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(54) **USING INVARIANT FACTORS FOR PULSE OXIMETRY**

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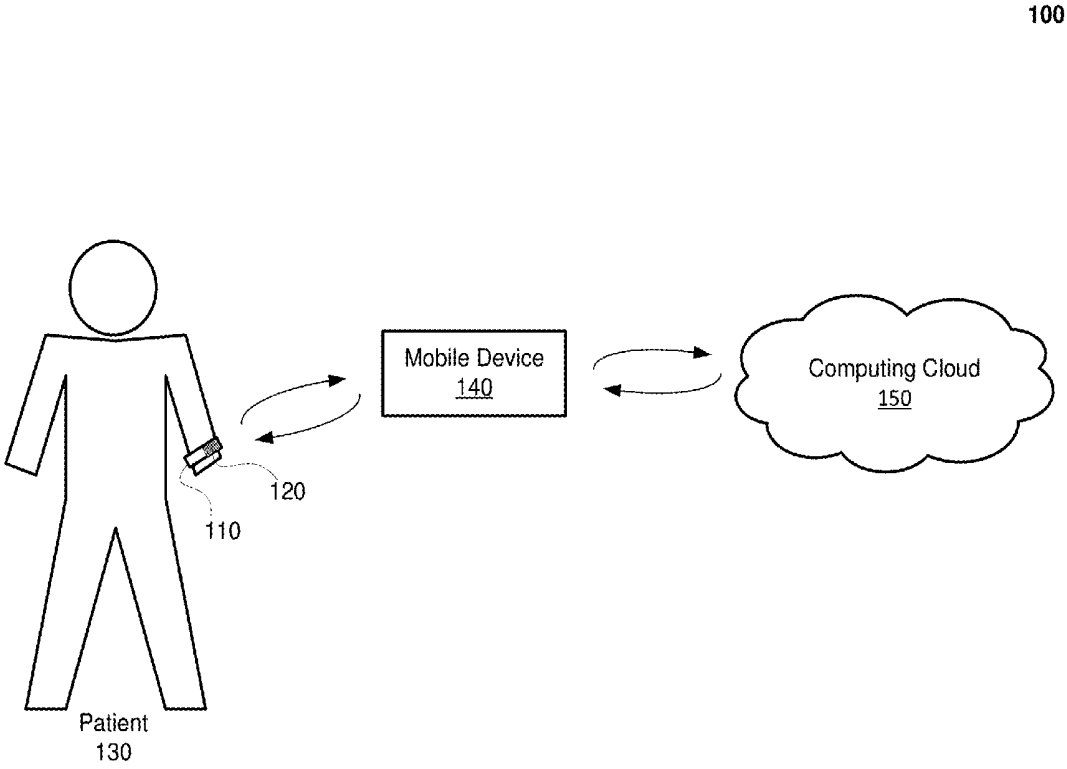
(57) **ABSTRACT**

An example method for performing pulse oximetry can commence with receiving at least three light signals of three different wavelengths reflected from a human tissue. The human tissue includes a pulsatile tissue and a non-pulsatile tissue. Based on the three light signals, values of at least three functions are determined. The three functions are invariant to an oxygen saturation in the pulsatile tissue and depend on location of a sensor operable to detect the three light signals and pressure of the sensor on the human tissue. Based on the values of the three functions, non-pulsatile components are analyzed for intensities of a red light signal and infrared light signal reflected from the human tissue. The non-pulsated components are removed from the intensities to allow correct estimates of a ratio of the absorption coefficients, with the ratio being used to determine the oxygen saturation in the pulsatile tissue.



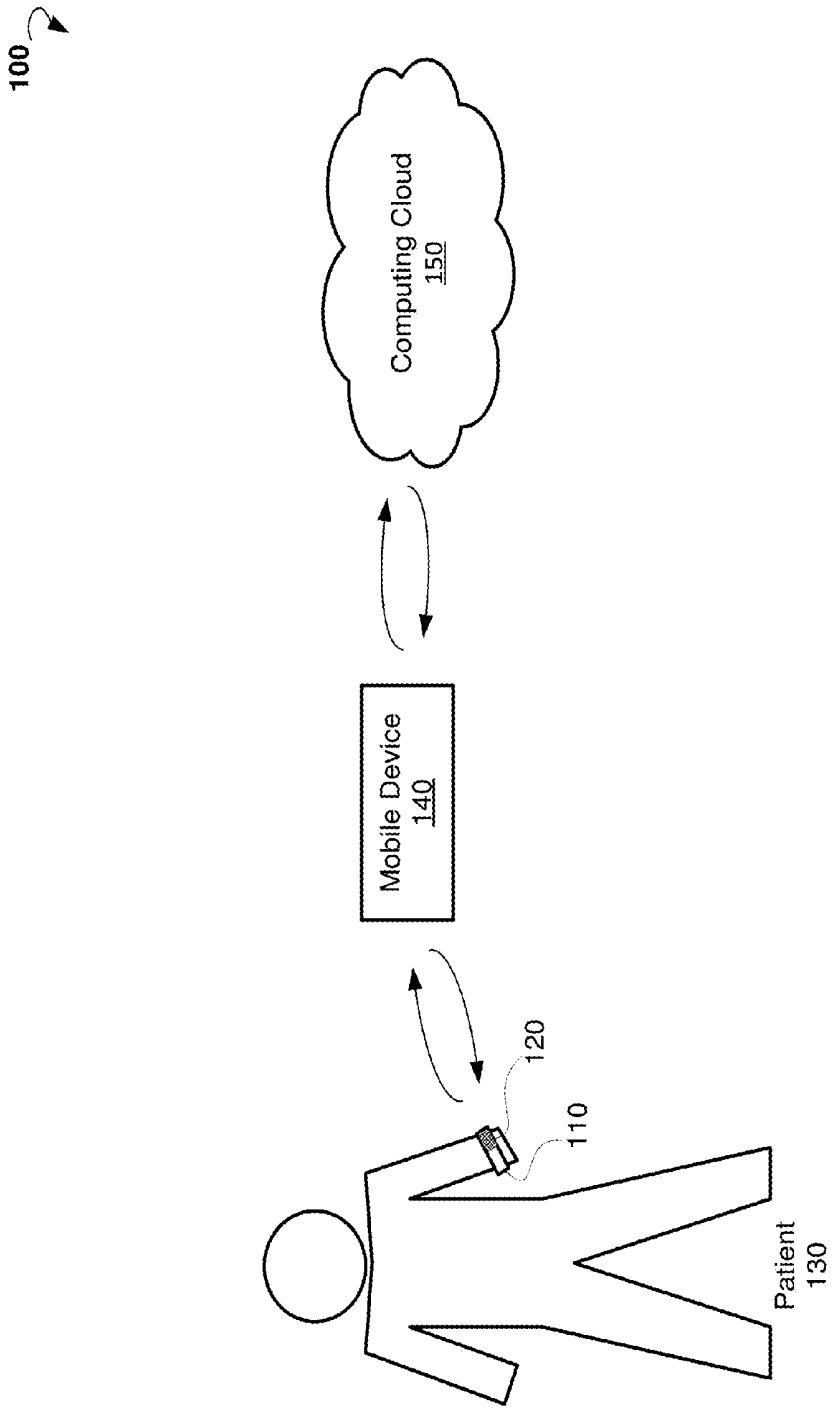

100
Computing Cloud
150
Mobile Device
140
120
110
Patient
130

FIG. 1

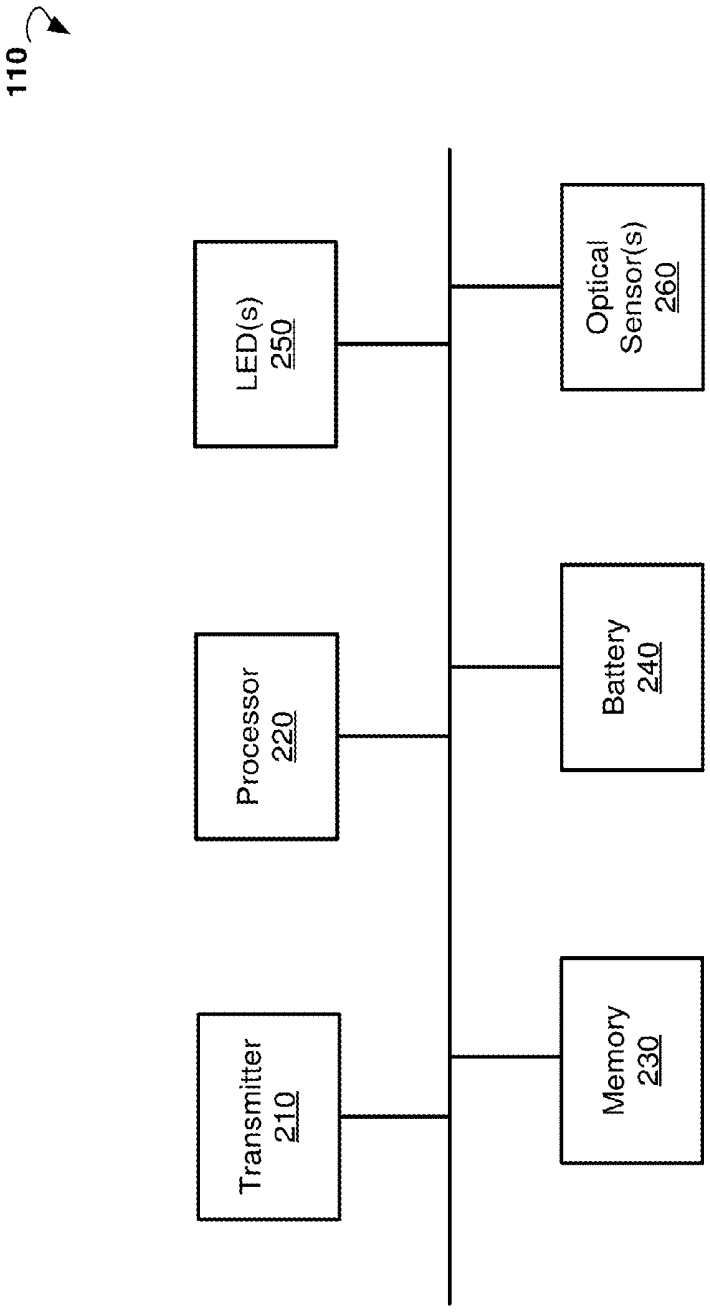

110
LED(s) 250
Optical Sensor(s) 260
Processor 220
Battery 240
Transmitter 210
Memory 230

FIG. 2

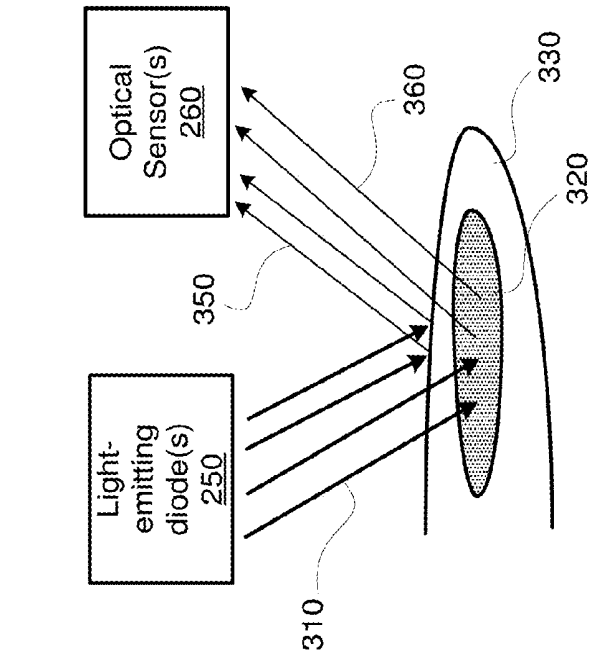

Optical Sensor(s) 260
Light-emitting diode(s) 250
310
320
330
350
360

FIG. 3B

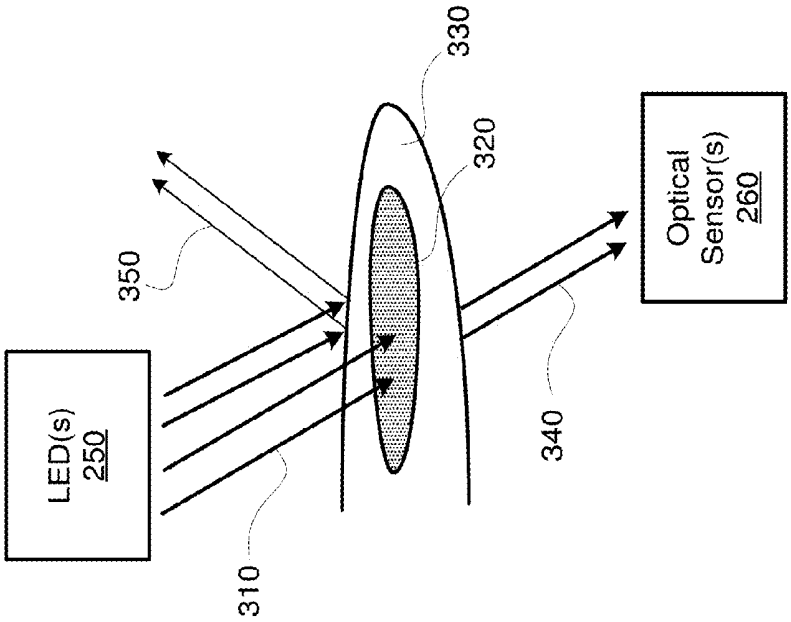

LED(s) 250
Optical Sensor(s) 260
310
320
330
340
350

FIG. 3A

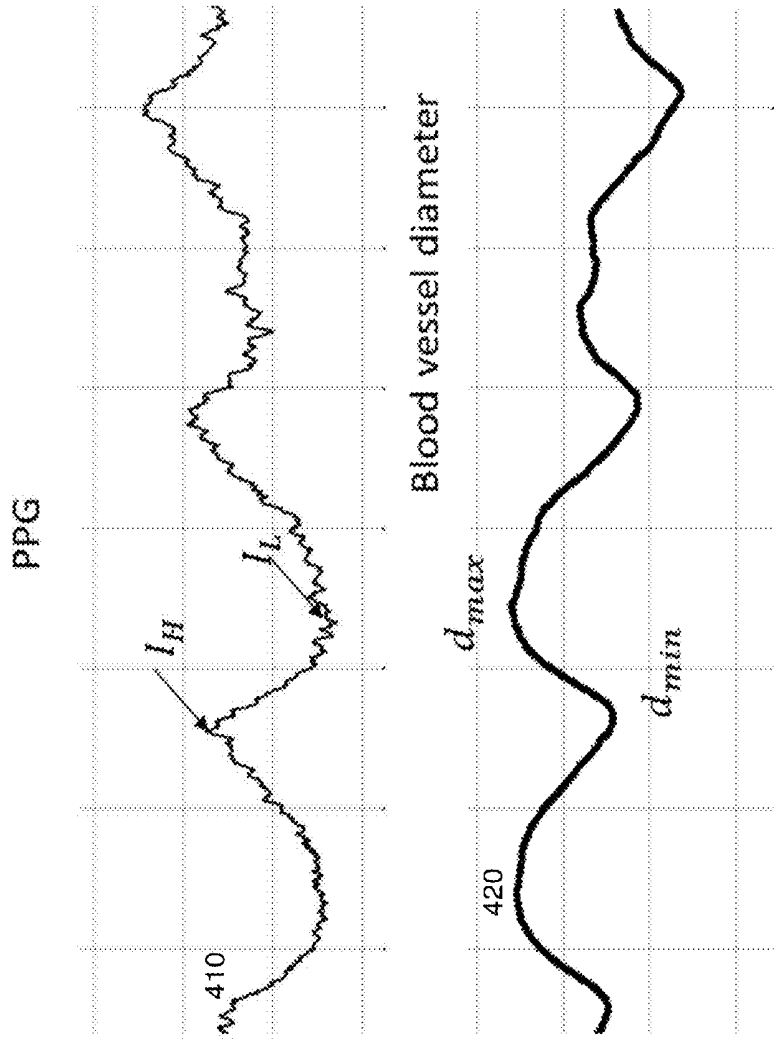



FIG. 4

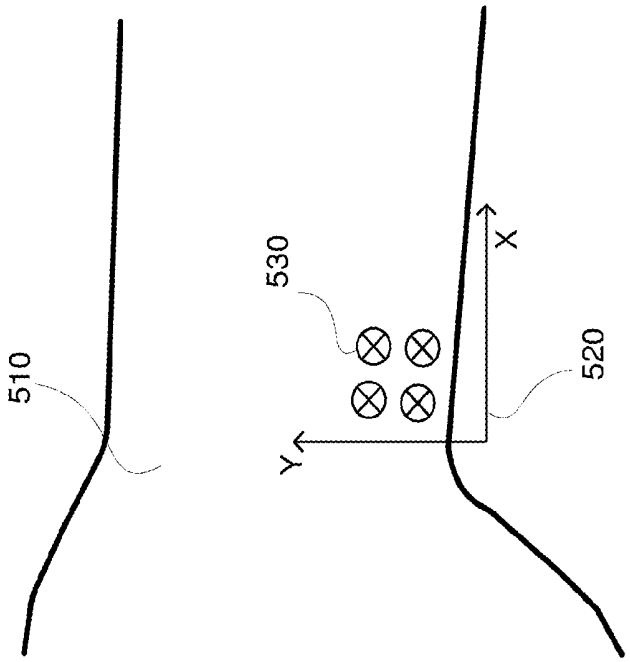



FIG. 5

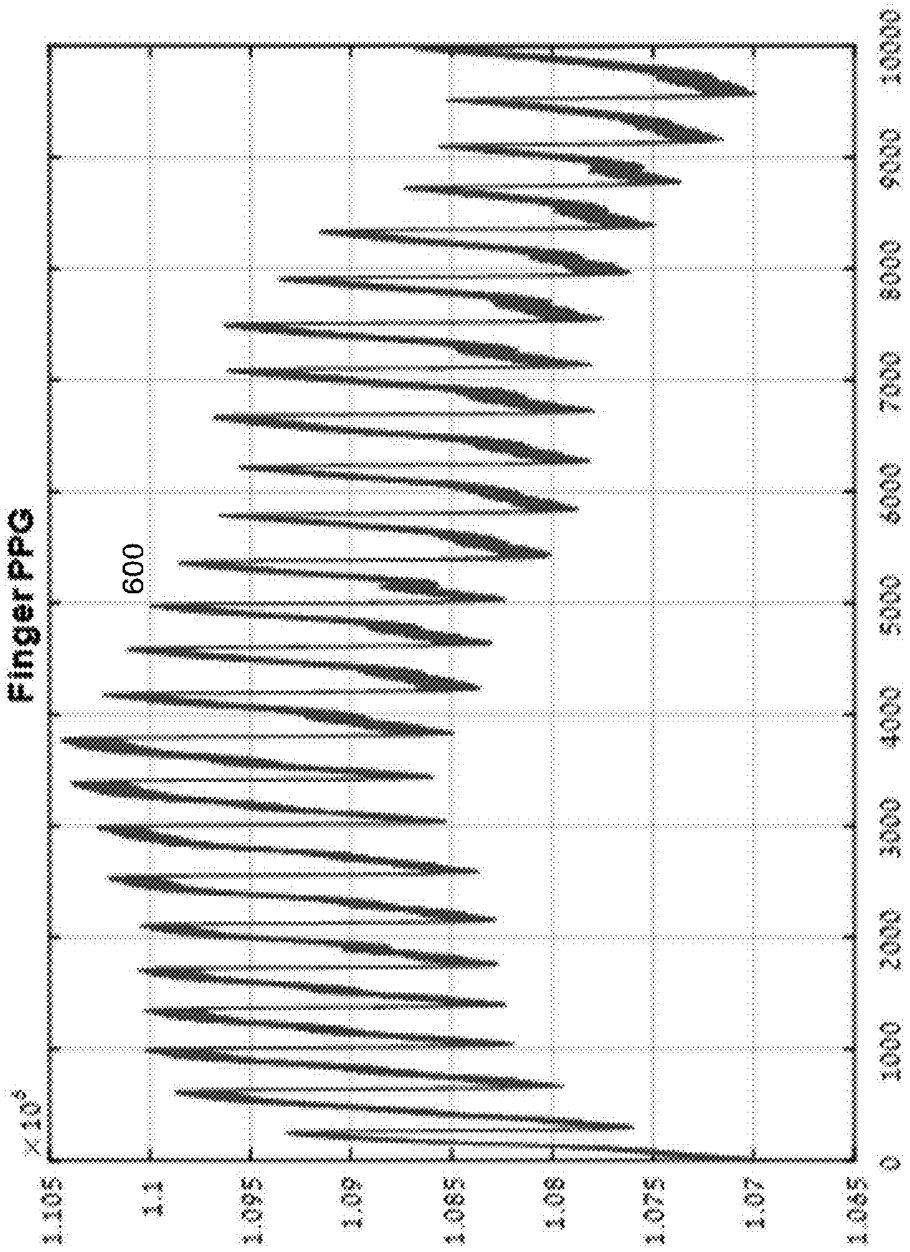

FingerPPG
600
×10^5
1.105
1.1
1.095
1.09
1.085
1.08
1.075
1.07
1.065
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

FIG. 6

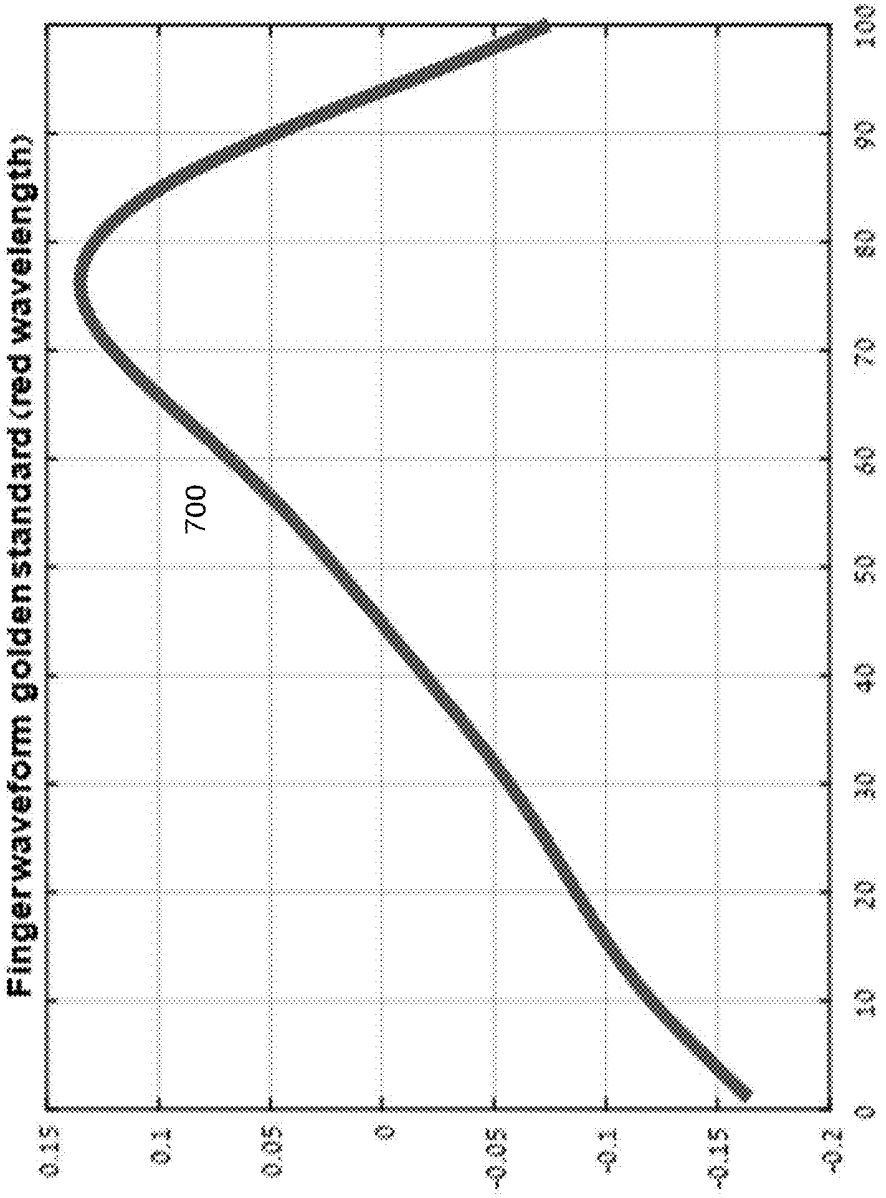

Fingerwaveform goldenstandard (red wavelength)
700
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
10
20
30
40
50
60
70
80
90
100

FIG. 7

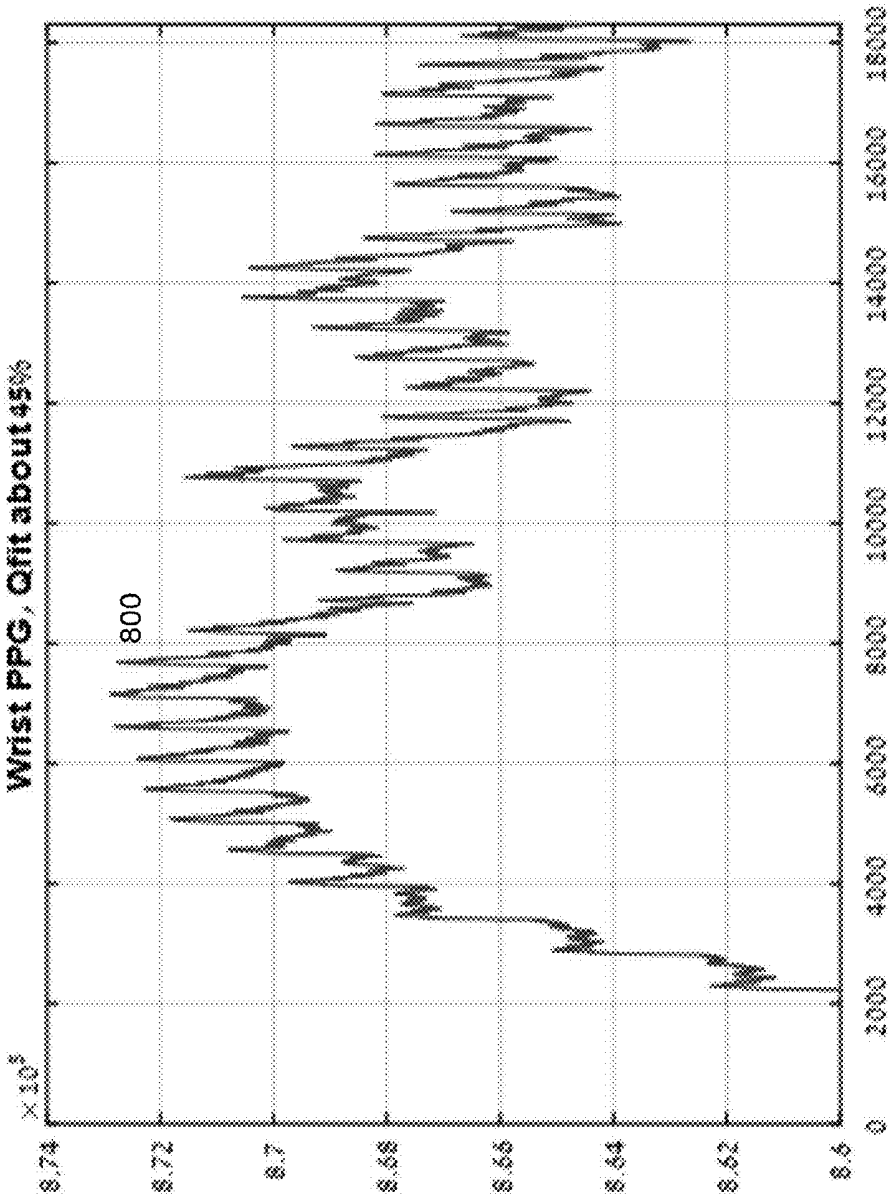

Wrist PPG, Qfit about 45%
800
×10^5
8.74
8.72
8.7
8.68
8.66
8.64
8.62
8.6
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

FIG. 8

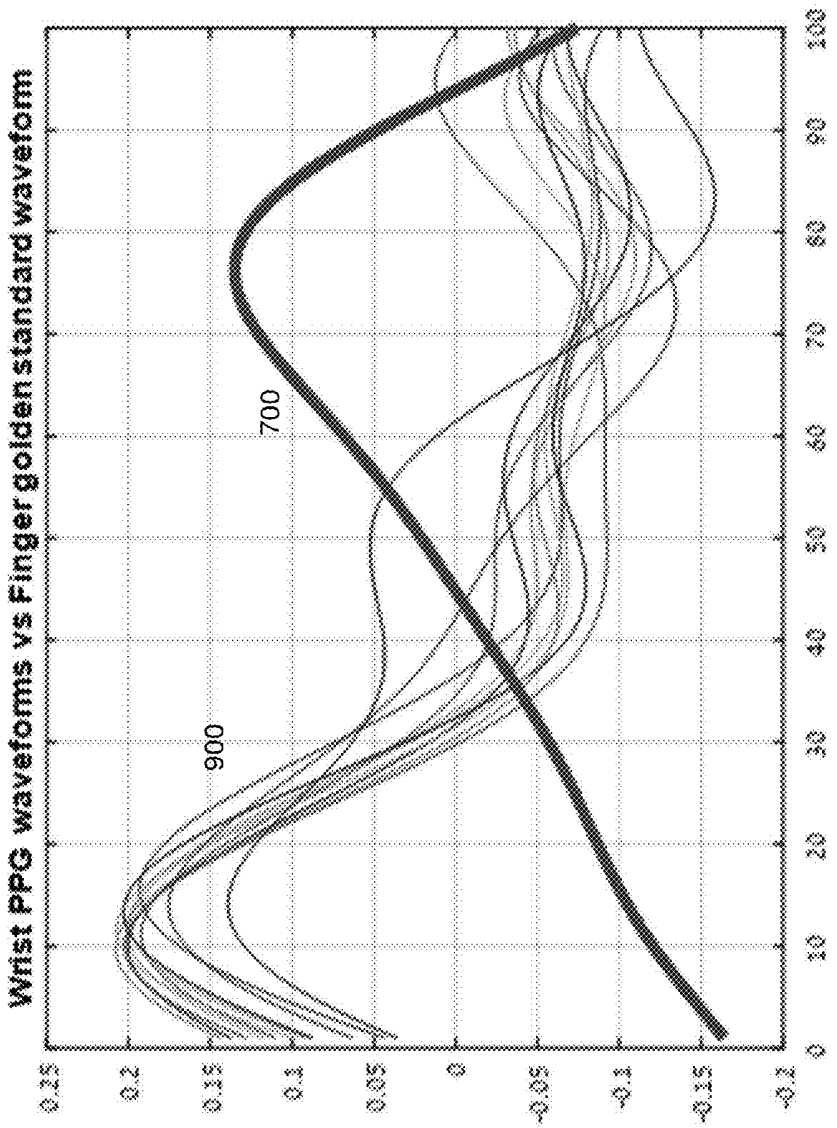

Wrist PPG waveforms vs Finger golden standard waveform
900
700
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
10
20
30
40
50
60
70
80
90
100

FIG. 9

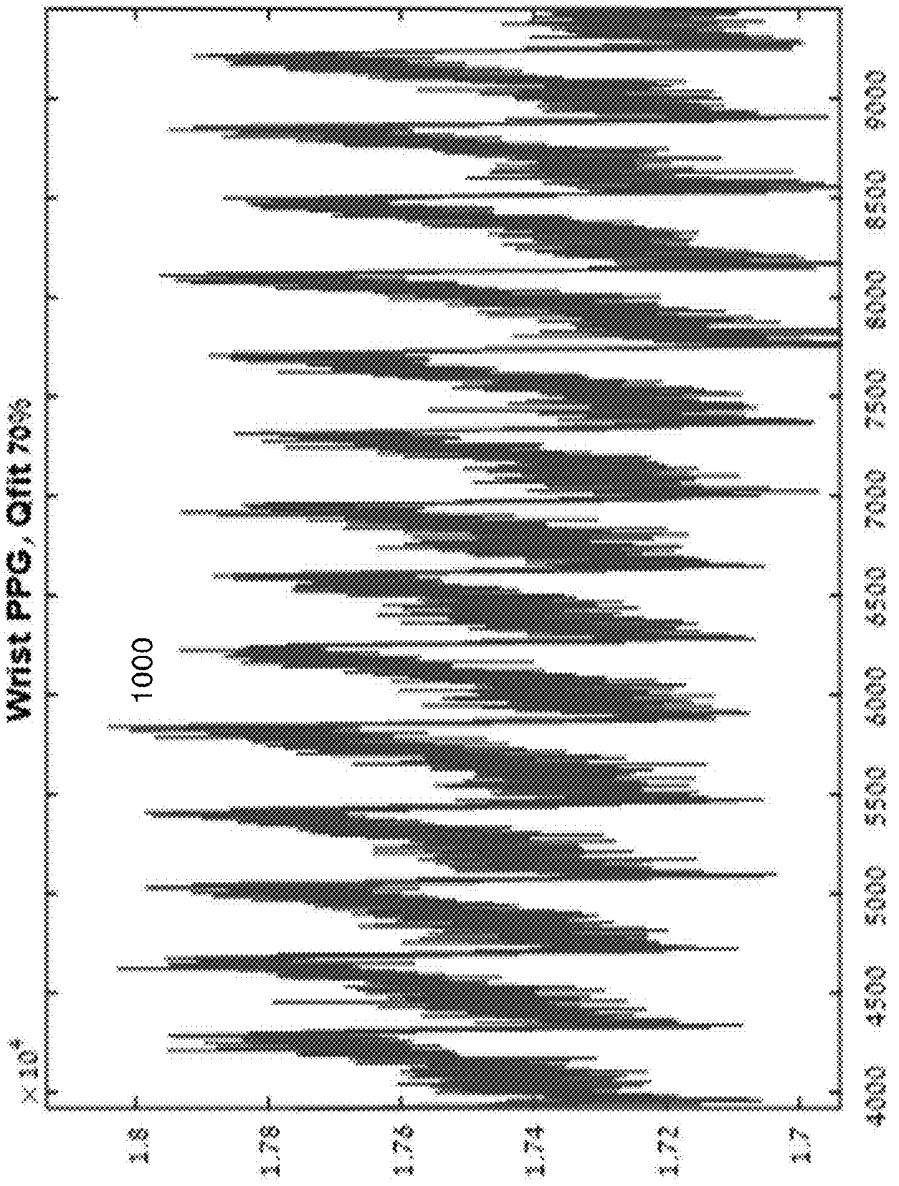

Wrist PPG, Qfit 70%
1000
×10^4
1.8
1.78
1.76
1.74
1.72
1.7
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000

FIG. 10

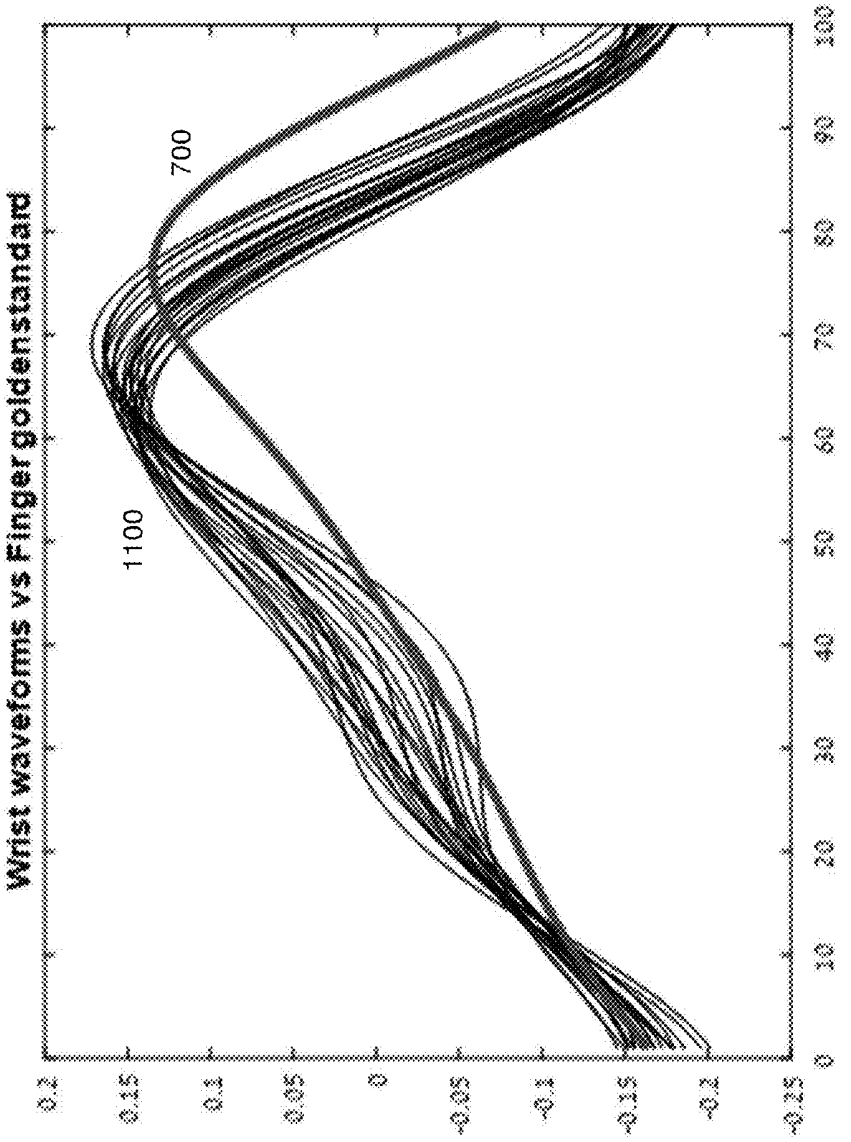

Wrist waveforms vs Finger goldenstandard
700
1100
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0
10
20
30
40
50
60
70
80
90
100

FIG. 11

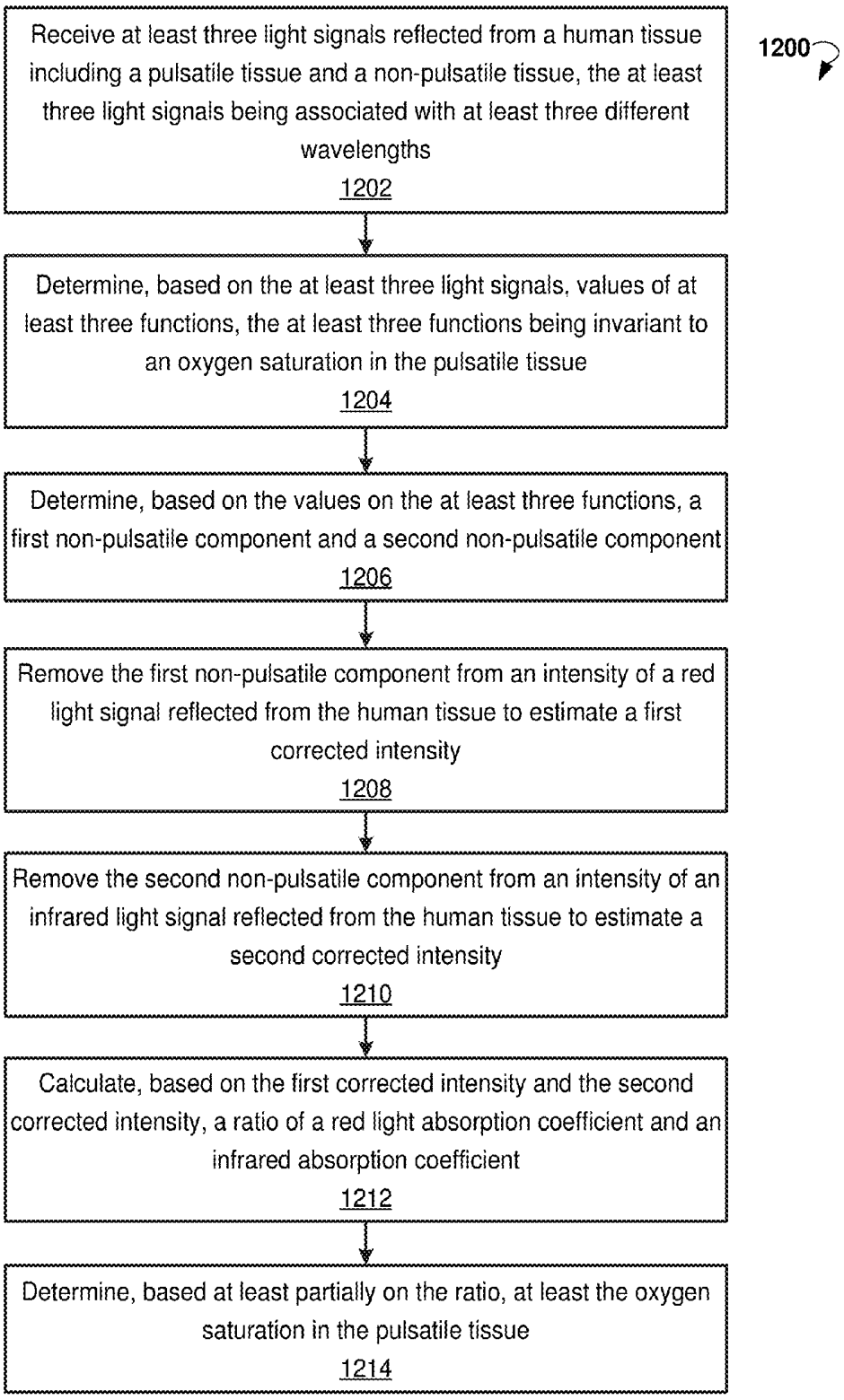

Receive at least three light signals reflected from a human tissue including a pulsatile tissue and a non-pulsatile tissue, the at least three light signals being associated with at least three different wavelengths
1202
1200
Determine, based on the at least three light signals, values of at least three functions, the at least three functions being invariant to an oxygen saturation in the pulsatile tissue
1204
Determine, based on the values on the at least three functions, a first non-pulsatile component and a second non-pulsatile component
1206
Remove the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity
1208
Remove the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity
1210
Calculate, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared absorption coefficient
1212
Determine, based at least partially on the ratio, at least the oxygen saturation in the pulsatile tissue
1214

FIG. 12

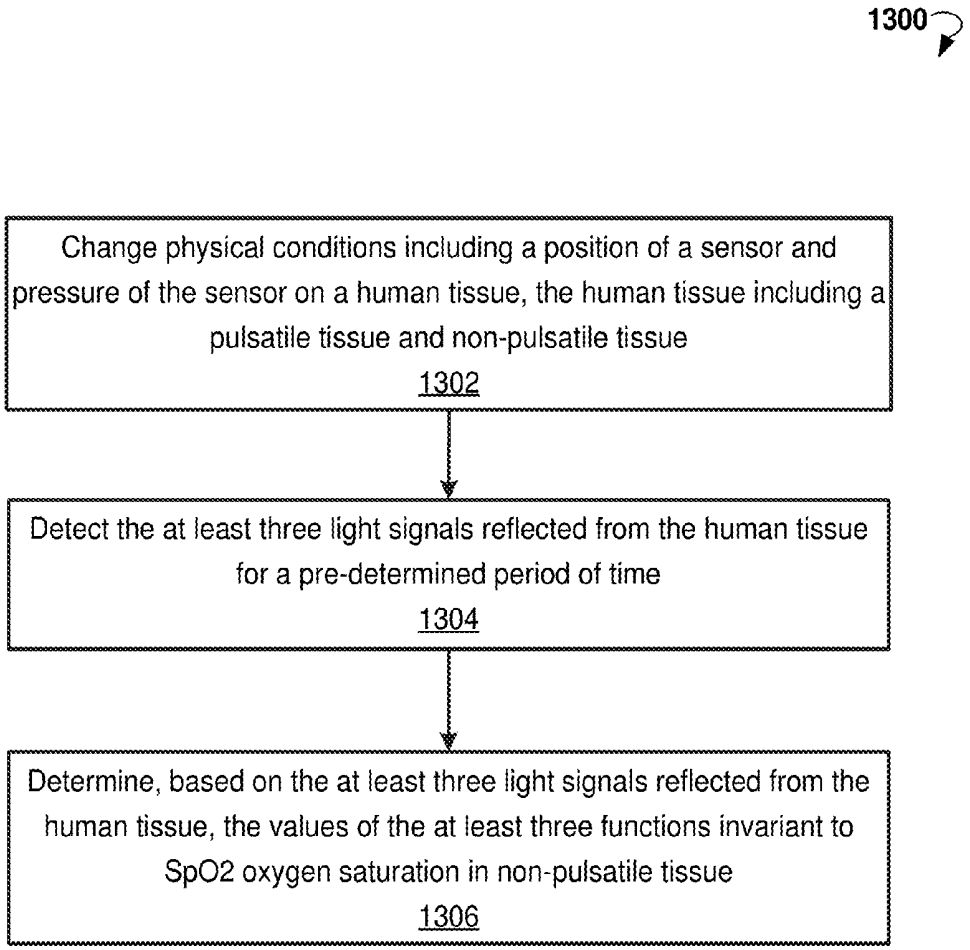

1300
Change physical conditions including a position of a sensor and pressure of the sensor on a human tissue, the human tissue including a pulsatile tissue and non-pulsatile tissue
1302
Detect the at least three light signals reflected from the human tissue for a pre-determined period of time
1304
Determine, based on the at least three light signals reflected from the human tissue, the values of the at least three functions invariant to SpO2 oxygen saturation in non-pulsatile tissue
1306

FIG. 13

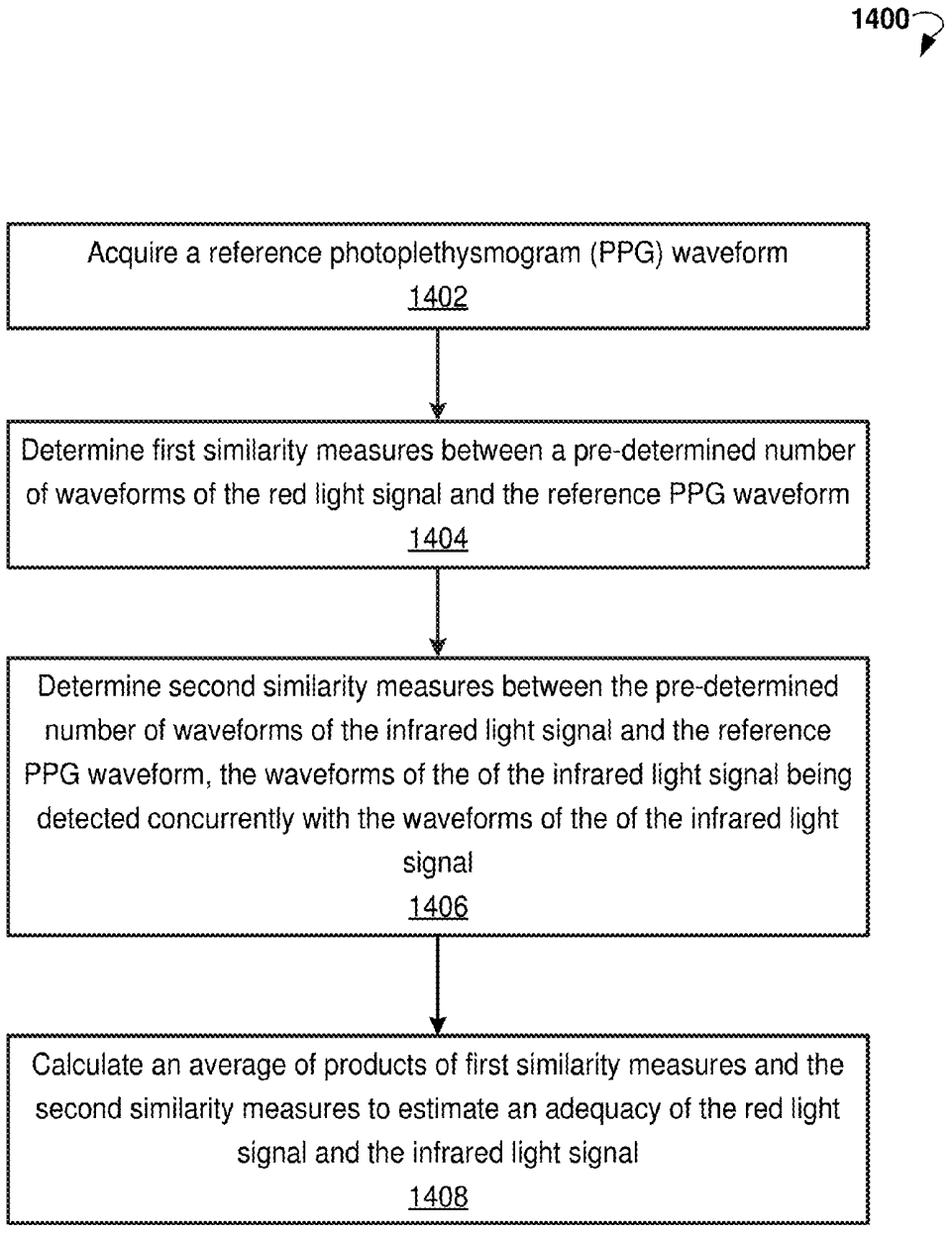

1400
Acquire a reference photoplethysmogram (PPG) waveform
1402
Determine first similarity measures between a pre-determined number of waveforms of the red light signal and the reference PPG waveform
1404
Determine second similarity measures between the pre-determined number of waveforms of the infrared light signal and the reference PPG waveform, the waveforms of the of the infrared light signal being detected concurrently with the waveforms of the of the infrared light signal
1406
Calculate an average of products of first similarity measures and the second similarity measures to estimate an adequacy of the red light signal and the infrared light signal
1408

FIG. 14

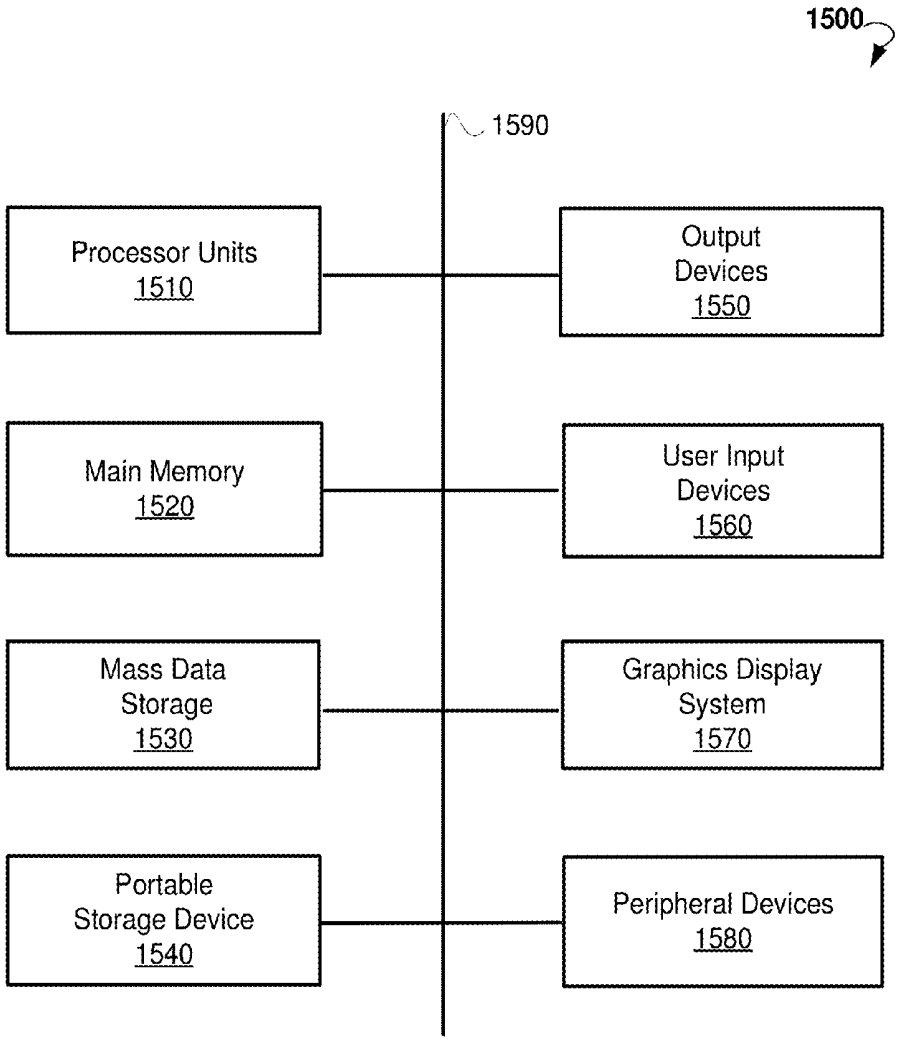

1500
1590
Processor Units
1510
Output
Devices
1550
Main Memory
1520
User Input
Devices
1560
Mass Data
Storage
1530
Graphics Display
System
1570
Portable
Storage Device
1540
Peripheral Devices
1580

FIG. 15

# USING INVARIANT FACTORS FOR PULSE OXIMETRY

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** The present application is a continuation-in-part of U.S. patent application Ser. No. 14/738,666, titled "Monitoring Health Status of People Suffering from Chronic Diseases", filed on Jun. 12, 2015, and is a continuation-in-part of U.S. patent application Ser. No. 14/738,636, titled "Wearable Device Electrocardiogram", filed on Jun. 12, 2015, and is also a continuation-in-part of U.S. patent application Ser. No. 14/738,711, titled "Pulse Oximetry", filed on Jun. 12, 2015. The disclosures of the aforementioned applications are incorporated herein by reference for all purposes.

## FIELD

**[0002]** The present application relates to systems and methods for monitoring the health status of people, and more specifically to systems and methods for performing pulse oximetry.

## BACKGROUND

**[0003]** It should not be assumed that any of the approaches described in this section qualify as prior art merely by virtue of their inclusion in this section.

**[0004]** Pulse oximetry is a method for estimating blood oxygen saturation by utilizing specialized light sources and optical sensors. Tuned light wavelengths are either transmitted through or reflected from a human tissue and are used to estimate a relative proportion of oxygenated blood. This estimated oxygen saturation, termed $SpO_2$, strongly correlates to arterial blood oxygen saturation. One of the advantages of pulse oximetry over other methods of determining oxygen saturation, such as blood sampling, is that the pulse oximetry is non-invasive, minimally intrusive, generally not painful, portable if it needs to be, and provides for continuous readings.

**[0005]** For a healthy human at normal altitudes, $SpO_2$ is typically 95% or above, with 90% or below indicating hypoxemia, and sustained periods of 80% or below possibly indicating serious medical complications. $SpO_2$ can reflect statuses of individuals suffering from various clinical disorders such as Chronic Obstructive Pulmonary Disease (COPD) or asthma, whether in a stable chronic condition or during an acute phase. Pulse oximetry is also useful in neonatal monitoring, surgical monitoring, or status evaluation when the possibility of oxygen depletion must be considered (pilot monitoring, deep sea diving, and so forth).

**[0006]** Certain clinical conditions can interfere with either the accuracy of pulse oximetry or affect interpretation of results. Diseases which affect peripheral circulation can make the $SpO_2$ an inaccurate estimate of arterial oxygenation. For example, anemia impedes utilization of blood oxygen regardless of the saturation level.

**[0007]** Human activity and behavior can also affect results of the pulse oximetry measurements. Movement of the sensor used in pulse oximetry can interfere with signal acquisition. Temperature changes can affect blood flow to the area being monitored with the sensor. Sweating can affect optical quality. Smoking can increase carbon monoxide which competes with oxygen to bind hemoglobin and can confuse most systems. Contrast dye injections can interfere with blood optical qualities.

**[0008]** Pulse oximetry depends on differences in light absorbance characteristics of oxygenated hemoglobin (oxyhemoglobin) and non-oxygenated hemoglobin (deoxyhemoglobin). The former absorbs light at about 660 nm (in the visible red range) and the latter absorbs light at about 940 nm (infrared). Both light signals, whether reflected or transmitted, fluctuate with the arterial pulse. The resulting signals, photoplethysmograms (PPGs), can indicate volume changes due to blood flow. Pulse oximetry utilizes the intensity change (light signal fluctuation at each heartbeat) for each wavelength to eliminate the confounding optical effects of other tissues (which remain constant). $SpO_2$ can be estimated using the Beer-Lambert Law, which relates to light absorbance due to the concentration of a substance in media, and empirically-derived reference curves from blood samples of hypoxic volunteers, based on the ratio of these changes in each wavelength (delta 660 nm/delta 940 nm), although other complex factors are often included in the calculations.

**[0009]** Typically, the light sources are light-emitting diodes (LEDs) optimized for output at each of the target wavelengths. A single optical sensor (often a photodiode) may be used for both. Each LED can be activated separately, and accompanied by a "dark" period where neither is on (to obtain ambient light levels). The sensor records light transmitted or reflected for each LED. The obtained signals can be processed in real time or offline.

**[0010]** The sensors can be utilized in either a transmission or a reflectance mode. In the transmission mode, the sensor is typically attached or clipped to a translucent body part (finger, toe, earlobe, and so forth). The LED light sources can be positioned on one side of a body part and the sensor can be positioned on the directly opposite side. The light passes through the entirety of the body part, from one side to the other, and is thus modulated by the pulsating arterial blood flow. In the reflectance mode, the light source and the sensor are on the same side of the body part (e.g. a forehead, finger, and wrist), and the light is reflected from the skin and the underlying near-surface tissues back to the sensor.

**[0011]** Despite the conceptually different optical paths in the reflectance pulse oximetry and transmission pulse oximetry, conventional transmission type signal processing can be used for determining of oxygen saturation. However, the sensor part may need to be adapted to enhance the reflectance signal and the usage of a transmission model for reflectance analysis can result in unstable and erroneous $SpO_2$ estimates.

**[0012]** Continued monitoring of chronic outpatients can be greatly enhanced by accurate $SpO_2$ measurements. A reflectance device can be worn on body parts such as a wrist or an ankle and would impose minimal burden on normal activities. Thus, developing reliable reflectance oximetry devices based on a specific light reflectance model holds great promise for outpatients suffering from chronic diseases.

## SUMMARY

**[0013]** This summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This summary is not intended to identify key features or essential features of the

claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

**[0014]** According to one aspect of the present disclosure, a system for performing pulse oximetry is provided. An example method includes receiving at least three light signals reflected from a human tissue. The human tissue includes a pulsatile tissue and a non-pulsatile tissue. The three light signals are associated with at least three different wavelengths. The method allows determining, based on the three light signals, values of at least three functions. The three functions are invariant to oxygen saturation in the pulsatile tissue. The method includes determining, based on the values of the three functions, a first non-pulsatile component and a second non-pulsatile component.

**[0015]** The method includes removing the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity. The method includes removing the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity. The method also includes calculating, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared light absorption coefficient. The method allows determining, based at least partially on the ratio of the first absorption coefficient and the second absorption coefficient, at least the oxygen saturation in the pulsatile tissue. The pulsatile tissue can include an artery, and the non-pulsatile tissue can include skin. The human tissue can include one of the following: a fingertip, a wrist, an ankle, a neck, a chest, and an earlobe.

**[0016]** In some embodiments, the three light signals include a red light signal, an infrared light signal, and an isosbestic light signal. In some embodiments, the isosbestic wavelength signal includes one of a near infrared light signal and a green light signal.

**[0017]** In some embodiments, values of the three functions are maximums of intensities of the three light signals. In certain embodiments, the first non-pulsatile component and the second non-pulsatile component are determined based on an empirically-derived lookup table.

**[0018]** In some embodiments, the three functions depend on physical conditions. The physical conditions can include at least a location of a sensor on the human tissue and a pressure exerted by the sensor on the human tissue. The sensor is operable to detect the three light signals.

**[0019]** In some embodiments, the method includes mapping the physical conditions to the values of the at least three functions. The following operations can be repeatedly performed. The physical conditions are changed by changing a location of the sensor and pressure of the sensor on the human tissue. The three light signals reflected from human tissue are detected for a predetermined period of time. The values of the three functions are determined based on the three light signals.

**[0020]** In some embodiments, the method includes acquiring a reference PPG waveform. The method allows determining first similarity measures between a pre-determined number of waveforms of the red light signal and the reference PPG waveform. The method includes determining second similarity measures between the pre-determined number of waveforms of the infrared light signal and the reference PPG waveform. The waveforms of the infrared light signal are detected concurrently with the waveforms of the infrared light signal. The method includes calculating an average of products of the first similarity measures and the second similarity measures to estimate an adequacy of the red light signal and the infrared light signal.

**[0021]** In some embodiments, the reference PPG waveform is obtained based on a PPG measured from a fingertip. In some embodiments, the similarity measure is determined using the following formula

$$\langle \vec{w}, \vec{f} \rangle = \max\left(0, \frac{\sum_{i=1}^{N} w_i f_i}{\sqrt{\sum_{i=1}^{N} w_i^2}\sqrt{\sum_{i=1}^{N} f_i^2}}\right),$$

wherein $\vec{W}$ is data representing the waveform of the red light signal or the waveform of the infrared light signal, and $\vec{f}$ is data representing the reference PPG waveform.

**[0022]** According to another example embodiment of the present disclosure, the steps of the method for performing pulse oximetry are stored on a non-transitory machine-readable medium comprising instructions, which when implemented by one or more processors perform the recited steps.

**[0023]** Other example embodiments of the disclosure and aspects will become apparent from the following description taken in conjunction with the following drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0024]** Embodiments are illustrated by way of example and not limitation in the figures of the accompanying drawings, in which like references indicate similar elements.

**[0025]** FIG. **1** is a block diagram showing an example system for performing pulse oximetry using a wearable device.

**[0026]** FIG. **2** is a block diagram showing components of an example device for performing pulse oximetry.

**[0027]** FIG. **3**A is a block diagram illustrating transmission pulse oximetry.

**[0028]** FIG. **3**B is a block diagram illustrating reflectance pulse oximetry.

**[0029]** FIG. **4** shows an example plot of a PPG and example plot of a blood vessel diameter.

**[0030]** FIG. **5** shows location of a sensor and pressure of the sensor during SpO2 measurements.

**[0031]** FIG. **6** illustrates an example plot of a PPG taken from a finger.

**[0032]** FIG. **7** illustrates example plots of a standard waveform of a PPG taken from a finger.

**[0033]** FIG. **8** illustrates an example plot of a PPG taken from a wrist.

**[0034]** FIG. **9** illustrates an example plot of waveforms of PPGs taken from a wrist and a standard waveform of a PPG taken from a finger.

**[0035]** FIG. **10** illustrates another example plot of a PPG taken from a wrist.

**[0036]** FIG. **11** illustrates an example plot of waveforms of PPGs taken from a wrist and a standard waveform of a PPG taken from a finger.

**[0037]** FIG. **12** is a flow chart showing an example method for performing pulse oximetry.

**[0038]** FIG. **13** is a flow chart showing an example method for mapping physical conditions of the pulse oximetry.

**[0039]** FIG. **14** is a flow chart showing an example method for estimating an adequacy of a PPG data.

**[0040]** FIG. **15** shows a diagrammatic representation of a computing device for a machine, within which a set of instructions for causing the machine to perform any one or more of the methodologies discussed herein can be executed.

## DETAILED DESCRIPTION

**[0041]** The following detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show illustrations in accordance with exemplary embodiments. These exemplary embodiments, which are also referred to herein as "examples," are described in enough detail to enable those skilled in the art to practice the present subject matter. The embodiments can be combined, other embodiments can be utilized, or structural, logical and electrical changes can be made without departing from the scope of what is claimed. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope is defined by the appended claims and their equivalents.

**[0042]** The present disclosure provides systems and methods for performing pulse oximetry. Embodiments of the present disclosure can allow measuring medical parameters, for example, a PPG of a patient in a non-intrusive manner while, for example, the patient is at home, at work, outdoors, traveling, or is located at some other stationary or mobile environment. Some embodiments of the present disclosure include a wearable device. The wearable device can be worn at a wrist, ankle, chest, neck, or positioned at other sites of a human body. The wearable device can allow measuring the PPG of the patient without requiring the patient to take an active role in the process. The PPG data collected by the pulse oximetry during an extended period of time can be analyzed to detect and track trends in medical parameters, for example, oxygen saturation, and to make conclusions concerning symptoms and a progression of one or more chronic diseases from which the patient may suffer.

**[0043]** Embodiments of the present disclosure may facilitate measurements of $SpO_2$ oxygen saturation in blood in a pulsating artery using a reflectance pulse oximetry. The present techniques may be used to exclude an additive component in PPG signals due to reflection from skin and other non-pulsatile tissue covering the pulsating artery. The technology described herein may allow for estimating adequacy of the PPG signals taking during reflectance pulse oximetry.

**[0044]** According to some example embodiments, a method for performing pulse oximetry includes receiving at least three light signals reflected from a human tissue. The human tissue includes a pulsatile tissue and a non-pulsatile tissue. The three light signals are associated with at least three different wavelengths. The method allows determining, based on the three light signals, values of at least three functions. The three functions are invariant to oxygen saturation in the pulsatile tissue. The method includes determining, based on the values on the three functions, a first non-pulsatile component and a second non-pulsatile component. The method includes removing the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity. The method includes removing the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity. The method also includes calculating, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared light absorption coefficient. The method allows determining, based partially on the ratio of the first absorption coefficient and the second absorption coefficient, at least the oxygen saturation in the pulsatile tissue.

**[0045]** Referring now to FIG. **1**, an example system **100** for performing pulse oximetry is shown. The system **100** can include at least a wearable device **110**. The wearable device **110** can include sensors **120**. In some embodiments, the wearable device **110** is worn by a patient **130** (for example, on a wrist, ankle, earlobe, neck, chest, fingertip, and the like) for an extended period of time. In various embodiments, the wearable device **110** can be carried out as a watch, a bracelet, a wristband, a belt, a neck band, and the like.

**[0046]** The wearable device **110** can be operable to constantly collect, via sensors **120**, sensor data from a patient **130**. Based on the sensor data, the wearable device **110** can be operable to generate PPG data, and, based on the PPG data, obtain further medical parameters, for example, oxygen saturation, pulse rate, and so forth.

**[0047]** In some embodiments, the system **100** includes a mobile device **140**. The mobile device **140** can be communicatively coupled to the wearable device **110**. In various embodiments, the mobile device **140** is operable to communicate with the wearable device **110** via a wireless connection such as, for example, Wi-Fi, Bluetooth, Infrared (IR), and the like. The mobile device **140** can include a mobile phone, a smart phone, a phablet, a tablet computer, a notebook, and so forth. The mobile device **140** can be operable to receive the sensors data and analyze the sensor data to generate PPG data.

**[0048]** In further embodiments, the system **100** may include a cloud-based computing resource **150** (also referred to as a computing cloud). In some embodiments, the cloud-based computing resource **150** includes one or more server farms/clusters comprising a collection of computer servers and is co-located with network switches and/or routers. In certain embodiments, the mobile device **140** is communicatively coupled to the computing cloud **150**. The mobile device **140** can be operable to send the sensor data to the computing cloud **150** for further analysis (for example, for extracting medical parameters from the sensor data and storing the results). The computing cloud **150** can be operable to run one or more applications and to provide reports regarding a health status of the patient, based on trends in medical parameters over time.

**[0049]** FIG. **2** is a block diagram illustrating components of wearable device **110**, according to an example embodiment. The example wearable device **110** includes a transmitter **210**, a processor **220**, memory storage **230**, a battery **240**, at least two LEDs **250**, and one or more optical sensors **260**. The wearable device **110** may comprise additional or different components to provide a particular operation or functionality. Similarly, in other embodiments, the wearable device **110** includes fewer components that perform similar or equivalent functions to those depicted in FIG. **2**.

**[0050]** The transmitter **210** can be configured to communicate with a network such as the Internet, a Wide Area Network (WAN), a Local Area Network (LAN), a cellular

network, and so forth, to send data streams (for example sensor data, PPG data, and messages).

**[0051]** The processor **220** can include hardware and/or software, which is operable to execute computer programs stored in memory **230**. The processor **220** can use floating point operations, complex operations, and other operations, including processing and analyzing sensor data.

**[0052]** In some embodiments, the battery **240** is operable to provide electrical power for operation of other components of the wearable device **110**. In some embodiments, the battery **240** is a rechargeable battery. In certain embodiments, the battery **240** is recharged using an inductive charging technology.

**[0053]** In various embodiments, the LEDs **250** are operable to emit light signals of a red wavelength (typically 660 nm) and infrared wavelength (660 nm). Each of the LEDs is activated separately and accompanied by a "dark" period where neither of the LEDs is on to obtain ambient light levels. In some embodiments, a single LED can be used to emit both the infrared and red light signals. The lights can be absorbed by human blood (mostly by hemoglobin). The methods for pulse oximetry are based on the fact that oxygenated hemoglobin absorbs more infrared light while deoxygenated hemoglobin absorbs more red light. Oxygenated hemoglobin allows more red light to pass through while deoxygenated hemoglobin allows more infrared light to pass through. The optical sensor(s) **260** (typically a photodiode) can receive light signals modulated by a human tissue. Based on the changes in the intensities of the modulated light signals, one or more medical parameters, such as, for example, oxygen saturation, arterial blood flow, pulse rate, and respiration, can be determined.

**[0054]** In some embodiments of the present disclosure, the LEDs **250** are also operable to emit light signals of isosbestic wavelengths (typically 810 nm and 520 nm). Both oxygenated hemoglobin and deoxygenated hemoglobin absorb the light of the isosbestic wavelengths equally.

**[0055]** The LEDs **250** and optical sensor(s) **260** can be utilized in either a transmission or a reflectance mode for pulse oximetry. In the transmission mode, the LEDs **250** and sensor **260** are typically attached or clipped to a translucent body part (e.g., a finger, toe, and earlobe). The LEDs **250** are located on one side of the body part while the optical sensor(s) **260** are located directly on the opposite site. The light passes through the entirety of the body part, from one side to the other, and is thus modulated by the pulsating arterial blood flow. In the reflectance mode, the LEDs **250** and optical sensor(s) **260** are located on the same side of the body part (e.g. a forehead, finger, and wrist), and the light is reflected from the skin and underlying near-surface tissues back to the optical sensor(s) **260**.

**[0056]** FIG. **3**A is a block diagram illustrating details of transmission pulse oximetry. The light signals **310** emitted by LEDs **250** in red and infrared wavelengths are transmitted through highly perfused pulsatile tissue **320** (for example, blood vessels in a fingertip or an earlobe). The light signals **340** modulated across the pulsatile tissue **320** can be detected by optical sensor(s) **260**. Some portions of the light signals **310** are reflected by non-pulsatile tissue **330** to produce a reflected light signal **350**.

**[0057]** FIG. **3**B is a block diagram illustrating details of reflectance pulse oximetry. Unlike the transmission pulse oximetry, light signals **310** emitted by LEDs **250** are reflected back to the optical sensor(s) **260** from both pulsatile tissue **320** (pulsating arteries) and non-pulsatile tissue **330** (e.g., skin and underlying tissue). In FIG. **3**B, the corresponding reflected light signals are denoted as signal **360** and signal **350**. The reflected signal **350** from non-pulsatile tissue **330** has a negligible significance in conventional transmission oximetry (see FIG. **3**A), as well as in strong signal reflectance oximetry when, for example, operated on a highly perfused tissue such as a fingertip or a forehead.

**[0058]** In case of a weak pulsatile signal, the non-pulsatile tissue reflection should be accounted for in order to avoid an erroneous $SpO_2$ reading. Therefore, the contribution of the non-pulsatile tissue needs to be identified and accounted for, to enable an accurate $SpO_2$ reading in such cases. The contribution of the non-pulsatile tissue depends on at least location of the optical sensor(s) **260** on the human tissue and a pressure of the sensor(s) **260** on the human tissue.

**[0059]** FIG. **4** shows a plot of example PPG **410** which can be obtained with reflectance pulse oximetry and a plot of blood vessel diameter **420**. The PPG **410** represents the intensity I of the light signal **310** (either the red light signal or the infrared light signal) as modulated by a human tissue mostly due to a blood flow in the blood vessel. The high peaks (maximums) $I_H$ of PPG **410** correspond to the low peaks $d_{min}$ of the blood vessel diameter **420** and the low peaks $I_L$ of the PPG **410** correspond to the high peaks $d_{max}$ of the blood vessel diameter **420**. The PPG **410** includes a component due to the reflection of a light from the non-pulsatile tissue (for example, skin).

Mapping of Measurement Conditions

**[0060]** In some embodiments, the detected signal I (the intensity of reflected light signal) is modeled as follows:

$$I=I_0(K_1+K_2e^{-cd}) \quad (1)$$

**[0061]** In formula (1), $I_0$ represents an incident light intensity, $K_1$ is a reflection coefficient of the non-pulsatile tissue (for example, a skin), $K_2$ indicates the absorption by pulsatile tissue, d represents (arterial) blood vessel diameter, and c is overall absorption coefficient of blood hemoglobin derived from a mixture of both oxygen-saturated and non-oxygen saturated hemoglobin. Each of oxygen-saturated and non-oxygen saturated hemoglobin has its own particular value of absorption coefficient c for a particular wavelength of emitted light **310**.

**[0062]** In the transmission oximetry, $K_1$ is small relative to $K_2$ and therefore is neglected in both red light measurements and infrared light measurements. In the reflectance pulse oximetry or in the low perfusion transmission oximetry, the reflection coefficient $K_1$ cannot be neglected since the detected signal I is weak in such cases.

**[0063]** As shown in FIG. **4**, the blood vessel diameter **420** changes periodically with the rhythm of the heart rate. The low peaks of the blood vessel diameter $d_{min}$ correspond to minimums of the absorption of the light by the blood and the high peaks of the light intensity $I_H$. The high peaks of the blood vessel diameter $d_{max}$ correspond to maximum absorption of the light by blood and the lowest peaks of the light intensity $I_L$. In some embodiments, the low peaks of the blood vessel diameter $d_{min}$ can be considered to be constant as they reflect lowest diastole. The high peaks of the blood vessel diameter $d_{max}$ may vary relatively slowly due to, for example, fluctuations of blood pressure.

**[0064]** The SpO2 oxygen saturation can be calculated based on the ratio R of hemoglobin absorbance's coefficients measured at the red and infrared wavelengths. In general, for any two different wavelengths k and l, the ratio R can be defined as:

$$R_{k,l} = \frac{c_k}{c_l} \tag{2}$$

**[0065]** The relationship between the ratio $R_{red,ir}$ and the SpO2 oxygen saturation is a non-linear, monotonically decreasing function. The relation between the ratio $R_{red,ir}$ may be described by an empirical curve function $f(.)$:

$$S=f(R_{red,ir}) \tag{3}$$

**[0066]** According to an example embodiment, the ratio $R_{k,l}$ may be calculated by the following process. In some embodiments, $V \geq 0$ denotes an arbitrary scalar representing the additive reflection component of the light from non-pulsatile tissue. A new term P is defined as:

$$P(I-V) = \log\left(\frac{I_H - V}{I_L - V}\right) \tag{4}$$

**[0067]** A linear approximation of (4) can be obtained for $I_H - I_L << I_L - V$:

$$P(I-V) = \log\left(1 + \frac{I_H - I_L}{I_L - V}\right) \approx \frac{I_H - I_L}{I_L - V} = \frac{\mathrm{AC}}{\mathrm{DC} - V} \tag{5}$$

**[0068]** Using Eq. 1, it can be shown that

$$P(I - I_0K_1) = \log\left(\frac{I_H - I_0K_1}{I_L - I_0K_1}\right) = \log\left(\frac{I_0K_2e^{-cd_{min}}}{I_0K_2e^{-cd_{max}}}\right) = c(d_{max} - d_{min}) \tag{6}$$

**[0069]** For any combination of two wavelengths, the ratio $R_{kl}$ can be calculated as follows:

$$R_{k,l} = \frac{P(I_k - I_0^kK_1^k)}{P(I_l - I_0^lK_1^l)} \approx \frac{AC_k(DC_l - I_0^lK_1^l)}{(DC_k - I_0^kK_1^k)AC_l} \tag{7}$$

**[0070]** The correct calculation of SpO2 oxygen saturation depends on accurate estimation of the additive reflection component V for the different wavelengths. The additive reflection component V also depends on physical conditions at which the pulse oximetry measurement are carried out. As illustrated in FIG. **5**, the physical conditions include at least a particular location (for example, given by coordinates x and y) of the sensor **260** on the human tissue, for example, the wrist **510** and pressure p with which the sensor **260** is pressed to the human tissue.

**[0071]** For example, when a patient removes the wearable device **110** from a wrist and then replaces it, sensor **260** is not placed at the same location. The location of the sensor **260** can be changed slightly, for example within 0.5 centimeter. Additive reflection component V is changed when the sensor **260** is replaced since reflected light comes through a different portion of non-pulsatile tissue. Therefore, a different additive reflection component V needs to be subtracted in Eq. (5).

**[0072]** In some embodiments, the light intensity for a particular wavelength is described as follows:

$$I(\bar{r},S,d)=I_0(K_1(\bar{r})+K_2(\bar{r})e^{-c(S)d}) \tag{8}$$

wherein vector $\bar{r}$ denotes the current physical conditions (x, y, p). Some embodiments assume that there is an invariant function G of the reflected signals with different wavelengths. The invariant function G is used to model the effect of the additive reflections from non-pulsatile tissue:

$$G(I_1, \ldots, I_1)=G(\vec{r}) \tag{9}$$

**[0073]** The function G $(1_1, \ldots, I_1)$ is an invariant on SpO2 oxygen saturation S and the blood vessel diameter d. The invariant function G depends on physical condition (x, y, p), that is a location of the sensor and pressure of the sensor on skin. If the value of the invariant function G changes after the wearable device **110** is taken off a wrist and then is placed back, it may indicate that physical conditions (x, y, p) are changed.

**[0074]** Some embodiments assume that there is a predetermined number of independent invariants of SpO2 oxygen saturation. The physical conditions of a current pulse oximetry measurement can be reconstructed by values of invariant functions. Mapping the physical conditions to respective additive reflections V may allow correcting a calculation of SpO2 oxygen saturation for the current physical conditions.

**[0075]** According to some example embodiments, the high peaks (maximums) of light intensity $I_H$ are used as an invariant function for each wavelength of the light:

$$I_H=I_0(K_1(\bar{r})+K_2(\bar{r})e^{-c(S)d_{min}}) \tag{10}$$

**[0076]** The high peaks $I_H$ depend on vector $(\bar{r}, S)$. The dependence on SpO2 oxygen saturation S is minimal due to the relatively small amount of light absorbed during low diameter diastole and therefore $I_H$ can be considered approximately invariant to S. For example, if vector $\vec{r}$ is three dimensional vector (x, y, p), wherein (x, y) is a location of the sensor and p is the pressure of the sensor on skin, then using $I_H$ values for intensity of lights of three wavelengths can be used to build a proper mapping for the physical conditions.

**[0077]** In some embodiments, the high peaks of the light intensity $I_H$ at isosbestic wavelengths are used as the invariants on SpO2 oxygen saturation S and blood vessel diameter d since the light absorption at the isosbestic wavelengths is independent of SpO2 oxygen saturation since when a light of an isosbestic wavelength is used, the reflection from the oxygenized blood is the same as reflection from the non-oxygenized blood. In some embodiments, the isosbestic wavelengths include a near infrared wavelength 810 nm (NIR) and a green wavelength 520 nm (green). The corresponding highest peaks for the light intensities $I_H^{NIR}$ and $I_H^{green}$ can be considered as exact invariants on SpO2 oxygen saturation.

**[0078]** In some embodiments, at the first usage of a wrist device **110**, the patient **130** is instructed to wear and remove the wearable device a few times. Each time the wearable device **110** is put on, the patient **130** intentionally slightly changes sensor location and pressure of the sensor. During

each time the user puts on the wearable device and wears it for a while, different physical conditions of SpO2 oxygen saturation are mapped to values to one or more invariant functions. For example, values of invariant functions $I_H^{ir}$, $I_H^{red}$, and $I_H^{NIR}$ can be determined for the different physical conditions. Mapping is completed until no new information (no new values of the invariant functions) is received. Due to the restricted degrees of freedom allowed by the wearable device, the mapping process is expected to conclude quickly. Once mapping is complete, the physical condition may be reconstructed by calculation the values of the three invariant functions during regular operations.

**[0079]** During regular operations of the wearable device **110**, each time the patient **130** puts the wearable device **110** on a wrist, values for invariant functions are determined and, based on the values of the invariant functions, proper values of additive reflection components for both an infrared light signal and red light signal is determined. In some embodiments, the additive refection components can be found via an empirically derived look up table. The proper value of additive refection components is then subtracted from peaks of PPG signals obtained with red and infrared lights to determine a correct ratio between hemoglobin absorbance's coefficients at the red and infrared wavelengths. The ratio is then used to obtain a correct value of $SpO_2$ oxygen saturation.

Signal Fit Criterion

**[0080]** Taking pulse oximetry measurements at a wrist requires high quality PPG signals to obtain a stable result. For optimal performance, the optical sensor **260** should be placed directly on top of a pulsating artery such as the radial artery. An accurate placement of a wearable device on a wrist is difficult to control. In some embodiments, a morphological signal fit criterion is used to ensure PPG data adequacy. The fit criterion uses the morphology of the optical PPG signal measured from a finger as a benchmark.

**[0081]** The blood vessel diameter changes with the periodic rhythm of the heart rate. The changes of the blood vessel diameter influence the pulsatile component of the reflectance signal, while the non-pulsatile additive reflection depends on the location of the sensor with respect to pulsating artery and on the pressure the sensor pressed to the skin.

**[0082]** The additive reflection in PPG measurements from a finger is negligible, which makes the measurement of PPG from a finger a benchmark for signal adequacy. Empirically, the waveform of PPG obtained at the wrist approaches the typical waveform of PPG at the finger when the sensor is placed directly on top of and sufficiently tight to the pulsating artery.

**[0083]** In some embodiments, a similarity between a waveform of PPG taken from a wrist and a standard waveform of PPG taken from a fingertip is determined to estimate an adequacy of the PPG taken from the wrist. In certain embodiments, a similarity measure between a wrist PPG waveform $\{w_i\}i=1^N$ and fingertip PPG waveform $\{f_i\}_{i=1}^N$ is calculated by the following formula:

$$\langle \vec{w}, \vec{f} \rangle = \max\left(0, \frac{\sum_{i=1}^{N} w_i f_i}{\sqrt{\sum_{i=1}^{N} w_i^2}\sqrt{\sum_{i=1}^{N} f_i^2}}\right)$$

**[0084]** In some embodiments, a signal fit score is defined as multiplication of similarity measure values for PPG taken with red light and PPG taken with infrared light, averaged over time:

$$Q_{fit} = \frac{1}{N}\sum_{k=1}^{N} \langle \vec{w}_{red}^{k}, \vec{f}_{red} \rangle \times \langle \vec{w}_{ir}^{k}, \vec{f}_{ir} \rangle \times 100\%$$

**[0085]** FIG. **6** illustrates example plot of a PPG **600** taken from a finger.

**[0086]** FIG. **7** illustrates example plots of a standard waveform **700** of a PPG taken from a finger. The waveform **700** is derived based on the PPG taken from a finger and can be used as standard waveform (a reference, a golden standard) for estimating adequacy of a PPG taken from a wrist.

**[0087]** FIG. **8** illustrates an example plot of a PPG taken from a finger. The waveforms of the PPG **800** are of markedly different morphology. The estimated adequacy of the PPG **800** is low since the signal fit score of PPG **800** is about 45%.

**[0088]** FIG. **9** illustrates an example plot waveforms **900** of PPGs taken from a wrist and the standard waveform **700** of a PPG taken from a finger.

**[0089]** FIG. **10** illustrates another example plot of a PPG **1000** taken from a wrist.

**[0090]** FIG. **11** illustrates an example plot of waveforms **1100** of PPG **1000** taken from a wrist and a standard waveform **700** of a PPG taken from a finger. The PPG **1000** is morphologically similar to a PPG taken from a wrist. The signal fit score of PPG **1000** is about 70%.

**[0091]** FIG. **12** is a flow chart showing steps of a method **1200** for performing pulse oximetry, according to an example embodiment. The method **1200** can be implemented using system **100** for performing pulse oximetry and a wearable device **110**. Method **1200** can commence in block **1202** with receiving at least three light signals reflected from a human tissue. The human tissue includes a pulsatile tissue (for example, an artery) and a non-pulsatile tissue (for example, skin). The three light signals are associated with at least three different wavelengths. In some embodiments, the three light signals include a red light signal, an infrared light signal, and an isosbestic light signal.

**[0092]** In block **1204**, the method **1200** proceeds with determining, based on the three light signals, values of at least three functions. The three functions are invariant to an oxygen saturation in the pulsatile tissue. In some embodiments, the three functions are maximums of intensities of the three light signals.

**[0093]** In block **1206**, the method **1200** can determine, based on the values on the at least three functions, a first non-pulsatile component and a second non-pulsatile component. In some embodiments, the determination can be based on an empirically-derived lookup table.

**[0094]** In block **1208**, the method **1200** can facilitate removing the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity.

**[0095]** In block **1210**, the method **1200** can facilitate removing the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity.

**[0096]** In block **1212**, the method **1200** proceeds with calculating, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared absorption coefficient.

**[0097]** In block **1214**, the method **1200** proceeds with determining, based at least partially on the ratio, at least the oxygen saturation in the pulsatile tissue.

**[0098]** FIG. **13** is a flow chart showing steps of a method **1300** for mapping physical conditions of the pulse oximetry, according to an example embodiment. The method **1300** can be implemented using system **100** for performing pulse oximetry and a wearable device **110**. Method **1300** can commence in block **1302** with changing physical conditions. The physical condition can include a location of a sensor on human tissue (for example at a wrist). The human tissue includes a pulsatile tissue (for example, a pulsating artery) and non-pulsatile tissue (for example, a skin). In some embodiments, to change the physical conditions, patient **130** may be instructed to remove the wearable device **110** and place it back on a wrist at a slightly different place.

**[0099]** In block **1304**, the method **1300** proceeds with detecting at least three light signals reflected from the human tissue for a predetermined period of time. The light signals are associated with three different wavelengths.

**[0100]** In block **1306**, the method allows determining, based on the three light signals, the values of the at least three functions invariant to $SpO_2$ oxygen saturation in pulsatile tissue. In some embodiments, the three functions are maximums of intensities of reflection of the three lights from the human tissue. The steps of the method **1300** can be repeated several times until no new values of the three invariant functions are received.

**[0101]** FIG. **14** is a flow chart showing steps of a method **1400** for estimating adequacy of a PPG data during pulse oximetry. The method **1400** may be implemented by system **100** for performing pulse oximetry and the wearable device **110**.

**[0102]** Method **1400** can commence in block **1402** with acquiring a reference PPG waveform. In some embodiments, the reference PPG waveform includes a standard PPG waveform received with pulse oximetry measurements at a fingertip.

**[0103]** In block **1404**, the method **1400** proceeds with determining first similarity measures between a pre-determined number of waveforms of the red light signal and the reference PPG waveform.

**[0104]** In block **1406**, the method **1400** proceeds with determining second similarity measures between the predetermined number of waveforms of the infrared light signal and the reference PPG waveform. The waveforms of the infrared light signal are detected concurrently with the waveforms of the infrared light signal.

**[0105]** In block **1408**, the method **1400** calculates an average of products of first similarity measures and the second similarity measures to estimate the adequacy of the red light signal and the infrared light signal.

**[0106]** FIG. **15** illustrates a computer system **1500** that may be used to implement embodiments of the present disclosure, according to an example embodiment. The computer system **1500** may serve as a computing device for a machine, within which a set of instructions for causing the machine to perform any one or more of the methodologies discussed herein can be executed. The computer system **1500** can be implemented in the contexts of the likes of computing systems, networks, servers, or combinations thereof. The computer system **1500** includes one or more processor units **1510** and main memory **1520**. Main memory **1520** stores, in part, instructions and data for execution by processor units **1510**. Main memory **1520** stores the executable code when in operation. The computer system **1500** further includes a mass data storage **1530**, a portable storage device **1540**, output devices **1550**, user input devices **1560**, a graphics display system **1570**, and peripheral devices **1580**. The methods may be implemented in software that is cloud-based.

**[0107]** The components shown in FIG. **15** are depicted as being connected via a single bus **1590**. The components may be connected through one or more data transport means. Processor units **1510** and main memory **1520** are connected via a local microprocessor bus, and mass data storage **1530**, peripheral devices **1580**, the portable storage device **1540**, and graphics display system **1570** are connected via one or more I/O buses.

**[0108]** Mass data storage **1530**, which can be implemented with a magnetic disk drive, solid state drive, or an optical disk drive, is a non-volatile storage device for storing data and instructions for use by processor units **1510**. Mass data storage **1530** stores the system software for implementing embodiments of the present disclosure for purposes of loading that software into main memory **1520**.

**[0109]** The portable storage device **1540** operates in conjunction with a portable non-volatile storage medium, such as a floppy disk, a compact disk, a Digital Versatile Disc (DVD), or USB storage device, to input and output data and code to and from the computer system **1500**. The system software for implementing embodiments of the present disclosure is stored on such a portable medium and input to the computer system **1500** via the portable storage device **1540**.

**[0110]** User input devices **1560** provide a portion of a user interface. User input devices **1560** include one or more microphones, an alphanumeric keypad, such as a keyboard, for inputting alphanumeric and other information, or a pointing device, such as a mouse, a trackball, stylus, or cursor direction keys. User input devices **1560** can also include a touchscreen. Additionally, the computer system **1500** includes output devices **1550**. Suitable output devices include speakers, printers, network interfaces, and monitors.

**[0111]** Graphics display system **1570** includes a liquid crystal display or other suitable display device. Graphics display system **1570** receives textual and graphical information and processes the information for output to the display device. Peripheral devices **1580** may include any type of computer support device to add additional functionality to the computer system.

**[0112]** The components provided in the computer system **1500** of FIG. **15** are those typically found in computer systems that may be suitable for use with embodiments of the present disclosure and are intended to represent a broad category of such computer components that are well known in the art. Thus, the computer system **1500** can be a personal computer, handheld computing system, telephone, mobile computing system, workstation, tablet, phablet, mobile phone, server, minicomputer, mainframe computer, or any other computing system. The computer may also include different bus configurations, networked platforms, multiprocessor platforms, and the like. Various operating systems

may be used including UNIX, LINUX, WINDOWS, MAC OS, PALM OS, ANDROID, IOS, QNX, and other suitable operating systems.

**[0113]** It is noteworthy that any hardware platform suitable for performing the processing described herein is suitable for use with the embodiments provided herein. Computer-readable storage media refer to any medium or media that participate in providing instructions to a central processing unit, a processor, a microcontroller, or the like. Such media may take forms including, but not limited to, non-volatile and volatile media such as optical or magnetic disks and dynamic memory, respectively. Common forms of computer-readable storage media include a floppy disk, a flexible disk, a hard disk, magnetic tape, any other magnetic storage medium, a Compact Disk Read Only Memory disk, DVD, Blu-ray disc, any other optical storage medium, RAM, Programmable Read-Only Memory, Erasable Programmable Read-Only Memory, Electronically Erasable Programmable Read-Only Memory, flash memory, and/or any other memory chip, module, or cartridge.

**[0114]** In some embodiments, the computer system **1500** may be implemented as a cloud-based computing environment, such as a virtual machine operating within a computing cloud. In other embodiments, the computer system **1500** may itself include a cloud-based computing environment, where the functionalities of the computer system **1500** are executed in a distributed fashion. Thus, the computer system **1500**, when configured as a computing cloud, may include pluralities of computing devices in various forms, as will be described in greater detail below.

**[0115]** In general, a cloud-based computing environment is a resource that typically combines the computational power of a large grouping of processors (such as within web servers) and/or that combines the storage capacity of a large grouping of computer memories or storage devices. Systems that provide cloud-based resources may be utilized exclusively by their owners or such systems may be accessible to outside users who deploy applications within the computing infrastructure to obtain the benefit of large computational or storage resources.

**[0116]** The cloud may be formed, for example, by a network of web servers that comprise a plurality of computing devices, such as the computer system **1500**, with each server (or at least a plurality thereof) providing processor and/or storage resources. These servers may manage workloads provided by multiple users (e.g., cloud resource customers or other users). Typically, each user places workload demands upon the cloud that vary in real-time, sometimes dramatically. The nature and extent of these variations typically depends on the type of business associated with the user.

**[0117]** Thus, methods and systems for performing pulse oximetry have been described. Although embodiments have been described with reference to specific example embodiments, it will be evident that various modifications and changes can be made to these example embodiments without departing from the broader spirit and scope of the present application. Accordingly, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

**1**. A method for performing a pulse oximetry, the method comprising:

receiving at least three light signals reflected from a human tissue including a pulsatile tissue and a non-pulsatile tissue, the at least three light signals being associated with at least three different wavelengths;

determining, based on the at least three light signals, values of at least three functions, the at least three functions being invariant to an oxygen saturation in the pulsatile tissue;

determining, based on the values on the at least three functions, a first non-pulsatile component and a second non-pulsatile component;

removing the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity;

removing the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity;

calculating, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared light absorption coefficient; and

determining, based at least partially on the ratio, at least the oxygen saturation in the pulsatile tissue.

**2**. The method of claim **1**, wherein the pulsatile tissue includes an artery and the non-pulsatile tissue includes skin.

**3**. The method of claim **1**, wherein the human tissue includes one of the following: a fingertip, a wrist, an ankle, a neck, a chest, and an earlobe.

**4**. The method of claim **1**, wherein the at least three light signals include a red light signal, an infrared light signal, and an isosbestic light signal, the isosbestic wavelength signal including one of a near infrared light signal and a green light signal.

**5**. The method of claim **1**, wherein values of the at least three functions are maximums of intensities of the at least three light signals.

**6**. The method of claim **1**, wherein the first non-pulsatile component and the second non-pulsatile component are determined based on an empirically-derived lookup table.

**7**. The method of claim **1**, wherein the at least three functions depend on physical conditions, the physical conditions including at least a location of a sensor on the human tissue and a pressure of the sensor on the human tissue, the sensor being operable to detect the at least three light signals.

**8**. The method of claim **7**, further comprising mapping the physical conditions to the values of the at least three functions by repeatedly performing the following operations:

changing the physical conditions;

detecting the at least three light signals for a predetermined period of time; and

determining, based on the at least three light signals, the values of the at least three functions.

**9**. The method of claim **1**, further comprising:

acquiring a reference photoplethysmogram (PPG) waveform;

determining first similarity measures between a pre-determined number of waveforms of the red light signal and the reference PPG waveform;

determining second similarity measures between the pre-determined number of waveforms of the infrared light signal and the reference PPG waveform, the waveforms

of the infrared light signal being detected concurrently with the waveforms of the infrared light signal; and

calculating an average of products of first similarity measures and the second similarity measures to estimate an adequacy of the red light signal and the infrared light signal.

**10**. The method of claim **9**, wherein the reference PPG waveform is obtained based on a PPG measured from a fingertip.

**11**. The method of claim **9**, wherein a similarity measure is determined using

$$\langle \vec{w}, \vec{f} \rangle = \max\left(0, \frac{\sum_{i=1}^{N} w_i f_i}{\sqrt{\sum_{i=1}^{N} w_i^2}\sqrt{\sum_{i=1}^{N} f_i^2}}\right),$$

wherein $\vec{W}$ is data representing the waveform of the red light signal or the waveform of the infrared light signal, and $\vec{f}$ is data representing reference PPG waveform.

**12**. A system for performing a pulse oximetry, the system comprising:

at least one optical sensor operable to detect at least three light signals reflected from a human tissue including a pulsatile tissue and a non-pulsatile tissue, the at least three light signals being associated with at least three different wavelengths; and

at least one processor communicatively coupled to the at least one optical sensor and operable to:

determine, based on the at least three light signals, values of at least three functions, the at least three functions being invariant to an oxygen saturation in the pulsatile tissue;

determine, based on the values of the at least three functions, a first non-pulsatile component and a second non-pulsatile component;

remove the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity;

remove the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity;

calculate, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared light absorption coefficient; and

determine, based at least partially on the ratio, at least the oxygen saturation in the pulsatile tissue.

**13**. The system of claim **12**, wherein the pulsatile tissue includes an artery and the non-pulsatile tissue includes skin.

**14**. The system of claim **12**, wherein the human tissue includes one of the following: a fingertip, a wrist, an ankle, a neck, a chest, and an earlobe.

**15**. The system of claim **12**, wherein the at least three light signals include a red light signal, an infrared light signal, and an isosbestic light signal, wherein the isosbestic wavelength signal includes one of a near infrared light signal and a green light signal.

**16**. The system of claim **12**, wherein values of the at least three functions are maximums of intensities of the at least three light signals.

**17**. The system of claim **12**, wherein the first non-pulsatile component and the second non-pulsatile component are determined based on an empirically-derived lookup table.

**18**. The system of claim **12**, wherein the at least three functions depend on physical conditions, the physical conditions including at least a location of the at least one optical sensor on the human tissue and a pressure of the at least one sensor to the human tissue.

**19**. The system of claim **18**, wherein the at least one processor is further operable to map the physical conditions to the values of the at least three functions by repeatedly performing the following operations:

changing the physical conditions;

detecting the at least three light signals for a predetermined period of time; and

determining, based on the at least three light signals, the values of the at least three functions.

**20**. The system of claim **12**, wherein the at least one processor is further operable to:

acquire a reference photoplethysmogram (PPG) waveform;

determine first similarity measures between a pre-determined number of waveforms of the red light signal and the reference PPG waveform;

determine second similarity measures between the predetermined number of waveforms of the infrared light signal and the reference PPG waveform, the waveforms of the infrared light signal being detected concurrently with the waveforms of the infrared light signal; and

calculate an average of products of first similarity measures and the second similarity measures to estimate an adequacy of the red light signal and the infrared light signal.

**21**. The system of claim **20**, wherein the reference PPG waveform is obtained based on a PPG measured from a fingertip.

**22**. The system of claim **20**, wherein a similarity measure is determined using

$$\langle \vec{w}, \vec{f} \rangle = \max\left(0, \frac{\sum_{i=1}^{N} w_i f_i}{\sqrt{\sum_{i=1}^{N} w_i^2}\sqrt{\sum_{i=1}^{N} f_i^2}}\right)$$

wherein $\vec{W}$ is data representing the waveform of the red light signal or the waveform of the infrared light signal, and $\vec{f}$ is data representing reference PPG waveform.

**23**. A non-transitory computer-readable storage medium having embodied thereon instructions, which when executed by a processor, perform steps of a method, the method comprising:

receiving at least three light signals reflected from a human tissue including a pulsatile tissue and a non-pulsatile tissue, the at least three light signals being associated with at least three different wavelengths;

determining, based on the at least three light signals, values of at least three functions, the at least three functions being invariant to an oxygen saturation in the pulsatile tissue;

determining, based on the values on the at least three functions, a first non-pulsatile component and a second non-pulsatile component;

removing the first non-pulsatile component from an intensity of a red light signal reflected from the human tissue to estimate a first corrected intensity;

removing the second non-pulsatile component from an intensity of an infrared light signal reflected from the human tissue to estimate a second corrected intensity;

calculate, based on the first corrected intensity and the second corrected intensity, a ratio of a red light absorption coefficient and an infrared light absorption coefficient; and

determining, based partially on the ratio, at least the oxygen saturation in the pulsatile tissue.

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|---|---|---|---|
| 专利名称(译) | 使用不变因子进行脉搏血氧饱和度测定 | | |
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摘要(译)

用于执行脉搏血氧测定的示例方法可以从接收从人体组织反射的三种不同波长的至少三个光信号开始。人体组织包括脉动组织和非脉动组织。基于三个光信号，确定至少三个函数的值。这三个功能对于脉动组织中的氧饱和度是不变的，并且取决于可操作以检测传感器在人体组织上的三个光信号和压力的传感器的位置。基于三个功能的值，分析非脉动成分的红光信号和从人体组织反射的红外光信号的强度。从强度中去除非脉动组分以允许正确估计吸收系数的比率，该比率用于确定脉动组织中的氧饱和度。