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(54) **SYSTEMS AND METHODS FOR DETERMINING RESPIRATION INFORMATION BASED ON INDEPENDENT COMPONENT ANALYSIS**

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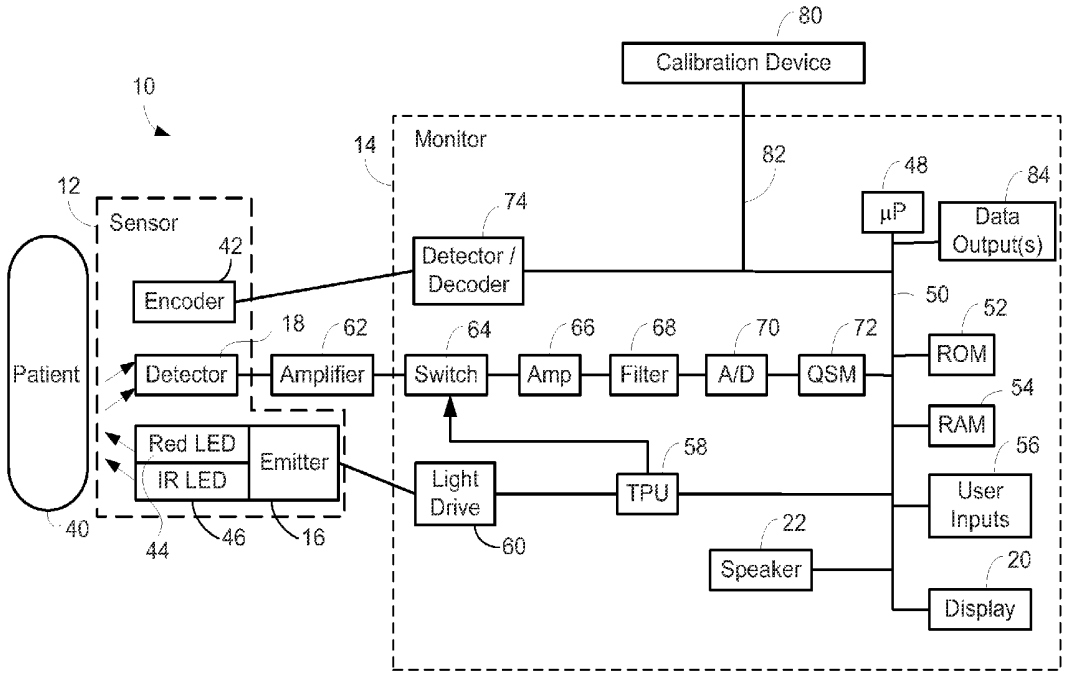
USPC **600/323**

(57) **ABSTRACT**

A patient monitoring system may receive a physiological signal such as a photoplethysmograph (PPG) signal. A plurality of respiration morphology signals may be determined from the PPG signal. Independent component analysis may be performed on the respiration morphology signals, resulting in a plurality of independent components. An independent component corresponding to a respiration source signal may be selected from the plurality of independent components. Respiration information such as respiration rate may be determined based at least in part on the selected independent component.



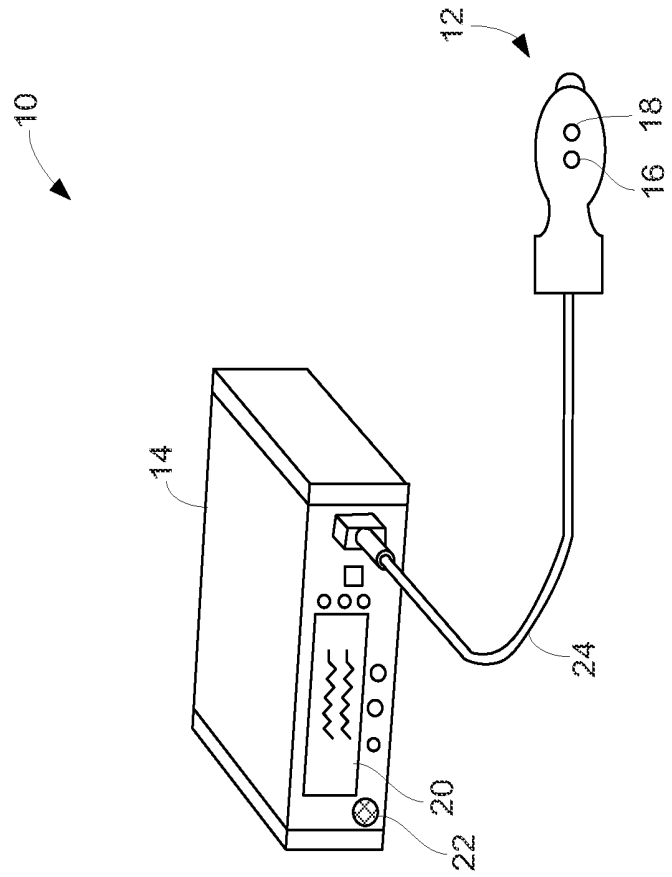


FIG. 1

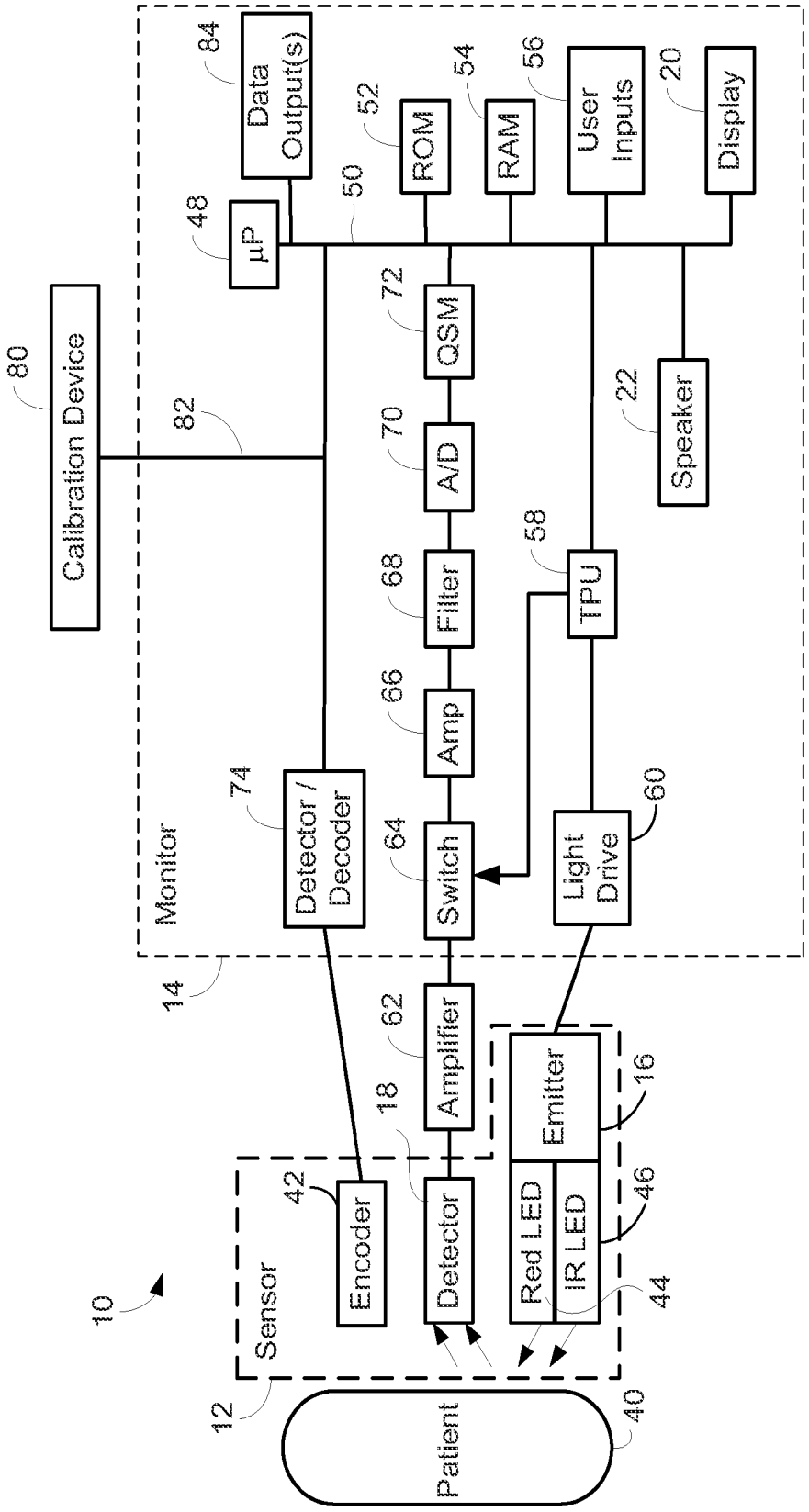

10
Sensor
12
Patient
40
Red LED
IR LED
44
46
Encoder
42
Detector
18
Emitter
16
Amplifier
62
Monitor
14
Detector / Decoder
74
Switch
64
Light Drive
60
Amp
66
Filter
68
TPU
58
A/D
70
QSM
72
Speaker
22
Calibration Device
80
82
µP
48
Data Output(s)
84
ROM
52
RAM
54
User Inputs
56
Display
20
50

FIG. 2

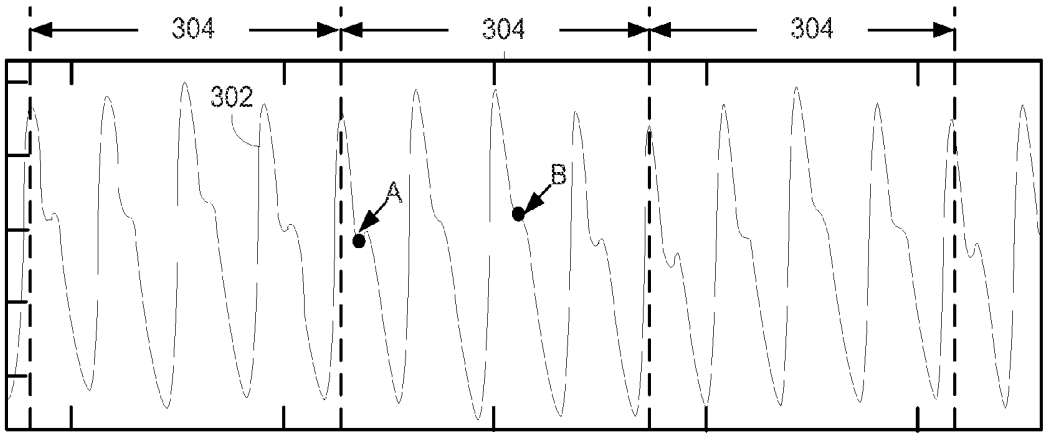


FIG. 3

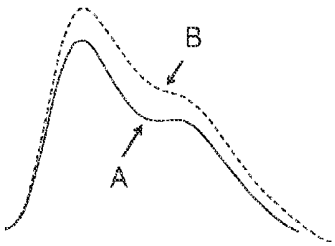


FIG. 4

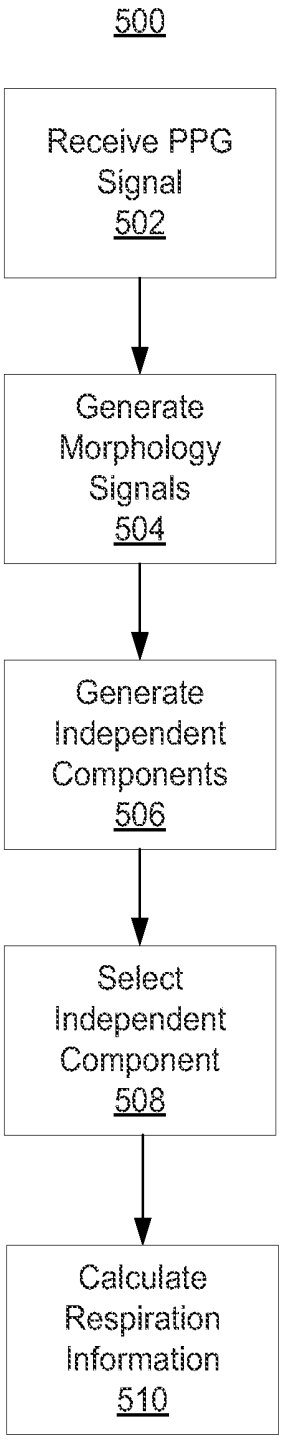

500
Receive PPG Signal 502
Generate Morphology Signals 504
Generate Independent Components 506
Select Independent Component 508
Calculate Respiration Information 510

FIG. 5

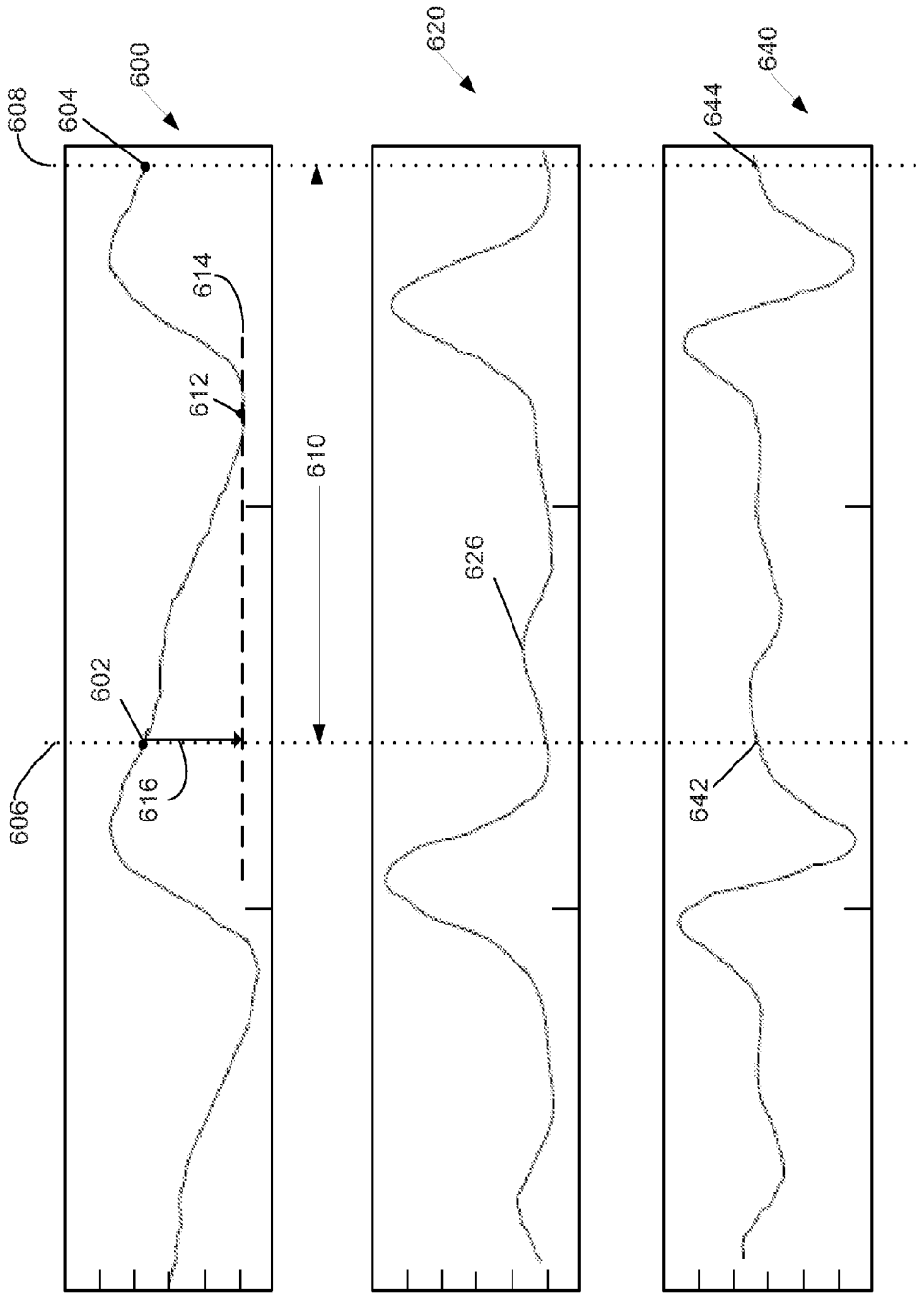


FIG. 6

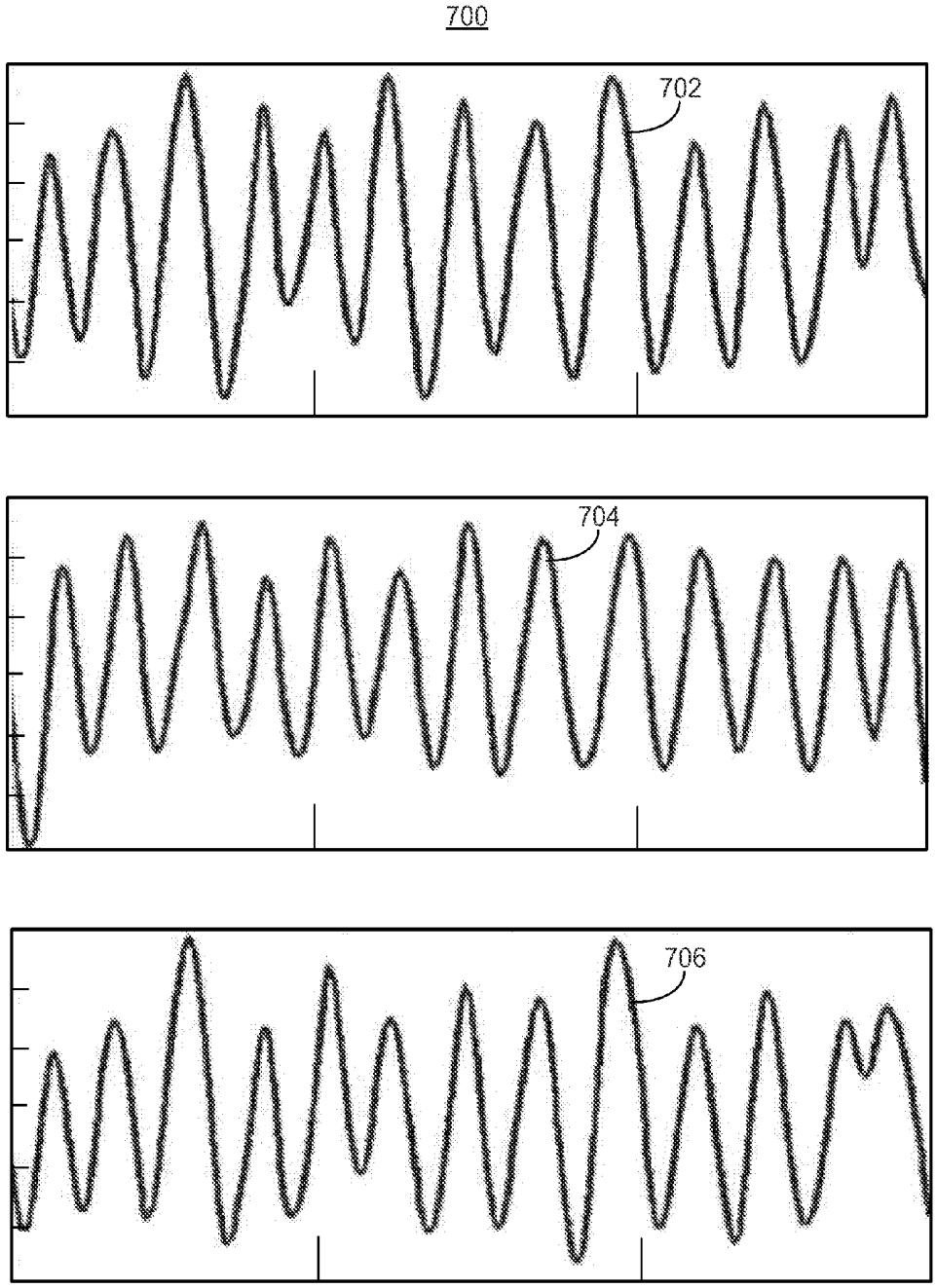


FIG. 7

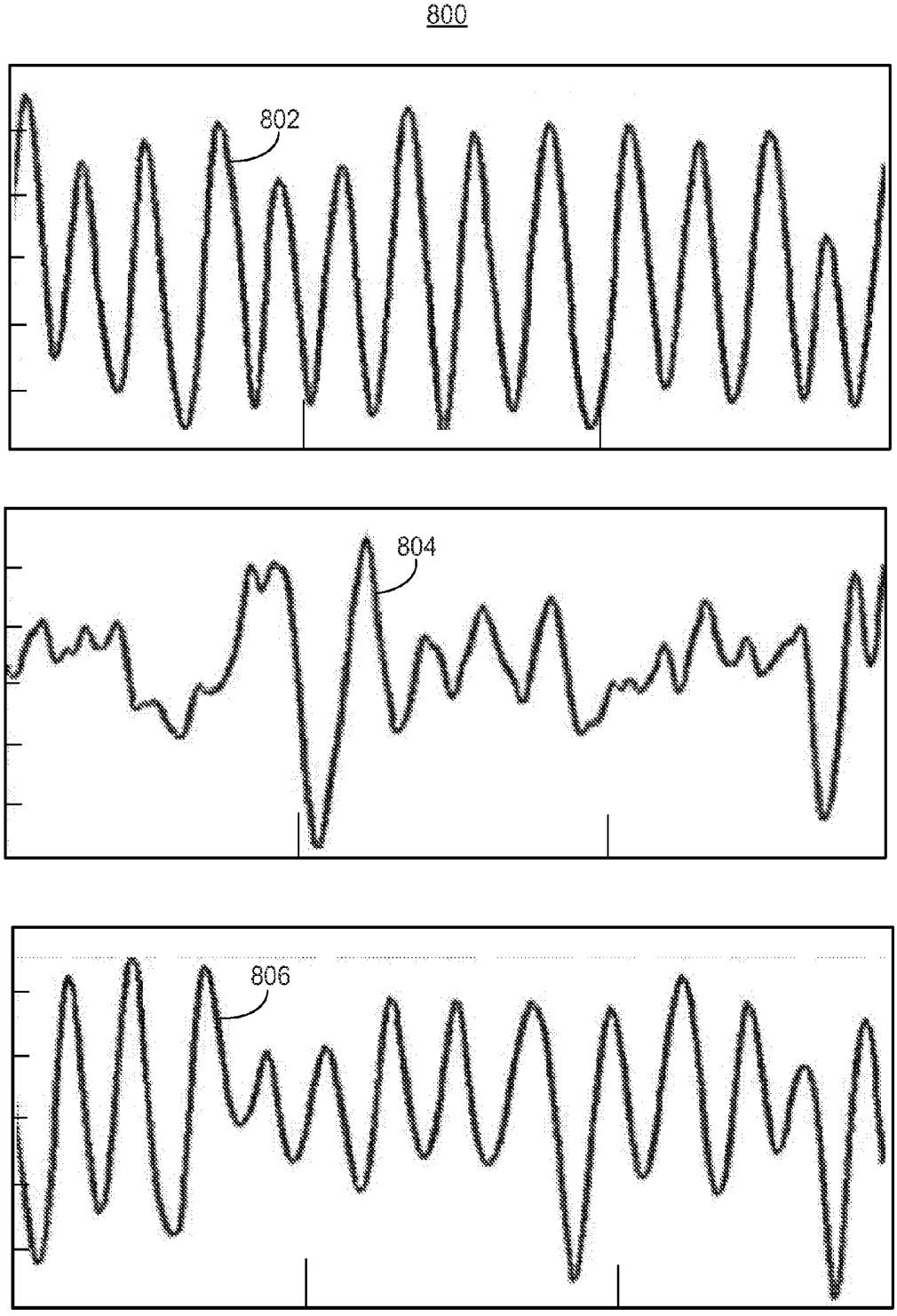


FIG. 8

SYSTEMS AND METHODS FOR DETERMINING RESPIRATION INFORMATION BASED ON INDEPENDENT COMPONENT ANALYSIS

[0001] The present disclosure relates to physiological signal processing, and more particularly relates to determining respiration information from a physiological signal based on independent component analysis.

SUMMARY

[0002] A method comprises receiving a photoplethysmograph (PPG) signal, processing, with processing equipment, the PPG signal to generate a plurality of respiration morphology signals, performing, with the processing equipment, independent component analysis on the plurality of respiration morphology signals to generate a plurality of independent components, selecting, with the processing equipment, an independent component that corresponds to a respiration source signal from the plurality of independent components, and determining, with the processing equipment, respiration information based at least in part on the selected independent component.

[0003] A non-transitory computer-readable storage medium has computer program instructions recorded thereon for receiving a PPG signal, processing the PPG signal to generate a plurality of respiration morphology signals, performing independent component analysis on the plurality of respiration morphology signals to generate a plurality of independent components, selecting an independent component that corresponds to a respiration source signal from the plurality of independent components, and determining respiration information based at least in part on the selected independent component.

[0004] A patient monitoring system comprises processing equipment configured to receive a photoplethysmograph (PPG) signal, process the PPG signal to generate a plurality of respiration morphology signals, perform independent component analysis on the plurality of respiration morphology signals to generate a plurality of independent components, select an independent component that corresponds to a respiration source signal from the plurality of independent components, and determine respiration information based at least in part on the selected independent component.

BRIEF DESCRIPTION OF THE FIGURES

[0005] The above and other features of the present disclosure, its nature and various advantages will be more apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings in which:

[0006] FIG. **1** shows an illustrative patient monitoring system in accordance with some embodiments of the present disclosure;

[0007] FIG. **2** is a block diagram of the illustrative patient monitoring system of FIG. **1** coupled to a patient in accordance with some embodiments of the present disclosure;

[0008] FIG. **3** shows an illustrative PPG signal that is modulated by respiration in accordance with some embodiments of the present disclosure;

[0009] FIG. **4** shows a comparison of portions of the illustrative PPG signal of FIG. **3** in accordance with some embodiments of the present disclosure;

[0010] FIG. **5** shows illustrative steps for determining respiration information from a PPG signal using independent component analysis in accordance with some embodiments of the present disclosure;

[0011] FIG. **6** shows an illustrative PPG signal, a first derivative of the PPG signal, and a second derivative of the PPG signal in accordance with some embodiments of the present disclosure;

[0012] FIG. **7** shows illustrative respiration morphology signals in accordance with some embodiments of the present disclosure; and

[0013] FIG. **8** shows illustrative independent components in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE FIGURES

[0014] A physiological signal such as a photoplethysmograph (PPG) signal may be indicative of pulsatile blood flow. Pulsatile blood flow may be dependent on a number of physiological functions such as cardiovascular function and respiration. The PPG signal may also include modulations based on non-physiological functions such as measurement noise and patient motion.

[0015] A typical range for a patient's respiration rate (e.g., 12-40 breaths per minute) may be may be less than a typical range for a patient's pulse rate (e.g., 60-150 beats per minute). Changes to the pulsatile blood flow caused by respiration may be identified as long-term modulations to the frequency, amplitude, and baseline of the PPG signal. It may be possible to identify these long-term modulations based on patterns in the morphology of the PPG signal. A number of morphology metrics have been identified that assist in identifying these long-term modulations due to respiration. Respiration morphology signals may be generated by calculating a series of these morphology metrics over time.

[0016] Although the respiration morphology signals may better capture the respiration information, these signals may still include information from a number of sources in addition to respiration. Each of the respiration morphology signals may be thought of as a mixed signal including a respiration source signal, a pulsatile source signal, a noise source signal, and source signals that are the result of other physiological or measurement phenomena. It may be desirable to separate the respiration source signal from the other source signals in order to more accurately determine respiration information. As is described herein, independent component analysis ("ICA") may be used to process a plurality of respiration morphology signals to generate a plurality of independent components. The independent component that corresponds to the respiration source signal may be selected from the resulting independent components, and respiration information such as respiration rate may be calculated based on the selected independent component.

[0017] For purposes of clarity, the present disclosure is written in the context of the physiological signal being a PPG signal generated by a pulse oximetry system. It will be understood that any other suitable physiological signal or any other suitable system may be used in accordance with the teachings of the present disclosure.

[0018] An oximeter is a medical device that may determine the oxygen saturation of the blood. One common type of oximeter is a pulse oximeter, which may indirectly measure the oxygen saturation of a patient's blood (as opposed to measuring oxygen saturation directly by analyzing a blood

sample taken from the patient). Pulse oximeters may be included in patient monitoring systems that measure and display various blood flow characteristics including, but not limited to, the oxygen saturation of hemoglobin in arterial blood. Such patient monitoring systems may also measure and display additional physiological parameters, such as a patient's pulse rate.

[0019] An oximeter may include a light sensor that is placed at a site on a patient, typically a fingertip, toe, forehead or earlobe, or in the case of a neonate, across a foot. The oximeter may use a light source to pass light through blood perfused tissue and photoelectrically sense the absorption of the light in the tissue. In addition, locations that are not typically understood to be optimal for pulse oximetry serve as suitable sensor locations for the monitoring processes described herein, including any location on the body that has a strong pulsatile arterial flow. For example, additional suitable sensor locations include, without limitation, the neck to monitor carotid artery pulsatile flow, the wrist to monitor radial artery pulsatile flow, the inside of a patient's thigh to monitor femoral artery pulsatile flow, the ankle to monitor tibial artery pulsatile flow, and around or in front of the ear. Suitable sensors for these locations may include sensors for sensing absorbed light based on detecting reflected light. In all suitable locations, for example, the oximeter may measure the intensity of light that is received at the light sensor as a function of time. The oximeter may also include sensors at multiple locations. A signal representing light intensity versus time or a mathematical manipulation of this signal (e.g., a scaled version thereof, a log taken thereof, a scaled version of a log taken thereof, etc.) may be referred to as the photoplethysmograph (PPG) signal. In addition, the term "PPG signal," as used herein, may also refer to an absorption signal (i.e., representing the amount of light absorbed by the tissue) or any suitable mathematical manipulation thereof. The light intensity or the amount of light absorbed may then be used to calculate any of a number of physiological parameters, including an amount of a blood constituent (e.g., oxyhemoglobin) being measured as well as a pulse rate and when each individual pulse occurs.

[0020] In some applications, the light passed through the tissue is selected to be of one or more wavelengths that are absorbed by the blood in an amount representative of the amount of the blood constituent present in the blood. The amount of light passed through the tissue varies in accordance with the changing amount of blood constituent in the tissue and the related light absorption. Red and infrared (IR) wavelengths may be used because it has been observed that highly oxygenated blood will absorb relatively less Red light and more IR light than blood with a lower oxygen saturation. By comparing the intensities of two wavelengths at different points in the pulse cycle, it is possible to estimate the blood oxygen saturation of hemoglobin in arterial blood.

[0021] When the measured blood parameter is the oxygen saturation of hemoglobin, a convenient starting point assumes a saturation calculation based at least in part on Lambert-Beer's law. The following notation will be used herein:

$$I(\lambda,t)=I_0(\lambda)\exp(-s\beta_0(\lambda)+(1-s)\beta_r(\lambda))l(t)) \quad (1)$$

where:

λ=wavelength;

t=time;

I=intensity of light detected;

I_0=intensity of light transmitted;

s=oxygen saturation;

β_0,β_r=empirically derived absorption coefficients; and

l(t)=a combination of concentration and path length from emitter to detector as a function of time.

[0022] The traditional approach measures light absorption at two wavelengths (e.g., Red and IR), and then calculates saturation by solving for the "ratio of ratios" as follows.

1. The natural logarithm of Eq. 1 is taken ("log" will be used to represent the natural logarithm) for IR and Red to yield

$$\log I=\log I_o-(s\beta_o+(1-s)\beta_r)l. \quad (2)$$

2. Eq. 2 is then differentiated with respect to time to yield

$$\frac{d\log I}{dt}=-(s\beta_o+(1-s)\beta_r)\frac{dl}{dt}. \quad (3)$$

3. Eq. 3, evaluated at the Red wavelength λ_R, is divided by Eq. 3 evaluated at the IR wavelength λ_{IR} in accordance with

$$\frac{d\log I(\lambda_R)/dt}{d\log I(\lambda_{IR})/dt}=\frac{s\beta_o(\lambda_R)+(1-s)\beta_r(\lambda_R)}{s\beta_o(\lambda_{IR})+(1-s)\beta_r(\lambda_{IR})}. \quad (4)$$

4. Solving for S yields

$$s=\frac{\frac{d\log I(\lambda_{IR})}{dt}\beta_r(\lambda_R)-\frac{d\log I(\lambda_R)}{dt}\beta_r(\lambda_{IR})}{\frac{d\log I(\lambda_R)}{dt}(\beta_o(\lambda_{IR})-\beta_r(\lambda_{IR}))-\frac{d\log I(\lambda_{IR})}{dt}(\beta_o(\lambda_R)-\beta_r(\lambda_R))}. \quad (5)$$

5. Note that, in discrete time, the following approximation can be made:

$$\frac{d\log I(\lambda,t)}{dt}\simeq\log I(\lambda,t_2)-\log I(\lambda,t_1). \quad (6)$$

6. Rewriting Eq. 6 by observing that log A−log B=log(A/B) yields

$$\frac{d\log I(\lambda,t)}{dt}\simeq\log\left(\frac{I(t_2,\lambda)}{I(t_1,\lambda)}\right). \quad (7)$$

7. Thus, Eq. 4 can be expressed as

$$\frac{\frac{d\log I(\lambda_R)}{dt}}{\frac{d\log I(\lambda_{IR})}{dt}}\simeq\frac{\log\left(\frac{I(t_1,\lambda_R)}{I(t_2,\lambda_R)}\right)}{\log\left(\frac{I(t_1,\lambda_{IR})}{I(t_2,\lambda_{IR})}\right)}=R, \quad (8)$$

where R represents the "ratio of ratios."

8. Solving Eq. 4 for S using the relationship of Eq. 5 yields

$$s = \frac{\beta_r(\lambda_R) - R\beta_r(\lambda_{IR})}{R(\beta_o(\lambda_{IR}) - \beta_r(\lambda_{IR})) - \beta_o(\lambda_R) + \beta_r(\lambda_R)}. \quad (9)$$

9. From Eq. 8, R can be calculated using two points (e.g., PPG maximum and minimum), or a family of points. One method applies a family of points to a modified version of Eq. 8. Using the relationship

$$\frac{d\log I}{dt} = \frac{dI/dt}{I}, \quad (10)$$

Eq. 8 becomes

$$\frac{\frac{d\log I(\lambda_R)}{dt}}{\frac{d\log I(\lambda_{IR})}{dt}} \simeq \frac{\frac{I(t_2,\lambda_R) - I(t_1,\lambda_R)}{I(t_1,\lambda_R)}}{\frac{I(t_2,\lambda_{IR}) - I(t_1,\lambda_{IR})}{I(t_1,\lambda_{IR})}} = \frac{[I(t_2,\lambda_R) - I(t_1,\lambda_R)]I(t_1,\lambda_{IR})}{[I(t_2,\lambda_{IR}) - I(t_1,\lambda_{IR})]I(t_1,\lambda_R)} = R, \quad (11)$$

which defines a cluster of points whose slope of y versus x will give R when

$$x = [I(t_2,\lambda_{IR}) - I(t_1,\lambda_{IR})]I(t_1,\lambda_R), \quad (12)$$

and

$$y = [I(t_2,\lambda_R) - I(t_1,\lambda_{IR})]I(t_1,\lambda_{IR}), \quad (13)$$

Once R is determined or estimated, for example, using the techniques described above, the blood oxygen saturation can be determined or estimated using any suitable technique for relating a blood oxygen saturation value to R. For example, blood oxygen saturation can be determined from empirical data that may be indexed by values of R, and/or it may be determined from curve fitting and/or other interpolative techniques.

[0023] FIG. **1** is a perspective view of an embodiment of a patient monitoring system **10**. System **10** may include sensor unit **12** and monitor **14**. In some embodiments, sensor unit **12** may be part of an oximeter. Sensor unit **12** may include an emitter **16** for emitting light at one or more wavelengths into a patient's tissue. A detector **18** may also be provided in sensor unit **12** for detecting the light originally from emitter **16** that emanates from the patient's tissue after passing through the tissue. Any suitable physical configuration of emitter **16** and detector **18** may be used. In an embodiment, sensor unit **12** may include multiple emitters and/or detectors, which may be spaced apart. System **10** may also include one or more additional sensor units (not shown) that may take the form of any of the embodiments described herein with reference to sensor unit **12**. An additional sensor unit may be the same type of sensor unit as sensor unit **12**, or a different sensor unit type than sensor unit **12**. Multiple sensor units may be capable of being positioned at two different locations on a subject's body; for example, a first sensor unit may be positioned on a patient's forehead, while a second sensor unit may be positioned at a patient's fingertip.

[0024] Sensor units may each detect any signal that carries information about a patient's physiological state, such as an electrocardiograph signal, arterial line measurements, or the pulsatile force exerted on the walls of an artery using, for example, oscillometric methods with a piezoelectric transducer. According to some embodiments, system **10** may include two or more sensors forming a sensor array in lieu of either or both of the sensor units. Each of the sensors of a sensor array may be a complementary metal oxide semiconductor (CMOS) sensor. Alternatively, each sensor of an array may be charged coupled device (CCD) sensor. In some embodiments, a sensor array may be made up of a combination of CMOS and CCD sensors. The CCD sensor may comprise a photoactive region and a transmission region for receiving and transmitting data whereas the CMOS sensor may be made up of an integrated circuit having an array of pixel sensors. Each pixel may have a photodetector and an active amplifier. It will be understood that any type of sensor, including any type of physiological sensor, may be used in one or more sensor units in accordance with the systems and techniques disclosed herein. It is understood that any number of sensors measuring any number of physiological signals may be used to determine physiological information in accordance with the techniques described herein.

[0025] In some embodiments, emitter **16** and detector **18** may be on opposite sides of a digit such as a finger or toe, in which case the light that is emanating from the tissue has passed completely through the digit. In some embodiments, emitter **16** and detector **18** may be arranged so that light from emitter **16** penetrates the tissue and is reflected by the tissue into detector **18**, such as in a sensor designed to obtain pulse oximetry data from a patient's forehead.

[0026] In some embodiments, sensor unit **12** may be connected to and draw its power from monitor **14** as shown. In another embodiment, the sensor may be wirelessly connected to monitor **14** and include its own battery or similar power supply (not shown). Monitor **14** may be configured to calculate physiological parameters (e.g., pulse rate, blood oxygen saturation (e.g., SpO_2), and respiration information) based at least in part on data relating to light emission and detection received from one or more sensor units such as sensor unit **12** and an additional sensor (not shown). In some embodiments, the calculations may be performed on the sensor units or an intermediate device and the result of the calculations may be passed to monitor **14**. Further, monitor **14** may include a display **20** configured to display the physiological parameters or other information about the system. In the embodiment shown, monitor **14** may also include a speaker **22** to provide an audible sound that may be used in various other embodiments, such as for example, sounding an audible alarm in the event that a patient's physiological parameters are not within a predefined normal range. In some embodiments, the system **10** includes a stand-alone monitor in communication with the monitor **14** via a cable or a wireless network link.

[0027] In some embodiments, sensor unit **12** may be communicatively coupled to monitor **14** via a cable **24**. In some embodiments, a wireless transmission device (not shown) or the like may be used instead of or in addition to cable **24**. Monitor **14** may include a sensor interface configured to receive physiological signals from sensor unit **12**, provide signals and power to sensor unit **12**, or otherwise communicate with sensor unit **12**. The sensor interface may include any suitable hardware, software, or both, which may allow communication between monitor **14** and sensor unit **12**.

[0028] As is described herein, monitor **14** may generate a PPG signal based on the signal received from sensor unit **12**. The PPG signal may consist of data points that represent a pulsatile waveform. The pulsatile waveform may be modulated based on the respiration of a patient. Respiratory modulations may include baseline modulations, amplitude modulations, frequency modulations, respiratory sinus arrhythmia, any other suitable modulations, or any combination thereof. Respiratory modulations may exhibit different phases, amplitudes, or both, within a PPG signal and may contribute to complex behavior (e.g., changes) of the PPG signal. For example, the amplitude of the pulsatile waveform may be modulated based on respiration (amplitude modulation), the frequency of the pulsatile waveform may be modulated based on respiration (frequency modulation), and a signal baseline for the pulsatile waveform may be modulated based on respiration (baseline modulation). Monitor **14** may analyze the PPG signal (e.g., by generating respiration morphology signals from the PPG signal and performing independent component analysis) to determine respiration information based on one or more of these modulations of the PPG signal.

[0029] As is described herein, respiration information may be determined from the PPG signal by monitor **14**. However, it will be understood that the PPG signal could be transmitted to any suitable device for the determination of respiration information, such as a local computer, a remote computer, a nurse station, mobile devices, tablet computers, or any other device capable of sending and receiving data and performing processing operations. Information may be transmitted from monitor **14** in any suitable manner, including wireless (e.g., WiFi, Bluetooth, etc.), wired (e.g., USB, Ethernet, etc.), or application-specific connections. The receiving device may determine respiration information as described herein.

[0030] FIG. **2** is a block diagram of a patient monitoring system, such as patient monitoring system **10** of FIG. **1**, which may be coupled to a patient **40** in accordance with an embodiment. Certain illustrative components of sensor unit **12** and monitor **14** are illustrated in FIG. **2**.

[0031] Sensor unit **12** may include emitter **16**, detector **18**, and encoder **42**. In the embodiment shown, emitter **16** may be configured to emit at least two wavelengths of light (e.g., Red and IR) into a patient's tissue **40**. Hence, emitter **16** may include a Red light emitting light source such as Red light emitting diode (LED) **44** and an IR light emitting light source such as IR LED **46** for emitting light into the patient's tissue **40** at the wavelengths used to calculate the patient's physiological parameters. In some embodiments, the Red wavelength may be between about 600 nm and about 700 nm, and the IR wavelength may be between about 800 nm and about 1000 nm. In embodiments where a sensor array is used in place of a single sensor, each sensor may be configured to emit a single wavelength. For example, a first sensor may emit only a Red light while a second sensor may emit only an IR light. In a further example, the wavelengths of light used may be selected based on the specific location of the sensor.

[0032] It will be understood that, as used herein, the term "light" may refer to energy produced by radiation sources and may include one or more of radio, microwave, millimeter wave, infrared, visible, ultraviolet, gamma ray or X-ray electromagnetic radiation. As used herein, light may also include electromagnetic radiation having any wavelength within the radio, microwave, infrared, visible, ultraviolet, or X-ray spectra, and that any suitable wavelength of electromagnetic radiation may be appropriate for use with the present techniques. Detector **18** may be chosen to be specifically sensitive to the chosen targeted energy spectrum of the emitter **16**.

[0033] In some embodiments, detector **18** may be configured to detect the intensity of light at the Red and IR wavelengths. Alternatively, each sensor in the array may be configured to detect an intensity of a single wavelength. In operation, light may enter detector **18** after passing through the patient's tissue **40**. Detector **18** may convert the intensity of the received light into an electrical signal. The light intensity is directly related to the absorbance and/or reflectance of light in the tissue **40**. That is, when more light at a certain wavelength is absorbed or reflected, less light of that wavelength is received from the tissue by the detector **18**. After converting the received light to an electrical signal, detector **18** may send the signal to monitor **14**, where physiological parameters may be calculated based on the absorption of the Red and IR wavelengths in the patient's tissue **40**.

[0034] In some embodiments, encoder **42** may contain information about sensor unit **12**, such as what type of sensor it is (e.g., whether the sensor is intended for placement on a forehead or digit) and the wavelengths of light emitted by emitter **16**. This information may be used by monitor **14** to select appropriate algorithms, lookup tables and/or calibration coefficients stored in monitor **14** for calculating the patient's physiological parameters.

[0035] Encoder **42** may contain information specific to patient **40**, such as, for example, the patient's age, weight, and diagnosis. This information about a patient's characteristics may allow monitor **14** to determine, for example, patient-specific threshold ranges in which the patient's physiological parameter measurements should fall and to enable or disable additional physiological parameter algorithms. This information may also be used to select and provide coefficients for equations from which measurements may be determined based at least in part on the signal or signals received at sensor unit **12**. For example, some pulse oximetry sensors rely on equations to relate an area under a portion of a PPG signal corresponding to a physiological pulse to determine blood pressure. These equations may contain coefficients that depend upon a patient's physiological characteristics as stored in encoder **42**.

[0036] Encoder **42** may, for instance, be a coded resistor that stores values corresponding to the type of sensor unit **12** or the type of each sensor in the sensor array, the wavelengths of light emitted by emitter **16** on each sensor of the sensor array, and/or the patient's characteristics and treatment information. In some embodiments, encoder **42** may include a memory on which one or more of the following information may be stored for communication to monitor **14**; the type of the sensor unit **12**; the wavelengths of light emitted by emitter **16**; the particular wavelength each sensor in the sensor array is monitoring; a signal threshold for each sensor in the sensor array; any other suitable information; physiological characteristics (e.g., gender, age, weight); or any combination thereof.

[0037] In some embodiments, signals from detector **18** and encoder **42** may be transmitted to monitor **14**. In the embodiment shown, monitor **14** may include a general-purpose microprocessor **48** connected to an internal bus **50**. Microprocessor **48** may be adapted to execute software, which may include an operating system and one or more applications, as part of performing the functions described herein. Also connected to bus **50** may be a read-only memory (ROM) **52**, a

random access memory (RAM) **54**, user inputs **56**, display **20**, data output **84**, and speaker **22**.

[0038] RAM **54** and ROM **52** are illustrated by way of example, and not limitation. Any suitable computer-readable media may be used in the system for data storage. Computer-readable media are capable of storing information that can be interpreted by microprocessor **48**. This information may be data or may take the form of computer-executable instructions, such as software applications, that cause the microprocessor to perform certain functions and/or computer-implemented methods. Depending on the embodiment, such computer-readable media may include computer storage media and communication media. Computer storage media may include volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules or other data. Computer storage media may include, but is not limited to, RAM, ROM, EPROM, EEPROM, flash memory or other solid state memory technology, CD-ROM, DVD, or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to store the desired information and that can be accessed by components of the system.

[0039] In the embodiment shown, a time processing unit (TPU) **58** may provide timing control signals to light drive circuitry **60**, which may control when emitter **16** is illuminated and multiplexed timing for Red LED **44** and IR LED **46**. TPU **58** may also control the gating-in of signals from detector **18** through amplifier **62** and switching circuit **64**. These signals are sampled at the proper time, depending upon which light source is illuminated. The received signal from detector **18** may be passed through amplifier **66**, low pass filter **68**, and analog-to-digital converter **70**. The digital data may then be stored in a queued serial module (QSM) **72** (or buffer) for later downloading to RAM **54** as QSM **72** is filled. In some embodiments, there may be multiple separate parallel paths having components equivalent to amplifier **66**, filter **68**, and/or A/D converter **70** for multiple light wavelengths or spectra received. Any suitable combination of components (e.g., microprocessor **48**, RAM **54**, analog to digital converter **70**, any other suitable component shown or not shown in FIG. **2**) coupled by bus **50** or otherwise coupled (e.g., via an external bus), may be referred to as "processing equipment."

[0040] In some embodiments, microprocessor **48** may determine the patient's physiological parameters, such as SpO_2, pulse rate, and/or respiration information, using various algorithms and/or look-up tables based on the value of the received signals and/or data corresponding to the light received by detector **18**. As is described herein, microprocessor **48** may generate respiration morphology signals and perform independent component analysis on the respiration morphology signals to determine respiration information from a PPG signal.

[0041] Signals corresponding to information about patient **40**, and particularly about the intensity of light emanating from a patient's tissue over time, may be transmitted from encoder **42** to decoder **74**. These signals may include, for example, encoded information relating to patient characteristics. Decoder **74** may translate these signals to enable microprocessor **48** to determine the thresholds based at least in part on algorithms or look-up tables stored in ROM **52**. In some embodiments, user inputs **56** may be used to enter information, select one or more options, provide a response, input settings, any other suitable inputting function, or any combination thereof. User inputs **56** may be used to enter information about the patient, such as age, weight, height, diagnosis, medications, treatments, and so forth. In some embodiments, display **20** may exhibit a list of values, which may generally apply to the patient, such as, for example, age ranges or medication families, which the user may select using user inputs **56**.

[0042] Calibration device **80**, which may be powered by monitor **14** via a communicative coupling **82**, a battery, or by a conventional power source such as a wall outlet, may include any suitable signal calibration device.

[0043] Calibration device **80** may be communicatively coupled to monitor **14** via communicative coupling **82**, and/or may communicate wirelessly (not shown). In some embodiments, calibration device **80** is completely integrated within monitor **14**. In some embodiments, calibration device **80** may include a manual input device (not shown) used by an operator to manually input reference signal measurements obtained from some other source (e.g., an external invasive or non-invasive physiological measurement system).

[0044] Data output **84** may provide for communications with other devices utilizing any suitable transmission medium, including wireless (e.g., WiFi, Bluetooth, etc.), wired (e.g., USB, Ethernet, etc.), or application-specific connections. Data output **84** may receive messages to be transmitted from microprocessor **48** via bus **50**. Exemplary messages to be sent in an embodiment described herein may include samples of the PPG signal to be transmitted to an external device for determining respiration information.

[0045] The optical signal attenuated by the tissue of patient **40** can be degraded by noise, among other sources. One source of noise is ambient light that reaches the light detector. Another source of noise is electromagnetic coupling from other electronic instruments. Movement of the patient also introduces noise and affects the signal. For example, the contact between the detector and the skin, or the emitter and the skin, can be temporarily disrupted when movement causes either to move away from the skin. Also, because blood is a fluid, it responds differently than the surrounding tissue to inertial effects, which may result in momentary changes in volume at the point to which the oximeter probe is attached.

[0046] Noise (e.g., from patient movement) can degrade a sensor signal relied upon by a care provider, without the care provider's awareness. This is especially true if the monitoring of the patient is remote, the motion is too small to be observed, or the care provider is watching the instrument or other parts of the patient, and not the sensor site. Processing sensor signals (e.g., PPG signals) may involve operations that reduce the amount of noise present in the signals, control the amount of noise present in the signal, or otherwise identify noise components in order to prevent them from affecting measurements of physiological parameters derived from the sensor signals.

[0047] FIG. **3** shows an illustrative PPG signal **302** that is modulated by respiration in accordance with some embodiments of the present disclosure. PPG signal **302** may be a periodic signal that is indicative of changes in pulsatile blood flow. Each cycle of PPG signal **302** may generally correspond to a pulse, such that a heart rate may be determined based on PPG signal **302**. Each respiratory cycle **304** may correspond to a breath. The period of a respiratory cycle may typically be longer than the period of a pulsatile cycle, such that any

changes in the pulsatile blood flow due to respiration occur over a number of pulsatile cycles. The volume of the pulsatile blood flow may also vary in a periodic manner based on respiration, resulting in modulations to the pulsatile blood flow such as amplitude modulation, frequency modulation, and baseline modulation. This modulation of PPG signal **302** due to respiration may result in changes to the morphology of PPG signal **302**.

[0048] FIG. **4** shows a comparison of portions of the illustrative PPG signal **302** of FIG. **3** in accordance with some embodiments of the present disclosure. The signal portions compared in FIG. **4** may demonstrate differing morphology due to respiration modulation based on the relative location of the signal portions within a respiratory cycle **304**. For example, a first pulse associated with the respiratory cycle may have a relatively low amplitude (indicative of amplitude and baseline modulation) as well as an obvious distinct dichrotic notch as indicated by point A. A second pulse may have a relatively high amplitude (indicative of amplitude and baseline modulation) as well as a dichrotic notch that has been washed out as depicted by point B. Frequency modulation may be evident based on the relative period of the first pulse and second pulse. Referring again to FIG. **3**, by the end of the respiratory cycle **304** the pulse features may again be similar to the morphology of A. Although the impact of respiration modulation on the morphology of a particular PPG signal **302** has been described herein, it will be understood that respiration may have varied effects on the morphology of a PPG signal other than those depicted in FIGS. **3** and **4**.

[0049] FIG. **5** shows illustrative steps for determining respiration information from a PPG signal using independent component analysis in accordance with some embodiments of the present disclosure. Although exemplary steps are described herein, it will be understood that steps may be omitted and that any suitable additional steps may be added for determining respiration information using independent component analysis. Although the steps described herein may be performed by any suitable device, in an exemplary embodiment, the steps may be performed by monitoring system **10**. At step **502**, monitoring system **10** may receive a PPG signal as described herein.

[0050] At step **504**, monitoring system **10** may generate one or more respiration morphology signals from the PPG signal. Although any number of respiration morphology signals may be generated from a PPG signal, in an exemplary embodiment, three respiration morphology signals may be generated. Although any respiration morphology signals may be generated, in an exemplary embodiment, a down signal, a delta of second derivative (DSD) signal, and a kurtosis signal may be generated. Although a respiration morphology signal may be generated in any suitable manner, in an exemplary embodiment, a respiration morphology signal may be generated based on calculating a series of morphology metrics based on a PPG signal. One or more morphology metrics maybe calculated for each portion of the PPG signal (e.g., for each fiducial defined portion), a series of morphology metrics may be calculated over time, and the series of morphology metrics may be processed to generate one or more respiration morphology signals.

[0051] FIG. **6** depicts exemplary signals used for calculating morphology metrics from a received PPG signal. The abscissa of each plot of FIG. **6** may represent time and the ordinate of each plot may represent magnitude. PPG signal **600** may be a received PPG signal, first derivative signal **620** may be a signal representing the first derivative of the PPG signal **600**, and second derivative signal **640** may be a signal representing the second derivative of the PPG signal **600**. As will be described herein, morphology metrics may be calculated for portions of these signals, and a series of morphology metric calculations calculated over time may be processed to generate the respiration morphology signals. Although particular morphology metric calculations are set forth below, each of the morphology metric calculations may be modified in any suitable manner.

[0052] Although morphology metrics may be calculated based on any suitable portions of the PPG signal **600** (as well as the first derivative signal **620**, second derivative signal **640**, and any other suitable signals that may be generated from the PPG signal **600**), in an exemplary embodiment, morphology metrics may be calculated for each fiducial-defined portion such as fiducial defined portion **610** of the PPG signal **600**. Exemplary fiducial points **602** and **604** are depicted for PPG signal **600**, and fiducial lines **606** and **608** demonstrate the location of fiducial points **602** and **604** relative to first derivative signal **620** and second derivative signal **640**.

[0053] Although it will be understood that fiducial points may be identified in any suitable manner, in exemplary embodiments fiducial points may be identified based on features of the PPG signal **600** or any derivatives thereof (e.g., first derivative signal **620** and second derivative signal **640**) such as peaks, troughs, points of maximum slope, dichrotic notch locations, pre-determined offsets, any other suitable features, or any combination thereof. Fiducial points **602** and **604** may define a fiducial-defined portion **610** of PPG signal **600**. The fiducial points **602** and **604** may define starting and ending points for determining morphology metrics, and the fiducial-defined portion **610** may define a relevant portion of data for determining morphology metrics. It will be understood that other starting points, ending points, and relative portions of data may be utilized to determine morphology metrics.

[0054] An exemplary morphology metric may be a down metric. The down metric is the difference between a first (e.g., fiducial) sample of a fiducial-defined portion (e.g., fiducial defined portion **610**) of the PPG signal (e.g., PPG signal **600**) and a minimum sample (e.g., minimum sample **612**) of the fiducial-defined portion of the PPG signal **600**. The down metric may also be calculated based on other points of a fiducial-defined portion. The down metric is indicative of physiological characteristics which are related to respiration, e.g., amplitude and baseline modulations of the PPG signal. In an exemplary embodiment, fiducial point **602** defines the first location for calculation of a down metric for fiducial-defined portion **610**. In the exemplary embodiment the minimum sample of fiducial-defined portion **610** is minimum point **612**, and is indicated by horizontal line **614**. The down metric may be calculated by subtracting the value of minimum point **612** from the value of fiducial point **602**, and is depicted as down metric **616**.

[0055] Another exemplary morphology metric may be a kurtosis metric for a fiducial-defined portion. Kurtosis measures the peakedness of the PPG signal **600** or a derivative thereof (e.g., first derivative signal **620** or second derivative signal **640**). In an exemplary embodiment, the kurtosis metric may be based on the peakedness of the first derivative signal **620**. The peakedness is sensitive to both amplitude and period (frequency) changes, and may be utilized as an input to generate respiration morphology signals that may be used to

determine respiration information such as respiration rate. Kurtosis may be calculated based on the following formulae:

$$D = \frac{1}{n}\sum_{i=1}^{n}\left(x_i' - \overline{x'}\right)^2$$

$$\text{Kurtosis} = \frac{1}{nD^2}\sum_{i=1}^{n}\left(x_i' - \overline{x'}\right)^4$$

where:

x_i'=ith sample of 1st derivative;

$\overline{x'}$=mean of 1st derivative of fiducial-defined portion;

n=set of all samples in the fiducial-defined portion

[0056] Another exemplary morphology metric may be a delta of the second derivative (DSD) between consecutive fiducial-defined portions, e.g., at consecutive fiducial points. Measurement points **642** and **644** for a DSD calculation are depicted at fiducial points **602** and **604** as indicated by fiducial lines **606** and **608**. The second derivative signal is indicative of the curvature of a signal. Changes in the curvature of the PPG signal **600** that can be identified with second derivative signal **640** are indicative of changes in internal pressure that occur during respiration, particularly changes near the peak of a pulse. By providing a metric of changes in curvature of the PPG signal, the DSD morphology metric may be utilized as an input to determine respiration information, such as respiration rate. The DSD metric may be calculated for each fiducial-defined portion by identifying the value of the second derivative signal **640** at the current fiducial point (e.g., fiducial point **642** of fiducial-defined portion **610**) and subtracting from that the value of the second derivative signal **640** at the next fiducial point (e.g., fiducial point **644** of fiducial-defined portion **610**).

[0057] Although a down metric, kurtosis metric, and DSD metric have been described, any suitable morphology metrics related to respiration may be calculated for use in generating respiration morphology metric signals. Other exemplary morphology metrics that may be relevant to determining a physiological parameter such as respiration information from a PPG signal may include an up metric, a skew metric, a ratio of samples metric (e.g., a b/a ratio metric or c/a ratio metric), a i_b metric, a peak amplitude metric, a center of gravity metric, and an area metric.

[0058] Referring again to FIG. **5**, at step **504** a series of morphology metric values may be calculated for each morphology metric (e.g., down, kurtosis, and DSD). In some embodiments, each series of morphology metric values may be further processed in any suitable manner to generate the respiration morphology signals. Although any suitable processing operations may be performed for each series of morphology metric values, in an exemplary embodiment, each series of morphology metric values may be filtered (e.g., based on frequencies associated with respiration) and interpolated to generate the plurality of respiration morphology signals. In an exemplary embodiment wherein a series of morphology metric values for the down metric, kurtosis metric, and DSD metric are generated for the received PPG signal, the resulting respiration morphology signals may be a down morphology signal, a kurtosis morphology signal, and a DSD morphology signal.

[0059] At step **506**, monitoring system **10** may generate a plurality of independent components using independent component analysis ("ICA"). ICA is a type of blind source separation ("BSS") technique for identifying a plurality of source signals from a plurality of mixed input signals. Each mixed input signal may include information from a number source signals. BSS techniques, including ICA, may separate the source signals from the plurality of mixed input signals. BSS techniques assume that the source signals are statistically independent of each other. BSS techniques are "blind" in the sense that they may be performed with little or no knowledge of the actual source signals or of the manner in which the source signals were mixed. ICA may minimize the amount of mutual information in the signals by removing third or higher order correlation from the signals.

[0060] In an exemplary embodiment, each respiration morphology signal may be a mixed input signal that includes a mixture of multiple source signals such as a respiration source signal, pulsatile source signal, interference source signal, noise source signal, or any other source signal that may be mixed within a received PPG signal or a respiration morphology signal generated therefrom. In order to determine respiration information, it may be desirable to separate and identify a respiration source signal from the mixed input signals.

[0061] ICA may be used as a BSS technique to separate and identify a respiration source signal based on a plurality of respiration morphology signals. ICA techniques may find representations of non-Gaussian data so that the components are statistically independent.

[0062] Although ICA may be performed on any plurality of respiration morphology signals, in an exemplary embodiment, three respiration morphology signals may be the mixed input signals. Although any suitable respiration morphology signals may be the mixed input signals, in an exemplary embodiment, the respiration morphology signals may be a down signal, a kurtosis signal, and a DSD signal.

[0063] Although any suitable ICA technique may performed on the respiration morphology signals to separate and identify a respiration source signal, in an exemplary embodiment, ICA may be performed as described in *Independent Component Analysis: Algorithms and Applications*, by Aapo Hyvärinen and Erkki Oja, published in *Neural Networks,* 13(4-5):411-430 (2000). This article, which describes techniques for pre-processing mixed input signals and a FastICA technique for performing ICA estimation from the mixed input signals, is hereby incorporated by reference in its entirety. Although pre-processing may not be necessary, in an exemplary embodiment, preprocessing may include centering, whitening, band-pass filtering, eigenvalue decomposition, dimensionality reduction, any other suitable pre-processing techniques, or any combination thereof.

[0064] In an exemplary embodiment, a FastICA technique may maximize non-gaussianity based on an approximation of negentropy (i.e., a measure of differential entropy that measures non-gaussianity). However, it will be understood that any suitable ICA technique (such as infomax, JADE, or any other suitable technique) may be utilized to separate and identify the source signals (including the respiration source signal) based on the plurality of respiration morphology signals.

[0065] Performing the ICA technique on the plurality of respiration morphology signals may result in a plurality of independent components. In an exemplary embodiment having inputs of a down signal, a kurtosis signal, and a DSD signal, the ICA technique may generate three independent

components, with one of the independent components corresponding to a respiration source signal.

[0066] FIG. **7** shows illustrative respiration morphology signals in accordance with some embodiments of the present disclosure, and FIG. **8** shows illustrative independent components generated from the signals of FIG. **7** in accordance with some embodiments of the present disclosure. The abscissa of each plot of FIGS. **7-8** may represent time and the ordinate of each plot may represent magnitude.

[0067] Each of the respiration morphology signals depicted in FIG. **7** may be generated as described herein. In an exemplary embodiment, the respiration morphology signals may include a down signal **702**, a kurtosis signal **704**, and a DSD signal **706**. ICA may be performed on the respiration morphology signals **702**, **704**, and **706** to generate independent components **802**, **804**, and **806** as described herein. Each of independent components **802**, **804**, and **806** may represent a source signal that was separated from the respiration morphology signals using ICA. It can be seen that signals **804** and **806** are degraded in terms of being a recognizable respiratory signal whereas signal **802** has been enhanced. Therefore, in some embodiments, signal **802** may be chosen as a respiration modulation signal to determine respiration information such as respiration rate. This may replace one or more of the original respiration modulation signals or be used to supplement them.

[0068] At step **508** monitoring system **10** may select the independent component that corresponds to the respiration source signal from the plurality of independent components. Although the independent component that corresponds to the respiration source signal may be selected in any suitable manner, in an exemplary embodiment, a confidence metric may be generated for each of the plurality of independent components. The confidence metric may be based on any suitable information relevant to identifying a signal as including respiration information, such as signal shape, an expected range of respiration rate, a comparison of a frequency associated with each independent component with recently calculated respiration rates, the periodicity of each independent component, any other suitable parameter, or any combination thereof. The independent component that corresponds to the respiration source signal may be selected based on the values of the confidence metrics.

[0069] At step **510** monitoring system **10** may calculate respiration information. The respiration information may be calculated based on the plurality of independent components, the plurality of respiration morphology signals, or any combination thereof. In some embodiments, respiration information such as respiration rate may be calculated based on the independent component that is identified as corresponding to the respiration source signal. Although respiration information such as respiration rate may be calculated from the selected independent component in any suitable manner, in some embodiments, the respiration rate may be calculated based on autocorrelation methods, Fourier analysis, wavelet transforms, any other suitable method, or any combination thereof. For example, in an embodiment, an autocorrelation may be performed for an independent component identified as corresponding to respiration information. Peaks of the autocorrelation signal may correspond to periodicity in the underlying respiration source signal, and the time between selected peaks may represent a period associated with the respiration rate.

[0070] In some embodiments, respiration information such as respiration rate may be calculated based on the selected independent component and one or more of the respiration morphology signals. In an exemplary embodiment, a confidence value may be calculated for the selected independent component and each of the respiration morphology signals. Although signals may be combined in any suitable manner, a combined signal may be generated based on weighting each of the signals based on the relative values of the confidence values. The signals may be combined at any stage of the analysis. For example, autocorrelation may be performed to generate an autocorrelation sequence for each of the respiration source signal and the one or more respiration morphology signals. An autocorrelation signal may be generated for each autocorrelation sequence in any suitable manner, such as by interpolating the autocorrelation sequence. The autocorrelation signals may be combined based on the confidence values associated with each one of the signals, and respiration information such as respiration rate may be determined from the combined autocorrelation signal for example, based on autocorrelation methods, Fourier analysis, wavelet transforms, any other suitable method, or any combination thereof.

[0071] The foregoing is merely illustrative of the principles of this disclosure and various modifications may be made by those skilled in the art without departing from the scope of this disclosure. The above described embodiments are presented for purposes of illustration and not of limitation. The present disclosure also can take many forms other than those explicitly described herein. Accordingly, it is emphasized that this disclosure is not limited to the explicitly disclosed methods, systems, and apparatuses, but is intended to include variations to and modifications thereof, which are within the spirit of the following claims.

What is claimed is:

1. A method comprising:

receiving a photoplethysmograph (PPG) signal;

processing, with processing equipment, the PPG signal to generate a plurality of respiration morphology signals;

performing, with the processing equipment, independent component analysis on the plurality of respiration morphology signals to generate a plurality of independent components;

selecting, with the processing equipment, an independent component that corresponds to a respiration source signal from the plurality of independent components; and

determining, with the processing equipment, respiration information based at least in part on the selected independent component.

2. The method of claim **1**, wherein the plurality of respiration morphology signals comprise one or more of a down signal, a difference in the second derivative signal, and a kurtosis signal.

3. The method of claim **1**, wherein selecting the independent component comprises:

determining a confidence value for each of the plurality of independent components; and

selecting an independent component from the plurality of independent components corresponding to the respiration source signal based on the confidence values.

4. The method of claim **1**, wherein determining respiration information comprises:

determining a confidence value for each of the selected independent component and the one or more respiration morphology signals;

generating a combined signal from the selected independent component and the one or more respiration morphology signals based on the confidence values; and

determining the respiration information based on the combined signal.

5. The method of claim **4**, wherein generating the combined signal comprises:

weighting each of the selected independent component and one or more respiration morphology signals based on the confidence values; and

combining the weighted selected independent component and one or more weighted respiration morphology signals.

6. The method of claim **1**, wherein determining the respiration information comprises:

generating an autocorrelation signal for the selected independent component; and

determining the respiration information based on the autocorrelation signal.

7. The method of claim **1**, wherein the respiration information comprises a respiration rate.

8. A non-transitory computer-readable storage medium, the computer-readable medium having computer program instructions recorded thereon for:

receiving a photoplethysmograph (PPG) signal;

processing the PPG signal to generate a plurality of respiration morphology signals;

performing independent component analysis on the plurality of respiration morphology signals to generate a plurality of independent components;

selecting an independent component that corresponds to a respiration source signal from the plurality of independent components; and

determining respiration information based at least in part on the selected independent component.

9. The computer-readable medium of claim **8**, wherein the plurality of respiration morphology signals comprise one or more of a down signal, a difference in the second derivative signal, and a kurtosis signal.

10. The computer-readable medium of claim **8**, wherein selecting the independent components comprises:

determining a confidence value for each of the plurality of independent components; and

selecting an independent component corresponding to the respiration source signal from the plurality of independent components based on the confidence values.

11. The computer-readable medium of claim **8**, wherein determining respiration information comprises:

determining a confidence value for each of the selected independent component and the one or more respiration morphology signals;

generating a combined signal from the selected independent component and the one or more respiration morphology signals based on the confidence values; and

determining the respiration information based on the combined signal.

12. The computer readable medium of claim **11**, wherein generating the combined signal comprises:

weighting each of the selected independent component and one or more respiration morphology signals based on the confidence values; and

combining the weighted selected independent component and one or more weighted respiration morphology signals.

13. The computer-readable medium of claim **8**, wherein determining the respiration information comprises:

generating an autocorrelation signal for the selected independent component; and

determining the respiration information based on the autocorrelation signal.

14. A patient monitoring system comprising processing equipment configured to:

receive a photoplethysmograph (PPG) signal;

process the PPG signal to generate a plurality of respiration morphology signals;

perform independent component analysis on the plurality of respiration morphology signals to generate a plurality of independent components;

select an independent component that corresponds to a respiration source signal from the plurality of independent components; and

determine respiration information based at least in part on the selected independent component.

15. The patient monitoring system of claim **14**, wherein the plurality of respiration morphology signals comprise one or more of a down signal, a difference in the second derivative signal, and a kurtosis signal.

16. The patient monitoring system of claim **14**, wherein the patient monitoring system is configured to:

determine a confidence value for each of the plurality of independent components; and

select an independent component corresponding to the respiration source signal from the plurality of independent components based on the confidence values to determine the selected independent component.

17. The patient monitoring system of claim **14**, wherein the patient monitoring system is configured to:

determine a confidence value for each of the selected independent component and the one or more respiration morphology signals;

generate a combined signal from the selected independent component and the one or more respiration morphology signals based on the confidence values; and

determine the respiration information based on the combined signal.

18. The patient monitoring system of claim **17**, wherein the patient monitoring system is configured to:

weight each of the selected independent component and one or more respiration morphology signals based on the confidence values; and

combine the weighted selected independent component and weighted one or more respiration morphology signals to generate the combined signal.

19. The patient monitoring system of claim **14**, wherein the patient monitoring system is configured to:

generate an autocorrelation signal for the selected independent component; and

determine the respiration information based on the autocorrelation signal.

20. The patient monitoring system of claim **14**, wherein the respiration information comprises a respiration rate.

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专利名称(译)	用于基于独立成分分析确定呼吸信息的系统和方法		
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[标]申请(专利权)人(译)	ADDISON PAUL STANLEY 沃森JAMES NICHOLAS DRIPPS JIMMY 奥克斯JAMES		
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摘要(译)

患者监测系统可以接收生理信号，例如光电容积描记器（PPG）信号。可以从PPG信号确定多个呼吸形态学信号。可以对呼吸形态学信号执行独立分量分析，从而产生多个独立分量。可以从多个独立组件中选择对应于呼吸源信号的独立组件。可以至少部分地基于所选择的独立分量来确定诸如呼吸率的呼吸信息。