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(54) **SYSTEMS AND METHODS FOR PROCESSING MULTIPLE PHYSIOLOGICAL SIGNALS**

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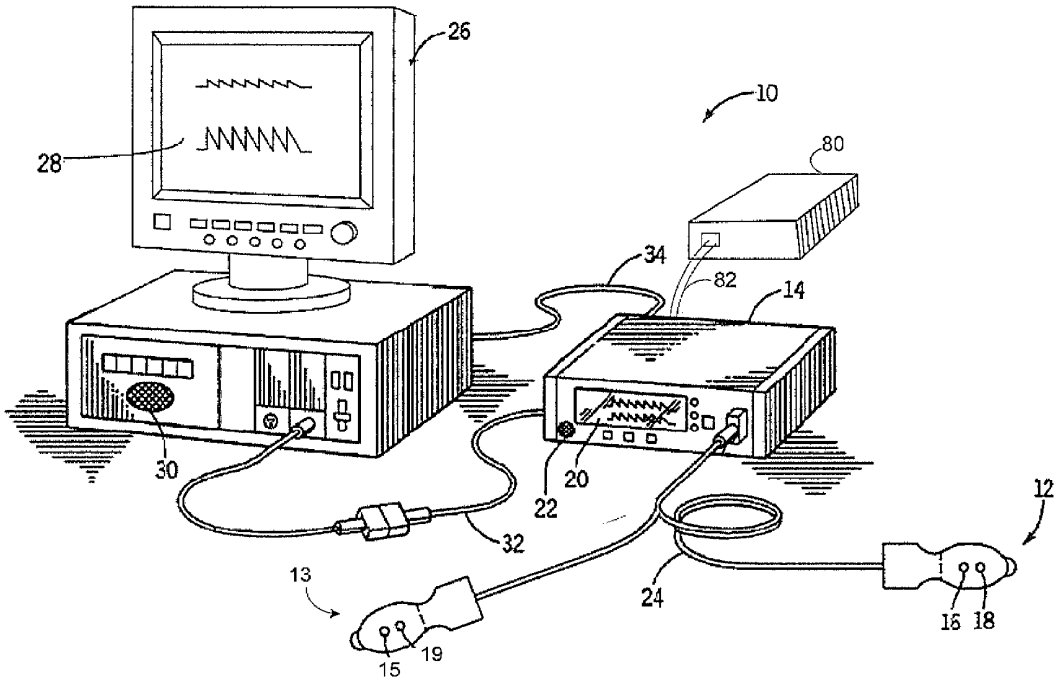
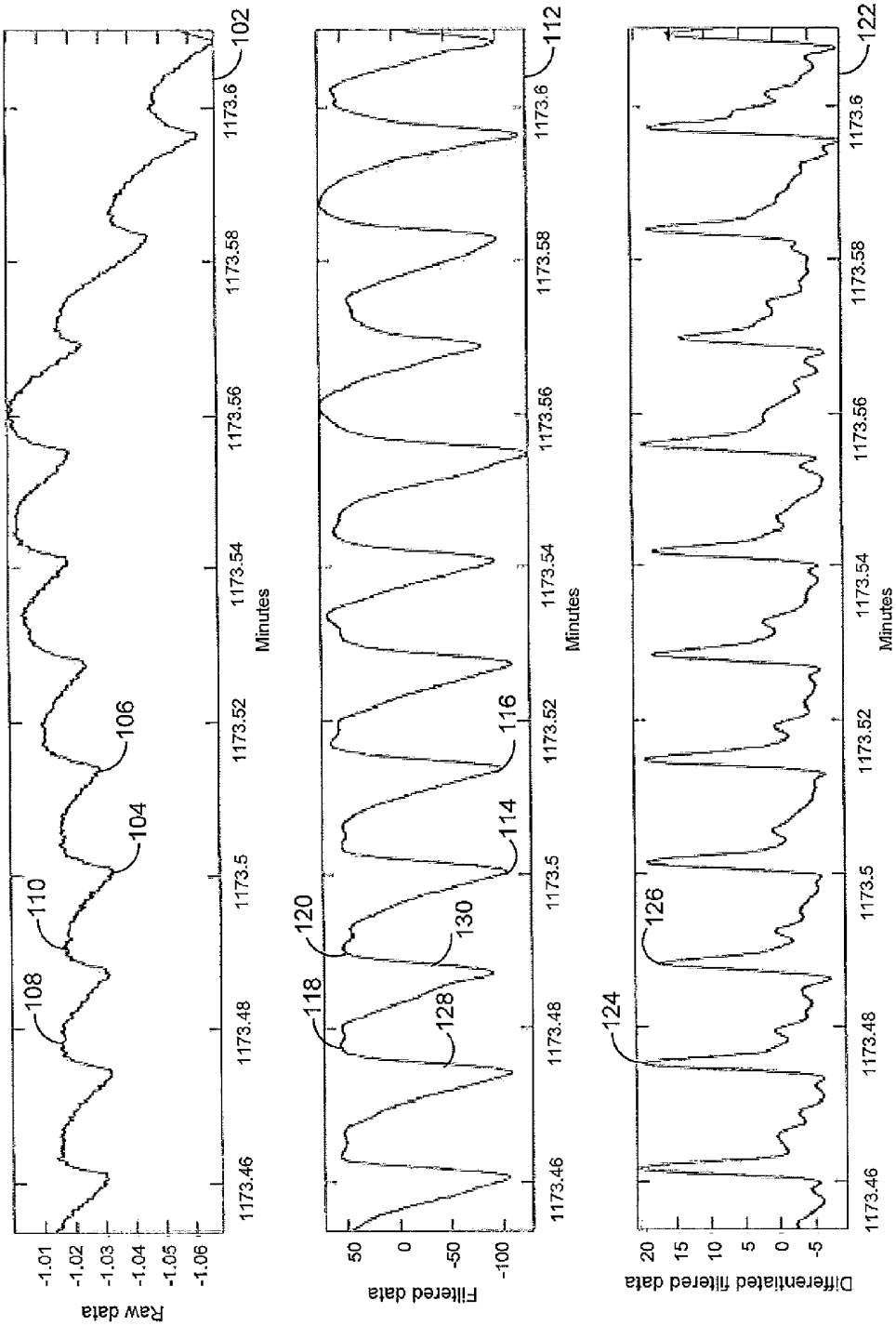
(57) **ABSTRACT**

Systems and methods are provided for patient monitors which apply different sets of signal processing operations to signals to identify multiple fiducials in physiological signals. PPG signals measured at two sensor sites may be processed with a first set of processing operations and analyzed to identify fiducials that allow the calculation of a diastolic DPTT. These PPG signals may then be processed with a different set of processing operations and the results analyzed to identify fiducials that allow the calculation of a systolic DPTT.

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-1.02
-1.03
-1.04
-1.05
-1.06
102
108
110
104
106
Filtered data
50
0
-50
-100
112
118
120
128
130
114
116
Differentiated filtered data
20
15
10
5
0
-5
122
124
126
1173.46
1173.48
1173.5
1173.52
1173.54
1173.56
1173.58
1173.6
Minutes

FIG. 1

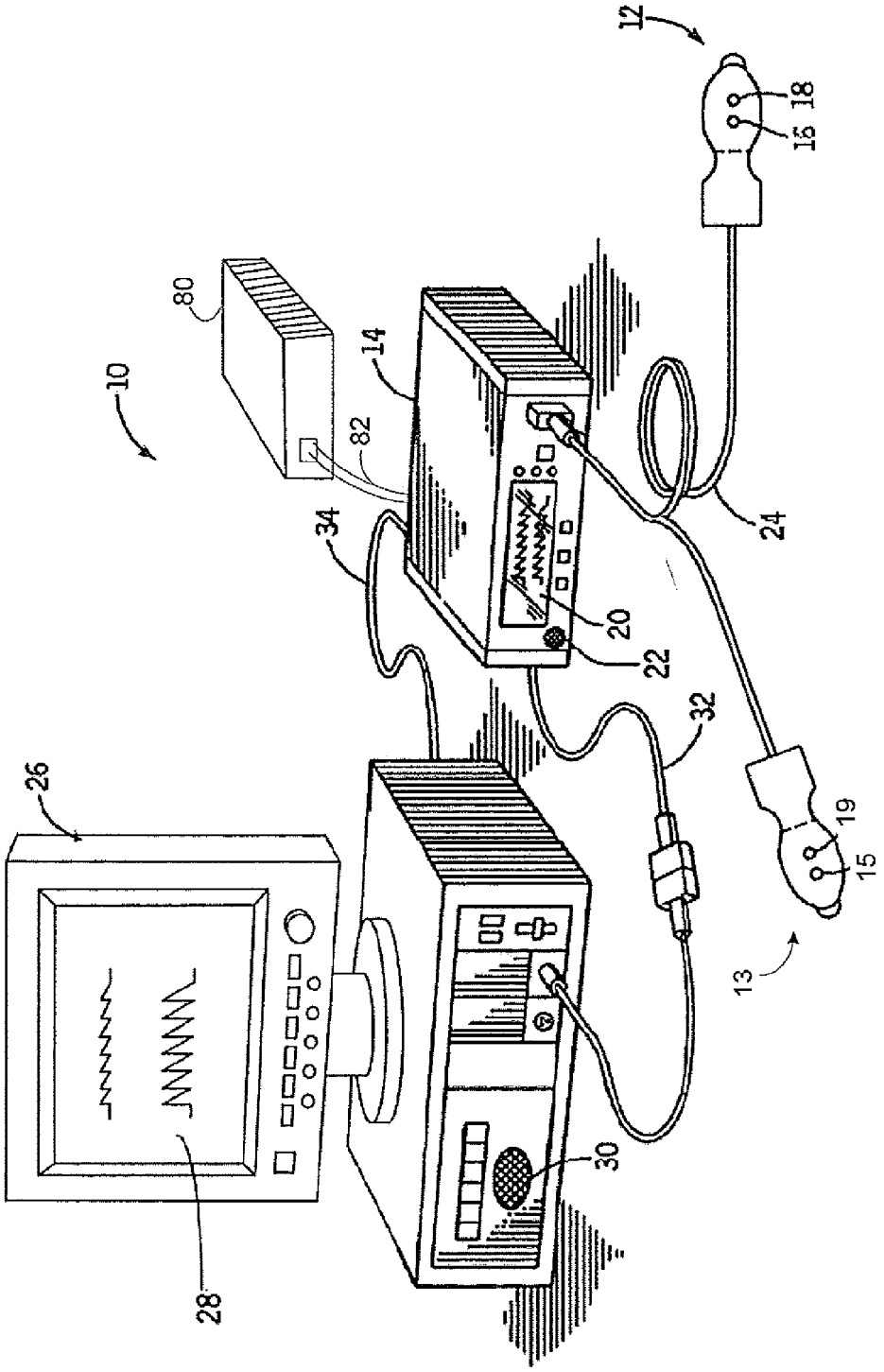
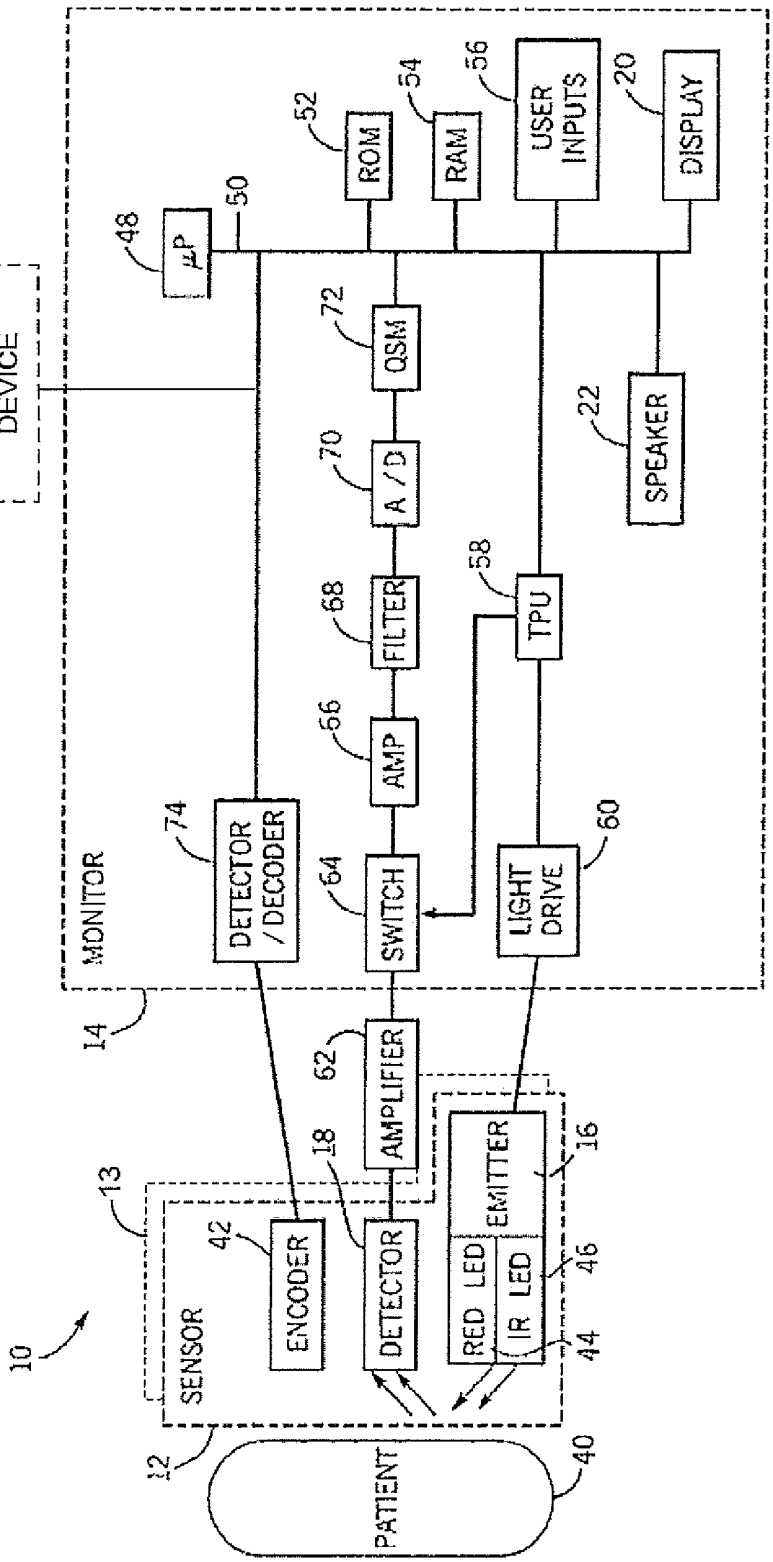


FIG. 2(a)


10
12
13
14
16
18
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22
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
80
SENSOR
ENCODER
DETECTOR
RED LED
IR LED
EMITTER
PATIENT
MONITOR
AMPLIFIER
SWITCH
AMP
FILTER
A/D
QSM
μP
ROM
RAM
USER INPUTS
DISPLAY
SPEAKER
TPU
LIGHT DRIVE
DETECTOR / DECODER
CALIBRATION DEVICE

FIG. 2(b)

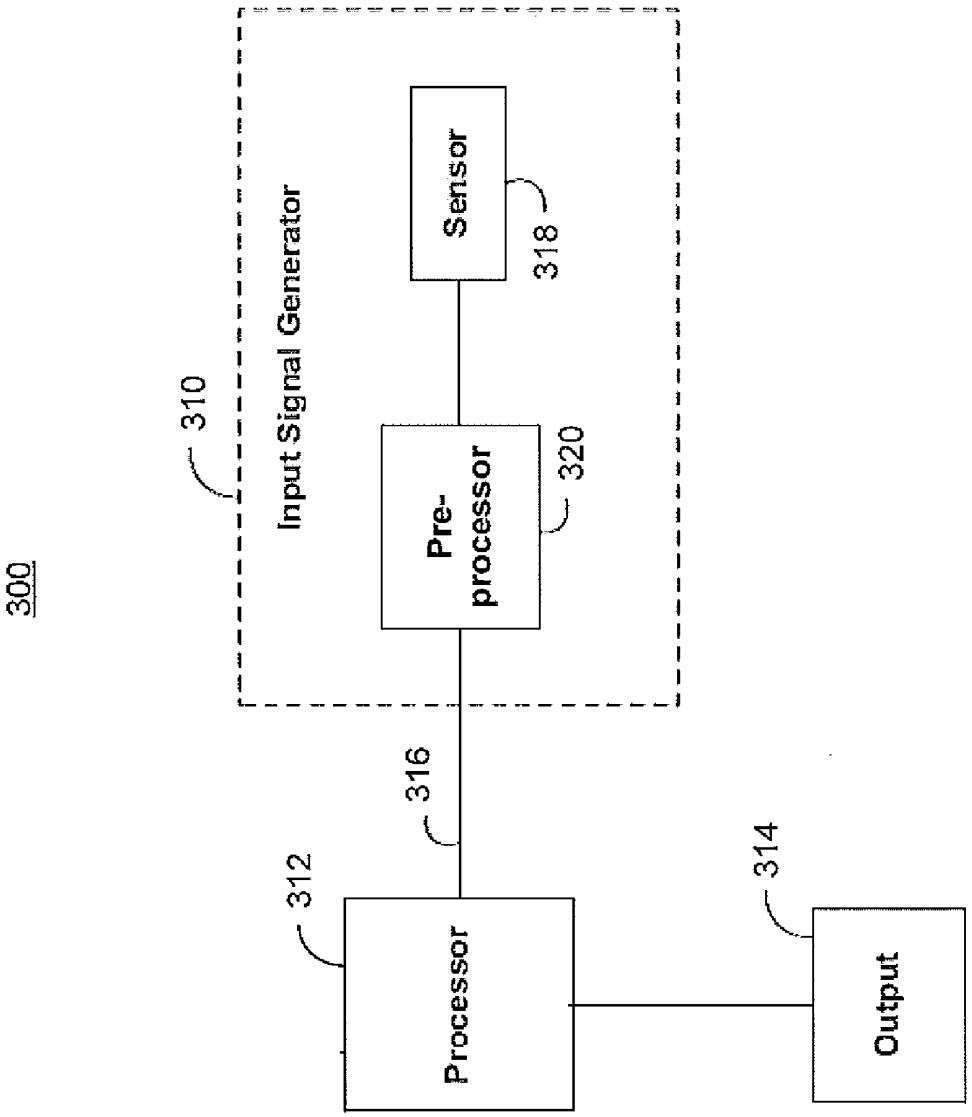
300
310
Input Signal Generator
Sensor
318
Pre-
processor
320
316
312
Processor
314
Output

FIG. 3

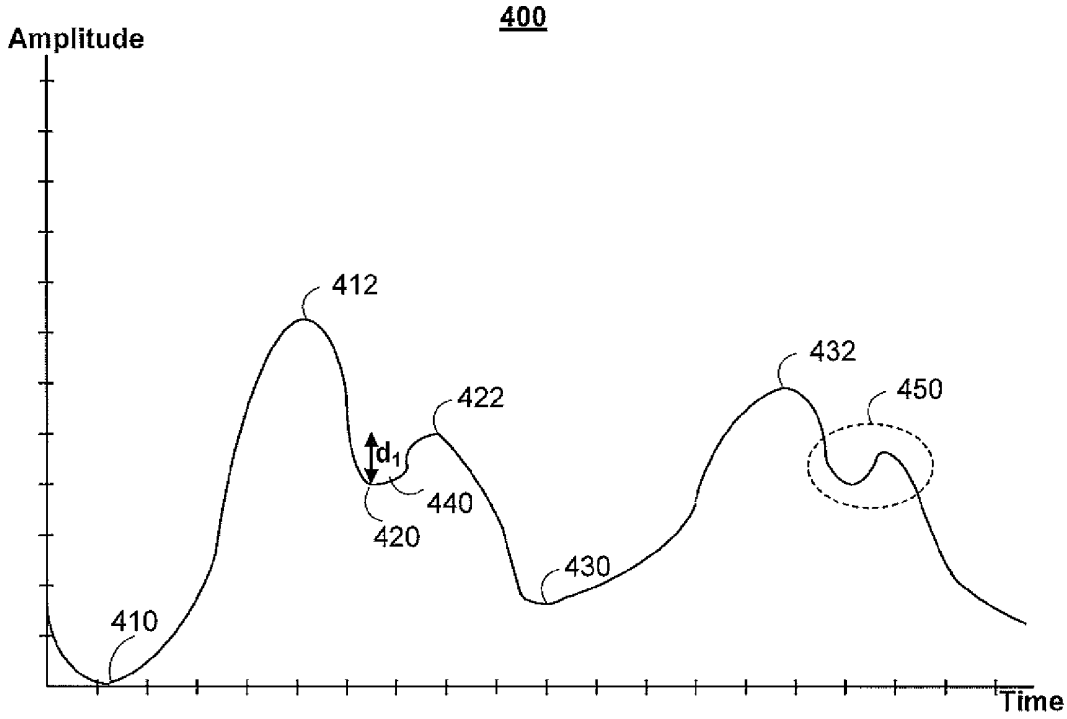

FIG. 4

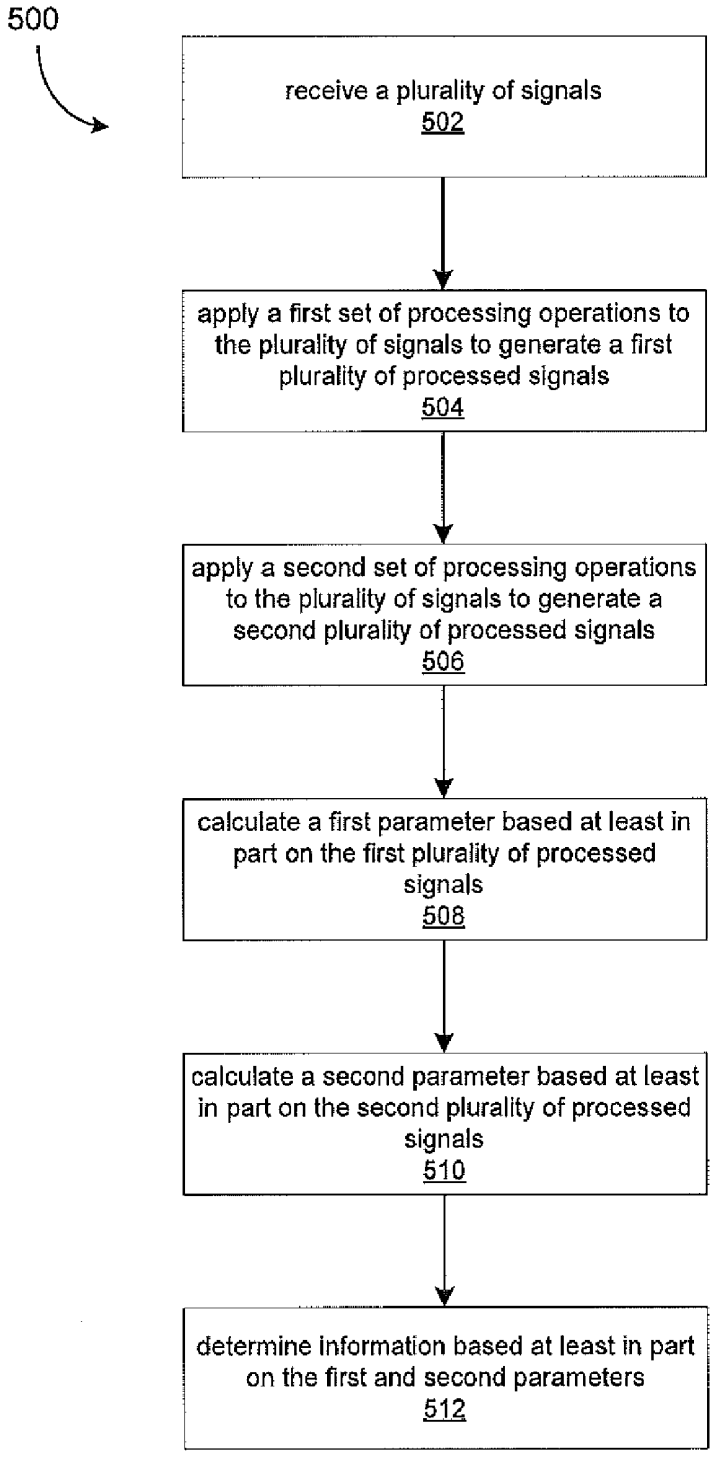
500
receive a plurality of signals
502
apply a first set of processing operations to the plurality of signals to generate a first plurality of processed signals
504
apply a second set of processing operations to the plurality of signals to generate a second plurality of processed signals
506
calculate a first parameter based at least in part on the first plurality of processed signals
508
calculate a second parameter based at least in part on the second plurality of processed signals
510
determine information based at least in part on the first and second parameters
512

FIG. 5

SYSTEMS AND METHODS FOR PROCESSING MULTIPLE PHYSIOLOGICAL SIGNALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/369,452, "SYSTEMS AND METHODS FOR PROCESSING MULTIPLE PHYSIOLOGICAL SIGNALS," filed Jul. 30, 2010 and incorporated by reference in its entirety herein.

SUMMARY

[0002] Continuous non-invasive blood pressure (CNIBP) monitoring systems allow a patient's blood pressure to be tracked continuously, unlike standard occlusion cuff techniques, and without the hazards of invasive arterial lines. Some such systems use multiple pulse oximetry type sensors located at multiple body sites on a patient to measure photoplethysmograph (PPG) signals. The resulting multiple PPG signals may be compared against each other to estimate the patient's blood pressure. When the locations of two sensors are at different distances from the heart or along different paths from the heart (e.g., at the finger and forehead), a differential pulse transit time (DPTT) may be determined. A DPTT may represent the difference in the arrival times of a portion of a cardiac wave between the two locations, and may be determined by comparing corresponding fiducial points in the two PPG signals (e.g., a maximum, minimum, or a notch). In some techniques, two DPTTs are determined in order to calculate multiple physiological parameters, such as systolic and diastolic blood pressure. These DPTTs may be determined during different phases of the PPG signal representing different physiological occurrences. For example, one DPTT may be determined when the cardiovascular system is in a systolic state and a second DPTT may be determined when the cardiovascular system is in a diastolic state.

[0003] The accuracy of a blood pressure calculation based on a DPTT determination may depend on the accuracy of the DPTT determination. For more accurate transit times to be measured, it is desirable for the fiducial points to be easily and unambiguously resolved. However, fiducial points may not always be confidently identified by examining a raw PPG signal. For example, the diastolic portion of a PPG signal often has a sharp trough whose minimum point serves as an easily identifiable fiducial point. However, the peaks of a PPG signal (corresponding to the systolic portion) are often rounded and exhibit wide"shoulders" that make it difficult to distinguish a unique maximum (particularly in signals measured at the finger and forehead). Further, the peaks of PPG signals often change maxima positions between cardiac cycles. To sharpen the peaks, existing systems may apply a single signal processing technique, such as differentiating the PPG signal. While differentiation may disambiguate the position of a peak point associated with the systolic period of the cardiac cycle, it can hinder finding a diastolic fiducial.

[0004] Systems and methods are provided herein for determining physiological information about a subject with a monitoring device. The device receives a plurality of physiological signals of a subject from one or more sensors and uses a processor to generate a first plurality of processed signals by applying a first set of processing operations to the plurality of physiological signals. The device also generates a second plurality of processed signals by applying a second set of processing operations to the plurality of physiological signals, with the second set of processing operations being different from the first set of processing operations. The device calculates a first parameter by comparing features of the first plurality of processed signals, and calculate a second parameter by comparing features of the second plurality of processed signals. The device then determines physiological information about the subject based at least in part on the first and second parameters.

[0005] In some embodiments, the plurality of physiological signals includes one or more photoplethysmograph signals. Multiple photoplethysmograph signals may be measured at multiple different body sites of the subject. The first set of processing operations may include taking one or more time derivatives and/or applying a low-pass filter prior to taking one or more time derivatives. In some embodiments, the first set of processing operations includes taking a single time derivative and the second set of processing operations includes taking two time derivatives.

[0006] In some embodiments, the device calculates the first parameter by comparing extrema between one or more of the first plurality of processed signals. The first parameter may be a differential pulse transit time and/or may be determined based at least in part on a linear combination of multiple fiducial points in the first plurality of processed signals. In some embodiments, the physiological information includes a blood pressure.

[0007] In certain embodiments, the systems and methods described herein are used in

[0008] CNIBP monitors which apply different sets of signal processing operations to signals to identify multiple fiducials. In some embodiments, PPG signals measured at two sensor sites may be processed with a first set of processing operations and compared to identify fiducials that allow the calculation of a diastolic DPTT. These PPG signals may then be processed with a different set of processing operations and the results compared to identify fiducials that allow the calculation of a systolic DPTT.

[0009] The methods and systems of the present disclosure will be illustrated with reference to the monitoring of a physiological signal (which may be a PPG signal); however, it will be understood that the disclosure is not limited to monitoring physiological signals and is usefully applied within a number of signal monitoring settings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] 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:

[0011] FIG. **1** illustrates a methodology using different signal processing operations that may be applied to a signal in accordance with an embodiment;

[0012] FIG. **2**(*a*) shows an illustrative patient monitoring system in accordance with an embodiment;

[0013] FIG. **2**(*b*) is a block diagram of the illustrative patient monitoring system of FIG. **2**(*a*) coupled to a patient in accordance with an embodiment;

[0014] FIG. **3** is a block diagram of an illustrative signal processing system in accordance with an embodiment;

[0015] FIG. **4** is an illustrative signal which may be analyzed in accordance with an embodiment; and

[0016] FIG. **5** is a flow chart of an illustrative process for determining physiological information in accordance with an embodiment.

DETAILED DESCRIPTION

[0017] As described above, information about a system, such as the physiological system of human subject, may be determined by applying multiple signal processing techniques to a set of signals. FIG. **1** depicts an illustrative example of multiple signal processing techniques applied to a single signal in accordance with the systems and methods described herein. In particular, plot **102** of FIG. **1** depicts a raw photoplethysmograph (PPG) signal generated by a reflectance probe positioned on a subject's forehead for approximately ten seconds. Though the location of the troughs of this signal (e.g., troughs **104** and **106**) may be more easily distinguished than the peaks (e.g., peaks **108** and **110**), neither peaks nor troughs are particularly distinct.

[0018] Plot **112** of FIG. **1** depicts the raw PPG signal of plot **102** after the PPG signal has been filtered with a band-pass filter with a pass-band of approximately 0.5 Hz-7.5 Hz. This filtering has sharpened the troughs (e.g., troughs **114** and **116**), allowing their locations to be more easily identified. Physiological parameter calculations based on the locations of these troughs as fiducial points, such as a diastolic blood pressure calculation, may be more accurate than calculations based on the troughs of the raw PPG signal of plot **102**. However, the peaks of the filtered signal (e.g., peaks **118** and **120**) may not exhibit a similar improvement in discernability over the peaks of the raw PPG signal of plot **102**, and indeed may be more difficult to distinguish than their counterparts in the raw PPG signal of plot **102**. These peaks may not readily provide accurate fiducial points to use in physiological parameter calculations. In calculations which require the identification of more than one fiducial point, a different approach may be desired.

[0019] Plot **122** of FIG. **1** depicts a time derivative of the filtered signal of plot **112**. The locations of the peaks of plot **122** (e.g., peaks **124** and **126**) are more easily distinguished than the peaks of plot **112**. The peaks of plot **122** correspond to the points of maximum slope in plot **112** (i.e. the upstrokes of the PPG signal). For example, peak **124** corresponds to upstroke **128** of plot **112** and peak **126** corresponds to upstroke **130** of plot **112**. The peaks of plot **122** may be used as fiducial points in a physiological parameter calculation, such as a systolic blood pressure calculation. The peaks of plot **122** may be used in combination with the fiducial points given by the troughs of plot **112** to determine a subject's systolic and diastolic blood pressure. In an embodiment, as discussed above, two different fiducial points, identified in signals measured at two different body sites of a subject, may allow two differential pulse transit times (DPTTs) to be calculated, which may then be used to determine the subject's systolic and diastolic blood pressure. Thus, different fiducial points may be identified from a physiological signal by applying different signal processing operations and locating fiducial points or features in the processed signals. The present disclosure relates to systems and methods for applying multiple processing operations to one or more physiological signals in order to identify multiple parameters based on features of the multiple processed physiological signals.

[0020] For illustrative purposes, the systems and techniques disclosed herein may be described in the context of continuous, non-invasive blood pressure monitoring (CNIBP) systems, oximetry systems, and other patient monitoring systems. However, the disclosed systems and methods may be suitable for any signal processing and monitoring application in which different fiducial points may be identified in multiple signals. In particular, the systems and methods described herein have application in any methodology that requires the identification of multiple fiducials from any periodic signal or any collection of signals.

[0021] 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 and blood pressure.

[0022] 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.

[0023] 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 which are not typically understood to be optimal for pulse oximetry serve as suitable sensor locations for the blood pressure 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.

[0024] 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.

[0025] 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:

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

where:

[0026] λ=wavelength;

[0027] t=time;

[0028] I=intensity of light detected;

[0029] I_0=intensity of light transmitted;

[0030] s=oxygen saturation;

[0031] β_0, β_r=empirically derived absorption coefficients; and

[0032] l(t)=a combination of concentration and path length from emitter to detector as a function of time.

[0033] 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.

[0034] 1. The natural logarithm of Eq. 1 is taken ("log" will be used to represent the natural logarithm) for IR and Red to yield

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

[0035] 2. Eq. 2 is then differentiated with respect to time to yield

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

[0036] 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

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

[0037] 4. Solving for s yields

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

[0038] 5. Note that, in discrete time, the following approximation can be made:

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

[0039] 6. Rewriting Eq. 6 by observing that log A−log B=log(A/B) yields

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

[0040] 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."

[0041] 8. Solving Eq. 4 for s using the relationship of Eq. 5 yields

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

[0042] 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

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

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.

[0043] FIG. **2**(*a*) is a perspective view of an embodiment of a patient monitoring system **10**. System **10** may include sensor unit **12** and monitor **14**. In an embodiment, sensor unit **12** may be part of a continuous, non-invasive blood pressure (CNIBP) monitoring system and/or 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 **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, such as sensor unit **13**, which may take the form of any of the embodiments described herein with reference to sensor unit **12**. For example, sensor unit **13** may include emitter **15** and detector **19**. Sensor unit **13** may be the same type of sensor unit as sensor unit **12**, or sensor unit **13** may be of a different sensor unit type than sensor unit **12**. Sensor units **12** and **13** may be capable of being positioned at two different locations on a subject's body; for example, sensor unit **12** may be positioned on a patient's forehead, while sensor unit **13** may be positioned at a patient's fingertip. [0026] Sensor units **12** and **13** 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 another embodiment, system **10** may include a plurality of sensors forming a sensor array in lieu of either or both of sensor units **12** and **13**. 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 an embodiment, 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 of sensor units **12** and **13** 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.

[0044] According to an embodiment, 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 an embodiment, 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.

[0045] In an embodiment, 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., heart rate, blood pressure, blood oxygen saturation) based at least in part on data relating to light emission and detection received from one or more sensor units such as sensor units **12** and **13**. In an alternative embodiment, 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 an embodiment, the monitor **14** includes a blood pressure monitor. In alternative embodiments, the system **10** includes a stand-alone blood pressure monitor in communication with the monitor **14** via a cable or a wireless network link.

[0046] In an embodiment, sensor unit **12** may be communicatively coupled to monitor **14** via a cable **24**. However, in other embodiments, a wireless transmission device (not shown) or the like may be used instead of or in addition to cable **24**.

[0047] In the illustrated embodiment, system **10** includes a multi-parameter patient monitor **26**. The monitor **26** may include a cathode ray tube display, a flat panel display (as shown) such as a liquid crystal display (LCD) or a plasma display, or may include any other type of monitor now known or later developed. Multi-parameter patient monitor **26** may be configured to calculate physiological parameters and to provide a display **28** for information from monitor **14** and from other medical monitoring devices or systems (not shown). For example, multi-parameter patient monitor **26** may be configured to display an estimate of a patient's blood oxygen saturation generated by monitor **14** (referred to as an "SpO_2" measurement), pulse rate information from monitor **14** and blood pressure from monitor **14** on display **28**. Multi-parameter patient monitor **26** may include a speaker **30**.

[0048] Monitor **14** may be communicatively coupled to multi-parameter patient monitor **26** via a cable **32** or **34** that is coupled to a sensor input port or a digital communications port, respectively and/or may communicate wirelessly (not shown). In addition, monitor **14** and/or multi-parameter patient monitor **26** may be coupled to a network to enable the sharing of information with servers or other workstations (not shown). Monitor **14** may be powered by a battery (not shown) or by a conventional power source such as a wall outlet.

[0049] Calibration device **80**, which may be powered by monitor **14** via a cable **82**, a battery, or by a conventional power source such as a wall outlet, may include any suitable signal calibration device. Calibration device **80** may be communicatively coupled to monitor **14** via cable **82**, and/or may communicate wirelessly (not shown). In other embodiments, calibration device **80** is completely integrated within monitor **14**. For example, calibration device **80** may take the form of any invasive or non-invasive blood pressure monitoring or measuring system used to generate reference blood pressure measurements for use in calibrating a CNIBP monitoring technique as described herein. Such calibration devices may include, for example, an aneroid or mercury sphygmomanometer and occluding cuff, a pressure sensor inserted directly into a suitable artery of a patient, an oscillometric device or any other device or mechanism used to sense, measure, determine, or derive a reference blood pressure measurement. 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).

[0050] Calibration device **80** may also access reference signal measurements stored in memory (e.g., RAM, ROM, or a storage device). For example, in some embodiments, calibration device **80** may access reference blood pressure mea-

surements from a relational database stored within calibration device **80**, monitor **14**, or multi-parameter patient monitor **26**. The reference blood pressure measurements generated or accessed by calibration device **80** may be updated in real-time, resulting in a continuous source of reference blood pressure measurements for use in continuous or periodic calibration. Alternatively, reference blood pressure measurements generated or accessed by calibration device **80** may be updated periodically, and calibration may be performed on the same periodic cycle or a different periodic cycle. Reference blood pressure measurements may be generated when recalibration is triggered.

[0051] FIG. **2**(*b*) is a block diagram of a patient monitoring system, such as patient monitoring system **10** of FIG. **2**(*a*), 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**(*b*). Because sensor units **12** and **13** may include similar components and functionality, only sensor unit **12** will be discussed in detail for ease of illustration. It will be understood that any of the concepts, components, and operation discussed in connection with sensor unit **12** may be applied to sensor unit **13** as well (e.g., emitter **16** and detector **18** of sensor unit **12** may be similar to emitter **15** and detector **19** of sensor unit **13**). It will be noted that patient monitoring system **10** may include one or more additional sensor units or probes, which may take the form of any of the embodiments described herein with reference to sensor units **12** and **13** (FIG. **2**(*a*)). These additional sensor units included in system **10** may take the same form as sensor unit **12**, or may take a different form. In an embodiment, multiple sensors (distributed in one or more sensor units) may be located at multiple different body sites on a patient.

[0052] 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 one embodiment, 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 single sensor, each sensor may be configured to emit a single wavelength. For example, a first sensor emits only a Red light while a second emits only an IR light. In another example, the wavelengths of light used are selected based on the specific location of the sensor.

[0053] 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 ultrasound, radio, microwave, millimeter wave, infrared, visible, ultraviolet, gamma ray or X-ray electromagnetic radiation. As used herein, light may also include 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**.

[0054] In an embodiment, 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**.

[0055] In an embodiment, encoder **42** may contain information about sensor **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.

[0056] 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, for example, blood pressure and other 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 pulse of a photoplethysmograph (PPG) signal to determine blood pressure. These equations may contain coefficients that depend upon a patient's physiological characteristics as stored in encoder **42**. Encoder **42** may, for instance, be a coded resistor which 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. In another embodiment, 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; or any combination thereof.

[0057] In an embodiment, 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**, and speaker **22**.

[0058] 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 instruc-

tions, 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 which can be used to store the desired information and which can be accessed by components of the system.

[0059] 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** fills up. In one embodiment, there may be multiple separate parallel paths having components equivalent to amplifier **66**, filter **68**, and/or AID converter **70** for multiple light wavelengths or spectra received.

[0060] In an embodiment, microprocessor **48** may determine the patient's physiological parameters, such as SpO_2, pulse rate, and/or blood pressure, 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**. 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 the microprocessor to determine the thresholds based at least in part on algorithms or look-up tables stored in ROM **52**. User inputs **56** may be used to enter information about the patient, such as age, weight, height, diagnosis, medications, treatments, and so forth. In an embodiment, 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**.

[0061] The optical signal through the tissue 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. In addition, because blood is a fluid, it responds differently than the surrounding tissue to inertial effects, thus resulting in momentary changes in volume at the point to which the oximeter probe is attached.

[0062] 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 or otherwise identify noise components in order to prevent them from affecting measurements of physiological parameters derived from the sensor signals.

[0063] Pulse oximeters, in addition to providing other information, can be utilized for continuous non-invasive blood pressure monitoring. As described in Chen et al., U.S. Pat. No. 6,599,251, the entirety of which is incorporated herein by reference, PPG and other pulse signals obtained from multiple probes can be processed to calculate the blood pressure of a patient. In particular, blood pressure measurements may be derived based on a comparison of time differences between certain components of the pulse signals detected at each of the respective probes. As described in U.S. patent application Ser. No. 12/242,238, filed on Sep. 30, 2008 and entitled "Systems and Methods For Non-Invasive Blood Pressure Monitoring," the entirety of which is incorporated herein by reference, blood pressure can also be derived by processing time delays detected within a single PPG or pulse signal obtained from a single pulse oximeter probe. In addition, as described in U.S. patent application Ser. No. 12/242,867, filed on Sep. 30, 2008 and entitled "Systems and Methods For Non-Invasive Continuous Blood Pressure Determination," the entirety of which is incorporated herein by reference, blood pressure may also be obtained by calculating the area under certain portions of a pulse signal. Finally, as described in U.S. patent application Ser. No. 12/242,862, filed on Sep. 30, 2008 and entitled "Systems and Methods For Maintaining Blood Pressure Monitor Calibration," the entirety of which is incorporated herein by reference, a blood pressure monitoring device may be recalibrated in response to arterial compliance changes.

[0064] As described above, some CNIBP monitoring techniques utilize two probes or sensors positioned at two different locations on a subject's body. The elapsed time, T, between the arrivals of corresponding points of a pulse signal at the two locations may then be determined using signals obtained by the two probes or sensors. The estimated blood pressure, p, may then be related to the elapsed time, T, by

$$p = a + b \cdot \ln(T) \tag{14}$$

where a and b are constants that may be dependent upon the nature of the subject and the nature of the signal detecting devices. Other suitable equations using an elapsed time between corresponding points of a pulse signal may also be used to derive an estimated blood pressure measurement.

[0065] In an embodiment, Eq. 14 may include a non-linear function which is monotonically decreasing and concave upward in Tin a manner specified by the constant parameters (in addition to or instead of the expression of Eq. 14). Eq. 14 may be used to calculate an estimated blood pressure from the time difference T between corresponding points of a pulse signal received by two sensors or probes attached to two different locations of a subject.

[0066] In an embodiment, constants a and b in Eq. 14 above may be determined by performing a calibration. The calibration may involve taking a reference blood pressure reading to

obtain a reference blood pressure P_0, measuring the elapsed time T_0 corresponding to the reference blood pressure, and then determining values for both of the constants a and b from the reference blood pressure and elapsed time measurement. Calibration may be performed at any suitable time (e.g., once initially after monitoring begins) or on any suitable schedule (e.g., a periodic or event-driven schedule).

[0067] In an embodiment, the calibration may include performing calculations mathematically equivalent to

$$a = c_1 + \frac{c_2(P_0 - c_1)}{\ln(T_0) + c_2} \text{ and} \quad (15)$$

$$b = \frac{P_0 - c_1}{\ln(T_0) + c_2} \quad (16)$$

to obtain values for the constants a and b, where c_1 and c_2 are parameters that may be determined, for example, based on empirical data.

[0068] In an embodiment, the calibration may include performing calculations mathematically equivalent to

$$a=P_0-(c_3T_0+c_4)\ln(T_0) \quad (17)$$

and

$$b=c_3T_0+c_4 \quad (18)$$

where a and b are first and second parameters and c_3 and c_4 are parameters that may be determined, for example, based on empirical data.

[0069] Parameters c_1, c_2, c_3, and c_4 may be predetermined constants empirically derived using experimental data from a number of different patients. A single reference blood pressure reading from a patient, including reference blood pressure P_0 and elapsed time T_0 from one or more signals corresponding to that reference blood pressure, may be combined with such inter-patient data to calculate the blood pressure of a patient. The values of P_0 and T_0 may be referred to herein as a calibration point. According to this example, a single calibration point may be used with the predetermined constant parameters to determine values of constants a and b for the patient (e.g., using Eqs. 15 and 16 or 17 and 18). The patient's blood pressure may then be calculated using Eq. 14. Recalibration may be performed by collecting a new calibration point and recalculating the constants a and b used in Eq. 14. Calibration and recalibration may be performed using calibration device **80** (FIG. **2**(*a*)).

[0070] In an embodiment, multiple calibration points from a patient may be used to determine the relationship between the patient's blood pressure and one or more PPG signals. This relationship may be linear or non-linear and may be extrapolated and/or interpolated to define the relationship over the range of the collected recalibration data. For example, the multiple calibration points may be used to determine values for parameters c_1 and c_2 or c_3 and c_4 (described above). These determined values will be based on information about the patient (intra-patient data) instead of information that came from multiple patients (inter-patient data). As another example, the multiple calibration points may be used to determine values for parameters a and b (described above). Instead of calculating values of parameters a and b using a single calibration point and predetermined constants, values for parameters a and b may be empirically derived from the values of the multiple calibration points. As yet another example, the multiple calibration points may be used directly to determine the relationship between blood pressure and PPG signals. Instead of using a predefined relationship (e.g., the relationship defined by Eq. 14), a relationship may be directly determined from the calibration points.

[0071] Additional examples of continuous and non-invasive blood pressure monitoring techniques are described in Chen et al., U.S. Pat. No. 6,566,251, which is hereby incorporated by reference herein in its entirety. The technique described by Chen et al. may use two sensors (e.g., ultrasound or photoelectric pulse wave sensors) positioned at any two locations on a subject's body where pulse signals are readily detected. For example, sensors may be positioned on an earlobe and a finger, an earlobe and a toe, or a finger and a toe of a patient's body.

[0072] FIG. **3** is an illustrative signal processing system **300** in accordance with an embodiment that may implement the non-invasive blood pressure techniques described herein. In this embodiment, input signal generator **310** generates an input signal **316**. As illustrated, input signal generator **310** may include pre-processor **320** coupled to sensor **318**, which may provide input signal **316**. In an embodiment, pre-processor **320** may be an oximeter and input signal **316** may be a PPG signal. In an embodiment, pre-processor **320** may be any suitable signal processing device and input signal **316** may include one or more PPG signals and one or more other physiological signals, such as an electrocardiogram (ECG) signal. It will be understood that input signal generator **310** may include any suitable signal source, signal generating data, signal generating equipment, or any combination thereof to produce signal **316**. Signal **316** may be a single signal, or may be multiple signals transmitted over a single pathway or multiple pathways.

[0073] Pre-processor **320** may apply one or more signal processing operations to the signal generated by sensor **318**. For example, pre-processor **320** may apply a pre-determined set of processing operations to the signal provided by sensor **318** to produce input signal **316** that can be appropriately interpreted by processor **312**, such as performing AID conversion. Pre-processor **320** may also perform any of the following operations on the signal provided by sensor **318**: reshaping the signal for transmission, multiplexing the signal, modulating the signal onto carrier signals, compressing the signal, encoding the signal, and filtering the signal.

[0074] In an embodiment, signal **316** may include PPG signals at one or more frequencies, such as a Red PPG signal and an IR PPG signal. In an embodiment, signal **316** may include signals measured at one or more sites on a patient's body, for example, a patient's finger, toe, ear, arm, or any other body site. In an embodiment, signal **316** may include multiple types of signals (e.g., one or more of an ECG signal, an EEG signal, an acoustic signal, an optical signal, a signal representing a blood pressure, and a signal representing a heart rate). Signal **316** may be any suitable biosignal or signals, such as, for example, electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal. The systems and techniques described herein are also applicable to any dynamic signals, non-destructive testing signals, condition monitoring signals, fluid signals, geophysical signals, astronomical signals, electrical signals, financial signals including financial indices, sound and

speech signals, chemical signals, meteorological signals including climate signals, any other suitable signal, and/or any combination thereof.

[0075] In an embodiment, signal **316** may be coupled to processor **312**. Processor **312** may be any suitable software, firmware, hardware, or combination thereof for processing signal **316**. For example, processor **312** may include one or more hardware processors (e.g., integrated circuits), one or more software modules, computer-readable media such as memory, firmware, or any combination thereof. Processor **312** may, for example, be a computer or may be one or more chips (i.e., integrated circuits). Processor **312** may, for example, be configured of analog electronic components. Processor **312** may perform the calculations associated with the information determination techniques of the present disclosure as well as the calculations associated with any calibration of processing system **300** or other auxiliary functions. For example, processor **312** may locate one or more fiducial points in one or more signals, determine one or more DPTTs, and compute one or more of a systolic blood pressure, a diastolic blood pressure and a mean arterial pressure. Processor **312** may perform any suitable signal processing of signal **316** to filter signal **316**, such as any suitable band-pass filtering, adaptive filtering, closed-loop filtering, any other suitable filtering, and/or any combination thereof. Processor **312** may also receive input signals from additional sources (not shown). For example, processor **312** may receive an input signal containing information about treatments provided to the patient. Additional input signals may be used by processor **312** in any of the calculations or operations it performs in accordance with processing system **300**.

[0076] Processor **312** may be coupled to one or more memory devices (not shown) or incorporate one or more memory devices such as any suitable volatile memory device (e.g., RAM, registers, etc.), non-volatile memory device (e.g., ROM, EPROM, magnetic storage device, optical storage device, flash memory, etc.), or both. The memory may be used by processor **312** to, for example, store data corresponding to blood pressure monitoring, including current blood pressure calibration values, blood pressure monitoring calibration thresholds, and patient blood pressure history. In an embodiment, processor **312** may store physiological measurements or previously received data from signal **316** in a memory device for later retrieval. In an embodiment, processor **312** may store calculated values, such as a systolic blood pressure, a diastolic blood pressure, a blood oxygen saturation, a differential pulse transit time, a fiducial point location or characteristic, or any other calculated values, in a memory device for later retrieval.

[0077] Processor **312** may be coupled to a calibration device. This coupling may take any of the forms described above with reference to calibration device **80** within system **10**. For example, the calibration device may be a stand-alone device that may be in wireless communication with processor **312**, or may be completely integrated with processor **312**. [0061] Processor **312** may be coupled to a calibration device that may generate, or receive as input, reference measurements for use in calibration calculations. This coupling may occur through a recalibration signal transmitted via a wired or wireless communications path. In an embodiment, processor **312** is capable of transmitting a command to calibration device **80** to initiate a recalibration procedure.

[0078] Processor **312** may be coupled to output **314**. Output **314** may be any suitable output device such as one or more medical devices (e.g., a medical monitor that displays various physiological parameters, a medical alarm, or any other suitable medical device that either displays physiological parameters or uses the output of processor **312** as an input), one or more display devices (e.g., monitor, PDA, mobile phone, any other suitable display device, or any combination thereof), one or more audio devices, one or more memory devices (e.g, hard disk drive, flash memory, RAM, optical disk, any other suitable memory device, or any combination thereof), one or more printing devices, any other suitable output device, or any combination thereof.

[0079] It will be understood that system **300** may be incorporated into system **10** (FIGS. **1** and **2**) in which, for example, input signal generator **310** may be implemented as parts of sensor units **12** and **13** (FIGS. **1** and **2**) and monitor **14** (FIGS. **1** and **2**) and processor **312** may be implemented as part of monitor **14** (FIGS. **1** and **2**). In sonic embodiments, portions of system **300** may be configured to be portable. For example, all or part of system **300** may be embedded in a small, compact object carried with or attached to the patient (e.g., a watch, other piece of jewelry, or a cellular telephone). In such embodiments, a wireless transceiver (not shown) may also be included in system **300** to enable wireless communication with other components of system **10** (FIGS. **1** and **2**). As such, system **10** (FIGS. **1** and **2**) may be part of a fully portable and continuous patient monitoring solution. In such embodiments, a wireless transceiver (not shown) may also be included in system **300** to enable wireless communication with other components of system **10**. For example, pre-processor **320** may output signal **316** over BLUETOOTH, 802.11, WiFi, WiMax, cable, satellite, Infrared, or any other suitable transmission scheme. In an embodiment, a wireless transmission scheme may be used between any communicating components of system **300**.

[0080] Pre-processor **320** or processor **312** may determine the locations of pulses within a periodic signal **316** (e.g., a PPG signal) using a pulse detection technique. For ease of illustration, the following pulse detection techniques will be described as performed by processor **312**, but any suitable processing device (e.g., pre-processor **320**) may be used to implement any of the techniques described herein.

[0081] An illustrative PPG signal **400** is depicted in FIG. **4**. Processor **312** may receive PPG signal **400**, and may identify local minimum point **410**, local maximum point **412**, local minimum point **420**, and local maximum point **422** in the PPG signal **400**. Processor **312** may pair each local minimum point with an adjacent maximum point. For example, processor **312** may pair points **410** and **412** to identify one segment, points **412** and **420** to identify a second segment, points **420** and **422** to identify a third segment and points **422** and **430** to identify a fourth segment. The slope of each segment may be measured to determine whether the segment corresponds to an upstroke portion of the pulse (e.g., a positive slope) or a downstroke portion of the pulse (e.g., a negative slope) portion of the pulse. A pulse may be defined as a combination of at least one upstroke and one downstroke. For example, the segment identified by points **410** and **412** and the segment identified by points **412** and **420** may define a pulse.

[0082] According to an embodiment, PPG signal **400** may include a dichrotic notch **450** or other notches (not shown) in different sections of the pulse (e.g., at the beginning (referred to as an ankle notch), in the middle (referred to as a dichrotic notch), or near the top (referred to as a shoulder notch)). Processor **312** may identify notches and either utilize or

ignore them when detecting the pulse locations. In some embodiments, processor **312** may compute the second derivative of the PPG signal to find the local minima and maxima points and may use this information to determine a location of, for example, a dichrotic notch. Additionally, processor **312** may interpolate between points in signal **316** or between points in a processed signal using any interpolation technique (e.g., zero-order hold, linear interpolation, and/or higher-order interpolation techniques). Some pulse detection techniques that may be performed by processor **312** are described in more detail in co-pending, commonly assigned U.S. patent application Ser. No. 12/242,908, filed Sep. 30, 2008 and entitled "SYSTEMS AND METHODS FOR DETECTING PULSES IN A PPG SIGNAL," which is incorporated by reference herein in its entirety.

[0083] FIG. **5** is a flow diagram **500** of illustrative steps involved in determining information from monitored signals in accordance with an embodiment. The steps of flow diagram **500** may be performed by processor **312** (FIG. **3**), or may be performed by any suitable processing device communicatively coupled to monitor **14** (FIGS. **1** and **2**). The steps of flow diagram **500** may be performed by a digital processing device, or implemented in analog hardware. In an embodiment, the steps of flow diagram **500** may be performed by a continuous, non-invasive blood pressure (CNIBP) monitoring system. It will be noted that the steps of flow diagram **500** may be performed in any suitable order, and one or more steps may be omitted entirely according to the context and application.

[0084] At step **502**, a plurality of signals may be received. A signal (e.g., a PPG signal) may be received from any suitable source (e.g., patient **40** of FIG. **2**(*b*)) using any suitable technique. A received signal may be generated by sensor unit **12** and/or sensor unit **13** (FIG. **2**(*a*)), which may each include any of the physiological sensors described herein, or any other sensor. A received signal may be signal **316**, which may be generated by a pre-processor **320** coupled between processor **312** and sensor **318** (FIG. **3**). A received signal may include multiple signals, for example, in the form of a multi-dimensional vector signal or a frequency- or time-multiplexed signal. In an embodiment, the plurality of signals received at step **502** may include two or more PPG signals, which may be measured at two or more respective different body sites of a subject.

[0085] The plurality of signals received at step **502** may include first and second physiological signals received as input signal **316** (FIG. **3**). In an embodiment, a first signal may be a Red PPG signal, and a second signal may be an IR PPG signal. In an embodiment, first and second signals may be different types of signals (e.g., a PPG signal and an ECG signal). In an embodiment, first and second signals may be obtained by first and second sensors located at approximately the same body site of a subject. In an embodiment, first and second signals may be obtained by first and second sensors located at different body sites of a subject. For example, first and second signals included in the plurality of signals may be electronic signals from pulse oximetry sensors located at two different body sites of a subject.

[0086] In an embodiment, more than two signals may be received at step **502**. For example, PPG signals at three or more frequencies may be obtained at step **502**, or PPG signals from three or more body sites, or any set of three or more signals (such as two PPG signals and an ECG signal). It will be noted that the steps of flow diagram **500** may be applied to any number of received signals in accordance with the techniques described herein.

[0087] At step **504**, one or more of the plurality of signals received at step **502** may be processed with a first set of processing operations This processing may result in a first plurality of processed signals. The processing may occur in conjunction with the receiving at step **502**, or after the signals are received at step **502**. A processing operation may be performed by any suitable processing device, such as processor **312** (FIG. **3**) and/or microprocessor **48** (FIG. **2**(*b*)), each of which may be a general-purpose computing device or a specialized processor. A processing operation may be performed by a separate, dedicated device, or by a series of devices (e.g., an analog filter and a programmed microprocessor).

[0088] Processor **312** (FIG. **3**) may transform the original and/or transformed signals into any suitable domain. In an embodiment, the processing at step **504** may include transforming a signal into another domain, for example, a Fourier, wavelet, spectral, scale, time, time-spectral, time-scale domain, or any transform space. A transformation may include a continuous wavelet transformation as described, for example, in Paul S. Addison, The Illustrated Wavelet Transform Handbook (Taylor & Francis Group 2002), which is hereby incorporated by reference herein in its entirety.

[0089] The processing at step **504** may include filtering a signal **316** (FIG. **3**) or mathematically manipulating one or multiple signals. For example, a processed signal may be a ratio of two signals. A processed signal may be based at least in part on past values of a signal, such as signal **316** (FIG. **3**), which may be retrieved by processor **312** (FIG. **3**) from a memory such as a buffer memory or RAM **54** (FIG. **2**(*b*)). Many examples of processing operations are discussed in detail herein, but it will be understood that the techniques of the present disclosure are not limited to these examples.

[0090] In an embodiment, the first set of processing operations of step **504** may include any one or more of the following: compressing, multiplexing, modulating, up-sampling, down-sampling, smoothing, taking a median or other statistic of the received signal, removing erroneous regions of the received signal, or any combination thereof. In an embodiment, a normalization step may be performed which divides the magnitude of a signal received at step **502** by a value. This value may be based on at least one of the maximum of the received signal, the minimum of the received signal and the mean of the received signal. In an embodiment, a signal received at step **502** may be normalized by dividing the signal by a DC component. In an embodiment, a signal received at step **502** may be normalized by dividing the signal by the standard deviation of the signal computed over a time window. In an embodiment, the first set of processing operations at step **504** may include one or more mathematical manipulations. Mathematical manipulations may include any linear or non-linear combination or signals or portions of signals, and may be performed in any suitable domain (e.g., time, frequency and wavelet domains).

[0091] In an embodiment, the first set of processing operations at step **504** may include one or more time derivatives. A time derivative may be calculated by input signal generator **310** (FIG. **3**) (alone or in conjunction with additional preprocessing steps), or may be calculated by processor **312** (FIG. **3**). In an embodiment, a time derivative may be calculated by any of a number of derivative/gradient determination

and approximation techniques, including those suitable for sampled data (e.g., forward difference, backward difference, central difference, higher-order methods, and any automated numerical or symbolic differentiation method).

[0092] In an embodiment, the first set of processing operations at step **504** may include filtering using any suitable filtering technique. For example, a signal received at sensor unit **12** (FIGS. **1** and **2**) may be filtered at step **504** by low pass filter **68** (FIG. **2**(*b*)) prior to undergoing additional processing at microprocessor **48** (FIG. **2**(*b*)) within patient monitoring system **10** (FIGS. **1** and **2**). Low pass filter **68** (FIG. **2**(*b*)) may selectively remove frequencies that may later be ignored by further processing or analysis steps, which may advantageously reduce computational time and memory requirements. In an embodiment, one or more signals received at step **502** may be high or band pass filtered at step **504** to remove low frequencies. Such a filter may be, for example, a derivative filter. Taking a derivative of a signal may selectively emphasize the signal's high frequency components. In an embodiment, one or more signals received at step **502** may be filtered at step **504** to remove a DC component. In an embodiment, a PPG signal may be band-pass filtered at step **504** to pass frequencies in the approximate range 0.5-3 Hz. In an embodiment, a PPG signal may be band-pass filtered at step **504** to pass frequencies in the approximate range 0.5-7.5 Hz. In an embodiment, the cutoff frequencies of a filter may be chosen based on the frequency response of the hardware platform underlying patient monitoring system **10** (FIGS. **1** and **2**). In an embodiment, a windowing operation may be performed at step **504** to suppress or amplify one or more portions of a signal received at step **502**.

[0093] Different processing operations may be applied to any one or more of the first and second signals received at step **502** and/or any components of a multi-component signal. For example, different operations may be applied to a signal taken from a first body site and a signal taken from a second body site. In an embodiment, a first received signal may be passed through a high-pass filter and a second received signal may not be passed through a high-pass filter.

[0094] Any of the operations described herein may be applied to a portion or portions of a received signal. An operation may be broken into one or more stages performed by one or more devices within signal processing system **300** of FIG. **3** (which may itself be a part of patient monitoring system **10** of FIGS. **1** and **2**). For example, a filtering technique may be applied by input signal generator **310** (FIG. **3**) prior to passing the resulting input signal **316** (FIG. **3**) to processor **312** (FIG, **3**), where it may undergo a transformation and/or the calculation of a time derivative. Embodiments of the steps of flow diagram **500** include any of the operations described herein performed in any suitable order.

[0095] At step **506**, a second plurality of processed signals may be generated by applying a second set of processing operations to one or more of the plurality of physiological signals received at step **502**. The second set of processing operations may be performed in accordance with any one or more of the processing operations described herein, including any combination of any of the processing operations described above with reference to the first set of processing operations in step **504**. In an embodiment, the second set of processing operations performed at step **506** is different from the first set of processing operations performed at step **504**.

[0096] For example, as discussed above with reference to FIG. **1**, the first set of processing operations may include applying a filtering operation, and the second set of processing operations may include applying the same filtering operation and then taking a time derivative. In an embodiment, the first set of processing operations may include a single time derivative and the second set of processing operations may include two time derivatives. In an embodiment, one or more of the first and second sets of processing operations may include taking N time derivatives, where N is a number greater than two. In an embodiment, a first set of processing operations may include taking M time derivatives and a second set of processing operations may include taking N time derivatives, where M and N are different.

[0097] At step **508**, a first parameter may be calculated based at least in part on the first plurality of processed signals. In an embodiment, a first parameter may be calculated at step **508** by comparing features of two or more of the first plurality of processed signals. A feature of a signal or processed signal may be any characterization of that signal, including, for example, the temporal location of a fiducial point, the spatial location of a fiducial point, or the amplitude of a fiducial point as discussed above. In an embodiment, a feature of a processed signal may be a calculated quantity based at least in part on a portion of the processed signal. For example, a feature of a processed signal may be a weighted or unweighted average of the processed signal over a window, a baseline value over a window, a magnitude or phase of a frequency component of a Fourier transform, a magnitude or phase or scale of a continuous wavelet transform, or any suitable calculated feature. In a further embodiment, comparing features of a first plurality of processed signals may include comparing features of portions of each of the first plurality of processed signals. For example, only the portions of a processed PPG signal corresponding to the upstroke of the received PPG signal may be used to calculate a first parameter at step **508**. It has been observed that a PPG signal may change dramatically in response to a patient's breathing and posture, which may lead to false indications of changes in physiological parameters based on the PPG signal. It has also been observed that the upstroke portion of a PPG signal is relatively robust to changes during patient movement, and thus may be a more useful indicator of certain underlying physiological phenomena than other portions of a PPG signal which are more open to variation and corruption. Thus, in an embodiment, the portion of a PPG signal around the upstroke may be selectively processed and analyzed for physiological information. For example, the first set of processing operations may include a windowing operation for identifying the portions of the PPG signal that correspond to an upstroke (e.g., by analyzing a gradient or smoothed gradient of the signal to identify upstroke portions), and additional processing operations may be applied only to the upstroke portions identified by the window. In an embodiment, one or more derivatives of a PPG signal may be derived only for the portions of the PPG signal in and around an upstroke portion.

[0098] In an embodiment, only a portion or portions of the first plurality of processed signals may be analyzed to identify fiducial points or other features of interest. For example, certain segments of a signal may be identified (e.g., an upstroke portion), and only those segments may be analyzed for the presence of certain features (e.g., extrema). Identifying segments of a signal may occur before or after any one or more of the processing operations included in the first set of processing operations, and thus the segments may be identified prior to completing the processing operations. Focusing

the calculation of the first parameter on identified segments of the received or processed signals may improve the efficiency of carrying out the steps of the flow diagram **500** by reducing the time spent analyzing portions of the signals that are less relevant to the information of interest (e.g., the noisier regions).

[0099] In an embodiment, calculating a first parameter at step **508** may include comparing corresponding extrema between two or more of the first plurality of processed signals. For example, a first parameter may be a time difference between the occurrence of corresponding peaks in two or more of the first plurality of processed signals. In another example, a first parameter may be a time difference between the occurrence of corresponding troughs in two or more of the first plurality of processed signals. In an embodiment, calculating a first parameter at step **508** may include comparing any corresponding fiducial points between two or more of the first plurality of processed signals. For example, a first parameter may be a time difference between the occurrence of corresponding zero crossings between two or more of the first plurality of processed signals, wherein the first set of processing operations may include taking a derivative. In another example, the first set of processing operations may include taking two time derivatives, and a fiducial point may be the minima of the first plurality of processed signals. The fiducial point may then be used to determine a first parameter.

[0100] In an embodiment, calculating a first parameter at step **508** may include comparing any fiducial points between two or more of the first plurality of processed signals, which may or may not directly correspond. For example, when the plurality of signals received at step **502** are PPG signals from a subject, a first parameter calculated at step **508** may be a time difference between a peak associated with one cardiac pulse in a first processed signal of the first plurality of processed signals, and a peak associated with a later cardiac pulse in a second processed signal of the first plurality of processed signals.

[0101] In an embodiment, the first parameter calculated at step **508** may include one or more summary statistics of similarities or differences between the first plurality of processed signals. For example, a first parameter calculated at step **508** may be an average differential pulse transit time (DPTT). Such a parameter may be calculated by averaging multiple DPTTs calculated between multiple pairs of signals from the first plurality of processed signals, based on the identification of corresponding fiducial points. Such a parameter may also be calculated by averaging multiple DPTTs calculated between a single pair or multiple pairs of signals from the first plurality of processed signals, based on the identification of multiple corresponding fiducial points (e.g., multiple corresponding peaks associated with multiple cardiac waves in a finger PPG and a forehead PPG).

[0102] In an embodiment, a first parameter may be calculated at step **508** based at least in part on a linear combination of multiple fiducial points identified in the first plurality of processed signals. For example, a weighted differential pulse transit time ($DPTT_{avg}$) may be calculated from one or more processed signals in accordance with:

$$DPTT_{avg}=x\ DPTT_{first}+y\ DPTT_{second}+(1-x-y)\ DPTT_{pleth} \quad (19)$$

where $DPTT_{first}$ is a DPTT calculated between fiducial points identified in a first derivative of one or more received signals, $DPTT_{second}$ is a DPTT calculated between fiducial points identified in a second derivative of one or more received signals, $DPTT_{pleth}$ is a DPTT calculated between fiducial points identified in a PPG signal which has not been differentiated (but which may have been filtered or otherwise processed), and x and y are non-negative weights whose sum is less than or equal to 1. Multiple different weighted DPTTs may be calculated and used to determine multiple different types of physiological information. For example, one weighted DPTT may be used to calculate a patient's systolic blood pressure, while another weighted DPTT may be used to calculate a patient's diastolic blood pressure. In some embodiments, different fiducials within a same set of processed signals can be used (e.g., a combination of peaks, valleys, maximum and minimum slopes identified in a first or second derivative of the signals). For example, DPTTs may be calculated from the times of the maximum peak and minimum trough of the second derivative of a pulse's upstroke, then combined via a weighted combination to provide a measurement useful in calculating mean arterial pressure (MAP).

[0103] Once a first parameter is calculated at step **508**, a second parameter may be calculated at step **510** based at least in part on the second plurality of processed signals. This order of processing and calculations is merely illustrative; it will be understood that either of the first or second processing steps, and the first and second parameter calculating steps may be performed in any suitable order, or simultaneously. In an embodiment, a second parameter may be calculated at step **510** by comparing features of two or more of the second plurality of processed signals. The features that may be compared and/or the parameters that may be calculated at step **510** may take the form of any of the features and/or parameters described herein, as well as any combination of such features and/or parameters, including those described above with reference to step **508**. For example, a second parameter calculated at step **508** may include a differential pulse transit time (DPTT), which may be calculated by determining the time delay between different fiducial points in the second plurality of processed signals. In an embodiment, a DPTT indicative of a patient's systolic blood pressure is determined by differentiating the PPG signals measured at two different patient body sites, identifying peaks in the differentiated PPG signals (corresponding to points of maximum positive slope in the undifferentiated PPG signals), and determining the time delay between the peaks. These PPG signals may be filtered prior to differentiating, for example, by a bandpass filter with a passband range approximately 0.5 Hz-7.5 Hz.

[0104] The first and second parameters determined at steps **508** and **510**, respectively, may be determined based on processing and comparison of any number of physiological signals (e.g., multiple PPG signals), including signals in which repeating features may be identified and processed either intra- or inter-pulsewise.

[0105] At step **512**, information about the subject based at least in part on the first and second parameters may be determined. In an embodiment, information determined at step **512** may be physiological information. For example, physiological information determined at step **512** may include a blood pressure of a subject (e.g., one or more of systolic and diastolic blood pressure). Some techniques that may be used to determine blood pressure based at least in part on parameters calculated from physiological signals are discussed above with reference to Eqs. 14-18. Other calculated parameters which benefit from this approach include: respiratory effort monitoring (in which changes in fiducial positioning may indicate localized changes in thoracic pressure), cardiac

output monitoring (in which improvements in PPG fiducial placement and processing may benefit contour analysis techniques) and autonomic response measurements (in which heart rate variability techniques sometimes require the continuous and accurate reporting of the current pulse period).

[0106] In an embodiment, physiological information may be determined based on empirically-derived relationships between the first and second parameters and the physiological information. For example, a first parameter (e.g., an amplitude of a peak of a first derivative of a PPG signal) may be approximated by a first weighted combination of systolic blood pressure and diastolic blood pressure. Similarly, a second parameter (e.g., an amplitude of a peak of a second derivative of a PPG signal) may be approximated by a second weighted combination of systolic blood pressure and diastolic blood pressure (different from the first weighted combination). Given the first and second parameters, the systolic and diastolic blood pressures may be determined using these relationships.

[0107] After information about the subject is determined at step **512**, the information determined may be output to an output device. Information may be output through a graphical representation, quantitative representation, qualitative representation, or combination of representations via output **314** (FIG. **3**) and may be controlled by processor **312** (FIG. **3**). In an embodiment, output **314** (FIG. **4**) may transmit physiological information by any means and through any format useful for informing a patient, a care provider, or a third party, of a patient's status and may involve recording the physiological information to a storage medium. Quantitative and/or qualitative information provided by output **314** (FIG. **3**) may be displayed on a display (e.g., display **28** of FIG. **2**(*a*)). A graphical representation may be displayed in one, two, or more dimensions and may be fixed or change with time. A graphical representation may be further enhanced by changes in color, pattern, or any other visual representation. Output **314** (FIG. **3**) may communicate the information by performing at least one of the following: presenting a screen on a display; presenting a message on a display; producing a tone or sound; changing a color of a display or a light source; producing a vibration; and sending an electronic message. Output **314** (FIG. **3**) may perform any of these actions in a device close to a patient, or at a mobile or remote monitoring device as described previously. In an embodiment, output **314** (FIG. **3**) may produce a continuous tone or beeping whose frequency changes in response to changes in a process of interest, such as a physiological process. In an embodiment, output **314** (FIG. **3**) may produce a colored or flashing light that changes in response to changes in a physiological process of interest.

[0108] After or during the information determination of step **512**, the steps of flow diagram **500** may be repeated. New signals may be received, or the information determination may continue on another portion of one or more of the previously received signal(s). In an embodiment, processor **312** (FIG. **3**) may continuously or periodically perform steps **502**-**512** and update the information (e.g., as the patient's condition changes). The process may repeat indefinitely, until there is a command to stop the monitoring and/or until some detected event occurs that is designated to halt the monitoring process. For example, it may be desirable to halt a monitoring process when a detected noise has become too great, a measurement quality has become too low, or, in a patient monitoring setting, when a patient has undergone a change in condition that can no longer be sufficiently well-monitored in a current monitoring configuration. In an embodiment, processor **312** (FIG. **3**) may perform the steps of flow diagram **500** at a prompt from a care provider via user inputs **56** (FIG. **2**(*b*)). In an embodiment, processor **312** (FIG. **3**) may perform the steps of flow diagram **500** at intervals that change according to patient status. For example, the steps of flow diagram **500** may be performed more often when a patient is undergoing rapid changes in physiological condition, and performed less often as the patient's condition stabilizes,

[0109] The steps of flow diagram **500** may be executed over a sliding window of a signal. For example, the steps of flow diagram **500** may involve analyzing the previous N samples of the signal, or the samples of the signal received in the previous T units of time. The length of the sliding window over which the steps of flow diagram **500** is executed may be fixed or dynamic. In an embodiment, the length of the sliding window may be based at least in part on the noise content of a signal. For example, the length of the sliding window may increase with decreasing measurement quality and/or increasing noise, as may be determined by a measurement quality assessment and/or a noise assessment. A subject's blood pressure may be monitored continuously using a moving PPG signal. PPG signal detection means may include a pulse oximeter and associated hardware, software, or both. A processor may continuously analyze the signal from the PPG signal detection means in order to continuously monitor a subject's blood pressure.

[0110] Any number of computational and/or optimization techniques may be performed in conjunction with the techniques described herein. For example, any known information regarding the physiological status of the patient may be stored in memory (e.g., ROM **52** or RAM **54** of FIG. **2**(*b*)). Such known information may be keyed to the characteristics of the patient, which may be input via user inputs **56** (FIG. **2**(*b*)) and used by monitor **14** (FIG. **2**(*b*)) to, for example, query a lookup table and retrieve the appropriate information. Additionally, any of the calculations and computations described herein may be optimized for a particular hardware implementation, which may involve implementing any one or more of a pipelining protocol, a distributed algorithm, a memory management algorithm, or any suitable optimization technique.

[0111] The foregoing is merely illustrative of the principles of this disclosure and various modifications can be made by those skilled in the art without departing from the scope and spirit of the 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 the 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 for determining physiological information about a subject, comprising:

receiving a plurality of physiological signals of a subject from one or more sensing devices; and

using one or more processing devices to:

generate a first plurality of processed signals by applying a first set of processing operations to the plurality of physiological signals;

generate a second plurality of processed signals by applying a second set of processing operations to the plurality of physiological signals, wherein the second set of processing operations is different from the first set of processing operations;

calculate a first parameter by comparing features of the first plurality of processed signals;

calculate a second parameter by comparing features of the second plurality of processed signals; and

determine physiological information about the subject based at least in part on the first and second parameters.

2. The method of claim **1**, wherein the plurality of physiological signals comprises a photoplethysmograph signal.

3. The method of claim **1**, wherein the plurality of physiological signals comprises two photoplethysmograph signals measured at two different body sites of the subject.

4. The method of claim **1**, wherein the first set of processing operations comprises taking one or more time derivatives.

5. The method of claim **4**, wherein the first set of processing operations comprises applying a low-pass filter prior to taking one or more time derivatives.

6. The method of claim **1**, wherein calculating the first parameter comprises comparing extrema between one or more of the first plurality of processed signals.

7. The method of claim **1**, wherein the first parameter is a differential pulse transit time.

8. The method of claim **1**, wherein the physiological information comprises a blood pressure.

9. The method of claim **8**, wherein the first set of processing operations comprises taking a single time derivative and the second set of processing operations comprises taking two time derivatives.

10. The method of claim **8**, wherein the first parameter is determined based at least in part on a linear combination of multiple fiducial points in the first plurality of processed signals.

11. A system for determining physiological information about a subject, comprising:

a signal input configured to receive a plurality of physiological signals of a subject from one or more sensing devices; and

one or more processing devices in communication with the signal input and configured to:

generate a first plurality of processed signals by applying a first set of processing operations to the plurality of physiological signals;

generate a second plurality of processed signals by applying a second set of processing operations to the plurality of physiological signals, wherein the second set of processing operations is different from the first set of processing operations;

calculate a first parameter by analyzing features of the first plurality of processed signals;

calculate a second parameter by analyzing features of the second plurality of processed signals; and

determine physiological information about the subject based at least in part on the first and second parameters.

12. The system of claim **11**, wherein the plurality of physiological signals comprises a photoplethysmograph signal.

13. The system of claim **11**, wherein the plurality of physiological signals comprises two photoplethysmograph signals measured at two different body sites of the subject.

14. The system of claim **11**, wherein the first set of processing operations comprises taking one or more time derivatives.

15. The system of claim **14**, wherein the first set of processing operations comprises applying a low-pass filter prior to taking one or more time derivatives.

16. The system of claim **11**, wherein calculating the first parameter comprises comparing extrema between one or more of the first plurality of processed signals.

17. The system of claim **11**, wherein the first parameter is a differential pulse transit time.

18. The system of claim **11**, wherein the physiological information comprises a blood pressure.

19. The system of claim **18**, wherein the first set of processing operations comprises taking a single time derivative and the second set of processing operations comprises taking two time derivatives.

20. The system of claim **18**, wherein the first parameter is determined based at least in part on a linear combination of multiple fiducial points in the first plurality of processed signals.

* * * * *

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摘要(译)

为患者监视器提供系统和方法，其将不同组的信号处理操作应用于信号以识别生理信号中的多个基准。在两个传感器位置处测量的PPG信号可以用第一组处理操作处理并且被分析以识别允许计算舒张DPTT的基准点。然后可以用不同的处理操作集处理这些PPG信号，并分析结果以识别允许计算收缩DPTT的基准点。