroke volume may be configured and arranged to be disposable, serviceable, interchangeable, and/or replaceable. These equivalents and alternatives along with obvious changes and modifications are intended to be included within the scope of the present disclosure. Accordingly, the foregoing disclosure is intended to be illustrative, but not limiting, of the scope of the disclosure as illustrated by the following claims.

EXAMPLES

Some specific example embodiments of the disclosure may be illustrated by one or more of the examples provided herein.

Example 1

In a ventilated animal subject, PEEP was gradually increased over five minutes from 5 to 40 cm H_2O and a roughly 50% decrease in PPG modulation (from 3.0% to 1.5%) was observed (FIG. **2**). In addition, a 65-70% decrease in PPG modulation (from 2.7% to % 0.9 and subsequently 2.4% to 0.8%) each of the two times that PEEP was increased in a single step from zero to 40 cm H_2O (FIG. **2**). Thus, modest reductions in PPG modulation occurred at 16:02:00 with when PEEP was increased from 20 to 30 cm H_2O, with very pronounced reductions in PPG amplitude for each of the periods when PEEP was increased to 40 cm H_2O.

This example indicates that that this particular animal subject experienced roughly 50% and later 65-70% reductions in stroke volume at a result of experiencing an airway pressure at or above 40 cm H_2O. Without necessarily limiting any particular embodiment to any specific mechanism of action, the smaller relative reduction in PPG modulation when PEEP was increased gradually may be due to difference in autonomic response.

What is claimed is:

1. A method of assessing changes in stroke volume or cardiac output of a ventilated subject, the method comprising:

sensing pressure in the ventilated subject's airway during at least one breathing cycle comprising an inhalation and an exhalation with an airway sensor;

sensing a blood volume in the ventilated subject during the at least one breathing cycle with a blood volume sensor;

producing a photoplethysmogram spanning the at least one breathing cycle using the blood volume sensed by the blood volume sensor;

determining, with a breathing assistance system, a ratio of the amplitude of the photoplethysmogram during inhalation to the amplitude of the photoplethysmogram during exhalation; and

determining, with the breathing assistance system, a change in cardiac output or stroke volume of the subject using the determined amplitude ratio.

2. The method of according to claim **1**, further comprising:

referencing a stroke volume to current active ventilation settings of the breathing assistance system; and

comparing changes in ventilation settings to the current active ventilation settings.

3. The method of according to claim **2**, further comprising:

determining a change in ventilation settings based on the change in cardiac output or stroke volume, wherein the change in ventilation settings comprises a change in a setting selected from the group consisting of positive end-expiratory pressure (PEEP), continuous positive

airway pressure, inspiratory pressure target, inspiratory volume target, I:E ratio, and combinations thereof.

4. The method of according to claim **2**, further comprising:

displaying at least one of a representative parameter of the sensed airway pressure, a sensed pulsatile blood volume, the produced photoplethysmogram, the determined photoplethysmogram amplitude ratio, the cardiac output, or the stroke volume, the determined change in the cardiac output, the stroke volume.

5. The method of according to claim **2**, wherein a representative parameter is a graphical representation of an actual parameter value.

6. The method of according to claim **2**, wherein a representative parameter is an actual parameter value.

7. The method of according to claim **2**, further comprising:

sensing a pulse rate of the subject.

8. The method of according to claim **7**, further comprising:

determining the stroke volume of the subject from the determined photoplethysmogram amplitude ratio;

calculating a cardiac output by multiplying the stroke volume by the pulse rate.

9. The method of according to claim **2**, further comprising:

changing the current active ventilation settings based on the comparing of the changes in ventilation settings to the current active ventilation settings,

wherein the current active ventilation settings include at least one of positive-end expiratory pressure (PEEP), ratio of inspiratory time to expiratory time (I:E ratio), peak inspiratory pressure, volume delivered, and percent support.

10. The method of according to claim **1**, further comprising:

determining the stroke volume of the subject from the determined photoplethysmogram amplitude ratio;

referencing the stroke volume to a parameter selected from a group consisting of zero end-expiratory pressure, current active breathing assistance system control settings, and combinations thereof.

11. A method of assessing a relative strength of an autonomic neural response of a subject connected to a breathing assistance system, the method comprising:

determining a cardiac output of the subject at a first airway pressure;

changing the subject's airway pressure to a second airway pressure via the breathing assistance system;

monitoring the cardiac output of the subject at the second airway pressure;

comparing, with the breathing assistance system, the cardiac output of the subject at the second airway pressure with the cardiac output of the subject at the first airway pressure;

measuring a time required for the cardiac output of the subject at the second airway pressure to return to the cardiac output of the subject at a first airway pressure;

comparing, with the breathing assistance system, the required time to a reference time; and

determining, with the breathing assistance system, the relative strength of an autonomic neural response of the subject using the comparing of the required time to the reference time.

12. The method of according to claim **11**, further comprising:

displaying at least one of a representative parameter of a sensed airway pressure, a pulsatile blood volume, a cardiac output and a stroke volume.

13. The method of according to claim **11**, further comprising:

displaying at least one of the required time and the reference time.

14. The method of according to claim **11**, further comprising:

displaying the determined relative strength of the autonomic neural response of the subject.

15. A processor comprising memory and a device, wherein the memory stores logic instructions and the device-executes the logic instructions stored on the memory, the logic instructions comprising:

instructions to produce a photoplethysmogram spanning at least one breathing cycle using processed sensor input;

instructions to determine a ratio of an amplitude of the photoplethysmogram during inhalation to an amplitude of the photoplethysmogram during exhalation; and

instructions to determine a change in cardiac output or stroke volume of a subject using the determined ratio.

16. The processor of claim **15**, wherein the logic instructions further comprise:

instructions to monitor pressure in the subject's airway during at least one breathing cycle comprising an inhalation and an exhalation; and

instruction to monitor pulsatile volume of blood in a tissue of the subject as a function of time.

17. The processor of claim **15**, wherein the logic instructions further comprise:

instructions to determine the stroke volume of the subject from the determined photoplethysmogram amplitude ratio;

instructions to calculate a cardiac output by multiplying the stroke volume by the pulse rate; and

instructions to display at least one of a representative parameter of an airway pressure, a pulsatile blood volume, the produced photoplethysmogram, the determined photoplethysmogram amplitude ratio, the cardiac output, the stroke volume, or the determined change in the cardiac output.

18. The method of according to claim **17**, wherein the representative parameter is a graphical representation of an actual parameter value.

19. The method of according to claim **15**, wherein the logic instructions further comprise:

instructions to sense a pulse rate of the subject.

20. The method of according to claim **19**, wherein the logic instructions further comprise:

instructions to calculate a cardiac output by multiplying a stroke volume by the pulse rate.

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专利名称(译)	确定血液动力学效应的方法		
公开(公告)号	US9414769	公开(公告)日	2016-08-16
申请号	US13/971478	申请日	2013-08-20
[标]申请(专利权)人(译)	柯惠有限合伙公司		
申请(专利权)人(译)	COVIDIEN LP		
当前申请(专利权)人(译)	COVIDIEN LP		
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IPC分类号	A61B5/08 A61B5/029 A61B5/1455 A61B5/0205 A61B5/00		
CPC分类号	A61B5/029 A61B5/14551 A61B5/0205 A61B5/0806 A61B5/4035		
助理审查员(译)	TRAN，THO		
优先权	61/097763 2008-09-17 US		
其他公开文献	US20130338514A1		
外部链接	Espacenet USPTO		

摘要(译)

在一些实施例中，本公开涉及用于收集，处理和/或显示每搏输出量和/或心输出量数据的装置，系统和/或方法。例如，用于评估接收气道支持的受试者的心输出量和/或每搏输出量的变化的装置可包括处理器;气道传感器，其与处理器连通，其中气道传感器被配置和布置成随时间感测受试者的气道，肺和/或胸膜腔内的压力;血液传感器，其中血液容量传感器被配置和布置成随时间检测受试者组织中的脉动血量;显示器，其配置和布置成显示气道压力，脉动血容量，光电容积描记图，光电容积描记图比，确定的心输出量和/或每搏输出量或其组合的代表。评估从呼吸辅助系统接收气道支持的受试者的心输出量或每搏输出量的变化的方法可以包括感测受试者的气道中的压力作为时间的函数，感测受试者的组织中的血液的脉动体积作为函数时间，从感测的脉动体积产生光电容积描记图，确定吸气期间光电容积描记图的幅度与呼气期间光电容积描记图的幅度之比，并使用确定的比率确定受试者的心输出量或每搏输出量的变化。