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(54) **PHYSIOLOGICAL METRIC ESTIMATION RISE AND FALL LIMITING**

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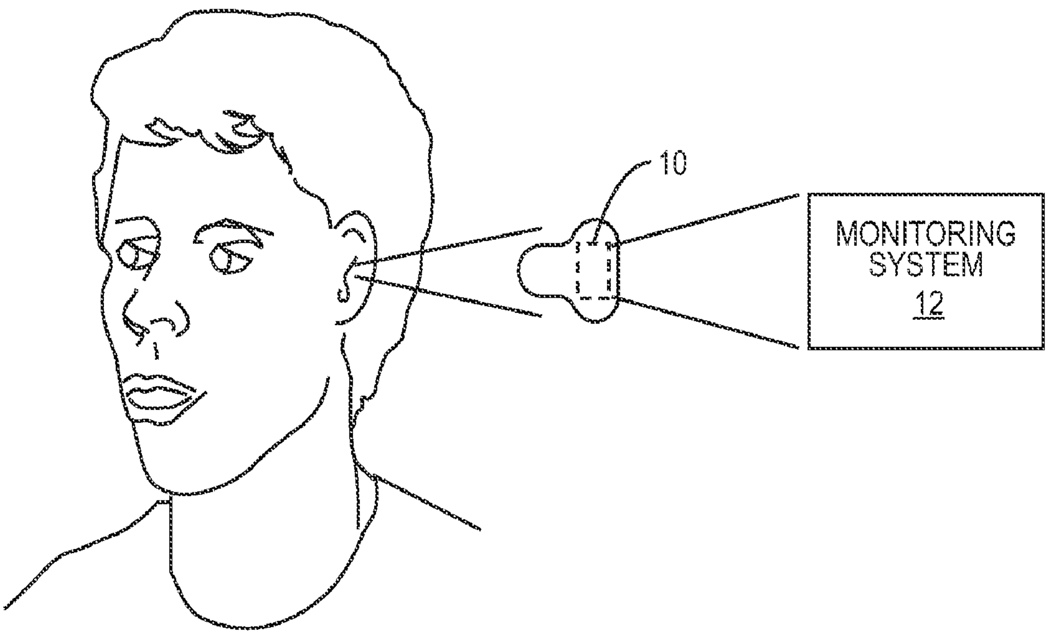
(57) **ABSTRACT**

Methods and apparatus disclosed herein use a filtering technique to improve the accuracy of the results achieved when processing data provided by a physiological sensor. The disclosed filtering technique corrects many of the accuracy problems associated with physiological sensors, particularly PPG sensors. Broadly, the filtering technique adjusts a current filtered estimate of a physiological metric as a function of a rate limit based on a comparison between an instantaneous estimate of the physiological metric and the current filtered estimate.



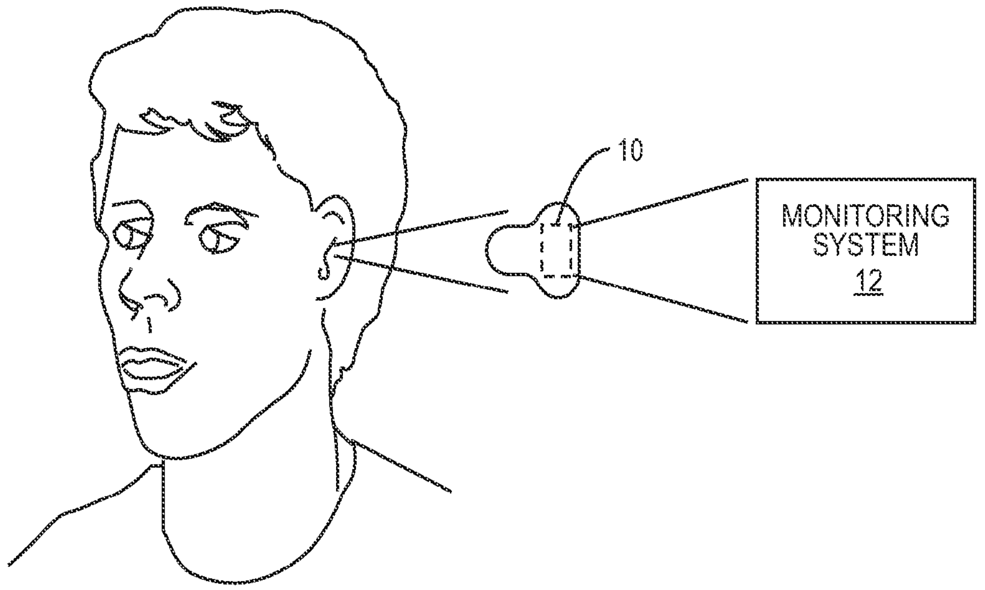


FIG. 1

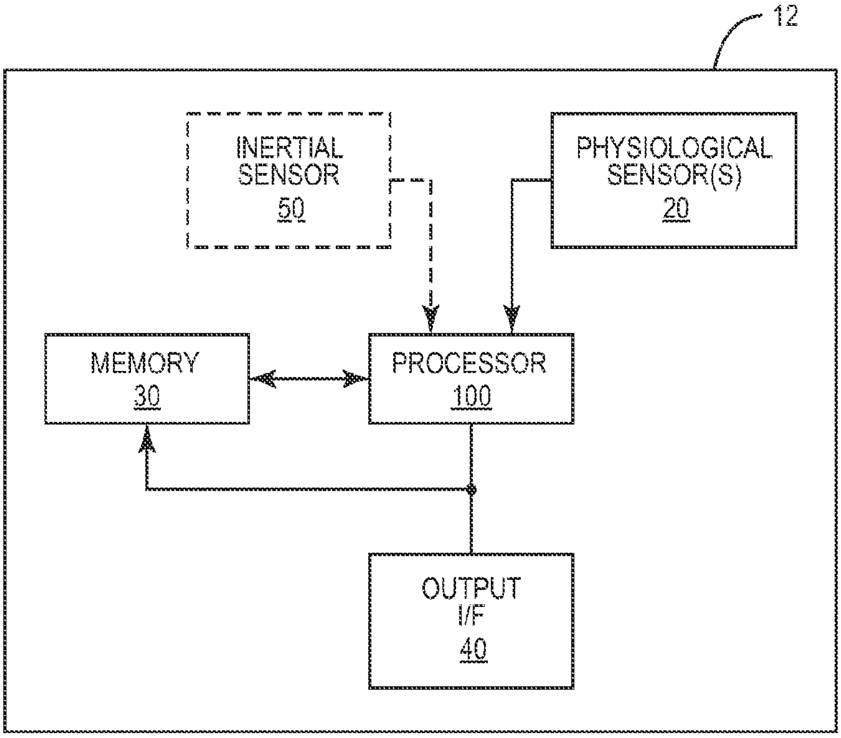

12
INERTIAL SENSOR 50
PHYSIOLOGICAL SENSOR(S) 20
MEMORY 30
PROCESSOR 100
OUTPUT I/F 40

FIG. 2

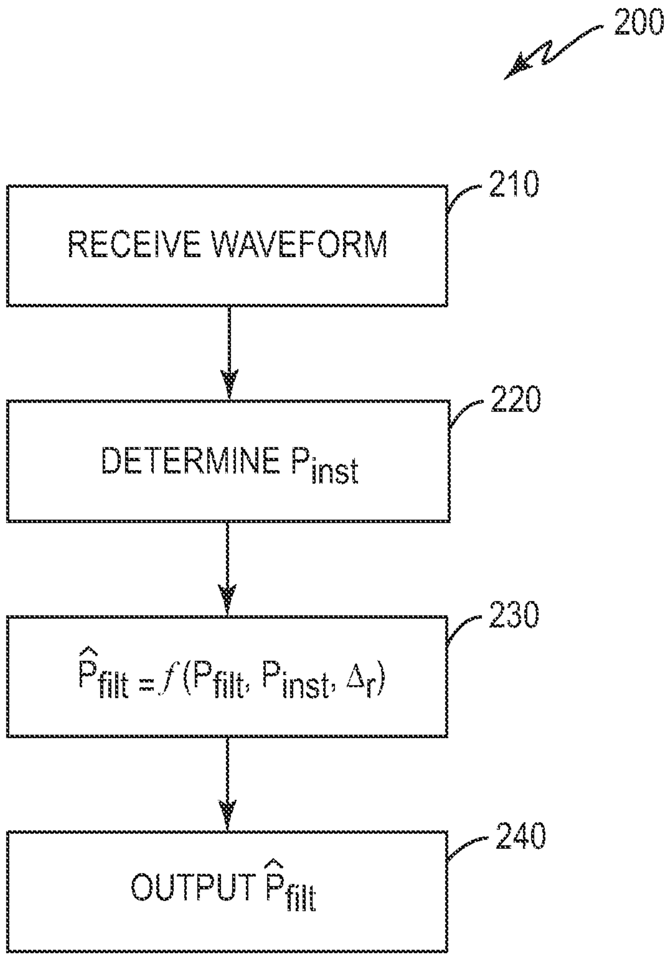

200
210
RECEIVE WAVEFORM
220
DETERMINE P_{inst}
230
$\hat{P}_{filt} = f(P_{filt}, P_{inst}, \Delta_r)$
240
OUTPUT $\hat{P}_{filt}$

FIG. 3

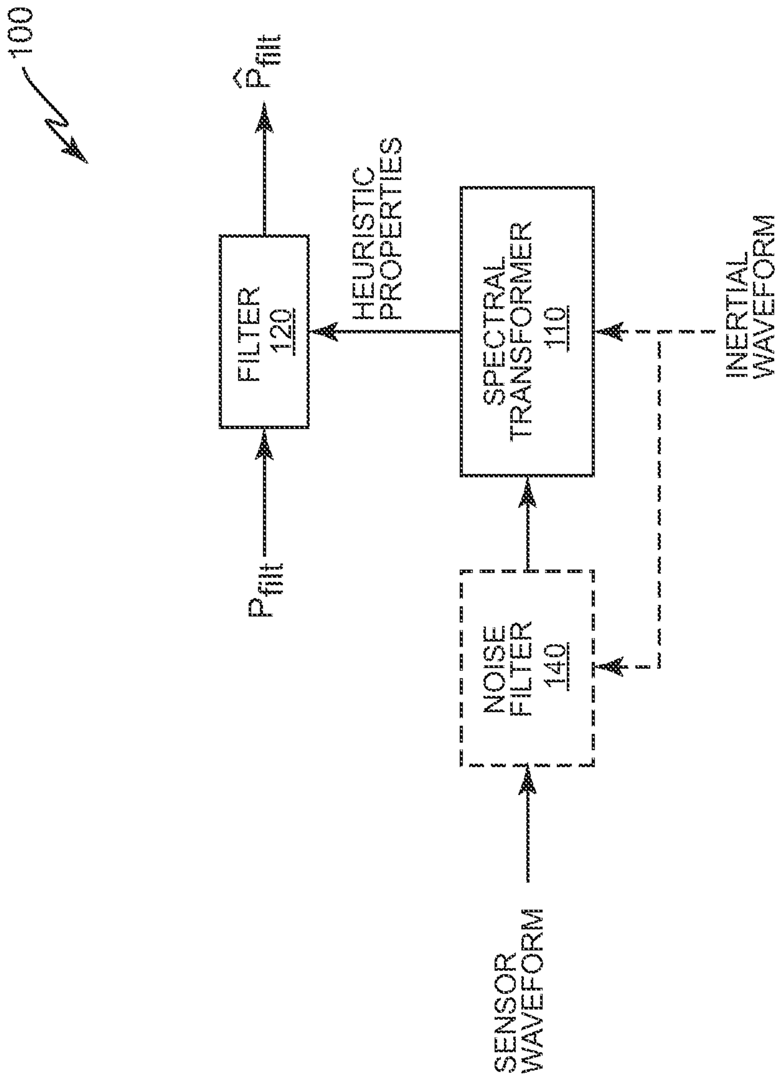

100
$\hat{P}_{filt}$
HEURISTIC PROPERTIES
FILTER 120
P_{filt}
SPECTRAL TRANSFORMER 110
INERTIAL WAVEFORM
NOISE FILTER 140
SENSOR WAVEFORM

FIG. 4

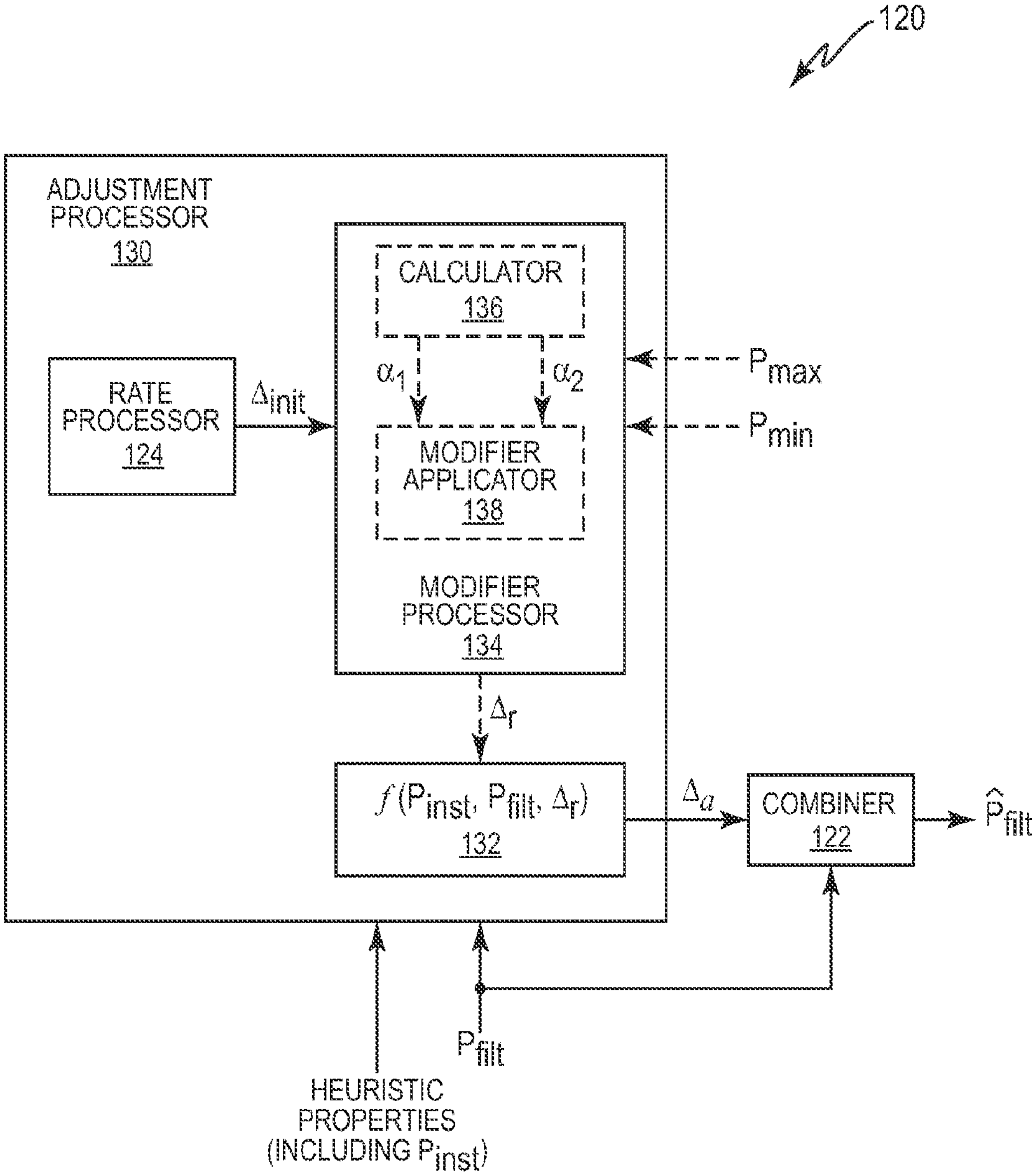

120
ADJUSTMENT PROCESSOR
130
CALCULATOR
136
RATE PROCESSOR
124
Δ_{init}
α_1
α_2
P_{max}
P_{min}
MODIFIER APPLICATOR
138
MODIFIER PROCESSOR
134
Δ_r
$f(P_{inst}, P_{filt}, \Delta_r)$
132
Δ_a
COMBINER
122
$\hat{P}_{filt}$
P_{filt}
HEURISTIC PROPERTIES (INCLUDING P_{inst})

FIG. 5

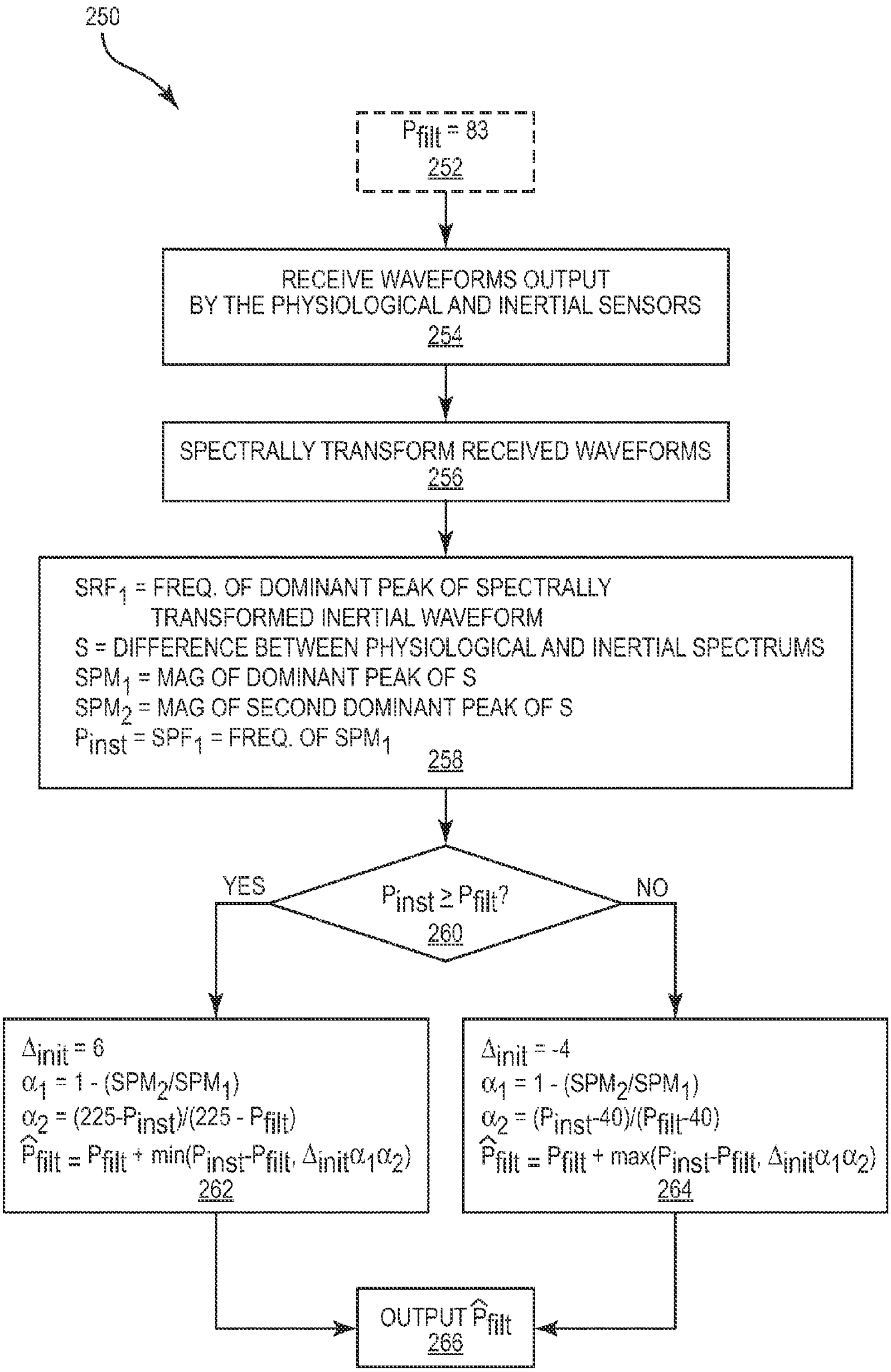

250
P filt = 83
252
RECEIVE WAVEFORMS OUTPUT BY THE PHYSIOLOGICAL AND INERTIAL SENSORS
254
SPECTRALLY TRANSFORM RECEIVED WAVEFORMS
256
SRF1 = FREQ. OF DOMINANT PEAK OF SPECTRALLY TRANSFORMED INERTIAL WAVEFORM
S = DIFFERENCE BETWEEN PHYSIOLOGICAL AND INERTIAL SPECTRUMS
SPM1 = MAG OF DOMINANT PEAK OF S
SPM2 = MAG OF SECOND DOMINANT PEAK OF S
P inst = SPF1 = FREQ. OF SPM1
258
YES
P inst ≥ P filt?
260
NO
Δ init = 6
α1 = 1 - (SPM2/SPM1)
α2 = (225-P inst)/(225 - P filt)
P̂ filt = P filt + min(P inst-P filt, Δ init α1 α2)
262
Δ init = -4
α1 = 1 - (SPM2/SPM1)
α2 = (P inst-40)/(P filt-40)
P̂ filt = P filt + max(P inst-P filt, Δ init α1 α2)
264
OUTPUT P̂ filt
266

FIG. 6

PHYSIOLOGICAL METRIC ESTIMATION RISE AND FALL LIMITING

[0001] The embodiments disclosed herein generally relate to photoplethysmograph (PPG) sensors for monitoring heart rate and other physiological metrics, and more particularly relate to noise reduction techniques for PPG sensors.

BACKGROUND

[0002] Personal health monitors provide users with the ability to monitor their overall health and fitness by enabling the user to monitor heart rate or other physiological information during exercise, athletic training, rest, daily life activities, physical therapy, etc. Such devices are becoming increasingly popular as they become smaller and more portable.

[0003] A heart rate monitor represents one example of a personal health monitor. A common type of heart rate monitor uses a chest strap monitor that includes surface electrodes to detect muscle action potentials from the heart. Because such surface electrodes provide a relatively noise free signal, the information produced by monitors that use surface electrodes is highly accurate. However, most users find chest strap monitors uncomfortable and inconvenient.

[0004] Another type of heart rate monitor uses PPG sensors disposed in an ear bud. The ear provides an ideal location for a monitor because it is a relatively immobile platform that does not obstruct a person's movement or vision. PPG sensors proximate the ear have, e.g., access to the inner ear canal and tympanic membrane (for measuring core body temperature), muscle tissue (for monitoring muscle tension), the pinna and earlobe (for monitoring blood gas levels), the region behind the ear (for measuring skin temperature and galvanic skin response), and the internal carotid artery (for measuring cardiopulmonary functioning). The ear is also at or near the point of the body's exposure to environmental breathable toxins of interest (volatile organic compounds, pollution, etc.), noise pollution experienced by the ear, lighting conditions for the eye, etc. Further, as the ear canal is naturally designed for transmitting acoustical energy, the ear provides a good location for monitoring internal sounds, such as the heartbeat, breathing rate, mouth motion, etc.

[0005] PPG sensors measure the relative blood flow using an infrared or other light source that projects light that is ultimately transmitted through or reflected off tissue, and is subsequently detected by a photodetector and quantified. For example, higher blood flow rates result in more light being scattered by the blood, which ultimately increases the intensity of the light that reaches the photodetector. By processing the signal output by the photodetector, a monitor using PPG sensors may measure the blood volume pulse (the phasic change in blood volume with each heartbeat), the heart rate, heart rate variability, and other physiological information. PPG sensors are generally small and may be packaged such that they do not encounter the comfort and/or convenience issues associated with other conventional health monitors. However, PPG sensors are also more sensitive to motion artifact noise than are many other types of sensors, and thus are more prone to accuracy problems.

SUMMARY

[0006] The filtering techniques disclosed herein improve the accuracy of a heart rate and/or other physiological metrics provided by a monitor, e.g., one using photoplethysmograph (PPG) sensors. In general, the disclosed filtering technique improves the accuracy by adjusting an estimate of a heart rate as a function of a rate limit associated with the heart rate.

[0007] One exemplary method processes data provided by a physiological sensor, e.g., a PPG sensor, to reduce the noise and therefore improve the accuracy of a physiological metric, e.g., a heart rate. The method comprises determining, based on a physiological waveform received from a physiological sensor, an instantaneous estimate of a physiological metric, and comparing the instantaneous estimate to a current filtered estimate of the physiological metric. The method further includes computing a revised filtered estimate of the physiological metric as a function of the current filtered estimate and a rate limit based on the comparison between the instantaneous estimate and the current filtered estimate, and outputting the revised filtered estimate.

[0008] One exemplary physiological processor processes data provided by a physiological sensor, e.g., a PPG sensor, to reduce the noise and therefore improve the accuracy of a physiological metric, e.g., a heart rate. The processor comprises a spectral transformer and a filter. The spectral transformer is configured to determine, based on a received waveform, an instantaneous estimate of the physiological metric. The filter is configured to compare the instantaneous estimate to a current filtered estimate of the physiological metric, and output a revised filtered estimate of the physiological metric computed as a function of the current filtered estimate and a rate limit based on the comparison between the instantaneous estimate and the current filtered estimate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** shows an exemplary heart rate monitor disposed in an ear bud.

[0010] FIG. **2** shows a block diagram of an exemplary physiological monitoring system disposed in a housing.

[0011] FIG. **3** shows an exemplary process for determining physiological information from data provided by a physiological sensor.

[0012] FIG. **4** shows an exemplary block diagram for the processor of FIG. **2**, as configured to implement the process of FIG. **3**.

[0013] FIG. **5** shows an exemplary block diagram for the filter of FIG. **4**.

[0014] FIG. **6** shows another exemplary process for determining physiological information from data provided by a physiological sensor.

DETAILED DESCRIPTION

[0015] Many of the embodiments disclosed herein are derived from new findings on how vital signs, PPG signals, and acceleration changes within the human body during activity. By understanding the relationship between these changes, a method has been invented to track heart rate and other vital signs in the midst of motion artifact noise and other types of noise that may otherwise lead to erroneous estimations of heart rate and other vital signs.

[0016] The filtering technique disclosed herein improves the accuracy of the results achieved when processing data, e.g., heart rate data, provided by a physiological sensor. FIG. **1** shows an exemplary monitoring system **12** disposed in an ear bud **10**. The ear bud **10** may comprise a wireless or wired ear bud that communicatively couples to a remote device, e.g., a music player, a smart phone, a personal data assistant, etc. The monitoring system **12** monitors the heart rate and/or other physiological metrics, and outputs such physiological information to the user and/or to other processing functions. While the monitoring system **12** disclosed herein is presented as being part of an ear bud **10**, it will be appreciated that monitoring system **12** may be disposed into any device that secures to the body of a user, e.g., a device that secures to an ear, finger, toe, limb (arm, leg, ankle, etc.), wrist, nose, etc. In some embodiments, the device may comprise a patch, e.g., a bandage, designed to attach the system **12** to any desired location on the user's body.

[0017] FIG. **2** shows a block diagram of an exemplary monitoring system **12** according to one exemplary embodiment. System **12** comprises a processor **100** coupled to one or more physiological sensors **20**, a memory **30**, and an output interface **40**. As discussed further herein, system **12** may also include an optional inertial sensor **50** configured to sense energy, e.g., motion, external to the system **12**. Physiological sensor(s) **20** produce a physiological waveform responsive to the physiological state of the user. Processor **100** processes the physiological waveform using the filtering technique disclosed herein, along with information stored in memory **30**, to determine a heart rate and/or one or more physiological metrics with improved accuracy. Output interface **40** outputs the determined physiological metric(s). It will be appreciated that output interface may comprise a transceiver for transmitting the data output by the processor **100** to a remote device. Alternatively or additionally, the output interface may provide the output data to a user interface, e.g., a display, a database, another processor, and/or a processing function.

[0018] In exemplary embodiments, the physiological sensors **20** comprise photoplethysmograph (PPG) sensors that generate an electrical physiological waveform responsive to detected light intensity. PPG sensors comprise light intensity sensors that generally rely on optical coupling of light into the blood vessels. As used herein, the term "optical coupling" refers to the interaction or communication between excitation light entering a region and the region itself. For example, one form of optical coupling may be the interaction between excitation light generated from within a light-guiding ear bud **10** and the blood vessels of the ear. Light guiding ear buds are described in co-pending U.S. Patent Application Publication No. 2010/0217102, which is incorporated herein by reference. In one embodiment, the interaction between the excitation light and the blood vessels may involve excitation light entering the ear region and scattering from a blood vessel in the ear such that the intensity of the scattered light is proportional to blood flow within the blood vessel. Another form of optical coupling may result from the interaction between the excitation light generated by an optical emitter within the ear bud and the light-guiding region of the ear bud.

[0019] Processor **100** determines one or more physiological metrics from the physiological waveform and filters the determined metric(s) to produce a revised physiological metric having an improved accuracy. The determined physiological metric may also refer to a physiological assessment computed from one or more physiological metrics. For simplicity, the following describes the processor **100** in terms of determining a heart rate. However, the processor **100** may alternatively or additionally determine other physiological metrics, e.g., a respiration rate, a heart rate variability (HRV), a pulse pressure, a systolic blood pressure, a diastolic blood pressure, a ste0p rate, an oxygen uptake (VO_2), an R-R interval (which represents the interval between successive R-peaks in an ECG waveform), a maximal oxygen uptake (VO_2 max), calories burned, trauma, cardiac output and/or blood analyte levels including percentage of hemoglobin binding sites occupied by oxygen (SPO_2), percentage of methomoglobins, a percentage of carbonyl hemoglobin, and/or a glucose level. Alternatively or additionally, processor **100** may determine and filter one or more physiological assessments, e.g., a ventilatory threshold, lactate threshold, cardiopulmonary status, neurological status, aerobic capacity (VO_2 max), and/or overall health or fitness. Though heart rate is used as an example of a specific physiological metric that may be accurately extracted using the embodiments disclosed herein, it should be understood that other physiological metrics may also be derived using these embodiments. Periodically changing vital signs, such as, but not limited to, heart rate, respiration rate, R-R interval, circadian changes, blood-gas level changes, and the like may be particularly suited for signal extraction under the described embodiments.

[0020] FIG. **3** shows an exemplary method **200** that may be implemented by processor **100** to compute a revised heart rate. After processor **100** receives the physiological waveform from the sensor(s) **20** (block **210**), the processor **100** determines an instantaneous estimate P_{inst} of the heart rate. After comparing p_{inst} to a current filtered estimate P_{filt}, which may be retrieved from memory **30**, processor **100** computes a revised filtered estimate $\hat{P}_{filt}$ of the heart rate as a function of P_{filt} and a rate limit Δ_r based on the comparison (block **230**), where Δ_r may also be retrieved from memory **30**. Processor **100** subsequently outputs the revised filtered estimate $\hat{P}_{filt}$ to output **40** (block **240**). It will be appreciated that processor **100** may also store the revised filtered estimate $\hat{P}_{filt}$ in memory **30**, e.g., so that it may be used in subsequent calculations and/or as a current filtered estimate P_{filt}. As used herein, the rate limit represents a limit to the rate of change for the heart rate. For example, the rate limit may represent the rate of change in beats per minute (BPM) that the heart rate may experience in a 1 second frame period. Such a rate limit may be determined based on empirical evidence, and is generally predetermined. It will be appreciated that the rate limit may be expressed as the rate of change experienced for any length frame period, where for example, the rate limit in BPM/s is multiplied by the length of the frame period (in seconds).

[0021] FIG. **4** shows a block diagram of an exemplary processor **100** configured to process the physiological waveform provided by the sensor(s) **20**. Processor **100** comprises a spectral transformer **110** and a filter **120**. Spectral transformer **110** spectrally transforms the physiological waveform received from the sensor(s) **20** to determine one or more heuristic properties of the physiological waveform and provides the heuristic properties to the filter **120**. For example, the spectral transformer **110** may evaluate the spectrally transformed waveform to identify the spectral peak having the largest amplitude. The spectral transformer **110** then defines the frequency of the peak with the largest amplitude as the instantaneous estimate p_{inst} of the heart rate. Filter **120** filters the instantaneous estimate P_{inst} of the heart rate to compute the revised filter estimate $\hat{P}_{filt}$ as a function of P_{filt} and Δ_r based on a comparison between P_{filt} and p_{inst}.

[0022] To illustrate, consider the following example. If the instantaneous heart rate is greater than or equal to the current filtered heart rate, filter **120** may compute the revised filter estimate as a function of a rising/increasing heart rate limit Δ_{r+} and the current filtered heart rate, e.g., according to:

$$\hat{P}_{filt}=P_{filt}+\min(\Delta_{r+}, P_{inst}-P_{filt}),$$

where, the rising heart rate limit Δ_{r+} is, e.g., 6 BPM in a 1 second frame period. If, however, the instantaneous heart rate is less than the current filtered heart rate, filter **120** may compute the revised filter estimate as a function of a falling heart rate limit Δ_{r-} and the current filtered heart rate, e.g., according to:

$$\hat{P}_{filt}=P_{filt}+\max(\Delta_{r-}, P_{inst}-P_{filt}), \quad (2)$$

where, the falling heart rate limit Δ_{r-} is, e.g., −4.

[0023] FIG. **5** shows a block diagram of an exemplary filter **120**. In one embodiment, filter **120** comprises an adjustment processor **130** and a combiner **122**. Combiner **122** combines an adjustment parameter Δ_a output by adjustment processor **130** with P_{filt} to compute the revised filtered estimate $\hat{P}_{filt}$ of the heart rate. Adjustment processor **130** comprises a function processor **132** configured to compute Δ_a as a function of the rate limit Δ_r and the current filtered estimate P_{filt} responsive to the comparison between the instantaneous estimate P_{inst} and the current filtered estimate P_{filt}. Using the previous example, when $P_{inst} \geq P_{filt}$, function processor **132** may compute the adjustment parameter Δ_a according to:

$$\Delta_a=\min(\Delta_{r+}, P_{inst}-P_{filt}) \quad (3)$$

[0024] If, however $P_{inst}<P_{filt}$, function processor **132** may compute the adjustment parameter Δ_a according to:

$$\Delta_a=\max(\Delta_{r-}, P_{inst}-P_{filt}). \quad (4)$$

[0025] In some embodiments, adjustment processor **130** selects either the rising or falling rate limit used by function processor **132** based on the comparison between the instantaneous estimate and the current filtered estimate. Alternatively, filter **120** may include a rate processor **124** that selects an initial rate limit Δ_{init}, which may comprise the rising or falling rate limit, based on the comparison between the instantaneous estimate and the current filtered estimate. In still another embodiment, the function processor **132** may comprise different processing paths associated with different comparison results, where adjustment processor **130** selects one of the processing paths based on the comparison between the instantaneous estimate and the current filtered estimate, where each processing path is associated with a different one of Equations (1)/(3) and (2)/(4), and where each processing path includes the corresponding rate limit.

[0026] It will also be appreciated that the different values disclosed herein for the rising and falling rate limits are exemplary and non-limiting. In some embodiments, the magnitude of the rising rate limit may equal the magnitude of the falling rate limit. Alternatively or additionally, while the rising and falling rate limits may respectively comprise positive and negative values, such is not required. For example, when the falling rate limit is set to a positive value, Equation (4) may be modified according to:

$$\Delta_a=-\min(\Delta_{r-}, P_{filt}-P_{inst}) \quad (5)$$

[0027] Similar modifications to Equation (**3**) may be made when the rising rate limit is set to a negative value.

[0028] Adjustment processor **130** may further include a modifier processor **134** configured to compute one or more modifiers based on one or more of the heuristic properties, and further configured to determine the rate limit as a function of the modifier(s) and an initial rate limit Δ_{init}, e.g., as provided by rate processor **124**. Accordingly, modifier processor **134** includes a calculator **136** and a modifier applicator **138**. Calculator **136** computes one or more modifiers based on the one or more heuristic properties of the physiological waveform provided by the spectral transform. In some embodiments, the modifier(s) represent a reliability of the initial rate limit Δ_{init}. Modifier applicator **138** subsequently applies the computed modifier(s) to the initial rate limit Δ_{init}, e.g., by summing and/or multiplying the initial rate limit Δ_{init} by the computed modifier(s), to determine the rate limit Δ_r used by function processor **132**. It will be appreciated that the modifier(s) may be applied to any initial rate limit Δ_{init}, including the rising rate limit, the falling rate limit, or both, and that when function processor **132** uses different processing paths based on the comparison between P_{inst} and P_{filt}, the modifiers are applied to the rate limits of one or more of the processing paths as needed/desired.

[0029] In one exemplary embodiment, calculator **136** computes a spectral modifier a, based on heuristic properties of the physiological waveform comprising spectral characteristics of the instantaneous estimate of the heart rate. The spectral modifier quantifies the reliability (or confidence) that the spectral transformer **110** associated the instantaneous estimate with the correct spectral peak. Broadly, when there is a large difference in magnitude between the spectral peak having the largest magnitude and the spectral peak having the next largest magnitude, there is a high degree of confidence that the largest spectral peak corresponds to the instantaneous heart rate of interest. More particularly, the spectral transformer **110** may provide the spectral characteristics for some number of the spectral peaks of the spectrally transformed waveform, e.g., the magnitude(s) of two or more spectral peaks. For example, the spectral transformer may provide the magnitude of the largest spectral peak SPM_1 and the magnitude of the second largest spectral peak SPM_2 to the calculator **136**. Based on the provided spectral magnitudes, calculator **136** calculates the spectral modifier. For example, calculator **136** may compute the spectral modifier according to:

$$\alpha_1 = 1 - \frac{SPM_2}{SPM_1}. \quad (6)$$

[0030] Subsequently, modifier applicator **138** applies the spectral modifier according to:

$$\Delta_r=\alpha_1\Delta_{init} \quad (7)$$

[0031] It will be appreciated that applicator **138** may apply the spectral modifier to the initial rate limit Δ_{init} using linear means, e.g., multiplication, addition, subtraction, and/or division, or using non-linear means, e.g., norm, RMS, min, or max functions. It should be noted that if the magnitude of the largest peak (SPM_1) and the magnitude of the 2^{nd} largest peak (SPM_2) are identical, then $\alpha_1=0$, such that the rate limit Δ_r is zero. With the rate limit at zero, the reported physiological metric $\hat{P}_{filt}$ (which in this specific case is the reported heart rate) may not change.

[0032] In another exemplary embodiment, calculator **136** computes a boundary modifier α_2 as a function of boundary values bounding the heart rate based on the comparison between the instantaneous estimate and the current filtered estimate. The boundary modifier also quantifies the reliability (or confidence) that the spectral transformer **110** associated the instantaneous estimate of the heart rate with the correct spectral peak based on the difference between the current filtered estimate and the instantaneous estimate. When there is a large difference between the instantaneous and current filtered estimates, there is a low degree of confidence that the instantaneous estimate is correct. More particularly, when the instantaneous estimate is greater than or equal to the current filtered estimate, the calculator **136** may compute the boundary modifier according to:

$$\alpha_2 = \frac{P_{max} - P_{inst}}{P_{max} - P_{filt}}, \tag{8}$$

where P_{max} represents an upper boundary for the heart rate. For example, P_{max} may be set equal to 225 BPM. When the instantaneous estimate is less than the current filtered estimate, the calculator **136** may compute the boundary modifier according to:

$$\alpha_2 = \frac{P_{inst} - P_{min}}{P_{filt} - P_{min}}, \tag{9}$$

where P_{min} represents a lower boundary for the heart rate. For example, P_{min} may be set equal to 40 BPM. Subsequently, modifier applicator **138** applies the boundary modifier according to:

$$\Delta_r = \alpha_2 \Delta_{init} \tag{10}$$

[0033] It will be appreciated that applicator **138** may apply the boundary modifier to the initial rate limit Δ_{init} using linear means, e.g., multiplication, addition, subtraction, and/or division, or using non-linear means, e.g., norm, RMS, min, or max functions. It will also be appreciated that the upper and lower heart rate boundaries are based on empirical evidence, which indicates that most people, whether at rest or exercising, have a heart rate between 40 and 225 BPM.

[0034] In still another embodiment, calculator **136** may compute the spectral and boundary modifiers, as previously described. Subsequently, applicator **138** applies the spectral and boundary modifiers according to:

$$\Delta_r = \alpha_1 \alpha_2 \Delta_{init} \tag{11}$$

[0035] It will be appreciated that applicator **138** may apply the spectral and boundary modifiers to the initial rate limit Δ_{init} using linear means, e.g., multiplication, addition, subtraction, and/or division, or using non-linear means, e.g., norm, RMS, min, or max functions. It will further be appreciated that other modifier(s) determined based on one or more heuristic properties of the physiological waveform may be additionally or alternatively applied to the initial rate limit Δ_{init} to determine Δ_r.

[0036] Embodiments disclosed heretofore filter an estimate of the heart rate derived from a spectral transformation of the physiological waveform output by the sensor(s) **20**. While such filtering improves the accuracy of the output heart rate, it will be appreciated that the accuracy may further be improved through the use of noise reduction techniques applied to the physiological waveform and/or to the instantaneous estimate before applying the filtering technique. For example, processor **100** may include an optional noise filter **140** (FIG. **4**) configured to filter the physiological waveform output by the sensor(s) **20** to generate a noise-reduced waveform, e.g., a waveform free of breathing noise. In this example, spectral transformer **110** determines the instantaneous estimate and/or other spectral information used during the filtering process based on the noise-reduced waveform. In so doing, the processor **100** reduces the noise present in the instantaneous estimate and/or the revised filtered estimate. Alternatively or additionally, system **12** may include an optional inertial sensor **50** (FIG. **2**), e.g., a motion sensor, configured to receive an inertial waveform representative of external energy, e.g., external motion. The motion sensor **50** may comprise one or more of any number of types of sensors, including but not limited to an accelerometer, an optical emitter/detector pair, an optical detector, a CCD camera, a piezoelectric sensor, a thermal sensor, or any type of sensor capable of capturing motion information. Exemplary optical emitters comprise one or more light emitting diodes, laser diodes, organic light-emitting diodes, miniature light emitters, electromagnetic emitters, etc. It will be appreciated that the sensors disclosed herein are not limited to optical wavelengths of the electromagnetic spectrum. In some embodiments, emitters and/or detectors configured for shorter or longer wavelengths may be used to accommodate shorter or longer wavelengths in the electromagnetic spectrum. The optical detector may comprise a photodetector, an electromagnetic detector, a photodiode, etc. In the filtering embodiment, spectral transformer **110** determines the instantaneous estimate and/or other spectral information used during the filtering process based on the inertial spectrum determined for the inertial waveform and the physiological spectrum determined for the physiological waveform. In so doing, the processor **100** reduces noise attributable to external energy/motion, e.g., energy due to a poor fit of the ear bud, shadows, etc., to reduce the noise present in the instantaneous estimate and/or the revised filtered estimate. For example, the spectral transformer may subtract the physiological and inertial spectrums to determine a reduced noise spectrum, and then may identify the frequency associated with the spectral peak having the largest magnitude as the instantaneous estimate of the heart rate. In still another embodiment, noise filter **140** may receive the inertial waveform and filter the physiological waveform based on the inertial waveform to generate the noise reduced waveform, where the spectral transformer **110** determines the instantaneous estimate and/or other spectral information based on the noise-reduced waveform.

[0037] FIG. **6** shows one exemplary method **250** for the embodiment where the spectral and boundary modifiers are used to compute the rate limit used to determine $\hat{P}_{filt}$, and where the inertial waveform provided by an inertial sensor **50** is used to reduce noise as described herein. In this exemplary embodiment, P_{filt} optionally comprises a current filtered heart rate initially set equal to 83 BPM (block **252**). Spectral transformer **110** spectrally transforms the physiological and inertial waveforms respectively received from the physiological and inertial sensors (blocks **254**, **256**). The spectral transformer **110** subsequently identifies the frequency of the dominant peak of the spectrally transformed inertial waveform (SRF_1), computes the difference between the physiological and inertial spectrums (S), identifies the magnitudes of the dominant and second dominant peaks of S (SPM_1 and SPM_2, respectively), sets P_{inst} equal to the frequency of the dominant peak (SPF_1) (block **258**), and provides at least P_{inst} to the filter **120**. After comparing to P_{filt} to P_{inst} (block **260**), filter **120** performs a filtering operation based on the comparison. For example, filter **120** performs the operations of block **262** when $P_{inst} \geq P_{filt}$, and performs the operations of block **264** when $P_{inst} < P_{filt}$. Subsequently, the processor outputs $\hat{P}_{filt}$ (block **266**).

[0038] The embodiments disclosed herein improve the accuracy of heart rates determined based on physiological waveforms provided by physiological sensors, particularly noise sensitive sensors, e.g., PPG sensors. In particular, the embodiments disclosed herein reduce the impact of noise sources not previously addressed by past systems, e.g., motion noise due to a user's jaw movement and/or breathing, shadow/sunlight flicker due to a user's movement into and out of shaded areas, light noise due to ambient light being detected by the photodetector, etc.

[0039] While the present invention is described in terms of PPG sensors, it will be appreciated that sensors **20** may comprise any sensor able to generate a physiological waveform, e.g., an electroencephalogram (EEG) waveform, and electrocardiogram (ECG) waveform, a radio frequency (RF) waveform, an electro-optical physiological waveform, a thermoelectric waveform, and electro-photoacoustic waveform including a photacoustic waveform, an electro-mechanical physiological waveform, and/or an electro-nuclear physiological waveform.

[0040] The present invention may, of course, be carried out in other ways than those specifically set forth herein without departing from essential characteristics of the invention. The present embodiments are to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

What is claimed is:

1. A physiological processor configured to process a waveform provided by a photoplethysmography sensor, the processor comprising:

a spectral transformer configured to determine, based on the waveform, an instantaneous estimate of a heart rate; and

a filter configured to:

compare the instantaneous estimate to a current filtered estimate of the heart rate; and

output a revised filtered estimate of the heart rate computed as a function of the current filtered estimate and a rate limit based on the comparison between the instantaneous estimate and the current filtered estimate.

2. A method of processing data provided by a physiological sensor, the method comprising:

receiving a physiological waveform from the physiological sensor;

determining, based on the physiological waveform, an instantaneous estimate of a physiological metric;

comparing the instantaneous estimate to a current filtered estimate of the physiological metric;

computing a revised filtered estimate of the physiological metric as a function of the current filtered estimate and a rate limit based on the comparison between the instantaneous estimate and the current filtered estimate; and

outputting the revised filtered estimate.

3. The method of claim **2** further comprising computing an adjustment parameter as a function of the current filtered estimate, the instantaneous estimate, and the rate limit based on the comparison between the instantaneous estimate and the current filtered estimate, wherein computing the revised filter estimate comprises combining the current filtered estimate with the adjustment parameter.

4. The method of claim **2** wherein the rate limit comprises an increasing rate limit, and wherein computing the revised filtered estimate comprises computing the revised filtered estimate as a function of the current filtered estimate and the increasing rate limit when the instantaneous estimate is greater than or equal to the current filtered estimate.

5. The method of claim **2** wherein the rate limit comprises a decreasing rate limit, and wherein computing the revised filtered estimate comprises computing the revised filtered estimate as a function of the current filtered estimate and the decreasing rate limit when the instantaneous estimate is less than the current filtered estimate.

6. The method of claim **2** further comprising determining the rate limit as a function of one or more heuristic properties of the physiological waveform.

7. The method of claim **6** wherein determining the rate limit as a function of one or more heuristic properties of the physiological waveform comprises determining the rate limit as a function of a sum of two or more of the heuristic properties.

8. The method of claim **6** wherein determining the rate limit as a function of one or more heuristic properties of the physiological waveform comprises determining the rate limit as a function of a product of two or more of the heuristic properties.

9. The method of claim **6** further comprising computing one or more modifiers based on the one or more heuristic properties, wherein determining the rate limit as a function of one or more heuristic properties of the physiological waveform comprises determining the rate limit as a function of the one or more modifiers and an initial rate limit.

10. The method of claim **9** wherein computing the one or more modifiers comprises computing a first modifier based on a boundary value associated with the physiological metric and the one or more heuristic properties, and wherein determining the rate limit as a function of the one or more modifiers and the initial rate limit comprises applying the first modifier to the initial rate limit.

11. The method of claim **9** wherein the one or more heuristic properties comprise spectral characteristics of the physiological waveform, wherein computing the one or more modifiers comprises computing a first modifier based on the spectral characteristics of the physiological waveform, wherein determining the rate limit as a function of the one or more modifiers and the initial rate limit comprises applying the first modifier to the initial rate limit.

12. The method of claim **11** wherein computing the one or more modifiers further comprises computing a second modifier based on a boundary value associated with the physiological metric and the one or more heuristic properties, and wherein determining the rate limit as a function of the one or more modifiers and the initial rate limit comprises applying the first and second modifiers to the initial rate limit.

13. The method of claim **11** wherein determining the instantaneous estimate comprises spectrally transforming the received waveform to identify one or more spectral peaks, and determining the instantaneous estimate based on one or more characteristics of a first spectral peak, said first spectral peak having a larger amplitude than the remaining spectral peaks, and wherein computing the first modifier comprises computing the first modifier based on a ratio between a second spectral peak and the first spectral peak, said second spectral peak having a smaller amplitude than the first spectral peak and a larger amplitude than the remaining spectral peaks.

14. The method of claim 2 wherein determining the instantaneous estimate comprises processing the physiological waveform to reduce noise in the instantaneous estimate.

15. The method of claim 14 wherein processing the physiological waveform comprises receiving an inertial waveform from an inertial sensor and processing the physiological waveform based on the inertial waveform to reduce the noise in the instantaneous estimate.

16. The method of claim 14 wherein processing the physiological waveform comprises filtering the physiological waveform to reduce the noise in the physiological waveform.

17. The method of claim 2 wherein the rate limit comprises at least one of an increasing and a decreasing rate limit, the method further comprising selecting at least one of the increasing and decreasing rate limits based on the comparison between the instantaneous estimate and the current filtered estimate.

18. The method of claim 2 wherein outputting the revised filter estimate comprises outputting the revised filter estimate to at least one of a user interface, a transceiver, a database, a processor, and a processing function.

19. The method of claim 2 wherein the physiological metric comprises a heart rate.

20. The method of claim 2 wherein receiving the physiological waveform comprises receiving the physiological waveform from a photoplethysmography (PPG) sensor.

21. A physiological processor configured to process a physiological waveform provided by a physiological sensor, the processor comprising:

a spectral transformer configured to determine, based on the physiological waveform, an instantaneous estimate of a physiological metric; and

a filter configured to:

compare the instantaneous estimate to a current filtered estimate of the physiological metric; and

output a revised filtered estimate of the physiological metric as a function of the current filtered estimate and a rate limit based on the comparison between the instantaneous estimate and the current filtered estimate.

22. The physiological processor of claim 21 wherein the filter comprises:

an adjustment processor configured to compute an adjustment parameter as a function of the current filtered estimate, the instantaneous estimate, and the rate limit based on the comparison between the instantaneous estimate and the current filtered estimate; and

a combiner configured to combine the current filtered estimate with the adjustment parameter to compute the revised filter estimate of the physiological metric.

23. The physiological processor of claim 21 wherein the rate limit comprises an increasing rate limit, and wherein the filter is configured to output the revised filtered estimate as a function of the current filtered estimate and the increasing rate limit when the instantaneous estimate is greater than or equal to the current filtered estimate.

24. The physiological processor of claim 21 wherein the rate limit comprises a decreasing rate limit, and wherein the filter is configured to output the revised filtered estimate as a function of the current filtered estimate and the decreasing rate limit when the instantaneous estimate is less than the current filtered estimate.

25. The physiological processor of claim 21 wherein the filter comprises an adjustment processor configured to determine the rate limit as a function of one or more heuristic properties of the physiological waveform.

26. The physiological processor of claim 25 wherein the adjustment processor is configured to determine the rate limit as a function of a sum of two or more of the heuristic properties.

27. The physiological processor of claim 25 wherein the adjustment processor is configured to determine the rate limit as a function of a product of two or more of the heuristic properties.

28. The physiological processor of claim 25 wherein the adjustment processor comprises a modifier processor configured to calculate one or more modifiers based on the one or more heuristic properties, and wherein the adjustment processor determines the rate limit by determining the rate limit as a function of the one or more modifiers and an initial rate limit.

29. The physiological processor of claim 28 wherein modifier processor comprises:

a calculator configured to compute a first modifier based on a boundary value associated with the physiological metric and the one or more heuristic properties; and

a modifier applicator configured to apply the first modifier to the initial rate limit to determine the rate limit.

30. The physiological processor of claim 28 wherein the one or more heuristic properties comprise spectral characteristics of the physiological waveform, and wherein the modifier processor comprises:

a calculator configured to compute a first modifier based on the spectral characteristics of the physiological waveform; and

a modifier applicator configured to apply the first modifier to the initial rate limit to determine the rate limit.

31. The physiological processor of claim 30 wherein the calculator is further configured to compute a second modifier based on a boundary value associated with the physiological metric and the one or more heuristic properties, and wherein the modifier applicator is configured to apply the first and second modifiers to the initial rate limit to determine the rate limit.

32. The physiological processor of claim 30 wherein the spectral transformer is configured to spectrally transform the physiological waveform to identify one or more spectral peaks, and to determine the instantaneous estimate based on one or more characteristics of a first spectral peak, said first spectral peak having a larger amplitude than the remaining spectral peaks, and wherein the calculator is configured to compute the first modifier based on a ratio between a second spectral peak and the first spectral peak, said second spectral peak having a smaller amplitude than the first spectral peak and a larger amplitude than the remaining spectral peaks.

33. The physiological processor of claim 21 further comprising an inertial sensor configured to receive an inertial waveform, wherein the spectral transformer is configured to determine the instantaneous estimate based on the inertial waveform to reduce the noise in the instantaneous estimate.

34. The physiological processor of claim 21 further comprising an inertial sensor configured to receive an inertial waveform and a noise filter configured to filter the physiological waveform based on the inertial waveform to generate a noise-reduced waveform, wherein the spectral transformer is configured to determine the instantaneous estimate based on the noise-reduced waveform to reduce the noise in the instantaneous estimate.

35. The physiological processor of claim **21** further comprising a noise filter configured to filter the physiological waveform to generate a noise-reduced waveform, wherein the spectral transformer is configured to determine the instantaneous estimate based on the noise-reduced waveform to reduce the noise in the physiological waveform.

36. The physiological processor of claim **21** wherein the rate limit comprises at least one of an increasing and a decreasing rate limit, and wherein the filter comprises a rate processor configured to select at least one of the increasing and decreasing rate limits based on the comparison between the instantaneous estimate and the current filtered estimate.

37. The physiological processor of claim **21** further comprising an output element configured to receive the revised filter estimate from the filter, said output element comprising at least one of a user interface, transceiver, a database, a processor, and a processing function

38. The physiological processor of claim **21** wherein the physiological metric comprises a heart rate.

39. The physiological processor of claim **21** wherein the physiological sensor comprises a photoplethysmography (PPG) sensor.

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申请(专利权)人(译)	VALENCELL INC.		
当前申请(专利权)人(译)	VALENCELL INC.		
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摘要(译)

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