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(54) **MOTION COMPENSATION IN PHOTOPLETYSMOGRAPHY-BASED HEART RATE MONITORING**

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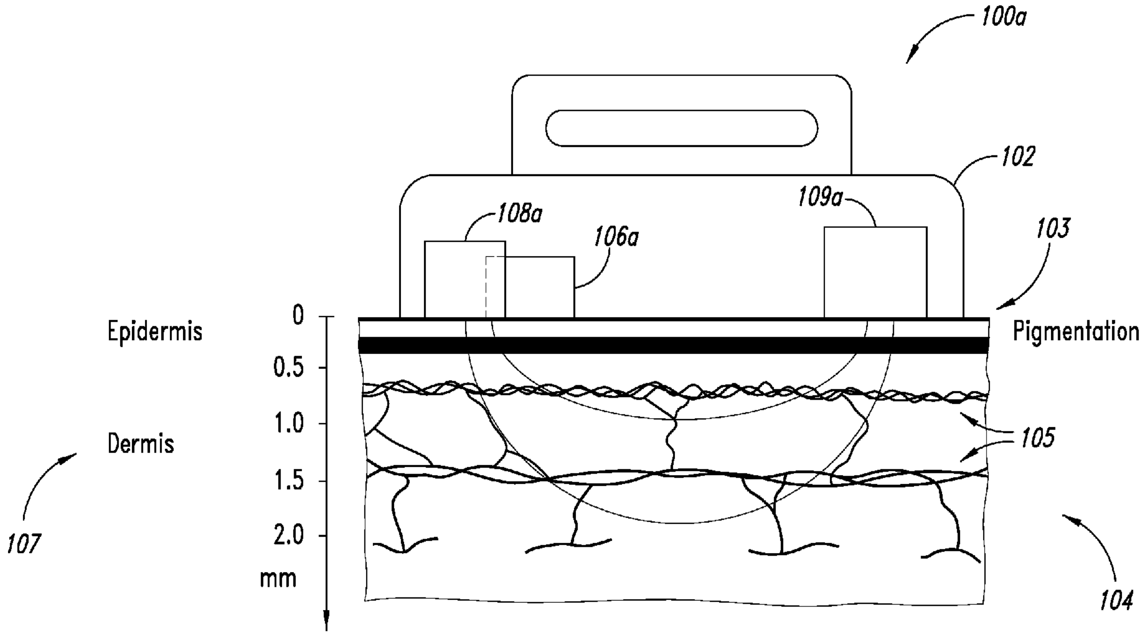
(57) **ABSTRACT**

A method and apparatus for determining a heart rate of a biological body are disclosed. In the method and apparatus, light having a first wavelength and light having a second wavelength are emitted at the biological body. The first wavelength is associated with a first absorption coefficient for blood components and the second wavelength is associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient. A first reflected signal is captured as a result of the light having the first wavelength being reflected from the biological body and a second reflected signal is captured as a result of the light having the second wavelength being reflected from the biological body. A heart rate signal is obtained based on the first and second reflected signals. A heart rate of the biological body is determined based on the heart rate signal.



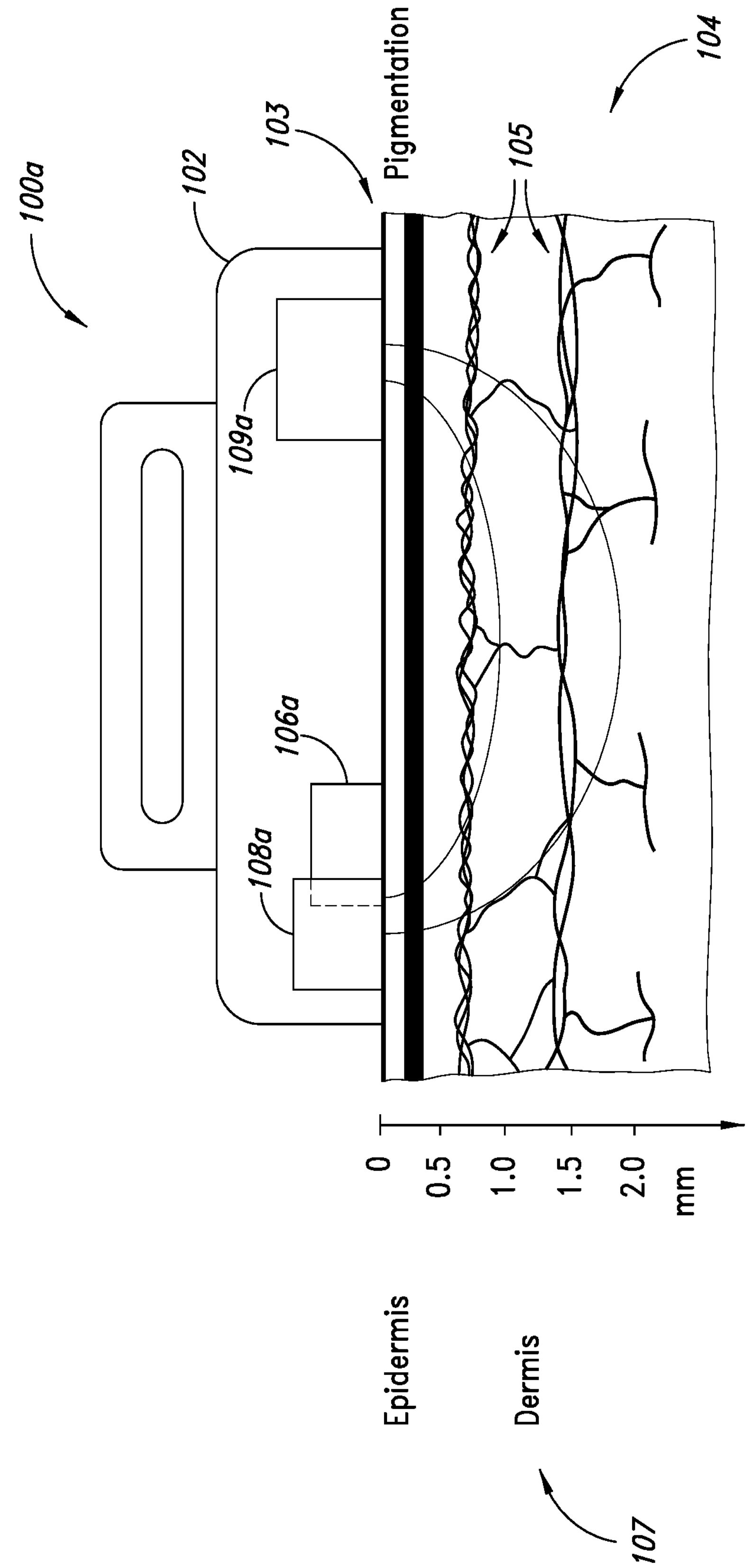
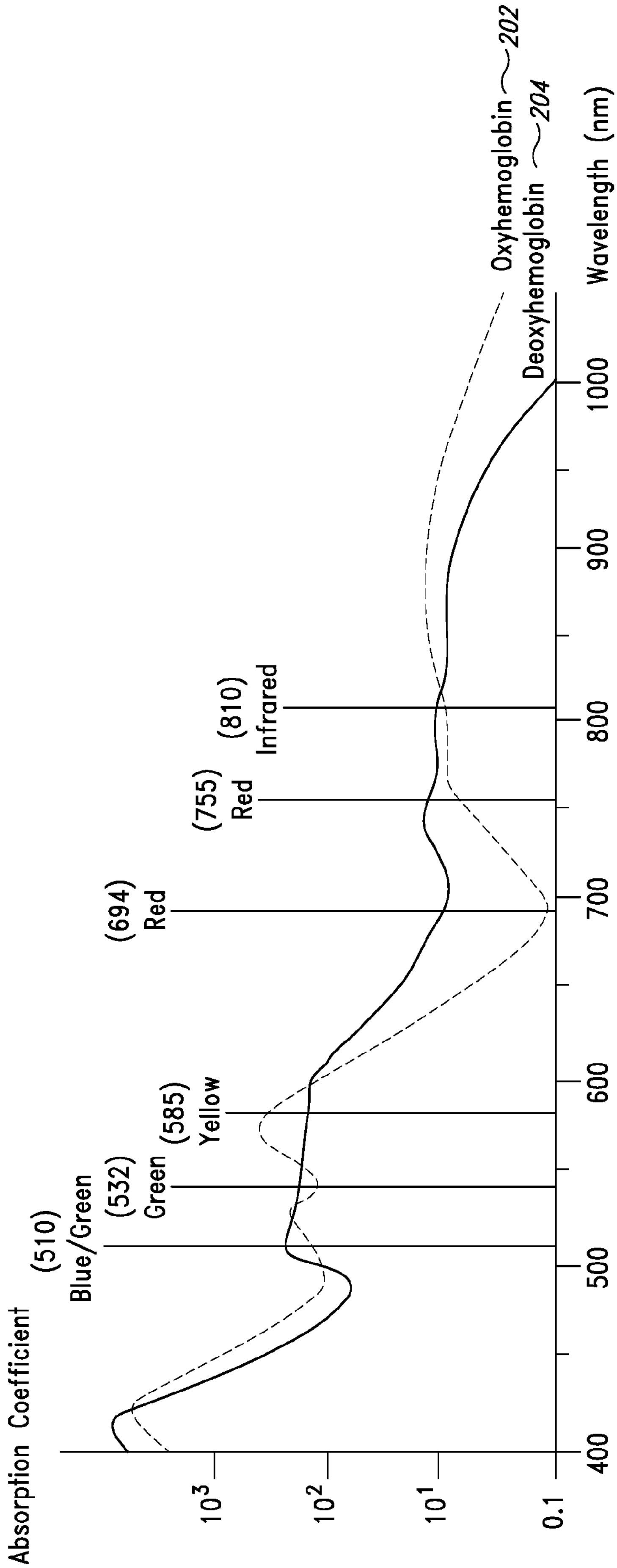

100a
102
103
Pigmentation
104
105
109a
106a
108a
0
0.5
1.0
1.5
2.0
mm
Epidermis
Dermis
107

FIG. 1



Absorption Coefficient
10^3
10^2
10^1
0.1
(510) Blue/Green
(532) Green
(585) Yellow
(694) Red
(755) Red
(810) Infrared
400
500
600
700
800
900
1000
Oxyhemoglobin ~202
Deoxyhemoglobin ~204
Wavelength (nm)

FIG. 2

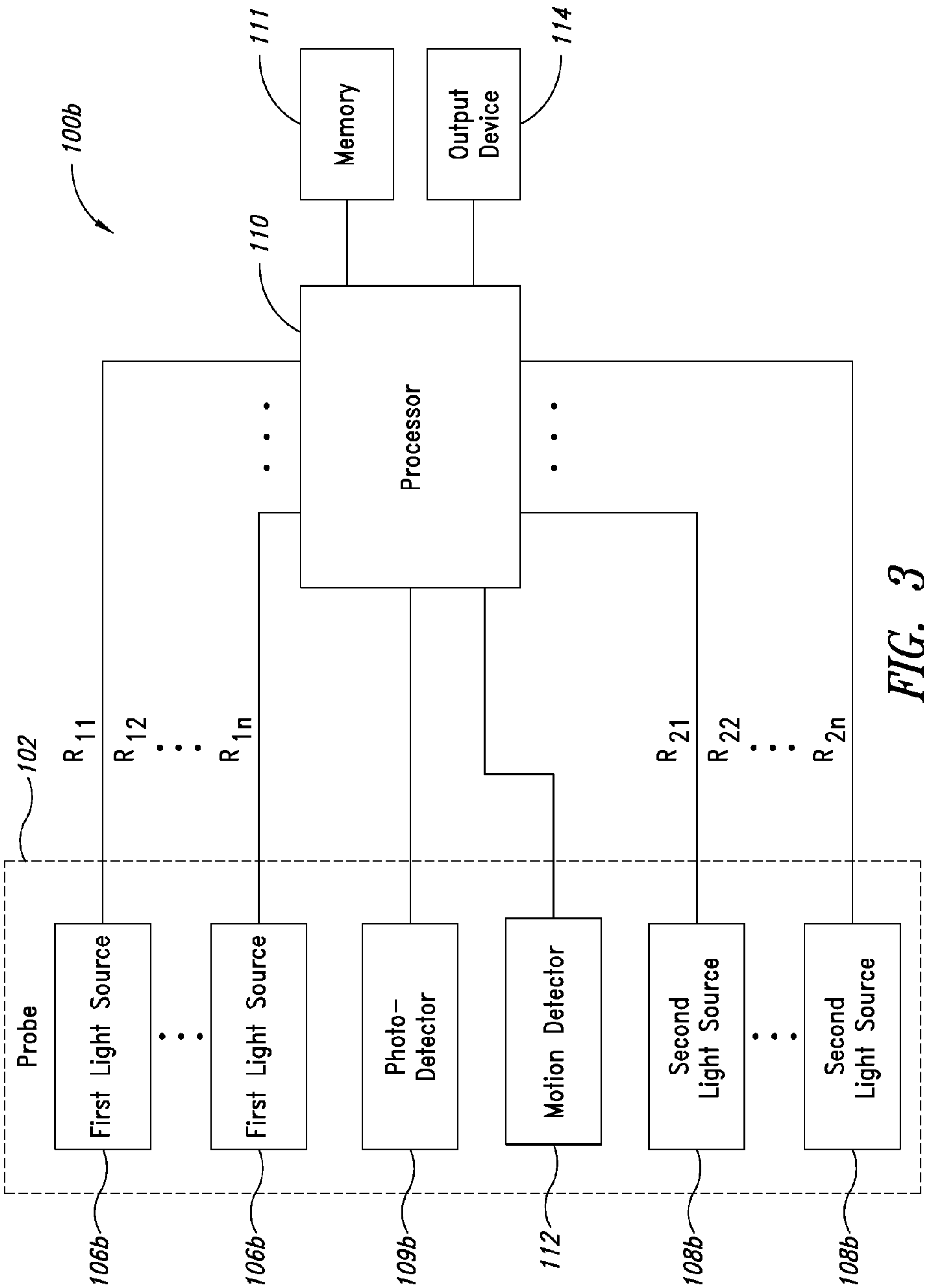

100b
111
Memory
114
Output Device
110
Processor
102
R_{11}
R_{12}
R_{1n}
R_{21}
R_{22}
R_{2n}
Probe
First Light Source
First Light Source
Photo-Detector
Motion Detector
Second Light Source
Second Light Source
106b
106b
109b
112
108b
108b

FIG. 3

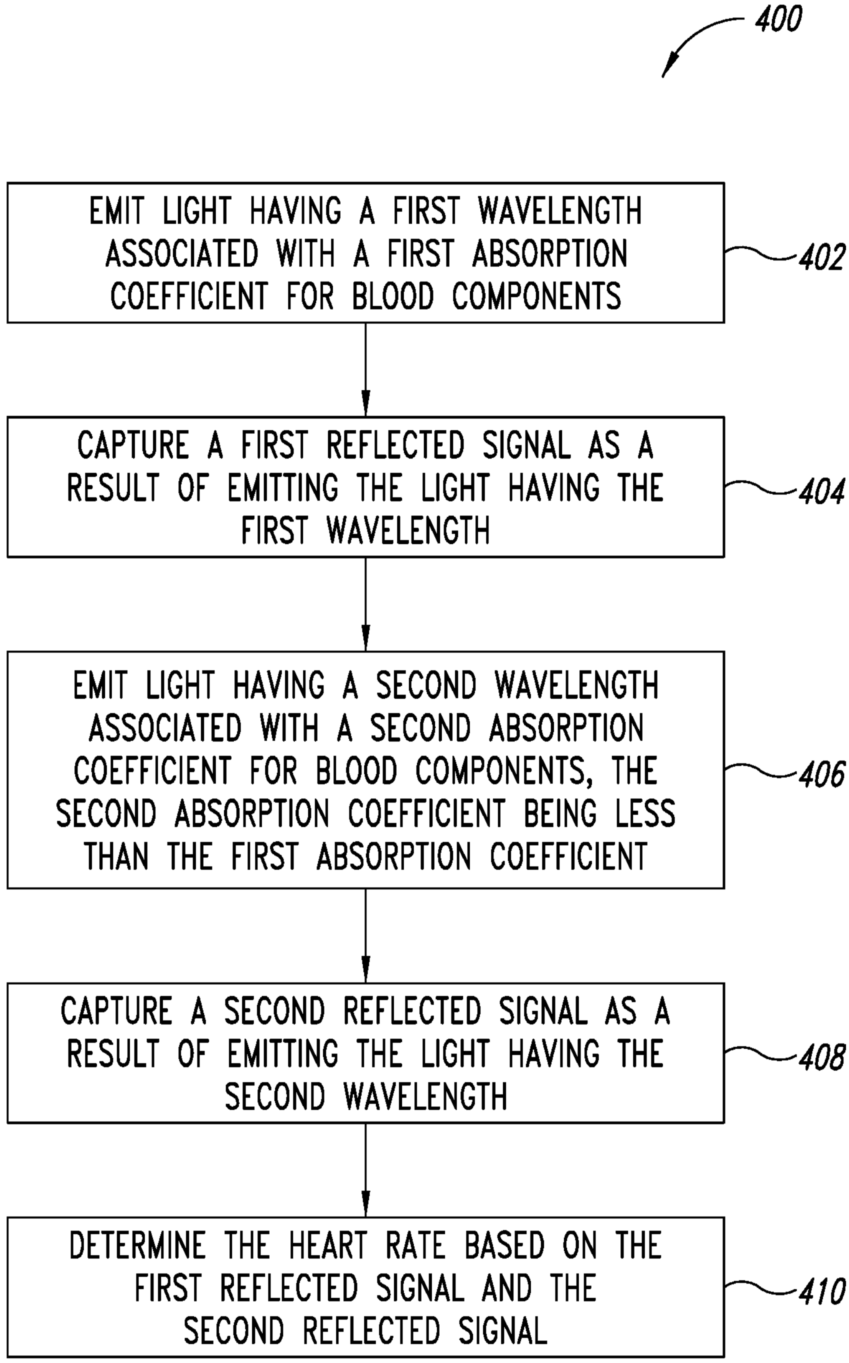

400
EMIT LIGHT HAVING A FIRST WAVELENGTH ASSOCIATED WITH A FIRST ABSORPTION COEFFICIENT FOR BLOOD COMPONENTS
402
CAPTURE A FIRST REFLECTED SIGNAL AS A RESULT OF EMITTING THE LIGHT HAVING THE FIRST WAVELENGTH
404
EMIT LIGHT HAVING A SECOND WAVELENGTH ASSOCIATED WITH A SECOND ABSORPTION COEFFICIENT FOR BLOOD COMPONENTS, THE SECOND ABSORPTION COEFFICIENT BEING LESS THAN THE FIRST ABSORPTION COEFFICIENT
406
CAPTURE A SECOND REFLECTED SIGNAL AS A RESULT OF EMITTING THE LIGHT HAVING THE SECOND WAVELENGTH
408
DETERMINE THE HEART RATE BASED ON THE FIRST REFLECTED SIGNAL AND THE SECOND REFLECTED SIGNAL
410

FIG. 4

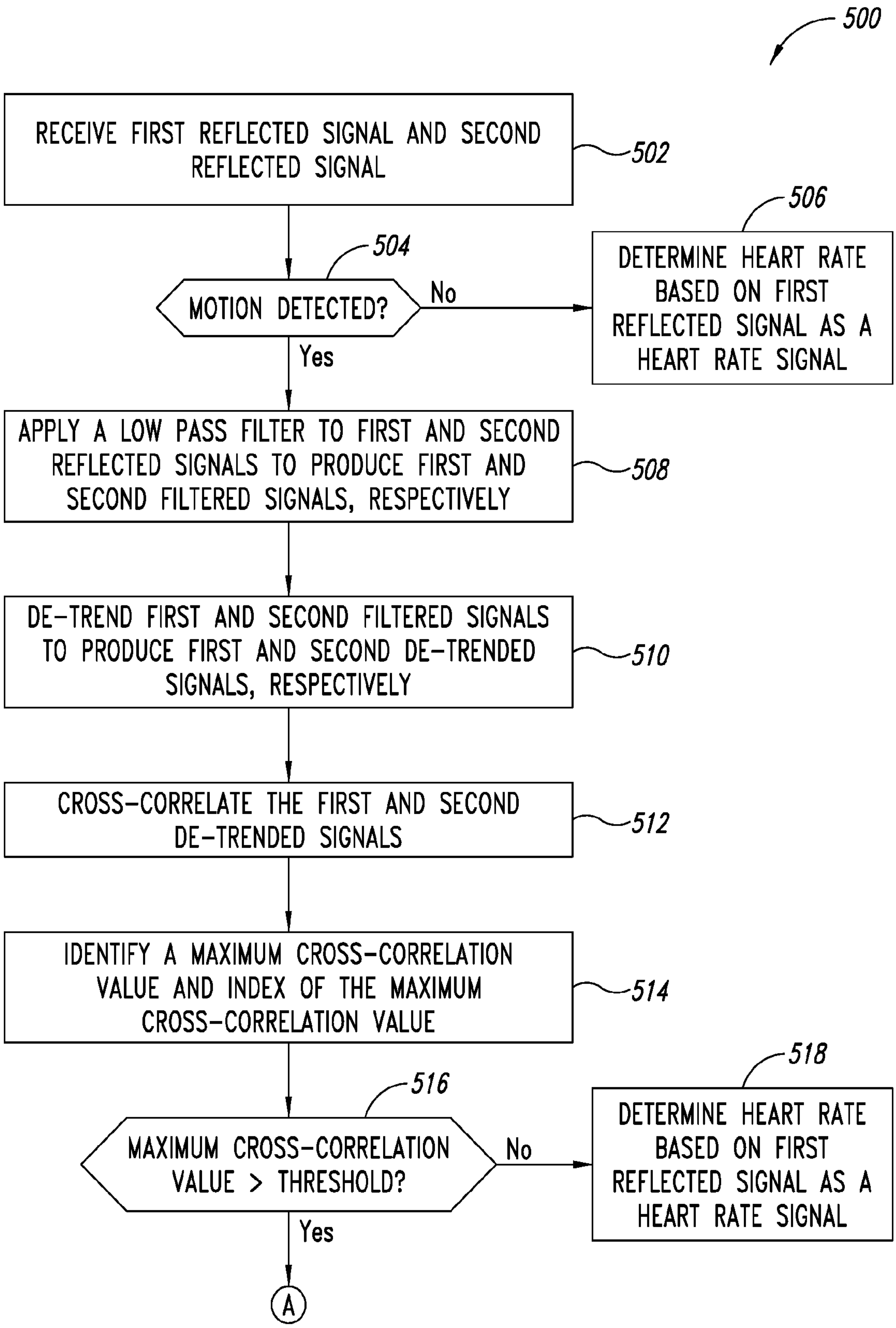

500
RECEIVE FIRST REFLECTED SIGNAL AND SECOND REFLECTED SIGNAL
502
504
MOTION DETECTED?
No
506
DETERMINE HEART RATE BASED ON FIRST REFLECTED SIGNAL AS A HEART RATE SIGNAL
Yes
APPLY A LOW PASS FILTER TO FIRST AND SECOND REFLECTED SIGNALS TO PRODUCE FIRST AND SECOND FILTERED SIGNALS, RESPECTIVELY
508
DE-TREND FIRST AND SECOND FILTERED SIGNALS TO PRODUCE FIRST AND SECOND DE-TRENDED SIGNALS, RESPECTIVELY
510
CROSS-CORRELATE THE FIRST AND SECOND DE-TRENDED SIGNALS
512
IDENTIFY A MAXIMUM CROSS-CORRELATION VALUE AND INDEX OF THE MAXIMUM CROSS-CORRELATION VALUE
514
516
MAXIMUM CROSS-CORRELATION VALUE > THRESHOLD?
No
518
DETERMINE HEART RATE BASED ON FIRST REFLECTED SIGNAL AS A HEART RATE SIGNAL
Yes
A

FIG. 5A

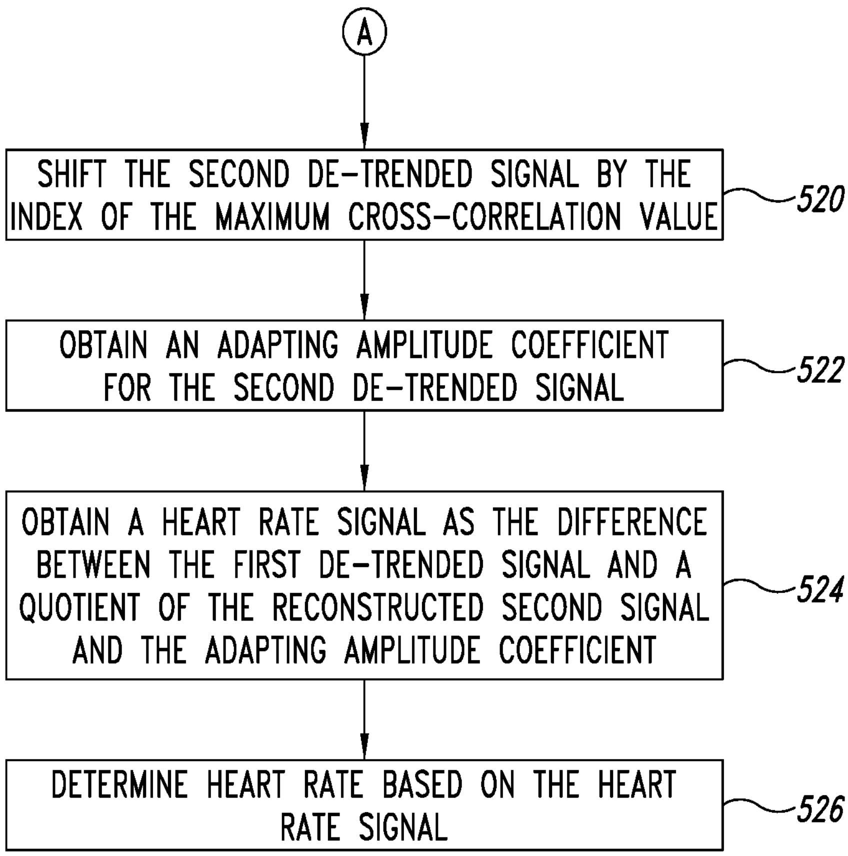

A
SHIFT THE SECOND DE-TRENDED SIGNAL BY THE INDEX OF THE MAXIMUM CROSS-CORRELATION VALUE
520
OBTAIN AN ADAPTING AMPLITUDE COEFFICIENT FOR THE SECOND DE-TRENDED SIGNAL
522
OBTAIN A HEART RATE SIGNAL AS THE DIFFERENCE BETWEEN THE FIRST DE-TRENDED SIGNAL AND A QUOTIENT OF THE RECONSTRUCTED SECOND SIGNAL AND THE ADAPTING AMPLITUDE COEFFICIENT
524
DETERMINE HEART RATE BASED ON THE HEART RATE SIGNAL
526

FIG. 5B

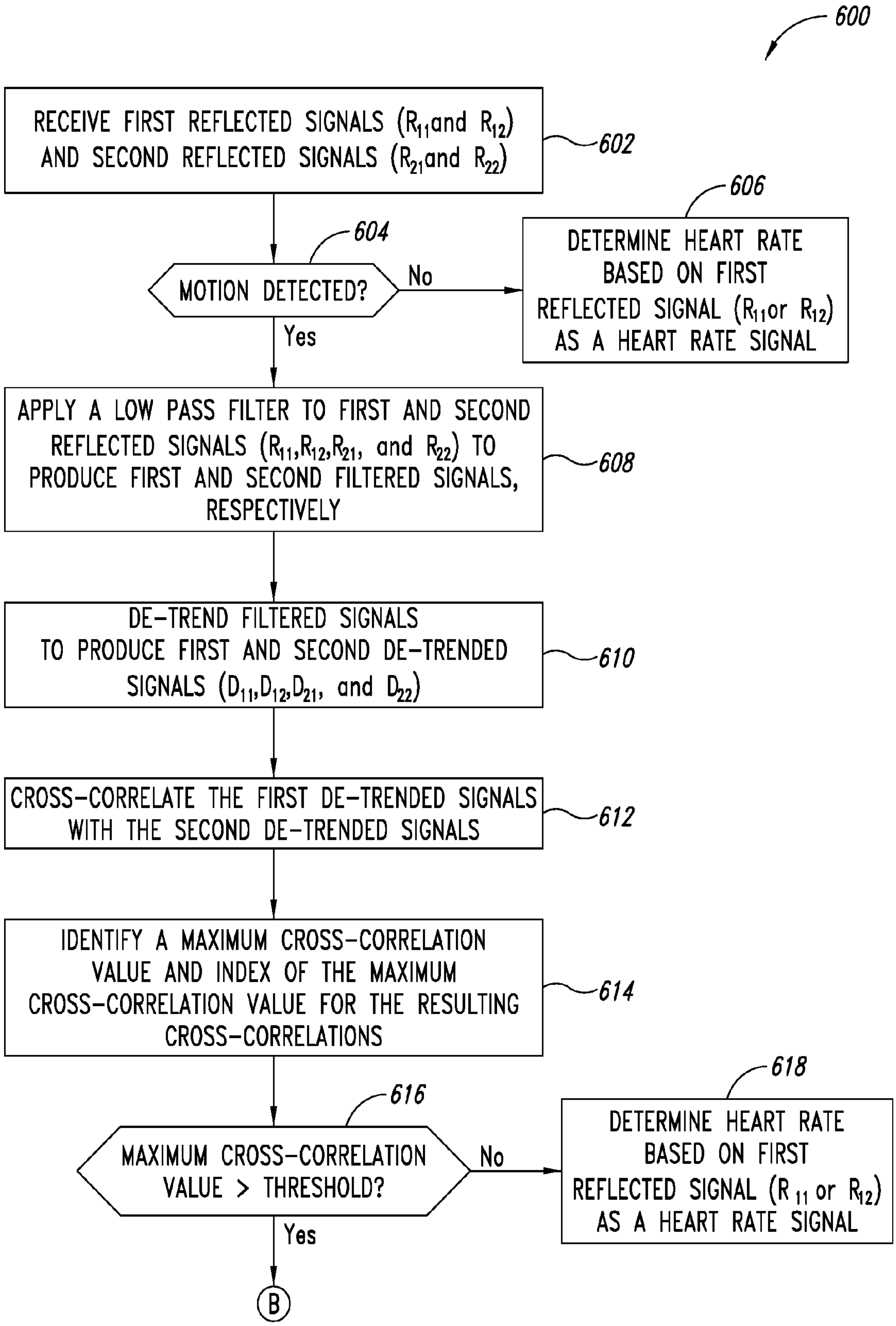

600
RECEIVE FIRST REFLECTED SIGNALS (R_{11} and R_{12}) AND SECOND REFLECTED SIGNALS (R_{21} and R_{22})
602
MOTION DETECTED?
604
No
Yes
DETERMINE HEART RATE BASED ON FIRST REFLECTED SIGNAL (R_{11} or R_{12}) AS A HEART RATE SIGNAL
606
APPLY A LOW PASS FILTER TO FIRST AND SECOND REFLECTED SIGNALS (R_{11}, R_{12}, R_{21}, and R_{22}) TO PRODUCE FIRST AND SECOND FILTERED SIGNALS, RESPECTIVELY
608
DE-TREND FILTERED SIGNALS TO PRODUCE FIRST AND SECOND DE-TRENDED SIGNALS (D_{11}, D_{12}, D_{21}, and D_{22})
610
CROSS-CORRELATE THE FIRST DE-TRENDED SIGNALS WITH THE SECOND DE-TRENDED SIGNALS
612
IDENTIFY A MAXIMUM CROSS-CORRELATION VALUE AND INDEX OF THE MAXIMUM CROSS-CORRELATION VALUE FOR THE RESULTING CROSS-CORRELATIONS
614
MAXIMUM CROSS-CORRELATION VALUE > THRESHOLD?
616
No
Yes
DETERMINE HEART RATE BASED ON FIRST REFLECTED SIGNAL (R_{11} or R_{12}) AS A HEART RATE SIGNAL
618
B

FIG. 6A

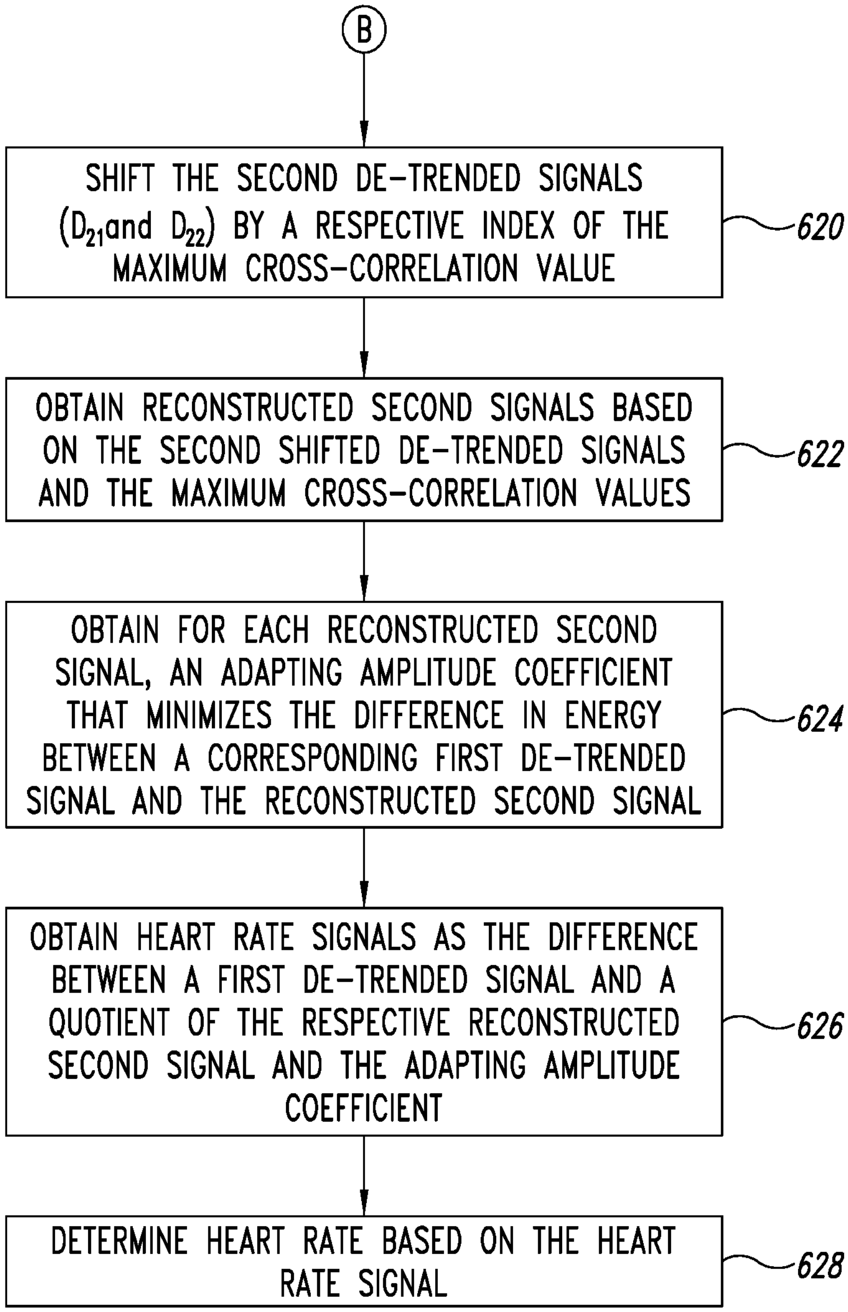

B
SHIFT THE SECOND DE-TRENDED SIGNALS ($D_{21}$and D_{22}) BY A RESPECTIVE INDEX OF THE MAXIMUM CROSS-CORRELATION VALUE
620
OBTAIN RECONSTRUCTED SECOND SIGNALS BASED ON THE SECOND SHIFTED DE-TRENDED SIGNALS AND THE MAXIMUM CROSS-CORRELATION VALUES
622
OBTAIN FOR EACH RECONSTRUCTED SECOND SIGNAL, AN ADAPTING AMPLITUDE COEFFICIENT THAT MINIMIZES THE DIFFERENCE IN ENERGY BETWEEN A CORRESPONDING FIRST DE-TRENDED SIGNAL AND THE RECONSTRUCTED SECOND SIGNAL
624
OBTAIN HEART RATE SIGNALS AS THE DIFFERENCE BETWEEN A FIRST DE-TRENDED SIGNAL AND A QUOTIENT OF THE RESPECTIVE RECONSTRUCTED SECOND SIGNAL AND THE ADAPTING AMPLITUDE COEFFICIENT
626
DETERMINE HEART RATE BASED ON THE HEART RATE SIGNAL
628

FIG. 6B

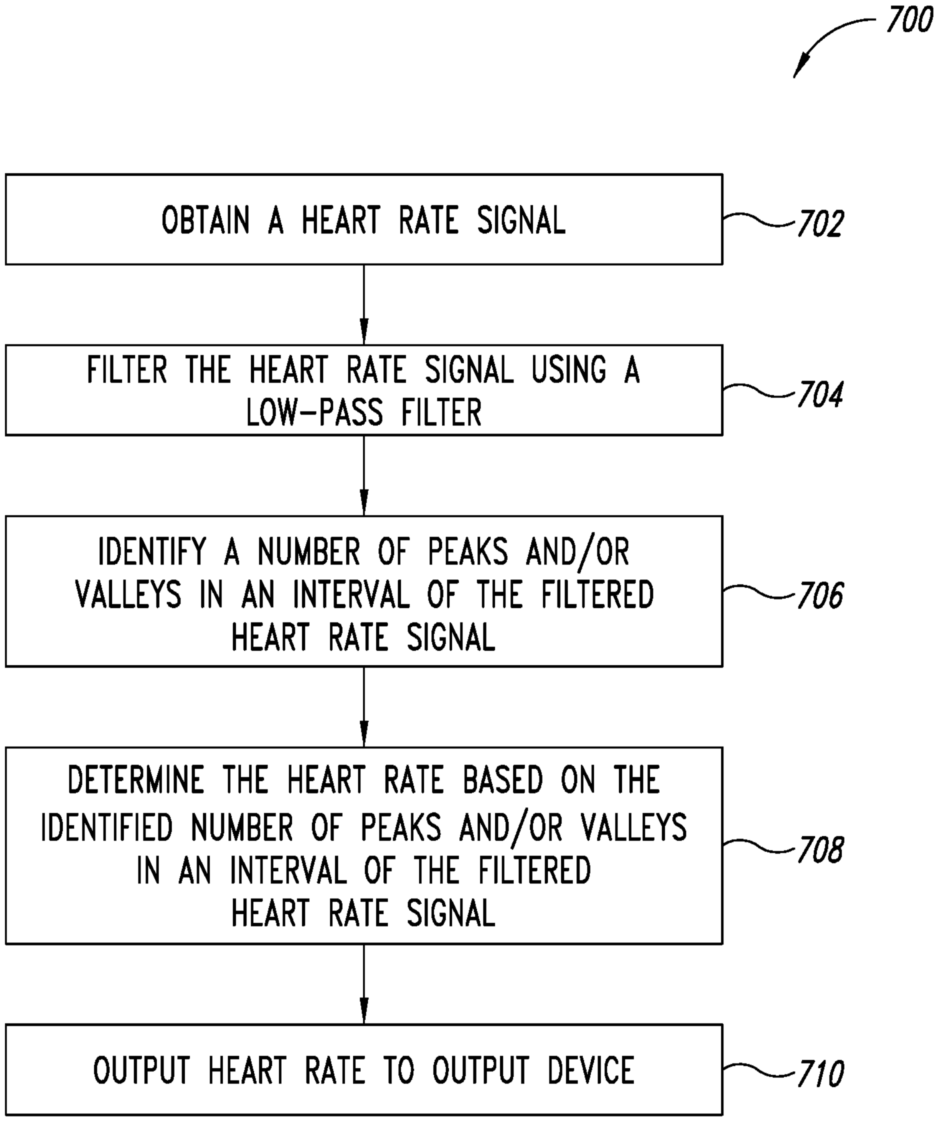

700
OBTAIN A HEART RATE SIGNAL
702
FILTER THE HEART RATE SIGNAL USING A LOW-PASS FILTER
704
IDENTIFY A NUMBER OF PEAKS AND/OR VALLEYS IN AN INTERVAL OF THE FILTERED HEART RATE SIGNAL
706
DETERMINE THE HEART RATE BASED ON THE IDENTIFIED NUMBER OF PEAKS AND/OR VALLEYS IN AN INTERVAL OF THE FILTERED HEART RATE SIGNAL
708
OUTPUT HEART RATE TO OUTPUT DEVICE
710

FIG. 7

MOTION COMPENSATION IN PHOTOPLETYSMOGRAPHY-BASED HEART RATE MONITORING

BACKGROUND

[0001] Technical Field

[0002] The present disclosure relates to photopletysmography (PPG)-based heart rate determination under motion conditions. In particular, the present disclosure relates to a device that compensates motion artifacts introduced in a PPG signal.

[0003] Description of the Related Art

[0004] PPG-based heart rate monitoring and determination is sensitive to noise artifacts. The noise artifacts can be introduced as a result of movement of a biological body or a heart rate measurement device used to perform the heart rate measurement. The noise corrupts a heart rate signal detected by the heart rate measurement device using PPG techniques. Further, the noise makes heart rate determination unreliable.

BRIEF SUMMARY

[0005] A device may be summarized as including: a first light source configured to emit light having a first wavelength at a biological body, the first wavelength being associated with a first absorption coefficient for blood components; a second light source configured to emit light having a second wavelength at the biological body, the second wavelength being associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient; a photodetector configured to capture a first reflected signal as a result of the light having the first wavelength being reflected from the biological body and capture a second reflected signal as a result of the light having the second wavelength being reflected from the biological body; and a processor coupled to the photodetector and configured to receive the first reflected signal and the second reflected signal from the photodetector, obtain a heart rate signal as a difference between the first reflected signal and the second reflected signal and determine a heart rate of the biological body based on the heart rate signal.

[0006] The processor may be further configured to: obtain an amplitude adapting coefficient for the second reflected signal; and obtain the heart rate signal as a difference between the first reflected signal and a quotient of the second reflected signal and the amplitude adapting coefficient. The amplitude adapting coefficient may be a divisor of the second reflected signal that minimizes a difference in energy between the first reflected signal and the quotient of the second reflected signal and the amplitude adapting coefficient. The processor may be further configured to: cross-correlate the first reflected signal and the second reflected signal to produce a cross-correlation function between the first reflected signal and the second reflected signal; identify a maximum of the cross-correlation function; identify a time index corresponding to the maximum of the cross-correlation function; and shift the second reflected signal by the time index prior to obtaining the heart rate signal using the second reflected signal shifted by the time index. The processor may be further configured to: low-pass filter the first reflected signal and the second reflected signal; and de-trend the first reflected signal and the second reflected signal. A cutoff frequency of the low pass filter may be 4 Hertz or lower. The device may further include a motion detector coupled to the processor and configured to output a signal to the processor indicating whether the device was displaced, wherein: the processor is further configured to determine the heart rate based on the heart rate signal if the signal to the processor indicates that the device was displaced. The device may further include an output device coupled to the processor and configured to receive the heart rate from the processor and display the heart rate.

[0007] A method may be summarized as including: emitting light having a first wavelength at a biological body, the first wavelength being associated with a first absorption coefficient for blood components; capturing a first reflected signal as a result of the light having the first wavelength being reflected from the biological body; emitting light having a second wavelength at the biological body, the second wavelength being associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient; capturing a second reflected signal as a result of the light having the second wavelength being reflected from the biological body; obtaining a heart rate signal as a difference between the first reflected signal and the second reflected signal; and determining a heart rate of the biological body based on the heart rate signal.

[0008] The method may further include: scaling the second reflected signal by a reciprocal of an amplitude adapting coefficient before obtaining the heart rate signal as the difference between the first reflected signal and the second reflected signal using the second reflected signal scaled by the reciprocal of the amplitude adapting coefficient. The amplitude adapting coefficient may be a divisor of the second reflected signal that minimizes a difference in energy between the first reflected signal and the quotient of the second reflected signal and the amplitude adapting coefficient. The method may further include: time shifting the second reflected signal prior to obtaining the heart rate signal using the time shifted second reflected signal. The second reflected signal may be shifted by a time index corresponding to a maximum cross-correlation value between the first reflected signal and the second reflected signal. The method may further include: filtering the first and second reflected signals; and de-trending the first and second reflected signals.

[0009] A system may be summarized as including: a first light source; a second light source; a photodetector; a processor; and a computer-readable storage medium having stored thereon instructions that, when executed by the processor, cause the processor to: instruct the first light source to emit light having a first wavelength at a biological body, the first wavelength being associated with a first absorption coefficient for blood components; instruct the second light source to emit light having a second wavelength at the biological body, the second wavelength being associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient; receive a first reflected signal captured by the photodetector as a result of the light having the first wavelength being reflected from the biological body and a second reflected signal captured by the photodetector as a result of the light having the second wavelength being reflected from the biological body; obtain a heart rate signal based on the first reflected signal and the second reflected signal; and determine a heart rate of the biological body based on the heart rate signal.

[0010] The instructions may further cause the processor to obtain the heart rate signal as a difference between the first reflected signal and the second reflected signal. The instructions may further cause the processor to: obtain an amplitude adapting coefficient for the second reflected signal; adjust an amplitude of the second reflected signal by the amplitude adapting coefficient to obtain an amplitude-adjusted second reflected signal; and obtain the heart rate signal as a difference between the first reflected signal and the amplitude-adjusted second reflected signal. The instructions may further cause the processor to: low-pass filter the first and second reflected signals to respectively produce first and second filtered signals; and de-trend the first and second filtered signals ahead of obtaining the heart rate signal. The first wavelength may be between 500 and 580 nanometers (nm) and the second wavelength may be between 680 and 700 nm.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0011] FIG. **1** shows a cross-sectional view of a probe of a heart rate measurement device positioned near the skin of a biological body.

[0012] FIG. **2** shows a diagram of the absorption coefficients of blood components for light of different wavelengths.

[0013] FIG. **3** shows a block diagram of a heart rate measurement device.

[0014] FIG. **4** shows a method for determining the heart rate of a biological body.

[0015] FIGS. **5**A and **5**B show a flow diagram of a method for compensating for motion in the heart rate measurement device.

[0016] FIGS. **6**A and **6**B show a flow diagram of a method for compensating for motion in the heart rate measurement device.

[0017] FIG. **7** shows a flow diagram of a method for determining the heart rate based on a heart rate signal.

DETAILED DESCRIPTION

[0018] FIG. **1** shows a cross-sectional view of heart rate measurement device **100***a* positioned near the skin **103** of a biological body **104**. The heart rate measurement device **100***a* is used to measure the heart rate of the biological body **104** using photopletysmography (PPG). The heart rate measurement device **100***a* includes a probe **102** having a first light source **106***a*, a second light source **108***a* and a photodetector **109***a*. The probe **102** is positioned near the skin **103** of the biological body **104** (and may, for example, be in contact with the skin **103**). Light emanating from the first light source **106***a* and the second light source **108***a* is captured by the photodetector **109***a* after having at least partially penetrated the biological body **104** and been reflected by the biological body **104**.

[0019] PPG is a non-invasive technique for heart rate measurement and detection. PPG relies on the principle that blood components, such as oxyhemoglobin and deoxyhemoglobin, reflect back light having certain wavelengths. Light emitted by the first light source **106***a* or the second light source **108***a* will reach a blood vessel **105** in the dermis **107**. Blood components reflect light having certain wavelengths (for example, green light of 500-550 nanometers (nm) and yellow light of about 580 nm) differently than light having other wavelengths (for example, red light of a wavelength slightly lower than 700 nm). The intensity of light reflected from the biological body changes due to the different absorption coefficients of the colors of light. The intensity of reflected light depends on the volume of blood in a vessel. When the volume of blood in vessel is relatively large the reflected light intensity is low (because the blood absorbs more light) and vice-versa. This variation is correlated with blood flow. Green light is a lot more sensitive to blood than red light because of its associated higher absorption coefficient. The variation of the received light intensity over time is due to volumetric variations.

[0020] PPG-based heart rate measurements are sensitive to movement of the biological body **104** or the heart rate measurement device **100***a* during measurement. For example, movement of the biological body **104** while a heart rate measurement is being made changes the area of the dermis **107** on which light is shone. As a result of the movement, noise is introduced in the reflected signal. Similarly, movement of the probe **102** (or light source emanating light having a wavelength or photodetector **109***a* thereof) also introduces noise in the reflected signal.

[0021] The heart rate measurement device **100***a* compensates for the noise, or in general artifacts, introduced in the reflected signal as a result of the movement. The heart rate measurement device **100***a* compensates for the noise by utilizing two light sources that emit light having different wavelengths, whereby one light source (referred to herein as the "first light source") has a wavelength with relatively high absorption coefficient for blood components and another light source (referred to herein as the "second light source") has a wavelength with relatively low absorption coefficient for blood components.

[0022] FIG. **2** shows a diagram of the absorption coefficients of blood components for light of different wavelengths. Graph **202** shows the absorption coefficients for oxyhemoglobin and graph **204** shows the absorption coefficients for deoxyhemoglobin for various light wavelengths. The lower is the absorption coefficient, the greater the transparency of the blood component to light. For example, oxyhemoglobin has high transparency for red light (having a wavelength of about 700 nm) as evidenced by the low absorption coefficient of 0.1. Accordingly, more red light is reflected than blue, green or yellow light (wavelengths in the range of 500-600 nm). Blue, green are largely absorbed by oxyhemoglobin and are not reflected.

[0023] When the first light source is used to provide light having a wavelength with a high absorption coefficient, the first reflected signal (denoted as R_1) has a signal component (S_1) that is representative of the heart rate. However, when the second light source is used to provide light having a wavelength with a low absorption coefficient, the second reflected signal (denoted as R_2) has a weak signal component (S_2) that is not representative of the heart rate because the light is not reflected by the blood components. However, the noise components (N_1 and N_2) of the respective first and second reflected signals are similarly affected by movement.

[0024] By modeling the first reflected signal as $R_1=S_1+N_1$ and the second reflected signal as $R_2=S_2+N_2$, the difference between the reflected signals is represented as:

$$R_2=S_1+N_1-(S_2+N_2)=(S_1-S_2)+(N_1-N_2) \quad \text{Equation (1).}$$

[0025] Because the signal component of the second reflected signal (S_2) is not reflected by the blood components, S_2 may not influence the signal term (S_1-S_2) of equation (1). The signal term may be simplified as: $S_1-S_2 \approx S_1$. The noise components are both similarly affected by movement of the biological body or the heart rate measurement device **100***a*. The noise components should substantially cancel one another out. That is, $N_1-N_2 \approx 0$. Accordingly, obtaining the difference between the first reflected signal and the second reflected signal may improve the received signal component used to determine the heart rate of the biological body. That is:

$$R_1-R_2 \approx S_1 \quad \text{Equation (2).}$$

[0026] FIG. **3** shows a block diagram of a heart rate measurement device **100***b*. The heart rate measurement device **100***b* comprises a processor **110**, memory **111**, one or more first light sources **106***b*, one or more second light sources **108***b*, a photodetector **109***b*, a motion detector **112** and an output device **114**. The one or more first light sources **106***b* and the one or more second light sources **108***b* may each be a light emitting diode (LED). Further, the photodetector **109***b* may be a photodiode and the motion detector **112** may be an accelerometer or a gyroscope. In addition, the processor **110** may be any type of device that is capable of performing computing functions. For example, the processor **110** may be a microcontroller, microprocessor or digital signal processor (DSP), among others.

[0027] The memory **111** may be any type of memory, such as volatile memory that includes random access memory (RAM), among others or non-volatile memory that includes read only memory (ROM), among others. The memory **111** may be a non-transitory computer-readable memory. The memory **111** may be used to store instructions that, when executed by the processor **110**, cause the processor **110** to perform the techniques described herein. For example, the memory **111** may store instruction that, when executed by the processor **110**, cause the processor **110** to obtain a heart rate signal or determine a heart rate of a biological body as described herein, among others. The output device **114** may be a display, such as a liquid crystal display, or speakers. In various embodiments, the output device **114** may be a communications port for transferring heart rate measurements to another device.

[0028] Although not shown in FIG. **3**, the heart rate measurement device **100***a* may include a front end (for example, an analog front end) disposed between the processor **110** and the photodetector **109***b*. The front end may condition or amplify a signal received from the photodetector **109***b* and correct acquisition of the signal received from the photodetector **109***b*. In some embodiments, the front end may be part of the processor **110**, whereby the processor amplifies, conditions or corrects the acquisition of the signal from the photodetector **109***b*.

[0029] The heart rate measurement device **100***a* is used to measure the heart rate of a biological body using PPG as described herein. The one or more first light sources **106***b*, one or more second light sources **108***b*, photodetector **109***b* and motion detector **112** may be part of the probe **102** of the heart rate measurement device **100***b*.

[0030] The one or more first light sources **106***b*, one or more second light sources **108***b*, photodetector **109***b*, motion detector **112** and output device **114** are coupled to the processor **110**. The processor **110** sends a first control signal to the one or more first light sources **106***b* instructing the one or more first light sources **106***b* to emit light having a first wavelength. As described herein, the emitted light may be blue, green or yellow light that has a relatively high absorption coefficient for blood. The first control signal may indicate the period of time for which the light should be emitted or a first light source **106***b* may be configured to emit the light for the period of time in response to receipt of the first control signal.

[0031] The photodetector **109***b* then captures the first reflected signal resulting from reflection of the first wavelength light by the biological body. The photodetector **109***b* outputs the captured first reflected signal to the processor **110**.

[0032] The processor **110** then sends a second control signal to the one or more second light sources **106** instructing the one or more second light sources **106***b* to emit light having a second wavelength. As described herein, the emitted light may be red and may have a relatively low absorption coefficient by blood components. The second control signal may indicate the period of time for which the light should be emitted or a second light source **108***b* may be configured to emit the light for the period of time in response to receipt of the second control signal. The photodetector **109***b* then captures the second reflected signal resulting from reflection of second wavelength light by the biological body. The photodetector **109***b* transmits the second reflected signal to the processor **110**. The second reflected signal may be identified as such due to the fact that it has been captured at the same time as or subsequent to emitting light by the second light source **108***b*.

[0033] In one embodiment, the heart rate measurement device **100***b* includes only one first light source **106***b* and only one second light source **108***b*. In this case, the first light source **106***b* and the second light source **108***b* may alternate emitting light one at a time with an interval for a break therebetween. The positions of the first light source **106***b* and the second light source **108***b* may be equidistant from the photodetector **109***b*. For example, each light source **106***b*,**108***b* may be 3 millimeters (mm) to 5 mm from the photodetector **109***b*. The distance between each light source **106***b*,**108***b* and the photodetector **109***b* may be set to 4 mm. The first light source **106***b* and the second light source **108***b* may be positioned on opposite sides of the photodetector **109***b* or on the same side. The distance between the first light source **106***b* and the photodetector **109***b* may be the same as the distance between the second light source **108***b* and the photodetector **109***b*. Further, the first light source **106***b* and the second light source **108***b* may be positioned in close proximity to one another (for example, abutting or less than 1 mm apart) and on the same side of the photodetector **109***b*.

[0034] In another embodiment, the heart rate measurement device **100***b* includes two or more first light sources **106***b* and two or more second light sources **108***b*, whereby only one of the first light sources **106***b* and second light sources **108***b* emits light at a time. When two or more first light sources **106***b* and two or more second light sources **108***b* are used, the second and subsequent light sources of the two or more second light sources **108***b* may be positioned on opposite sides of the photodetector **109***b* as compared to the first of the two or more second light sources **108***b*. However, it may be necessary to have at least one pair (comprising a first light source **106***b* and a second light source **108***b*) positioned adjacent to each other or within close proximity of each other.

[0035] The motion detector **112** detects whether the heart rate measurement device **100***b* or light sources **106***b*,**108***b* or photodetector **109***b* thereof were moved during the capturing of the reflected signals. If movement is detected, the motion detector **112** sends a signal to the processor **110** indicating that movement was detected. Receipt of the signal by the processor **110** triggers the processor to perform motion compensation using the first and second reflected signals as described herein.

[0036] FIG. **4** shows a method **400** for determining the heart rate of a biological body. In the method **400**, the first light source **106***b*, at **402**, emits light having a first wavelength associated with a first absorption coefficient for blood components. At **404**, the photodetector **109***b* captures the first reflected signal as a result of emitting the light having the first wavelength. Then, at **406**, the second light source **108***b* emits light having a second wavelength associated with a second absorption coefficient for blood components. The second absorption coefficient is less than the first absorption coefficient. At **408**, the photodetector **109***b* captures a second reflected signal as a result of emitting the light having the second wavelength. The first reflected signal and the second reflected signal are provided to the processor **110**. In turn, the processor **110**, at **410** determines the heart rate based on a difference between the first reflected signal and the second reflected signal. It will of course be understood that the steps in FIG. **4** could be performed in many different orders, such as performing steps **406** and **408** before steps **402** and **404**.

[0037] FIGS. **5**A and **5**B show a flow diagram of a method for compensating for motion in the heart rate measurement device **100***b*. In the method **500**, at **502**, the processor **110** receives the first reflected signal and the second reflected signal. The first reflected signal may have been captured by the photodetector **109***b* as a result of reflection of light emitted by the first light source **106***b* and the second reflected signal may have been captured by the photodetector **109***b* as a result of light emitted by the second light source **108***b*. The processor **110** then determines, at **504**, whether motion has been detected. Determining whether motion is detected may be based on the output of the motion detector **112**. If motion is not detected, then motion compensation is not necessarily performed. The processor **110**, at **506**, determines the heart rate based on the first reflected signal as a heart rate signal.

[0038] Conversely, if motion is detected, the processor **110** at **508** applies a low-pass filter to the first reflected signal and the second reflected signal to produce a first filtered signal and a second filtered signal, respectively. The low-pass filter may remove electrical or thermal noise from the first and second reflected signals. The noise may be introduced in the first and second reflected signals by circuit components of the heart rate measurement device **100***b*. The low-pass filter may have a cutoff frequency that is higher than a typical heart rate. For example, the human heart rate is typically between 0.5 and 3 Hertz (Hz). If the heart rate measurement device **100***b* is used to measure the human heart rate, the cutoff frequency of the low-pass filter may be set to 4 Hz, thus capturing the 0.5 to 3 Hz band of human heart rate. Accordingly, heart rate information is not filtered out by the low-pass filtering.

[0039] The processor **110** then de-trends the first and second filtered signals to produce respective first and second de-trended signals at **510**. De-trending the first and second filtered signals removes an identified trend in the signals and enables analysis of the signals to focus on fluctuations or variations in the signals as opposed to a trend in the signals. The first filtered signal may be de-trended by linearly fitting the first filtered signal and subtracting the linearly-fitted signal from the first filtered signal.

[0040] The processor **110**, at **512**, cross-correlates the first and second de-trended signals. Denoting the first de-trended signal as $D_1(n)$ and the second de-trended signal as D_2 (n), the cross-correlation function of the first de-trended signal and the second de-trended signal is:

$$XCorr(\tau) = \sum_{\tau=-\infty}^{\tau=+\infty} D_1(n) D_2(n-\tau). \quad \text{Equation (3)}$$

[0041] The processor **110** then identifies a maximum cross-correlation value and an index of the maximum cross-correlation value at **514**. The maximum cross-correlation value may be the maximum value of the time-series correlation function (XCorr). The index may be the corresponding time index of the maximum cross-correlation value. The index may represent a time shift of the second de-trended signal that, when performed, results in a highest degree of similarity between the first de-trended signal and the second de-trended signal.

[0042] The processor **110** at **516** determines if the maximum cross-correlation value is greater than a threshold. The threshold may, for example, be a minimum correlation value such as 0.5. The threshold may be determined based on observed correlations in "no motion" conditions. Under these conditions, the first reflected signal has a strong signal component. The second reflected signal, on the other hand, has a poor signal component and has a heavy contribution of the noise component.

[0043] If the maximum cross-correlation value is below the threshold then the similarities between the first and second reflected signals may not be sufficient for performing motion compensation. Accordingly, if the maximum cross-correlation value is not greater than the threshold, the processor **110** at **518** determines the heart rate based on the first reflected signal as the heart rate signal.

[0044] If the maximum cross-correlation value is greater than the threshold, the processor **110** performs motion compensation as described herein. In motion compensation, the second de-trended signal is used to remove the additive noise affecting the first de-trended signal as a result of the motion.

[0045] At **520**, the processor **110** shifts the second de-trended signal by the index of the maximum cross-correlation value. As a result, the first de-trended signal and the second de-trended signal become aligned to maximize their correlation.

[0046] The processor **110** obtains an adapting amplitude coefficient for the second de-trended signal at **522**. The adapting amplitude coefficient minimizes the difference in energy between the first de-trended signal and the second de-trended signal. To obtain the adapting amplitude coefficient the following energy function is determined:

$$E(\alpha) = \int \left(D_1 - \frac{D_2}{\alpha}\right)^2. \quad \text{Equation (4)}$$

[0047] A minimum of the energy function is identified and the adapting amplitude coefficient is the input to the function (Coeff=α) corresponding to the minimum of the energy function. In the above equation, α minimizes the energy using the least squares technique. However, as may be recognized other frameworks for determining an energy minimizing coefficient may be used.

[0048] The processor **110** at **524** obtains a heart rate signal as the difference between the first de-trended signal and a quotient of the second de-trended signal and the adapting amplitude coefficient. The heart rate signal is accordingly determined as:

$$H = D_1 - \frac{D_2}{Coeff}. \quad \text{Equation (5)}$$

[0049] The processor **110** at **526** then determines the heart rate based on the heart rate signal (H) as described herein. Determining the heart rate may include counting a number of peaks and/or valleys of the heart rate signal in an interval (for example, a 15 second interval) and obtaining the heart rate based on that number.

[0050] The method described with reference to FIGS. **5**A and **5**B may be used when the heart measurement device **100***b* utilizes one first light source **106***b* for emitting light captured as the first reflected signal and one second light source **108***b* for emitting light captured as the second reflected signal. When the heart measurement device **100***b* operates two or more first light sources **106***b* and two or more second light sources **108***b*, the processor **110** receives from the photodetector **109***b* more than two reflected signals.

[0051] If two first light sources **106***b* and two second light sources **108***b* are used, the processor **110** receives two first reflected signals (denoted as R_{11} and R_{12}) and two second reflected signals (denoted as R_{21} and R_{22}).

[0052] FIGS. **6**A and **6**B show a flow diagram of a method for compensating for motion in the heart rate measurement device **100***b*. At **602**, the processor **110** receives the first reflected signals (R_{11} and R_{12}) and the second reflected signals (R_{21} and R_{22}). The processor **110** then determines if motion is detected at **604**. If a negative determination is made, at **606**, the processor **110** determines the heart rate based on a first reflected signal (R_{11} or R_{12}) as a heart rate signal.

[0053] If a positive determination is made, at **608** the processor **110** applies a low pass filter to the first and second reflected signals (R_{11}, R_{12}, R_{21} and R_{22}) to produce filtered signals. At **610**, the processor de-trends the filtered signals to produce first de-trended signals (D_{11} and D_{12}) and second de-trended signals (D_{21} and D_{22}). Each signal is individually filtered and de-trended.

[0054] At **612**, the processor **110** cross-correlates the first de-trended signals with the second de-trended signals. The cross-correlation will produce four cross-correlation functions that are as follows: $XCorr_1=XCorr(D_{11}, D_{21})$, $XCorr_2=XCorr(D_{11},D_{22})$, $XCorr_3=XCorr(D_{12},D_{21})$ and $XCorr_4=XCorr(D_{12},D_{22})$.

[0055] For each resulting cross-correlation, the processor **110** at **614** identifies a maximum cross-correlation value and index of the maximum cross-correlation value. The indices of the maximum cross-correlation values and the maximum cross-correlation values are obtained as $[Ind_1,Val_1]=max(XCorr_1)$, $[Ind_2,Val_2]=max(XCorr_2)$, $[Ind_3,Val_3]=max(XCorr_3)$ and $[Ind_4,Val_4]=max(XCorr_4)$.

[0056] The processor **110** at **616** determines whether a maximum cross-correlation value of the identified maximum cross-correlation values exceeds a threshold. If a negative determination is made, the processor **110** at **618** determines the heart rate based on a first reflected signal. That is, the heart rate may be determined using R_{11} or R_{12}.

[0057] If a positive determination is made, the processor **110** performs motion compensation. The processor **110** shifts the second de-trended signals by a respective index of the maximum cross-correlation value at **620**. D_{21} may be shifted by Ind_1 or Ind_3. Further, D_{22} may be shifted by Ind_2 or Ind_4.

[0058] At **622**, the processor **110** obtains reconstructed second signals (C_1 and C_2) based on the second shifted de-trended signals and the maximum cross-correlation values. The reconstructed second signals are obtained as:

$$C_1 = \frac{R_{11} \cdot Val_1 + R_{12} \cdot Val_2}{Val_1 + Val_2} \quad \text{Equation (6)}$$

$$C_2 = \frac{R_{11} \cdot Val_3 + R_{12} \cdot Val_4}{Val_3 + Val_4}.$$

[0059] At **624**, for each reconstructed second signal, the processor **110** obtains an adapting amplitude coefficient that minimize the difference in energy between a corresponding first de-trended signal and the reconstructed second signal. The difference in energy between a first de-trended signal and a corresponding reconstructed second signal for each pair of the first de-trended signal and the corresponding reconstructed second signal as described herein. The energy is determined as:

$$E_1(\alpha) = \int \left(D_{11} - \frac{C_1}{\alpha}\right)^2 \quad \text{Equation (7)}$$

$$E_2(\alpha) = \int \left(D_{12} - \frac{C_2}{\alpha}\right)^2$$

[0060] A first adapting amplitude coefficient ($Coeff_1=a_1$) that minimizes $E_1(\alpha)$ is obtained as $[a_1, E_{1min}]=min(E_1(\alpha))$ and a second adapting amplitude coefficient ($Coeff_2=\alpha_2$) that minimizes $E_2(\alpha)$ is obtained as $[\alpha_2,E_{2min}]=min(E_2(\alpha))$.

[0061] At **626**, the processor **110** obtains heart rate signals. Each heart rate signal is a difference between a first de-trended signal and a quotient of the respective reconstructed second signal and the adapting amplitude coefficient. A first heart rate signal is obtained as

$$H_1 = D_{11} - \frac{C_1}{Coeff_1}$$

and a second heart rate signal is obtained as

$$H_2 = D_{12} - \frac{C_2}{Coeff_2}.$$

The processor **110** at **628** determines the heart rate based on a heart rate signal.

[0062] FIG. **7** shows a flow diagram of a method for determining the heart rate based on a heart rate signal. In the method **700**, the processor **110** obtains a heart rate signal as described herein at **702**. The processor **110** filters the heart rate signal using a low-pass filter at **704**. The cutoff frequency of the low-pass filter may be higher than a typical range of the heart rate. The processor **110** at **706** identifies a number of peaks and/or valleys in an interval of the filtered heart rate signal. At **708**, the processor **110** determines the heart rate based on the identified a number of peaks and/or valleys in an interval of the filtered heart rate signal. After determining the heart rate, the processor **110** at **710** outputs the heart rate to an output device, such as the output device **114** described with reference to FIG. **3** herein. The displayed heart rate may be used by health personnel for evaluating the health of the biological body, such as a human being or an animal.

[0063] The intensity of the emitted light having the first wavelength and the emitted light having the second wavelength may be regulated such that the two lights, when reflected, arrive at a photodetector having comparable DC values. The DC values may be higher than a spectral sensitivity of the photodetector. To ensure that the detected DC values are comparable, the emitted intensity of the light having the first wavelength may be set to be greater than the emitted light having the second wavelength.

[0064] The various embodiments described above can be combined to provide further embodiments.

[0065] These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

1. A device comprising:

a first light source configured to emit light having a first wavelength at a biological body, the first wavelength being associated with a first absorption coefficient for blood components;

a second light source configured to emit light having a second wavelength at the biological body, the second wavelength being associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient;

a photodetector configured to capture a first reflected signal as a result of the light having the first wavelength being reflected from the biological body and capture a second reflected signal as a result of the light having the second wavelength being reflected from the biological body; and

a processor coupled to the photodetector and configured to receive the first reflected signal and the second reflected signal from the photodetector, obtain a heart rate signal as a difference between the first reflected signal and the second reflected signal and determine a heart rate of the biological body based on the heart rate signal.

2. The device of claim **1**, wherein the processor is further configured to:

obtain an amplitude adapting coefficient for the second reflected signal; and

obtain the heart rate signal as a difference between the first reflected signal and a quotient of the second reflected signal and the amplitude adapting coefficient.

3. The device of claim **2**, wherein the amplitude adapting coefficient is a divisor of the second reflected signal that minimizes a difference in energy between the first reflected signal and the quotient of the second reflected signal and the amplitude adapting coefficient.

4. The device of claim **1**, wherein the processor is further configured to:

cross-correlate the first reflected signal and the second reflected signal to produce a cross-correlation function between the first reflected signal and the second reflected signal;

identify a maximum of the cross-correlation function;

identify a time index corresponding to the maximum of the cross-correlation function; and

shift the second reflected signal by the time index prior to obtaining the heart rate signal using the second reflected signal shifted by the time index.

5. The device of claim **1**, wherein the processor is further configured to:

low-pass filter the first reflected signal and the second reflected signal; and

de-trend the first reflected signal and the second reflected signal.

6. The device of claim **5**, wherein a cutoff frequency of the low pass filter is 4 Hertz or lower.

7. The device of claim **1**, further comprising a motion detector coupled to the processor and configured to output a signal to the processor indicating whether the device was displaced, wherein:

the processor is further configured to determine the heart rate based on the heart rate signal if the signal to the processor indicates that the device was displaced.

8. The device of claim **1**, further comprising an output device coupled to the processor and configured to receive the heart rate from the processor and display the heart rate, wherein the processor is further configured to:

identify a number of peaks and/or valleys in an interval of the heart rate signal; and

determine the heart rate based on the number of peaks and/or valleys in the interval.

9. A method, comprising:

emitting light having a first wavelength at a biological body, the first wavelength being associated with a first absorption coefficient for blood components;

capturing a first reflected signal as a result of the light having the first wavelength being reflected from the biological body;

emitting light having a second wavelength at the biological body, the second wavelength being associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient;

capturing a second reflected signal as a result of the light having the second wavelength being reflected from the biological body;

obtaining a heart rate signal as a difference between the first reflected signal and the second reflected signal; and

determining a heart rate of the biological body based on the heart rate signal.

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

scaling the second reflected signal by a reciprocal of an amplitude adapting coefficient before obtaining the heart rate signal as the difference between the first reflected signal and the second reflected signal using the second reflected signal scaled by the reciprocal of the amplitude adapting coefficient.

11. The method of claim **10**, wherein the amplitude adapting coefficient is a divisor of the second reflected signal that minimizes a difference in energy between the first reflected signal and the quotient of the second reflected signal and the amplitude adapting coefficient.

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

time shifting the second reflected signal prior to obtaining the heart rate signal using the time shifted second reflected signal.

13. The method of claim **12**, wherein the second reflected signal is shifted by a time index corresponding to a maximum cross-correlation value between the first reflected signal and the second reflected signal.

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

filtering the first and second reflected signals; and

de-trending the first and second reflected signals.

15. A system comprising:

a first light source;

a second light source;

a photodetector;

a processor; and

a computer-readable storage medium having stored thereon instructions that, when executed by the processor, cause the processor to:

instruct the first light source to emit light having a first wavelength at a biological body, the first wavelength being associated with a first absorption coefficient for blood components;

instruct the second light source to emit light having a second wavelength at the biological body, the second wavelength being associated with a second absorption coefficient for the blood components that is less than the first absorption coefficient;

receive a first reflected signal captured by the photodetector as a result of the light having the first wavelength being reflected from the biological body and a second reflected signal captured by the photodetector as a result of the light having the second wavelength being reflected from the biological body;

obtain a heart rate signal based on the first reflected signal and the second reflected signal; and

determine a heart rate of the biological body based on the heart rate signal.

16. The system of claim **15**, wherein the instructions further cause the processor to obtain the heart rate signal as a difference between the first reflected signal and the second reflected signal.

17. The system of claim **15**, wherein the instructions further cause the processor to:

obtain an amplitude adapting coefficient for the second reflected signal;

adjust an amplitude of the second reflected signal by the amplitude adapting coefficient to obtain an amplitude-adjusted second reflected signal; and

obtain the heart rate signal as a difference between the first reflected signal and the amplitude-adjusted second reflected signal.

18. The system of claim **15**, wherein the instructions further cause the processor to:

low-pass filter the first and second reflected signals to respectively produce first and second filtered signals; and

de-trend the first and second filtered signals ahead of obtaining the heart rate signal.

19. The system of claim **15**, wherein the first wavelength is between 500 and 580 nanometers (nm) and the second wavelength is between 680 and 700 nm.

20. The system of claim **15**, wherein:

the system further comprises:

a third light source;

a fourth light source;

the instructions further cause the processor to:

instruct the third light source to emit light having the first wavelength;

instruct the fourth light source to emit light having the second wavelength; and

receive a third reflected signal captured by the photodetector as a result of the light emitted by the third source being reflected from the biological body and a fourth reflected signal captured by the photodetector as a result of the light emitted by the fourth source being reflected from the biological body.

21. The system of claim **20**, wherein the instructions further cause the processor to:

cross-correlate the first and third reflected signals with the second and fourth reflected signals to obtain a plurality of cross-correlation functions;

identify a plurality of maximum cross-correlation values of the respective plurality cross-correlation functions, the plurality of maximum cross-correlation values including at least a first, second, third and fourth maximum cross-correlation value, the first, second, third and fourth maximum cross-correlation values having associated first, second, third and fourth indices, respectively;

determine that a maximum cross-correlation value of the plurality of maximum cross-correlation values exceeds a threshold; and

shift the second reflected signal by the second index and shift the fourth reflected signal by the fourth index to produce a second shifted signal and a fourth shifted signal.

22. The system of claim **21**, wherein the instructions further cause the processor to:

obtain a first reconstructed signal based on the first and third reflected signals and the first and third maximum cross-correlation values and a second reconstructed signal based on the first and third reflected signals and the second and fourth maximum cross-correlation values;

identify a first amplitude adapting coefficient of the first reconstructed signal and a second amplitude adapting coefficient of the second reconstructed signal; and

scale the first reconstructed signal by the first amplitude adapting coefficient and the second reconstructed signal by the second amplitude adapting coefficient to respectively produce first and second scaled signals.

23. The system of claim **22**, wherein obtaining the heart rate signal includes obtaining a first heart rate signal as a difference between the first reflected signal and the first reconstructed signal and a second heart rate signal as a difference between the second reflected signal and the second reconstructed signal.

24. The system of claim **23**, wherein determining the heart rate of the biological body further includes determining the heart rate of the biological body based at least in part on the first heart rate signal or the second heart rate signal.

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摘要(译)

公开了一种用于确定生物体的心率的方法和设备。在该方法和设备中，在生物体处发射具有第一波长的光和具有第二波长的光。第一波长与血液成分的第一吸收系数相关联，第二波长与血液成分的第二吸收系数相关联，第二吸收系数小于第一吸收系数。由于具有第一波长的光从生物体反射而捕获第一反射信号，并且由于具有第二波长的光从生物体反射而捕获第二反射信号。基于第一和第二反射信号获得心率信号。基于心率信号确定生物体的心率。