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(54) **PHOTOPLETHYSMOGRAPH FILTERING USING EMPIRICAL MODE DECOMPOSITION**

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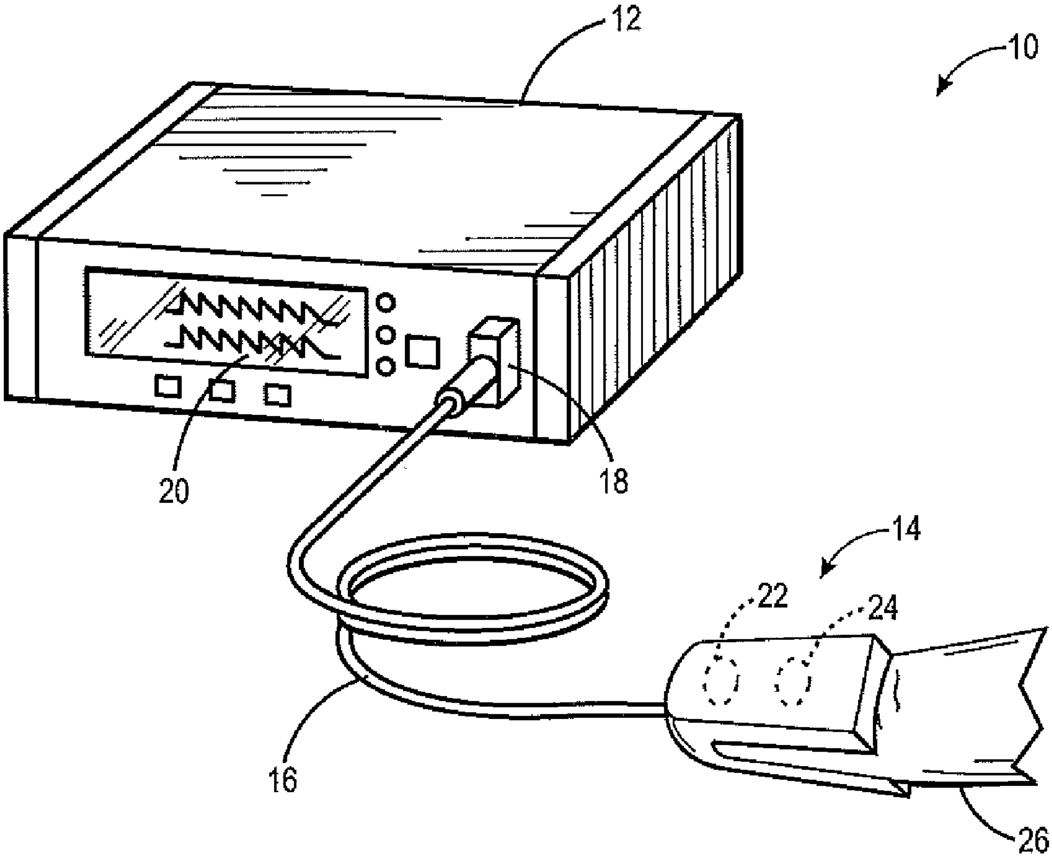
(57) **ABSTRACT**

Present embodiments relate to systems, methods, and devices for decomposing a physiological signal of a patient using empirical mode decomposition (EMD). In one embodiment, the EMD algorithm may involve identifying a frequency component, referred to as an intrinsic mode function, in the physiological signal. The physiological signal may be decomposed into one or more intrinsic mode functions through multiple iterations of the EMD algorithm. Each subsequent mode function may have a different frequency component of the original physiological signal input into the EMD algorithm. In some embodiments, each mode function may be further analyzed and/or processed to determine various physiological data corresponding to blood flow in the patient.



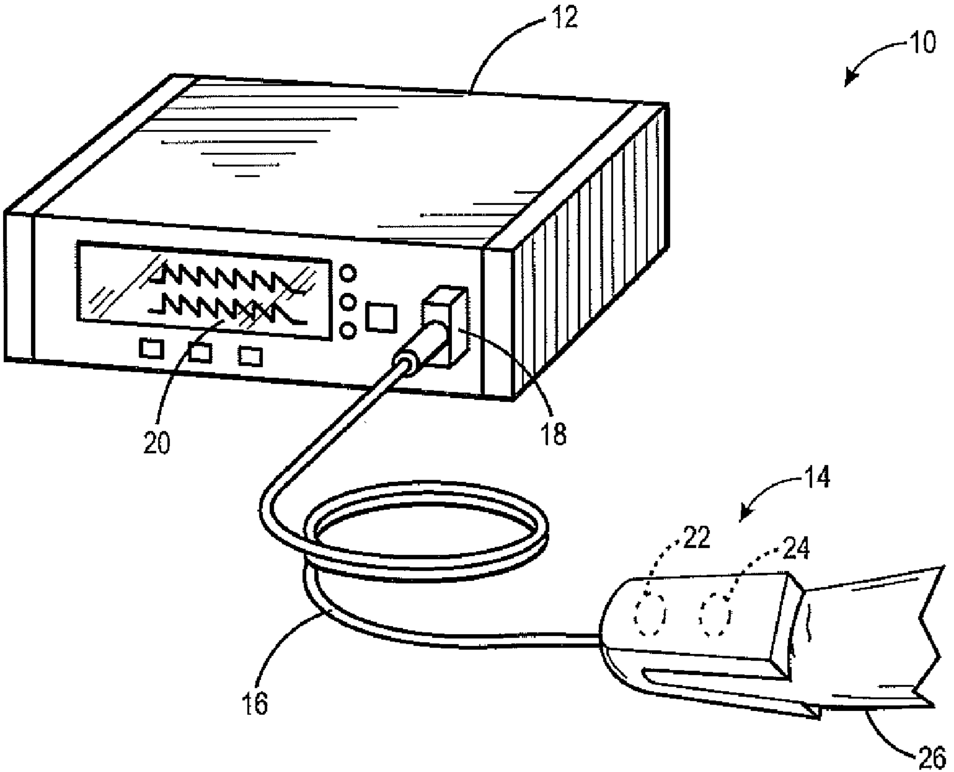
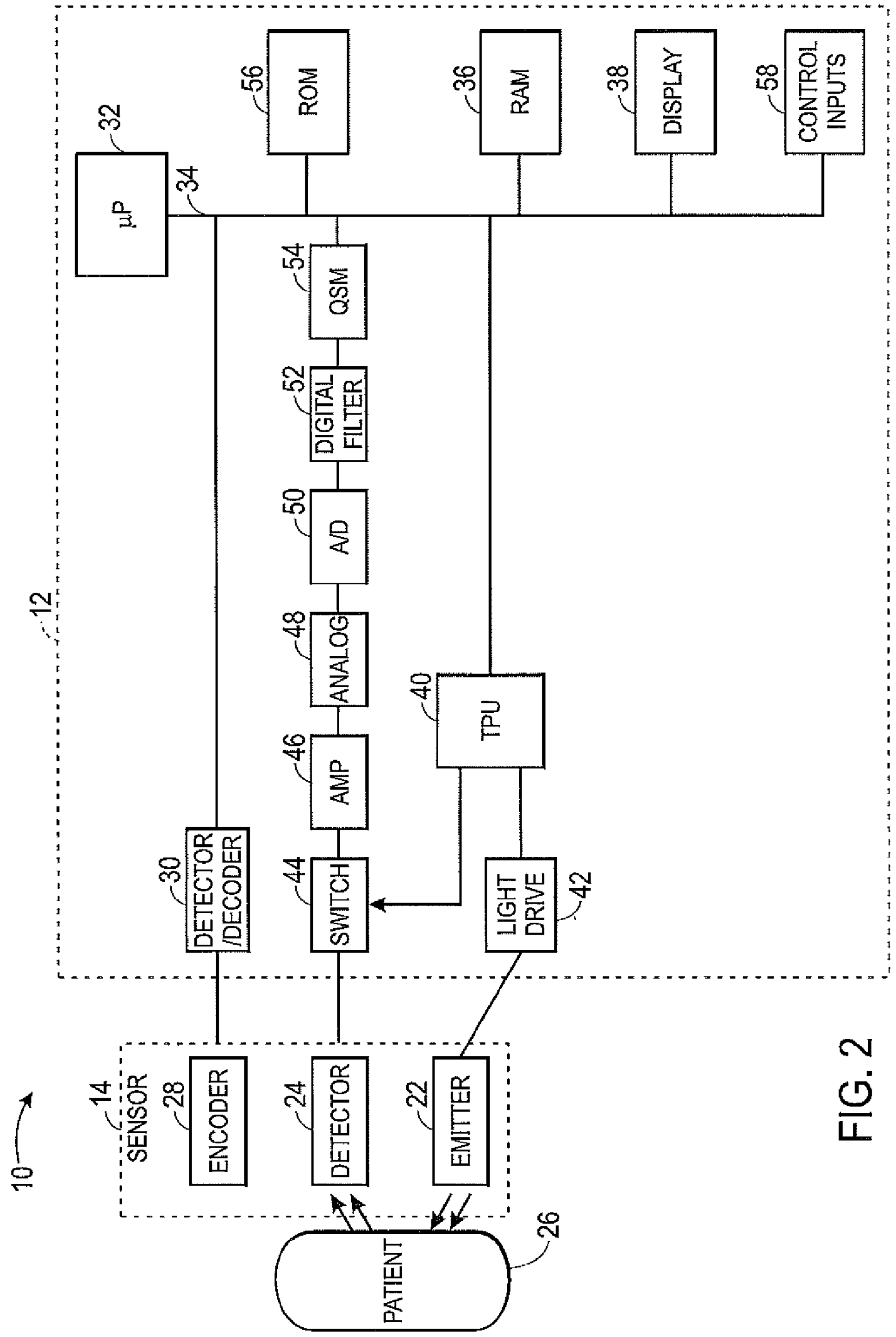


FIG. 1


10
14
SENSOR
28
ENCODER
24
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22
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SWITCH
42
LIGHT DRIVE
46
AMP
48
ANALOG
50
A/D
52
DIGITAL FILTER
54
QSM
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TPU
32
µP
34
56
ROM
36
RAM
38
DISPLAY
58
CONTROL INPUTS

FIG. 2

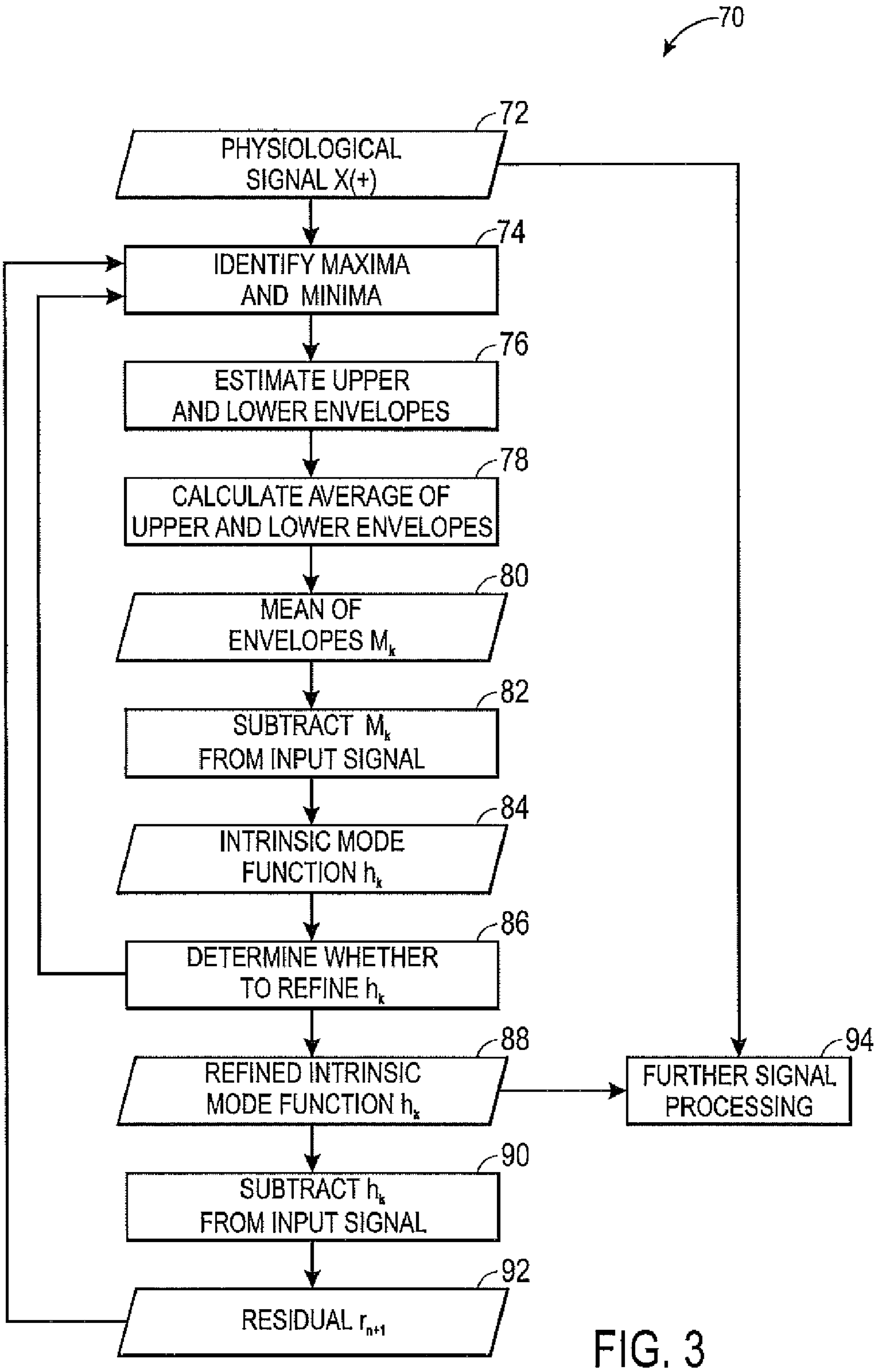
70
72
PHYSIOLOGICAL SIGNAL X(+)
74
IDENTIFY MAXIMA AND MINIMA
76
ESTIMATE UPPER AND LOWER ENVELOPES
78
CALCULATE AVERAGE OF UPPER AND LOWER ENVELOPES
80
MEAN OF ENVELOPES M_k
82
SUBTRACT M_k FROM INPUT SIGNAL
84
INTRINSIC MODE FUNCTION h_k
86
DETERMINE WHETHER TO REFINE h_k
88
REFINED INTRINSIC MODE FUNCTION h_k
94
FURTHER SIGNAL PROCESSING
90
SUBTRACT h_k FROM INPUT SIGNAL
92
RESIDUAL r_{n+1}

FIG. 3

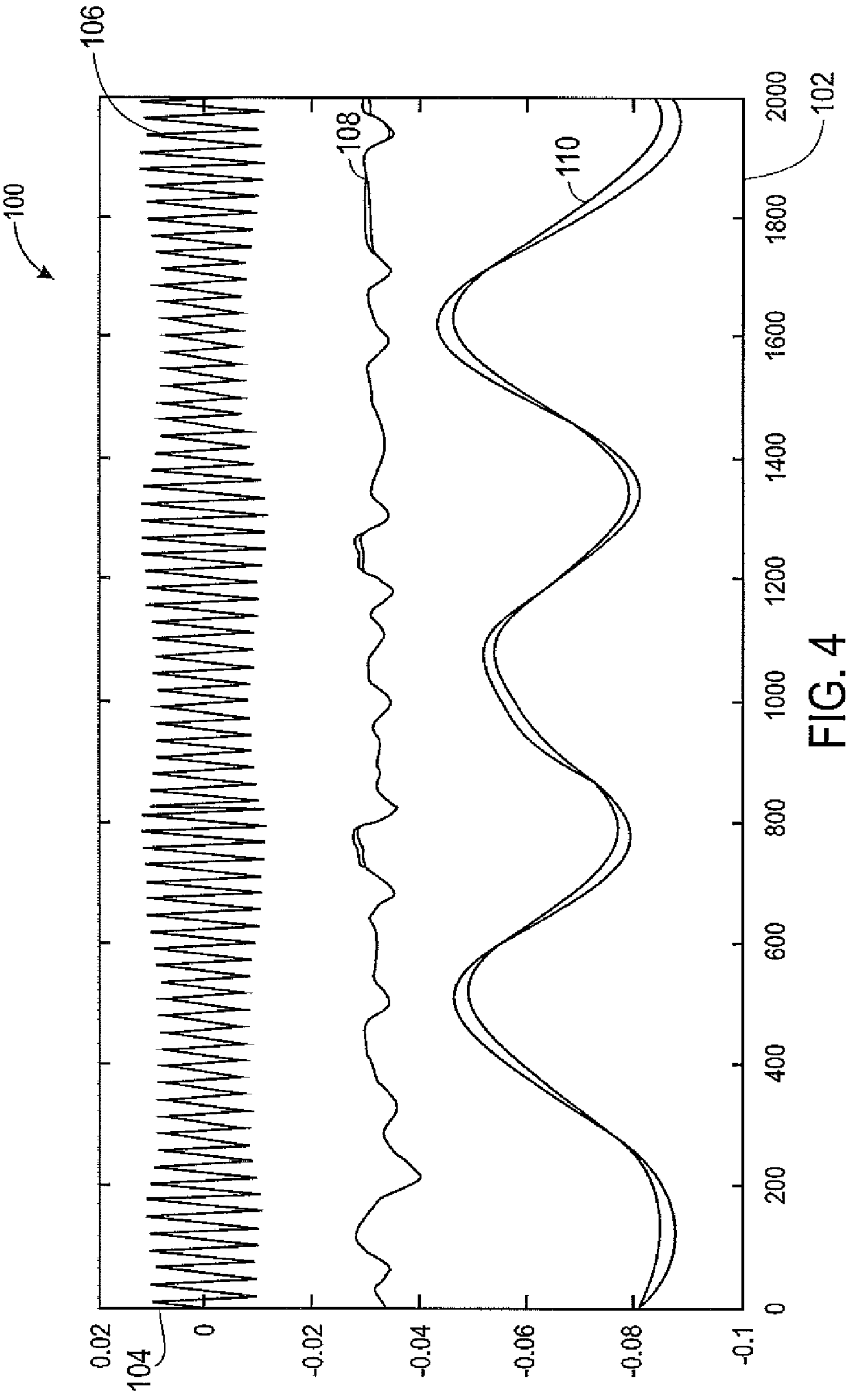
100
106
108
110
102
104
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
0
200
400
600
800
1000
1200
1400
1600
1800
2000

FIG. 4

PHOTOPLETHYSMOGRAPH FILTERING USING EMPIRICAL MODE DECOMPOSITION

BACKGROUND

[0001] The present disclosure relates generally to non-invasive measurement of physiological parameters and, more particularly, using empirical mode decomposition to process physiological signals.

[0002] This section is intended to introduce the reader to various aspects of art that may be related to various aspects of the present disclosure, which are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present disclosure. Accordingly, it should be understood that these statements are to be read in this light, and not as admissions of prior art.

[0003] Pulse oximetry may be defined as a non-invasive technique that facilitates monitoring of a patient's blood flow characteristics. Specifically, these blood flow characteristic measurements may be acquired using a non-invasive sensor that passes light through a portion of a patient's tissue and photo-electrically senses the absorption and scattering of the light through the tissue. One or more physiological characteristics may then be calculated based upon the amount of light absorbed or scattered. More specifically, the light passed through the tissue is typically selected to be of one or more wavelengths that may be absorbed or scattered by the blood in an amount correlative to the amount of the blood constituent present in the blood. The amount of light absorbed and/or scattered, which may be referred to as a plethysmograph waveform or a pulse oximetry signal, may then be used to estimate, for example, blood oxygen saturation of hemoglobin in a patient's arterial blood and/or the patient's heart rate.

[0004] However, typical algorithms used to calculate heart rate and/or blood oxygen saturation may not determine other physiological information which may be determinable from the plethysmograph waveform. In fact, as many physiological conditions may affect a patient's blood flow characteristics, the plethysmograph waveform may have signal characteristics which reflect various other physiological conditions. For example, in addition to oscillatory patterns corresponding to heart rate which may be found in the plethysmograph waveform, other oscillatory patterns which provide information on conditions such as respiratory rate, respiratory effort, heart arrhythmia, etc. may also be found in the plethysmograph waveform.

SUMMARY

[0005] Certain aspects commensurate in scope with the originally disclosed embodiments are set forth below. It should be understood that these aspects are presented merely to provide the reader with a brief summary of certain forms the embodiments might take and that these aspects are not intended to limit the scope of the presently disclosed subject matter. Indeed, the embodiments may encompass a variety of aspects that may not be set forth below.

[0006] Present embodiments relate to systems, methods, and devices for decomposing a physiological signal of a patient using empirical mode decomposition (EMD). In one embodiment, the EMD algorithm may involve identifying a frequency component, referred to as an intrinsic mode function, in the physiological signal. The physiological signal may be decomposed into one or more intrinsic mode functions through multiple iterations of the EMD algorithm. Each subsequent mode function may have a different frequency component of the original physiological signal input into the EMD algorithm. Further, each mode function may be analyzed and/or processed to determine various physiological data corresponding to blood flow in the patient.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Advantages of the presently disclosed subject matter may become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0008] FIG. **1** is a perspective view of a pulse oximeter system in accordance with an embodiment;

[0009] FIG. **2** is a block diagram of the pulse oximeter system of FIG. **1**, in accordance with an embodiment;

[0010] FIG. **3** is a flow chart depicting a process for use by the system of FIG. **1** for decomposing a physiological signal using empirical mode decomposition, in accordance with an embodiment; and

[0011] FIG. **4** is a plot representing intrinsic mode functions obtained using the process of FIG. **3** on a physiological signal, in accordance with an embodiment.

DETAILED DESCRIPTION

[0012] One or more specific embodiments of the present disclosure will be described below. In an effort to provide a concise description of these embodiments, not all features of an actual implementation are described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

[0013] Present embodiments relate to systems and methods of processing physiological signals corresponding to blood flow in a patient. Specifically, empirical mode decomposition ("EMD") techniques may be applied to a physiological signal of the patient to decompose the signal into one or more components. The components decomposed from a signal may be referred to as "intrinsic mode functions," which may each include a different frequency component of the original signal. Thus, each intrinsic mode function decomposed from a physiological signal may correspond to a physiological condition of the patient, including, for example, a pulse rate, respiratory rate, respiratory effort, sympathetic nervous activity, or any other repetitive variation affecting the patient's blood flow characteristics.

[0014] EMD may decompose a physiological signal, such that frequency components of the physiological signal (i.e., the intrinsic mode functions) may be analyzed within the time domain. In particular, the intrinsic mode functions may be analyzed with respect to time, such that the scale and frequency content of each mode function may vary in time. Furthermore, in accordance with the present techniques, the decomposition of the physiological signal is based only on the signal itself, and not on any predetermined frequencies or basis functions. Thus, the intrinsic mode functions obtained from the physiological signal represent the original frequency and scale content of the physiological signal with respect to time.

[0015] Using EMD may be particularly useful for physiological signals which may include frequency variations attributable to any number of physiological causes (e.g., pulse variations, respiratory variations, etc.). Such variations in a physiological signal may occur at specific times or in specific intervals, and analyzing the variations in the time domain may enable the determination of different causes for the variations in the physiological signal. Thus, EMD techniques may provide further physiological information not available under other methods of signal processing which transform time-domain signals out of the time domain and into the frequency domain or wavelet domain. For example, time information may not be preserved when using Fourier transforms, and certain physiological information may not be attainable by using only Fourier transforms to analyze a physiological signal.

[0016] A physiological signal may include a plethysmographic waveform, a pulse oximetry signal, or any other signal corresponding to blood flow in a patient. Physiological information determined from a physiological signal may include any repetitive variation in the patient which affects blood flow characteristics of the patient. For example, physiological information may include a pulse beat, respiratory rate, respiratory effort, sympathetic nervous activity, etc. Physiological information may also include less predictable variations corresponding to a patient's blood flow, which may be used to indicate heart arrhythmia or other heart irregularities.

[0017] In one embodiment, a physiological signal such as a pulse oximetry signal may be obtained from a patient by using a pulse oximetry system. FIG. **1** illustrates a perspective view of a pulse oximetry system **10**, which may include a patient monitor **12** and a pulse oximeter sensor **14**. A sensor cable **16** may connect the sensor **14** to the patient monitor **12** via an electrical or optical connection **18**. The sensor **14** may include an emitter **22** and a detector **24**. The emitter **22** may emit a light beam into the pulsatile tissue of a patient **26**. The emitted light may propagate through the pulsatile tissue, and the detector **24** may receive a resulting waveform from the pulsatile tissue of the patient **26** and guide the received waveform back to the patient monitor **12** via the sensor cable **16**. The sensor **14** may be, for example, a reflectance-type sensor or a transmission-type sensor. Based on signals received from the sensor **14**, the patient monitor **12** may determine certain physiological parameters that may appear on a display **20**.

[0018] A simplified block diagram of a pulse oximeter system **10** is illustrated in FIG. **2**, in accordance with an embodiment. Specifically, certain components of the sensor **14** and the monitor **12** are illustrated in FIG. **2**. The sensor **14** may include an emitter **22**, a detector **24**, and an encoder **28**. The emitter **22** may be capable of emitting at least two wavelengths of light, e.g., RED and infrared (IR) light, into the tissue of a patient **26**, where the RED wavelength may be between about 600 nanometers (nm) and about 700 nm, and the IR wavelength may be between about 800 nm and about 1000 nm. The emitter **22** may include a single emitting device, for example, with two light emitting diodes (LEDs) or the emitter **22** may include a plurality of emitting devices with, for example, multiple LED's at various locations. Regardless of the number of emitting devices, the emitter **22** may be used to measure, for example, water fractions, hematocrit, or other physiologic parameters of the patient **26**. As used herein, the term "light" may refer to one or more of ultrasound, radio, microwave, millimeter wave, infrared, visible, ultraviolet, gamma ray or X-ray electromagnetic radiation, and may also include modulated light, such as light modulated at sufficiently high frequencies (e.g., approximately 50 MHz to 3.0 GHz) to cause resolvable photon density waves to propagate through the patient's **26** tissue.

[0019] In one embodiment, the detector **24** may be capable of detecting light at various intensities and wavelengths. In operation, light enters the detector **24** after propagating through the tissue of the patient **26**. The detector **24** may convert the light at a given intensity, which may be directly related to the absorbance and/or reflectance of light in the tissue of the patient **26**, into an electrical signal. That is, when more light at a certain wavelength is absorbed or reflected, less light of that wavelength is typically received from the tissue by the detector **24**. After converting the received light to an electrical signal, the detector **24** may send the signal to the monitor **12**, where physiological characteristics may be calculated based at least in part on the absorption of light in the tissue of the patient **26**. In some embodiments, physiological characteristics may also be calculated based in part on the scattering of light in the tissue of the patient **26**. Furthermore, physiological characteristics may be determined based on one or more signal characteristics (oscillatory patterns) of the signal. The electrical signal converted by the detector **24** may also be referred to as a physiological signal, and may be in the form of a plethysmogram or any other representation corresponding to the light received from the patient **26** at the detector **24**.

[0020] The sensor **14** may also include an encoder **28**, which may contain information about the sensor **14**, such as what type of sensor it is (e.g., whether the sensor is intended for placement on a forehead or digit) and the wavelengths of light emitted by the emitter **22**. This information may allow the monitor **12** to select appropriate algorithms and/or calibration coefficients or to derive a filter for estimating the patient's physiological characteristics. The encoder **28** may, for instance, be a memory on which one or more of the following information may be stored for communication to the monitor **102**. In some embodiments, the data or signal from the encoder **28** may be decoded by a detector/decoder **30** in the monitor **12**.

[0021] Signals from the detector **24** and the encoder **28** may be transmitted to the monitor **12**. The monitor **12** may include one or more processors **32** coupled to an internal bus **34**. Also connected to the bus may be a RAM memory **36**, ROM memory **56**, and a display **38**. A time processing unit (TPU) **40** may provide timing control signals to light drive circuitry **42**, which controls when the emitter **22** is activated, and if multiple light sources are used, the multiplexed timing for the different light sources. TPU **40** may also control the gating-in of signals from detector **24** through a switching circuit **44**. These signals are sampled at the proper time, depending at least in part upon which of multiple light sources is activated, if multiple light sources are used. The received signal from the detector **24** may be passed through an amplifier **46**, an analog filter **48**, and an analog-to-digital (A/D) converter **50**, and/or a digital filter **52** for amplifying, filtering, digitizing, and/or processing the electrical signals from the sensor **14**. After amplifying, filtering, digitizing, and/or processing, the digital data may then be stored in a queued serial module

(QSM) **54**, for later downloading to RAM **36** as QSM **54** fills up. In an embodiment, there may be multiple parallel paths for separate amplifiers, filters, and A/D converters for multiple light wavelengths or spectra received.

[0022] In some embodiments, based at least in part upon the physiological signal corresponding to the light provided by the detector **24**, the processor **32** may use various algorithms to determine physiological information. The processor **32** may also access memory (e.g., RAM **36** or ROM **56**) to access stored algorithms. In one or more embodiments, the processor **32** may apply algorithms such as empirical mode decomposition (EMD) algorithms, to extract frequency components from the physiological signal. The frequency components, also referred to as intrinsic mode functions or mode functions, may be analyzed to determine physiological information including, for example, pulse beat, respiration rate, respiratory effort, sympathetic nervous activity, or any other repetitive variation in heart rhythm.

[0023] One embodiment of a process **70** for applying an empirical mode decomposition (EMD) algorithm to obtain intrinsic mode functions from a physiological signal is provided as a flow chart in FIG. **3**. The process **70** may be applied to any physiological signal X(t) **72**, including a pulse oximetry signal, a plethysmographic signal, or any other signal corresponding to blood flow in a patient. The physiological signal X(t) **72** may be a portion of the digitized signal generated by the detector **24** in the system **10** (as in FIG. **1**). For example, the physiological signal X(t) **72** may span a window of time and may include certain number of samples. The window size of the physiological signal X(t) **72** may be selected by the processor **32**, and may be based on the sampling interval of the detector **24** and/or a desired sample size of the physiological signal X(t) **72** to be decomposed. Furthermore, in some embodiments, the process **70** may be performed on overlapping time windows (e.g., a 20 second window that advances every second).

[0024] The process **70** may determine (block **74**) the local maxima and minima of the input signal X(t) **72**. The determination (block **74**) of the local maxima and minima may be based on the type of intrinsic mode function to be extracted. For example, if an intrinsic mode function corresponding to a pulse rate is to be extracted from the physiological signal X(t) **72**, the determination of the local maxima and minima may be designed to ignore artifacts substantially smaller than a typical or recent pulse amplitude. The physiological signal X(t) **72** may also include physiological signal characteristics which may not be useful in determining the pulse rate. For example, the dicrotic notch may not be a relevant signal characteristic for determining pulse rate. Thus, when the process **70** is extracting an intrinsic mode function corresponding to pulse rate, the determination (block **74**) of the local maxima and minima of the physiological signal X(t) **72** may also be designed to ignore the dicrotic notch. Accounting for and ignoring artifacts and/or non-relevant physiological signal characteristics may be performed by the processor **32** using filters or any other suitable signal processing techniques. For embodiments involving multiple signals (e.g., multiple wavelength signals and/or signals from multiple detectors), timing information and clock cycles for the samples from each signal may be used to differentiate the multiple signals, such that the local maxima and minima of each of the multiple signals may be identified. As will be discussed, the process **70** may have more than one iteration using the output of the process **70** as a new input, and criteria for determining (block **74**) the local maxima and minima may be modified at each subsequent iteration.

[0025] Furthermore, for embodiments using overlapping time windows, determining (block **74**) the local maxima and minima of the physiological signal X(t) **72** may also involve using the maxima and minima information already determined in a previous time window. The previously determined maxima and minima may be compared with the new samples in the non-overlapping portion of the new window. Such a technique may save time in searching a previously analyzed window for local maxima and minima.

[0026] Once the local maxima and minima of the physiological signal X(t) **72** are identified, the process **70** may estimate (block **76**) upper and lower envelopes based on the local maxima and minima. In one embodiment, upper and lower envelopes may be constructed by fitting cubic splines to the identified maxima and minima of the physiological signal X(t) **72**. In estimating (block **76**) the upper and lower envelopes, the process **70** may account for local maxima and minima not occurring at the beginning and/or end of the window of physiological signal X(t) **72**. For example, estimating (block **76**) the upper and lower envelopes may duplicate the nearest identified maxima and minima at the beginning and/or end of the data window. In estimating (block **76**) the upper and lower envelopes, the process may also compensate for changes in the physiological signal X(t) **72** which may be due to non-physiological causes, such as adjustments of the internal gain of the pulse oximetry system **10**, adjustments in the source intensity (e.g., from the emitter **22** and/or light drive **42** of the system **10**), and/or periods of interruption in the physiological signal, such as during sensor **14** adjustments or during periods when the sensor **14** is disconnected. Furthermore, in embodiments involving multiple signals (e.g., multiple wavelength signals and/or signals from multiple detectors), timing information and clock cycles for the samples from each signal may be used, such that cubic splines may be fitted for the appropriate data values of each respective signal.

[0027] Once the upper and lower envelopes have been estimated (block **76**), the process **70** may then calculate (block **78**) the mean m_k **80** of the upper and lower envelopes. By subtracting (block **82**) the mean m_k **80** of the upper and lower envelopes from the original physiological signal X(t) **72**, the process **70** produces an intrinsic mode function h_k **84**. This relationship is represented in equation (1), below:

$$X(t)-m_k=h_k \qquad \text{equation (1)}$$

[0028] By definition, the intrinsic mode function h_k **84** may have the same number of extrema (i.e., maxima and minima) as the physiological signal X(t) **72**, and may represent an oscillatory mode of the physiological signal X(t) **72**. As discussed, the physiological signal X(t) **72** may be a representation of blood flow in a patient **26**, which may include one or more oscillatory patterns (e.g., oscillatory concentrations of blood cells, oscillatory ratios of oxygenated to deoxygenated hemoglobin, etc.) resulting from certain physiological conditions of the patient **26**. The empirical mode decomposition process **70** may identify such repeating signal characteristics by decomposing the physiological signal X(t) **72** into intrinsic mode functions h_k **84**. As a intrinsic mode function h_k **84** is decomposed from the original physiological signal X(t) **72** without leaving the time domain, the original scale of the intrinsic mode function h_k **84** may be preserved in time. Thus, in some embodiments, the intrinsic mode function h_k **84** may be further analyzed and/or processed with respect to time. Retaining time information may be valuable when analyzing physiological signals, as the timing of physiological causes may be important in identifying certain conditions of the patient **26**.

[0029] In some embodiments, the process **70** may include iterative refinement of each intrinsic mode function h_k **84**, which may involve repeating the steps **74**, **76**, **78**, and **82** until the process determines (block **86**) that the intrinsic mode function h_k **84** is refined. If the intrinsic mode function h_k **84** is determined to be not sufficiently refined, the intrinsic mode function h_k **84** may be subtracted from the input signal, and steps **74**, **76**, **78**, and **82** may be performed on the residual of this subtraction. Iterations of this portion of the process **70** may be performed until the intrinsic mode function h_k **84** is sufficiently refined.

[0030] Determining (block **86**) whether the intrinsic mode function h_k **84** is sufficiently refined may involve comparing a statistical measure of an intrinsic mode function h_k **84** to a predetermined threshold and/or to a statistical measure of an intrinsic mode function h_k **84** from a previous iteration (e.g., comparing statistical measures of h_2 and h_3). Such statistical measures may include calculating the kurtosis of an intrinsic mode function h_k **84**, which should asymptotically decrease as lower-frequency modes are decomposed from the signal. For example, a higher kurtosis may indicate that more of the variance of an intrinsic mode function h_k **84** is a result of relatively infrequent and extreme deviations (which may be more indicative of noise or other non-physiological conditions), as opposed to a more frequent and less extreme deviation (which may be more indicative of a physiological characteristic). Some embodiments may also involve statistical measures such as quantifying the variability in the amplitude, maxima, or minima of the input signal. Furthermore, some embodiments may include determining the number of minima, maxima, zero crossings, or any other indication of the number of cycles expressed by an intrinsic mode function h_k **84**.

[0031] In some embodiments, the skewness of the derivative of an intrinsic mode function h_k **84** may also be used to determine whether substantially all of the oscillatory content of the physiological signal X(t) **72** has been decomposed. For example, the skewness of the derivative of a mode should decrease as the physiological signal X(t) **72** waveform is refined and as mode estimates are decomposed from the signal X(t) **72**. Once the skewness of a mode estimate does not decrease when compared to a previous mode estimate, then the intrinsic mode function h_k **84** may be refined, as indicated by the refined intrinsic mode function h_k **88**. It should be noted that in some iterations of the process **70**, the intrinsic mode function h_k **84** may be determined (block **86**) to be sufficiently refined. Thus, in some iterations of the process **70**, the intrinsic mode function h_k **84** may be the same as the refined intrinsic mode function h_k **88**, and the refined intrinsic mode function h_k **88** may simply be referred to henceforth as the intrinsic mode function h_k **88**.

[0032] The process **70** may involve finding more than one intrinsic mode function h_k **88**, as a patient's **26** blood flow may be affected by more than one system (e.g., circulatory system and respiratory system), and the physiological signal X(t) **72** may include more than one oscillatory mode. For example, the first intrinsic mode function h_k **88** found from the physiological signal X(t) **72** may be referred to as an intrinsic mode function h_0. To find a subsequent intrinsic mode function h_1, the intrinsic mode function h_0 may be subtracted (block **90**) from the original physiological signal X(t) **72**, resulting in the residual r_{n+1} **92**, as represented in the equation below:

$$X(t)-h_k=r_{n+1} \qquad \text{equation (2)}$$

[0033] The residual r_{n+1} **92** may then be used as the input signal for each subsequent iteration (where the k of h_k represents the iteration number) of the process **70**, and the maxima and minima of the residual r_{n+1} **92** may be identified (block **74**). As discussed, the maxima and minima identification for each subsequent residual r_{n+1} **92** may be modified according to typical characteristics of the physiological signal X(t) **72**, the number of iterations k, the number of intrinsic mode functions h_k **88** already calculated, and/or the type of intrinsic mode function h_k **88** to be extracted from the physiological signal X(t) **72**.

[0034] As the intrinsic mode function h_0 has already been subtracted (block **90**) from the physiological signal X(t) **72** to produce the residual r_{n+1} **92**, the remaining features in the residual may be less extreme than the features of the physiological signal X(t) **72**. For example, the maxima identified in the residual r_{n+1} **92** may be smaller than the previously identified maxima of the physiological signal X(t) **72**, and the minima identified in the residual r_{n+1} **92** may be larger than the previously identified minima of the physiological signal X(t) **72**. Thus, subsequent iteration of the process **70** (iteration k=1) on the residual r_{n+1} **92** may produce an intrinsic mode function h_1 having a lower order frequency compared to the first intrinsic mode function h_0. Each subsequent intrinsic mode function h_k **88** may represent a progressively lower order frequency component of the physiological signal X(t) **72**, and the sum of all identified intrinsic mode functions h_k **88** of a physiological signal X(t) **72** may be approximately equal to the total oscillatory content of the physiological signal X(t) **72**. In other words, each subsequent iteration of the EMD algorithm may produce an intrinsic mode function h_k **88** having the next most distinguishing features of the physiological signal X(t) **72**, and when the physiological signal X(t) **72** has been refined (i.e., decomposed), all of the distinguishing features may be extracted in the form of intrinsic mode functions h_k **88**.

[0035] In some embodiments, the process **70** may continue until substantially all of the oscillatory content of the physiological signal X(t) **72** is decomposed into intrinsic mode functions h_k **88**. For example, methods of determining whether substantially all of the oscillatory content in the physiological signal X(t) **72** waveform has been sufficiently decomposed may involve analyzing each residual r_{n+1} **92** and determining whether the residual r_{n+1} **92** is smaller than a predetermined value, or whether it is a monotonic function. If the residual r_{n+1} **92** is smaller than a predetermined value and/or if the residual r_{n+1} **92** is a monotonic function, then the process **70** may have identified substantially all the intrinsic mode functions h_k **84** of the physiological signal X(t) **72**.

[0036] In one embodiment, the number of iterations in the process **70** (and the number of intrinsic mode functions h_k **88** extracted) may also be based on the type of physiological information to be determined from the intrinsic mode functions h_k **88**. For example, the process **70** may have substantially refined the physiological signal X(t) **72** once all relevant intrinsic mode functions h_k **88** have been extracted. In some embodiments, the process **70** may still continue to provide further estimations of intrinsic mode functions h_k **88** to account for changes in the signal detected by the detector **24**

(e.g., signal interruptions, system **10** changes, etc.), and/or to provide more accurate estimates of the intrinsic mode functions h_k **88**.

[0037] Performing the process **70** on a physiological signal may decompose the signal into multiple intrinsic mode functions h_k **88**. In some embodiments, the multiple intrinsic mode functions h_k **88** may each be further processed (block **94**) to determine various physiological information, if any, indicated by each extracted mode function. In accordance with the present techniques, any suitable signal processing techniques may be combined with the EMD algorithm to further enhance the utilization of the intrinsic mode functions and/or aid in the determination of physiological parameters and indications. Signal processing may be performed on any extracted mode function, and may include comparisons of any mode function with a pre-decomposed physiological signal.

[0038] Signal processing may be performed by any suitable processor (e.g., microprocessor **32**) in the system **10**, and may include other elements in the system **10** (FIG. **2**). For example, signal processing techniques may include calibration of the system **10**, power-saving techniques, multiplexing, amplification, and/or digitization of signals. Specific conditions of the system **10** and/or the patient **26** from which a physiological signal is being measured may also be used to process signals in some embodiments. For example, calculations may be made based on a type of sensor **14** used, a measurement site of the sensor **14** on the patient **26**, and/or a physiological condition of a patient **26**. Determinations may also be made as to whether the sensor **14** is applied to an appropriate tissue site on the patient **26**. In addition, certain physiologic assumptions may also be used, including limits on typical and/or possible ranges of a physiological parameter or a rate of change of a physiological parameter.

[0039] In some embodiments, signal processing techniques (block **94**) may also involve linear and/or non-linear filters which may be adjustable or adaptable based on one or more metrics, trends, patterns, and/or distributions of the inputs or outputs of the filters. Such filters may include, for example, Kalman filters, adaptive comb filters, adaptive noise cancellers, joint process filters, and lattice filters. Furthermore, a physiological signal and/or a mode function of the physiological signal may be normalized, resealed, and/or transformed in the frequency and/or wavelet domains. Various techniques may also be used for computing ratios or other combinations of the components (e.g. from multiple wavelengths or detectors) of the physiological signal or intrinsic mode functions extracted from the physiological signal. For example, such techniques may include linear regression, linear combination, multivariate analysis, principal component analysis (PCA), other suitable matrix techniques, or independent component analysis (ICA). Furthermore, signal processing techniques may include use of neural nets, fuzzy logic, genetic-based algorithms, or any other learning-based algorithms. Analysis of parallel or alternative estimates or algorithms, such as a Hidden Markov Model, may also be used.

[0040] Signal processing techniques (block **94**) may include the combination of a physiological signal with additional sensors, including motion, pressure, temperature, or ultrasound sensors. The additional sensors may provide data to be used with the physiological signal which may aid in distinguishing physiological signals from artifacts or other non-physiological components. Furthermore, the empirical mode decomposition algorithm used herein may be used along with Hilbert Spectral Analysis in the Hilbert-Huang Transform, but is not limited to this combination of techniques.

[0041] Turning now to FIG. **4**, the graph **100** provides examples of three intrinsic mode functions which may be decomposed from a physiological signal. The graph **100** depicts the amplitude **104** and time course of each mode function **106**, **108**, and **110** over 2000 samples **102**. For example, the sampling interval may be approximately 17.5 ms, and a 2000 sample window may be approximately 35 seconds long. A first mode function **106** may typically represent the pulse rate, which may be approximately 100 beats per minute. The first mode function **106** may have the highest degree of oscillatory content in the physiological signal from which it has been decomposed.

[0042] The second mode function **108** illustrated in the graph **100** may represent another repetitive variation in heart rhythm. For example, the second mode function **108** may contain indications of arrhythmia, and could contain a waveform at approximately half the frequency of a pulse rate. Analyzing the waveform of the extracted mode function may also enable a health practitioner to determine clinical conditions, such as, for example, bi-Gemini, which may appear as alternating large and small pulses. Furthermore, in the absence of waveform characteristics indicative of heart rhythm, the second mode function **108** may also indicate the patient's **26** respiration, as respiratory related changes in intra-thoracic pressure may also impact the rate at which venous blood flows from peripheral to central venous circulation. The third mode function **110** may contain a waveform indicative of the patient's **26** respiration, if respiration is not already contained in a previous mode function. Alternatively, the third mode function **110** could reflect sympathetic nervous activity, such as Mayer waves.

[0043] The physiological information determined based on each mode function may not always follow a particular order, and may follow a different order from the examples given above. Further, not all extracted mode functions may provide physiological information. For example, in some situations, the decomposition of any of the mode functions may sometimes be affected by artifacts which may be mistaken for maxima and minima. Such motion artifacts may appear in any mode, depending on their frequency content and the relationship of their frequency to that of physiological signals. For example, high-frequency artifacts may appear in a first mode function. Such artifacts may be identified and/or reduced by using signal processing techniques as discussed with respect to FIG. **3**.

[0044] Furthermore, physiological parameters and indications may not be limited to the examples provided, and may include any physiological condition capable of affecting a patient's blood flow characteristics. For example, a physiological parameter or indication which may be determined using the present techniques may include arterial or venous oxygen saturation, pulse rate, continuous non-invasive blood pressure, pulse transit time, respiratory rate or effort, pulse amplitude, tissue perfusion, hypoxia, hyperoxia, bradycardia, tachycardia, arrhythmia, central or obstructive apnea, hypopnea, Cheyne-Stokes syndrome, hypovolemia, or sympathetic nervous activity (e.g., Mayer waves).

[0045] While the embodiments set forth in the present disclosure may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the disclosure is not intended to be limited to the particular forms disclosed. The disclosure is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosure as defined by the following appended claims.

What is claimed is:

1. A method comprising:

applying an empirical mode decomposition (EMD) algorithm on a physiological signal to produce one or more intrinsic mode functions, wherein the physiological signal corresponds to blood flow in a patient; and

determining one or more physiological parameters based on the one or more intrinsic mode functions.

2. The method of claim **1**, wherein applying the EMD algorithm comprises:

identifying a maxima and a minima of the physiological signal;

calculating an upper envelope and a lower envelope based on the maxima and the minima; and

subtracting a mean of the upper envelope and the lower envelope from the physiological signal to produce a first mode of the one or more intrinsic mode functions.

3. The method of claim **2**, wherein determining one or more physiological parameters comprises determining a pulse rate of the patient based on the first mode.

4. The method of claim **2**, comprising:

subtracting the first mode from the physiological signal to produce a residual;

identifying a maxima and a minima of the residual;

calculating an upper envelope and a lower envelope of the residual based on the maxima and the minima of the residual; and

subtracting a mean of the upper envelope and the lower envelope of the residual to produce a second mode of the one or more intrinsic functions.

5. The method of claim **4**, wherein determining one or more physiological parameters comprises determining a heart arrhythmia or a respiratory rate of the patient based on the second mode.

6. The method of claim **1**, comprising processing the one or more intrinsic mode functions by performing one or more of multiplexing, amplifying, digitizing, filtering, normalizing, resealing, and transforming the one or more intrinsic mode functions.

7. The method of claim **1**, wherein determining the one or more physiological parameters comprises computing a ratio of pulse amplitudes by using one or more of linear regression techniques, linear combination techniques, multivariate analysis, principal component analysis, and independent component analysis.

8. The method of claim **1**, wherein the one or more physiological parameters comprises one or more of arterial or venous oxygen saturation, pulse rate, continuous non-invasive blood pressure, pulse transit time, respiratory rate or effort, pulse amplitude, tissue perfusion, hypoxia, hyperoxia, bradycardia, tachycardia, arrhythmia, central or obstructive apnea, hypopnea, Cheyne-Stokes syndrome, hypovolemia, and sympathetic nervous activity.

9. A method of determining physiological information of a patient comprising:

identifying extrema in an input signal, wherein the input signal comprises a portion of a physiological signal of the patient;

calculating input signal envelopes based on the extrema of the input signal;

subtracting a mean of the input signal envelopes from the input signal to produce a first mode function;

subtracting the first mode function from the input signal to produce a residual signal;

identifying extrema in the residual signal;

calculating residual signal envelopes based on the extrema of the residual signal;

subtracting a mean of the residual signal envelopes from the residual signal to produce a second mode function; and

determining physiological information of the patient based on one or more of the first mode function and the second mode function.

10. The method of claim **9**, wherein the input signal comprises a time window of samples from the physiological signal.

11. The method of claim **10**, wherein the method is performed on a subsequent time window of samples from the physiological signal, wherein the subsequent time window overlaps with the time window.

12. The method of claim **9**, wherein identifying the extrema in the input signal comprises ignoring samples in the input signal corresponding to a dicrotic notch of the patient.

13. The method of claim **9**, wherein identifying the extrema in the input signal and identifying the extrema in the residual signal comprises ignoring samples not relevant to the physiological information to be determined by the first mode function and the second mode function.

14. The method of claim **9**, wherein a variance of the second mode function is compared with a variance of the first mode function, and wherein an additional iteration is performed to produce a refined second mode function if the variance of the second mode function is less than the variance of the first mode function, wherein the additional iteration comprises:

subtracting the second mode function from the residual signal to produce a second residual;

identifying extrema in the second residual;

calculating second residual envelopes based on the extrema of the second residual; and

subtracting a mean of the second residual envelopes from the second residual to produce a refined second mode function.

15. The method of claim **9**, comprising:

determining whether to refine the first mode function based on a comparison of statistical measures of the first mode function with threshold statistical measures; and

performing one or more iterations to produce a refined first mode function, wherein the one or more iterations each comprise:

- subtracting the first mode function from the input signal to produce an unrefined residual signal;
- identifying extrema in the unrefined residual signal;
- calculating unrefined residual signal envelopes based on the extrema of the unrefined residual signal; and
- subtracting a mean of the unrefined residual signal envelopes from the unrefined residual signal to produce a refined first mode function.

16. The method of claim **15**, wherein the statistical measures comprise one or more of a variance, a kurtoses, a skewness, a number of minima, a number of maxima, a number of zero crossings, and a number of cycles of the first mode function.

17. The method of claim **9**, comprising calculating subsequent mode functions until a number of cycles of a mode function is below a threshold.

18. The method of claim **9**, wherein determining physiological information of the patient comprises comparing one or more of the first mode function, the second mode function, and the input signal.

19. A system for determining physiological information of a patient, the system comprising:

a sensor configured to detect a physiological signal from the patient;

a patient monitor coupled to the sensor, wherein the patient monitor comprises:

a processor configured to apply an empirical mode decomposition (EMD) algorithm on the physiological signal to produce one or more intrinsic mode functions; and

a processor configured to process the one or more intrinsic mode functions to determine one or more physiological parameters.

20. The system of claim **19**, wherein the processor is configured to apply the EMD algorithm iteratively on the physiological signal to produce subsequent intrinsic mode functions.

21. The system of claim **19**, wherein the processor is configured to iteratively apply the EMD algorithm on the physiological signal until the one or more intrinsic mode functions represent substantially all physiological oscillations in the physiological signal.

22. The system of claim **19**, wherein the processor is configured to:

calculate statistical measures of the one or more intrinsic mode functions;

compare the calculated statistical measures with threshold statistical measures;

determine whether each of the one or more intrinsic mode functions is sufficiently refined based on the comparison; and

iteratively apply portions of the EMD algorithm on each of the one or more intrinsic mode functions until each of the one or more intrinsic mode functions is determined to be sufficiently refined.

23. The system of claim **19**, wherein the processor is configured to compare a first mode of the one or more intrinsic mode functions with a second mode of the one or more intrinsic mode functions, and wherein the processor is configured to produce a third mode of the one or more intrinsic mode functions based on a comparison of the first mode and the second mode.

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专利名称(译)	基于经验模式分解的光电容积描记器滤波		
公开(公告)号	US20110245628A1	公开(公告)日	2011-10-06
申请号	US12/751274	申请日	2010-03-31
[标]申请(专利权)人(译)	内尔科尔普里坦贝内特公司		
申请(专利权)人(译)	NELLCOR PURITAN BENNETT LLC		
当前申请(专利权)人(译)	COVIDIEN LP		
[标]发明人	BAKER JR CLARK R MCKENNA EDWARD M PETERS DANIEL LI YOUZHI		
发明人	BAKER, JR., CLARK R. MCKENNA, EDWARD M. PETERS, DANIEL LI, YOUZHI		
IPC分类号	A61B5/024 A61B5/026 A61B5/02 A61B5/08 A61B5/00		
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摘要(译)

本实施例涉及使用经验模式分解（EMD）来分解患者的生理信号的系统，方法和设备。在一个实施例中，EMD算法可以涉及识别生理信号中的频率分量，称为固有模式函数。可以通过EMD算法的多次迭代将生理信号分解成一个或多个固有模式函数。每个后续模式功能可以具有输入到EMD算法中的原始生理信号的不同频率分量。在一些实施例中，可以进一步分析和/或处理每个模式功能以确定与患者中的血流相对应的各种生理数据。