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(54) Title: SIGNAL PROCESSING MIRRORING TECHNIQUE

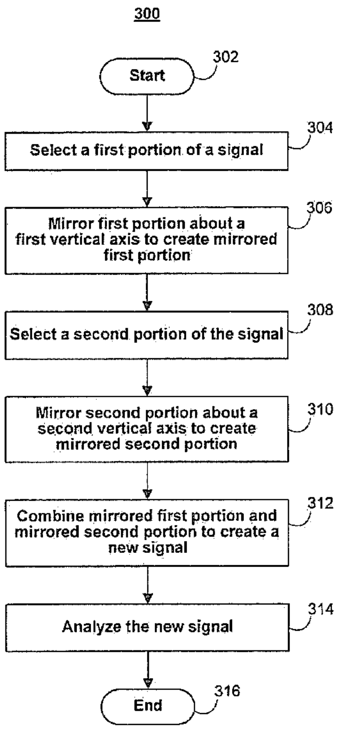

FIG. 5

(57) Abstract: Embodiments may include systems and methods capable of processing an original signal by selecting and mirroring portions of the signal to create a new signal for further analysis. In an embodiment, the signal may be a photoplethysmograph (PPG) signal and the new signal may be further analyzed using continuous wavelet transforms. Any suitable number of reconstructed new signals may be created from the original signal and scalograms may be derived at least in part from the new signals. Ridges may be extracted from the scalograms of the new signals and secondary scalograms may be further derived from the ridges. A sum along amplitudes technique may be applied to a selected scalogram and may be plotted as a function of the scale of the scalogram. Desired information, such as respiration information within the original signal, may be identified from the plot.

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Signal Processing Mirroring Technique

Cross-Reference to Related Applications

This application claims the benefit of United States Provisional Application No. 61/077,062, filed June 30, 2008 and United States Application No. 61/077,130, filed June 30, 2008, which are hereby incorporated by reference herein in their entireties.

Summary

The present disclosure relates to signal processing systems and methods, and more particularly, to systems and methods for processing an original signal by selecting and mirroring one or more portions of the original signal to create a new signal for further analysis.

In an embodiment, a signal may be selected and mirrored to create a new signal for further analysis. The signal may be from any suitable source and may contain one or more repetitive components. In an embodiment, the selected signal is a portion of the original signal. The portion may be selected using any suitable method based on its characteristics, or characteristics of the original signal (*e.g.*, using local maximum and minimum values, or using second derivatives to find one or more turning points, of the original signal). By selecting a portion of the original signal and mirroring that portion, undesirable artifacts caused by the non-selected portion of the signal during further analysis may be removed and other benefits may be achieved. In an embodiment, additional portions of the original signal may be selected, mirrored, and added to the new signal. Alternatively, separate new signals may be created from the various mirrored portions.

For purposes of illustration, and not by way of limitation, in an embodiment disclosed herein the original signal is a photoplethysmograph (PPG) signal obtained from any suitable source, such as a pulse oximeter, and selected portions are the up and down stroke of a pulse (a pulse is a portion of the PPG signal corresponding to a heart beat), which are used to create separate new signals for further analysis. Further analysis includes determining respiration rate from the PPG signal using Secondary Wavelet Feature Decoupling (SWFD) applied to the new signals. In an embodiment, mirroring up and down strokes to create separate new signals may result in an improved analysis of

the original PPG signal. Using a mirroring algorithm that includes forced symmetry (*e.g.*, mirroring a selected up stroke or down stroke about a desired axis creates a pulse that is symmetrical about that desired axis, and a new signal may be constructed from any suitable number of symmetrical pulses) may be beneficial because, for example, it removes undesired aspects of the original signal and improves the accuracy of the respiration rate determination. Using the mirroring algorithm may also significantly improve the number of samples, or the percentage of patient data, from which a patient's respiration rate may be determined effectively. Using the mirroring algorithm may further improve the standard deviation of the differences observed between computing the respiration rate using the mirroring algorithm and computing the respiration rate using another method (*e.g.*, by counting one or more respiration features in a patient's nasal thermistor signal). A tradeoff to using the mirroring algorithm, however, may include an increase in the amount of invalid data that may not be used to determine the patient's respiration rate. Data may be considered invalid if it is the result of excessive movement by a patient, or excessive changes in the spacing between a patient's heart beats or other excessive changes in the patient's heart rate. Data also may be considered invalid if the pulse oximeter probe has fallen off or become detached from the patient, or if the PPG signal is excessively corrupted due to noise.

In an embodiment, multiple up and down strokes are mirrored and combined to create new signals. The new signals are referred to herein as a "reconstructed up signal" for the series of pulses created from mirroring one or more up strokes selected from an original signal, or a "reconstructed down signal" for the series of pulses created from mirroring one or more down strokes selected from the original signal. The reconstruction process (i.e., the process of creating pulses by mirroring a series of selected up or down strokes, and creating a new signal from the pulses) may be performed in real time, using a time window smaller than the entire time window over which the original PPG signal may be collected, or the process may be performed offline, using the entire time window of data over which the PPG signal was collected.

Up and down strokes may be selected using any suitable approach. For example, one or more pulses of the original signal may be selected based upon maximum and minimum values of the signal, or using second derivatives to find one or more turning points of the original signal. In an embodiment, the PPG signal may be filtered using, for example, a bandpass or low pass filter to filter out frequencies higher and lower than the range of typical heart rates. Once a pulse is selected, its up stroke may be separated from its down stroke using any suitable method. For example, the up stroke may be separated from the down stroke at the point where the local maximum perpendicular to the two turning points may intersect the selected pulse.

In an embodiment, the reconstructed up and down signals may be further manipulated prior to further analysis. For example, each pulse of the mirrored signal may be expanded or shortened independently of the other pulses in the mirrored signals. For example, each of the pulses created by mirroring up or down strokes in the PPG embodiment may be stretched or compressed to make the time period for each pulse equal in size, where all of the time periods together equal the time period over which the original signal was collected or is being analyzed. Alternatively, each pulse of the mirrored signal may not be stretched to match a time period, but may instead be stretched or compressed to any desired size based at least in part on another time period or based at least in part on an individual or predetermined number of signal pulses. In an embodiment, for example, each mirrored up pulse may be stretched or compressed to match the size of the up stroke used in the mirroring combined with its corresponding down stroke. The same process may be performed on each mirrored down pulse. In an embodiment, the mirrored pulses may be equally stretched or compressed to match the time period over which the signal was collected or is being analyzed.

The frequency modulation that occurs when one or more of the pulses in the mirrored signals is stretched or compressed may be converted into amplitude modulation by increasing or decreasing the amplitude of each of the pulses in the mirrored signals in relation to the amount of individual stretching or compressing. This may increase the amplitude modulation that may already exist in the mirrored pulses due to, for example, baseline changes in an original PPG signal. Translating the effect of the frequency modulation into amplitude modulation within the mirrored signals may alter the effect of certain components within the original signal on the analysis of the original signal. The amplitude of, for example, the pulses in the mirrored signals may be modulated or augmented to create the reconstructed signals if each of the pulses was stretched or compressed independently of each other. Alternatively, the amplitude of each of the pulses in the mirrored signals may be the same if the frequency modulation applied to the mirrored signal stretched or compressed each pulse individually to create reconstructed signals with uniform amplitude. In an embodiment, the reconstructed signals may include pulses that may vary in amplitude and frequency.

The reconstructed up and down signals may be further analyzed using any suitable method, including for example (and as described below for purposes of illustration), SWFD. In an embodiment of the disclosure, only one reconstructed signal, instead of both reconstructed signals, may be analyzed. A primary up scalogram and a primary down scalogram may be derived at least in part from the reconstructed up signal and down signal using any suitable method. For example, the up scalogram and the down scalogram may be derived using continuous wavelet transforms, including using a mother wavelet of any suitable characteristic frequency or form such as the Morlet wavelet with a particular scaling factor value. The up scalogram and the down scalogram also may be derived over any suitable range of scales. The resultant up scalogram and down scalogram may include ridges corresponding to at least one area of increased energy that may be analyzed further using any suitable method, for example using secondary wavelet feature decoupling.

The up ridge and the down ridge of the up and down scalograms may be extracted using any suitable method. For example, the up ridge and the down ridge may represent that at a particular scale value, the PPG signal may contain high amplitudes corresponding to the characteristic frequency of that scale. By extracting and further analyzing the ridges, information concerning the nature of the signal component associated with the underlying physical process causing a primary band on the up and down scalograms may also be extracted when the primary band itself is, for example, obscured in the presence of noise or other erroneous signal features. Secondary wavelet feature decoupling may be applied to each of the up and down ridges to derive secondary up and down scalograms. The secondary wavelet feature decoupling technique may provide desired information about the primary band by examining the amplitude modulation of a secondary band, such amplitude modulation being based at least in part on the presence of the signal component in the PPG signal that may be related to the primary band. This secondary wavelet decomposition of the up and down ridges allows for information concerning the band of interest to be made available as secondary bands for each of the secondary up and down scalograms. The secondary up and down scalograms may be derived using wavelets within a range of scales from any suitable minimum value up to any suitable maximum value and may be derived using any suitable scaling factor value for the wavelet.

In an embodiment, secondary scalograms may be derived again at a lower scaling factor value so as to break up false ridges within the first set of secondary scalograms. The ridge fragments formed within the repeated secondary scalograms may be used to identify stable regions within the first set of secondary scalograms. The ridge fragments may be analyzed to select one or more desired ridges using any suitable method. For example, a time window that may vary both in width and in start position (e.g., start time) may be slid across the one or more up repeated scalograms and the one or more down repeated scalograms. The ridge fragments within the time window may be parameterized in terms of a weighting of the standard deviation of the path that the particular ridge fragment may take, in units of scale, the length of the ridge fragment, the proximity of the ridge fragment to other ridge fragments, and/or any other suitable weighting characteristics. The ridge having the highest weighting may be chosen for further processing. In an embodiment, the ridge having the highest weighting may be used to identify and select a stable region within one of the generated scalograms.

A sum along amplitudes technique may be applied to at least a portion of the band corresponding to the selected ridge or at least a portion (e.g., the identified stable region) of the selected secondary scalogram using any suitable method. The technique of applying a sum along amplitudes may be applied to any secondary wavelet feature decoupling method of any suitable original signal. Alternatively, the sum along amplitudes technique may be applied to the entire secondary up scalogram or secondary down scalogram. The sum along amplitudes technique also may be applied to any continuous wavelet transform of any suitable signal, such as a wavelet transform of the original PPG signal. The sum along amplitudes technique may sum the amplitudes (*e.g.*, the energy) for each scale within a range of scales across a time window. In an embodiment, the sum along amplitudes technique may be applied to a scalogram composite, or a superposition formed from the secondary scalograms. The sum along amplitudes function may be plotted as a function of any suitable value, such as scale value. From the plot, the first peak or edge moving from a direction of decreasing scale along the sum of scales may be identified. The first peak or edge may have analytical value in relation to the original signal from which the secondary wavelet transforms were derived.

In an embodiment, a signal processing method is provided. The method may include selecting a first portion of an original signal, mirroring the first portion of the original signal about a first vertical axis to create a mirrored first portion, selecting a subsequent second portion of the original signal, mirroring the second portion of the original signal about a second vertical axis to create a mirrored second portion, combining the mirrored first portion and the mirrored second portion to create a new signal, and analyzing the new signal.

In an embodiment, a system for processing a signal is provided. The system may include an input signal generator for generating the signal. The system may also include a processor coupled to the input signal generator. The processor is configured to select a first portion of an original signal, mirror the first portion of the original signal about a first vertical axis to create a mirrored first portion, select a subsequent second portion of the original signal, mirror the second portion of the original signal about a second vertical axis to create a mirrored second portion, combine the mirrored first portion and the mirrored second portion to create a new signal, and analyze the new signal. The system may also include an output coupled to the processor. The output is configured to display the new signal analyzed by the processor.

In an embodiment, a signal processing method is provided. The method may include transforming a signal using a wavelet transform, generating a scalogram based at least in part on the transformed signal, selecting a region of the scalogram, summing amplitudes for each scale in the region, identifying a maximum sum, and selecting a desired scale associated with the maximum sum.

In an embodiment, a system for processing a signal is provided. The system may include an input signal generator for generating the signal. The system may also include a processor coupled to the input signal generator. The processor is configured to transform the signal using a wavelet transform, generate a scalogram based at least in part on the transformed signal, select a region of the scalogram, sum amplitudes for each scale in the region, identify a maximum sum, and select a desired scale associated with the maximum sum. The system may also include an output coupled to the processor. The output is configured to display the desired scale selected by the processor.

In an embodiment, a method for determining a respiration rate from a photoplethysmograph signal is provided. The method may include selecting a first portion of the photoplethysmograph signal, mirroring the first portion of the photoplethysmograph signal about a first vertical axis to create a mirrored first portion, selecting a subsequent second portion of the photoplethysmograph signal, mirroring the second portion of the photoplethysmograph signal about a second vertical axis to create a mirrored second portion, combining the mirrored first portion and the mirrored second portion to create a new signal, transforming the new signal into a transformed signal using a wavelet transform, generating a scalogram based at least in part on the transformed signal, identifying a band on the scalogram, extracting ridge information or off-ridge information from the band, transforming the ridge information or the off-ridge information using a wavelet transform into a second transformed signal, generating a second scalogram based at least in part on the second transformed signal, analyzing at least a region of the second scalogram, and determining the respiration rate based on the analysis of the at least a region of the second scalogram.

Brief Description of the Drawings

The above and other features of the present disclosure, its nature and various advantages will be more apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings in which:

FIG. 1 shows an illustrative pulse oximetry system in accordance with an embodiment;

FIG. 2 is a block diagram of the illustrative pulse oximetry system of **FIG. 1** coupled to a patient in accordance with an embodiment;

FIGS. 3(a) and **3(b)** show illustrative views of a scalogram derived from a PPG signal in accordance with an embodiment;

FIG. 3(c) shows an illustrative scalogram derived from a signal containing two pertinent components in accordance with an embodiment;

FIG. 3(d) shows an illustrative schematic of signals associated with a ridge in **FIG. 3(c)** and illustrative schematics of a further wavelet decomposition of these newly derived signals in accordance with an embodiment;

FIGS. 3(e) and **3(f)** are flow charts of illustrative steps involved in performing an inverse continuous wavelet transform in accordance with embodiments;

FIG. 4 is a block diagram of an illustrative continuous wavelet processing system in accordance with an embodiment;

FIG. 5 is a flowchart of an illustrative process for selecting and mirroring portions of a signal to create a new signal for further analysis in accordance with an embodiment of the disclosure;

FIG. 6 is a schematic of an illustrative process for reconstructing an up stroke signal and a down stroke signal from an original signal in accordance with an embodiment of the disclosure;

FIG. 7 is a flowchart of an illustrative process for analyzing the reconstructed up stroke signal and down stroke signal of **FIG. 6** using secondary wavelet feature decoupling in accordance with an embodiment of the disclosure;

FIG. 8(a) shows a plot of a signal and an illustrative scalogram derived from the signal in accordance with an embodiment of the disclosure;

FIG 8(b) shows an up stroke signal reconstructed from the signal in **FIG. 8(a)** and an illustrative scalogram derived from the up stroke signal in accordance with an embodiment of the disclosure;

FIG 8(c) shows a down stroke signal reconstructed from the signal in **FIG 8(a)** and an illustrative scalogram derived from the down stroke signal in accordance with an embodiment of the disclosure; and

FIG. 9 is a flowchart of an illustrative process for applying a sum along amplitudes to a scalogram in accordance with an embodiment of the disclosure.

Detailed Description

The present disclosure relates to signal processing and, more particularly, to selecting and mirroring portions of a signal to create a new signal for further analysis. In one exemplary embodiment, the signal may be a PPG signal and the created signal may be further analyzed using continuous wavelet transforms.

In medicine, a plethysmograph is an instrument that measures physiological parameters, such as variations in the size of an organ or body part, through an analysis of the blood passing through or present in the targeted body part, or a depiction of these variations. An oximeter is an instrument that may determine the oxygen saturation of the blood. One common type of oximeter is a pulse oximeter, which determines oxygen saturation by analysis of an optically sensed plethysmograph.

A pulse oximeter is a medical device that may indirectly measure the oxygen saturation of a patient's blood (as opposed to measuring oxygen saturation directly by analyzing a blood sample taken from the patient) and changes in blood volume in the skin. Ancillary to the blood oxygen saturation measurement, pulse oximeters may also be used to measure the pulse rate of the patient. Pulse oximeters typically measure and display various blood flow characteristics including, but not limited to, the oxygen saturation of hemoglobin in arterial blood.

An oximeter may include a light sensor that is placed at a site on a patient, typically a fingertip, toe, forehead or earlobe, or in the case of a neonate, across a foot. The oximeter may pass light using a light source through blood perfused tissue and photoelectrically sense the absorption of light in the tissue. For example, the oximeter may measure the intensity of light that is received at the light sensor as a function of time. A signal representing light intensity versus time may be referred to as the photoplethysmogram (PPG) signal. The light intensity or the amount of light absorbed may then be used to calculate the amount of the blood constituent (*e.g.*, oxyhemoglobin) being measured as well as the pulse rate and when each individual pulse occurs.

The light passed through the tissue is selected to be of one or more wavelengths that are absorbed by the blood in an amount representative of the amount of the blood constituent present in the blood. The amount of light passed through the tissue varies in accordance with the changing amount of blood constituent in the tissue and the related light absorption. Red and infrared wavelengths may be used because it has been observed that highly oxygenated blood will absorb relatively less red light and more infrared light than blood with a lower oxygen saturation. By comparing the intensities of two wavelengths at different points in the pulse cycle, it is possible to estimate the blood oxygen saturation of hemoglobin in arterial blood.

When the measured blood parameter is the oxygen saturation of hemoglobin, a convenient starting point assumes a saturation calculation based on Lambert-Beer's law. The following notation will be used herein:

$$I(\lambda,t) = I_o(\lambda)\exp(-(s\beta_o(\lambda)+(1-s)\beta_r(\lambda))l(t)) \qquad (1)$$

where:

λ=wavelength;

t=time;

I=intensity of light detected;

I_o=intensity of light transmitted;

s=oxygen saturation;

β_o, β_r=empirically derived absorption coefficients; and

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

The traditional approach measures light absorption at two wavelengths (*e.g.*, red and infrared (IR)), and then calculates saturation by solving for the "ratio of ratios" as follows.

1. First, the natural logarithm of (1) is taken ("log" will be used to represent the natural logarithm) for IR and Red

$$\log I = \log I_o - (s\beta_o + (1-s)\beta_r)l \qquad (2)$$

2. (2) is then differentiated with respect to time

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

3. Red (3) is divided by IR (3)

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

4. Solving for s

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

Note in discrete time

$$\frac{d \log I(\lambda, t)}{dt} \approx \log I(\lambda, t_2) - \log I(\lambda, t_1)$$

Using log A-log B=log A/B,

$$\frac{d \log I(\lambda, t)}{dt} \approx \log\left(\frac{I(t_2, \lambda)}{I(t_1, \lambda)}\right)$$

So, (4) can be rewritten as

$$\frac{\frac{d \log I(\lambda_R)}{dt}}{\frac{d \log I(\lambda_{IR})}{dt}} \approx \frac{\log\left(\frac{I(t_1, \lambda_R)}{I(t_2, \lambda_R)}\right)}{\log\left(\frac{I(t_1, \lambda_{IR})}{I(t_2, \lambda_{IR})}\right)} = R \qquad (5)$$

where **R** represents the "ratio of ratios." Solving (4) for s using (5) gives

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

From (5), **R** can be calculated using two points (*e.g.*, PPG maximum and minimum), or a family of points. One method using a family of points uses a modified version of (5). Using the relationship

$$\frac{d\log I}{dt}=\frac{dI/dt}{I} \qquad (6)$$

now (5) becomes

$$\begin{aligned}\frac{\frac{d\log I(\lambda_R)}{dt}}{\frac{d\log I(\lambda_{IR})}{dt}} &\simeq \frac{\frac{I(t_2,\lambda_R)-I(t_1,\lambda_R)}{I(t_1,\lambda_R)}}{\frac{I(t_2,\lambda_{IR})-I(t_1,\lambda_{IR})}{I(t_1,\lambda_{IR})}}\\ &=\frac{[I(t_2,\lambda_R)-I(t_1,\lambda_R)]I(t_1,\lambda_{IR})}{[I(t_2,\lambda_{IR})-I(t_1,\lambda_{IR})]I(t_1,\lambda_R)}\\ &=R \qquad (7)\end{aligned}$$

which defines a cluster of points whose slope of y versus x will give **R** where

$$\begin{aligned}x(t)&=[I(t_2,\lambda_{IR})-I(t_1,\lambda_{IR})]I(t_1,\lambda_R)\\ y(t)&=[I(t_2,\lambda_R)-I(t_1,\lambda_R)]I(t_1,\lambda_{IR}) \qquad (8)\\ y(t)&=Rx(t)\end{aligned}$$

FIG. 1 is a perspective view of an embodiment of a pulse oximetry system **10**. System **10** may include a sensor **12** and a pulse oximetry monitor **14**. Sensor **12** may include an emitter **16** for emitting light at two or more wavelengths into a patient's tissue. A detector **18** may also be provided in sensor **12** for detecting the light originally from emitter **16** that emanates from the patient's tissue after passing through the tissue.

According to another embodiment and as will be described, system **10** may include a plurality of sensors forming a sensor array in lieu of single sensor **12**. Each of the sensors of the sensor array may be a complementary metal oxide semiconductor (CMOS) sensor. Alternatively, each sensor of the array may be charged coupled device (CCD) sensor. In another embodiment, the sensor array may be made up of a combination of CMOS and CCD sensors. The CCD sensor may comprise a photoactive region and a transmission region for receiving and transmitting data whereas the CMOS sensor may be made up of an integrated circuit having an array of pixel sensors. Each pixel may have a photodetector and an active amplifier.

According to an embodiment, emitter **16** and detector **18** may be on opposite sides of a digit such as a finger or toe, in which case the light that is emanating from the tissue has passed completely through the digit. In an embodiment, emitter **16** and detector **18** may be arranged so that light from emitter **16** penetrates the tissue and is reflected by the tissue into detector **18**, such as a sensor designed to obtain pulse oximetry data from a patient's forehead.

In an embodiment, the sensor or sensor array may be connected to and draw its power from monitor **14** as shown. In another embodiment, the sensor may be wirelessly connected to monitor **14** and include its own battery or similar power supply (not shown). Monitor **14** may be configured to calculate physiological parameters based at least in part on data received from sensor **12** relating to light emission and detection. In an alternative embodiment, the calculations may be performed on the monitoring device itself and the result of the oximetry reading may be passed to monitor **14**. Further, monitor **14** may include a display **20** configured to display the physiological parameters or other information about the system. In the embodiment shown, monitor **14** may also include a speaker **22** to provide an audible sound that may be used in various other embodiments, such as for example, sounding an audible alarm in the event that a patient's physiological parameters are not within a predefined normal range.

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

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

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

FIG. 2 is a block diagram of a pulse oximetry system, such as pulse oximetry system **10** of **FIG. 1**, which may be coupled to a patient **40** in accordance with an embodiment. Certain illustrative components of sensor **12** and monitor **14** are illustrated in **FIG. 2**. Sensor **12** may include emitter **16**, detector **18**, and encoder **42**. In the embodiment shown, emitter **16** may be configured to emit at least two wavelengths of light (*e.g.*, *RED* and *IR*) into a patient's tissue **40**. Hence, emitter **16** may include a *RED* light emitting light source such as *RED* light emitting diode (LED) **44** and an *IR* light emitting light source such as *IR* LED **46** for emitting light into the patient's tissue **40** at the wavelengths used to calculate the patient's physiological parameters. In one embodiment, the *RED* wavelength may be between about 600 nm and about 700 nm, and the *IR* wavelength may be between about 800 nm and about 1000 nm. In embodiments where a sensor array is used in place of single sensor, each sensor may be configured to emit a single wavelength. For example, a first sensor emits only a *RED* light while a second only emits an *IR* light.

It will be understood that, as used herein, the term "light" may refer to energy produced by radiative sources and may include one or more of ultrasound, radio, microwave, millimeter wave, infrared, visible, ultraviolet, gamma ray or X-ray electromagnetic radiation. As used herein, light may also include any wavelength within the radio, microwave, infrared, visible, ultraviolet, or X-ray spectra, and that any suitable wavelength of electromagnetic radiation may be appropriate for use with the present techniques. Detector **18** may be chosen to be specifically sensitive to the chosen targeted energy spectrum of the emitter **16**.

In an embodiment, detector **18** may be configured to detect the intensity of light at the *RED* and *IR* wavelengths. Alternatively, each sensor in the array may be configured to detect an intensity of a single wavelength. In operation, light may enter detector **18** after passing through the patient's tissue **40**. Detector **18** may convert the intensity of the received light into an electrical signal. The light intensity is directly related to the absorbance and/or reflectance of light in the tissue **40**. That is, when more light at a certain wavelength is absorbed or reflected, less light of that wavelength is received from the tissue by the detector **18**. After converting the received light to an electrical signal, detector **18** may send the signal to monitor **14**, where physiological parameters may be calculated based on the absorption of the *RED* and *IR* wavelengths in the patient's tissue **40**. An example of a device configured to perform such calculations is the Model N600x pulse oximeter available from Nellcor Puritan Bennett LLC.

In an embodiment, encoder **42** may contain information about sensor **12**, such as what type of sensor it is (*e.g.*, whether the sensor is intended for placement on a forehead or digit) and the wavelengths of light emitted by emitter **16**. This information may be used by monitor **14** to select appropriate algorithms, lookup tables and/or calibration coefficients stored in monitor **14** for calculating the patient's physiological parameters.

Encoder **42** may contain information specific to patient **40**, such as, for example, the patient's age, weight, and diagnosis. This information may allow monitor **14** to determine, for example, patient-specific threshold ranges in which the patient's physiological parameter measurements should fall and to enable or disable additional physiological parameter algorithms. Encoder **42** may, for instance, be a coded resistor which stores values corresponding to the type of sensor **12** or the type of each sensor in the sensor array, the wavelengths of light emitted by emitter **16** on each sensor of the sensor array, and/or the patient's characteristics. In another embodiment, encoder **42** may include a memory on which one or more of the following information may be stored for communication to monitor **14**: the type of the sensor **12**; the wavelengths of light emitted by emitter **16**; the particular wavelength each sensor in the sensor array is monitoring; a signal threshold for each sensor in the sensor array; any other suitable information; or any combination thereof.

In an embodiment, signals from detector **18** and encoder **42** may be transmitted to monitor **14**. In the embodiment shown, monitor **14** may include a general-purpose microprocessor **48** connected to an internal bus **50**. Microprocessor **48** may be adapted to execute software, which may include an operating system and one or more applications, as part of performing the functions described herein. Also connected to bus

50 may be a read-only memory (ROM) **52**, a random access memory (RAM) **54**, user inputs **56**, display **20**, and speaker **22**.

RAM **54** and ROM **52** are illustrated by way of example, and not limitation. Any suitable computer-readable media may be used in the system for data storage. Computer-readable media are capable of storing information that can be interpreted by microprocessor **48**. This information may be data or may take the form of computer-executable instructions, such as software applications, that cause the microprocessor to perform certain functions and/or computer-implemented methods. Depending on the embodiment, such computer-readable media may include computer storage media and communication media. Computer storage media may include volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules or other data. Computer storage media may include, but is not limited to, RAM, ROM, EPROM, EEPROM, flash memory or other solid state memory technology, CD-ROM, DVD, or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by components of the system.

In the embodiment shown, a time processing unit (TPU) **58** may provide timing control signals to a light drive circuitry **60,** which may control when emitter **16** is illuminated and multiplexed timing for the *RED* LED **44** and the *IR* LED **46**. TPU **58** may also control the gating-in of signals from detector **18** through an amplifier **62** and a switching circuit **64**. These signals are sampled at the proper time, depending upon which light source is illuminated. The received signal from detector **18** may be passed through an amplifier **66**, a low pass filter **68**, and an analog-to-digital converter **70**. The digital data may then be stored in a queued serial module (QSM) **72** (or buffer) for later downloading to RAM **54** as QSM **72** fills up. In one embodiment, there may be multiple separate parallel paths having amplifier **66**, filter **68**, and A/D converter **70** for multiple light wavelengths or spectra received.

In an embodiment, microprocessor **48** may determine the patient's physiological parameters, such as SpO_2 and pulse rate, using various algorithms and/or look-up tables based on the value of the received signals and/or data corresponding to the light received by detector **18**. Signals corresponding to information about patient **40**, and particularly about the intensity of light emanating from a patient's tissue over time, may be transmitted from encoder **42** to a decoder **74**. These signals may include, for example, encoded information relating to patient characteristics. Decoder **74** may translate these signals to enable the microprocessor to determine the thresholds based on algorithms or look-up tables stored in ROM **52**. User inputs **56** may be used to enter information about the patient, such as age, weight, height, diagnosis, medications, treatments, and so forth. In an embodiment, display **20** may exhibit a list of values which may generally apply to the patient, such as, for example, age ranges or medication families, which the user may select using user inputs **56**.

The optical signal through the tissue can be degraded by noise and motion artifacts, among other sources. One source of noise is ambient light that reaches the light detector. Another source of noise is electromagnetic coupling from other electronic instruments. Movement of the patient also introduces noise and affects the signal. For example, the contact between the detector and the skin, or the emitter and the skin, can be temporarily disrupted when movement causes either to move away from the skin. In addition, because blood is a fluid, it responds differently than the surrounding tissue to inertial effects, thus resulting in momentary changes in volume at the point to which the oximeter probe is attached.

Motion artifact can degrade a pulse oximetry signal relied upon by a physician, without the physician's awareness. This is especially true if the monitoring of the patient is remote, the motion is too small to be observed, or the doctor is watching the instrument or other parts of the patient, and not the sensor site. Processing pulse oximetry (*i.e.*, PPG) signals may involve operations that reduce the amount of noise present in the signals or otherwise identify noise components in order to prevent them from affecting measurements of physiological parameters derived from the PPG signals.

It will be understood that the present disclosure is applicable to any suitable signals and that PPG signals are used merely for illustrative purposes. Those skilled in the art will recognize that the present disclosure has wide applicability to other signals including, but not limited to other biosignals (*e.g.*, electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal), dynamic signals, non-destructive testing signals, condition monitoring signals, fluid signals, geophysical signals, astronomical signals, electrical signals, financial signals including financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, and/or any other suitable signal, and/or any combination thereof.

In one embodiment, a PPG signal may be transformed using a continuous wavelet transform. Information derived from the transform of the PPG signal (*i.e.*, in wavelet space) may be used to provide measurements of one or more physiological parameters.

The continuous wavelet transform of a signal x(t) in accordance with the present disclosure may be defined as

$$T(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t)\psi^*\left(\frac{t-b}{a}\right)dt \qquad (9)$$

where $\psi^*(t)$ is the complex conjugate of the wavelet function $\psi(t)$, a is the dilation parameter of the wavelet and b is the location parameter of the wavelet. The transform given by equation (9) may be used to construct a representation of a signal on a transform surface. The transform may be regarded as a time-scale representation. Wavelets are composed of a range of frequencies, one of which may be denoted as the characteristic frequency of the wavelet, where the characteristic frequency associated with the wavelet is inversely proportional to the scale a. One example of a characteristic frequency is the dominant frequency. Each scale of a particular wavelet may have a different characteristic frequency. The underlying mathematical detail required for the implementation within a time-scale can be found, for example, in Paul S. Addison, The Illustrated Wavelet Transform Handbook (Taylor & Francis Group 2002), which is hereby incorporated by reference herein in its entirety.

The continuous wavelet transform decomposes a signal using wavelets, which are generally highly localized in time. The continuous wavelet transform may provide a higher resolution relative to discrete transforms, thus providing the ability to garner more information from signals than typical frequency transforms such as Fourier transforms (or any other spectral techniques) or discrete wavelet transforms. Continuous wavelet transforms allow for the use of multiple wavelets (*e.g.*, on the order of tens, hundreds, thousands, or any other number) that are each scaled in accordance with scales of interest of a signal such that smaller scale components of a signal are transformed using wavelets scaled more compactly than wavelets used to extract larger scale components of the signal. The window size of data to which each wavelet gets applied varies according to scale as well. Thus, a higher resolution transform is possible using continuous wavelets relative to discrete techniques.

In addition, transforms and operations that convert a signal or any other type of data into a spectral (*i.e.*, frequency) domain necessarily create a series of frequency transform values in a two-dimensional coordinate system where the two dimensions may be frequency and, for example, amplitude. For example, any type of Fourier transform would generate such a two-dimensional spectrum. In contrast, wavelet transforms, such as continuous wavelet transforms, are required to be defined in a three-dimensional coordinate system and generate a surface with dimensions of time, scale and, for example, amplitude. Hence, operations performed in a spectral domain cannot be performed in the wavelet domain; instead the wavelet surface must be transformed into a spectrum (*i.e.*, by performing an inverse wavelet transform to convert the wavelet surface into the time domain and then performing a spectral transform from the time domain). Conversely, operations performed in the wavelet domain cannot be performed in the spectral domain; instead a spectrum must first be transformed into a wavelet surface (*i.e.*, by performing an inverse spectral transform to convert the spectral domain into the time domain and then performing a wavelet transform from the time domain). Nor does a cross-section of the three-dimensional wavelet surface along, for example, a particular point in time equate to a frequency spectrum upon which spectral-based techniques may be used. At least because wavelet space includes a time dimension, spectral techniques and wavelet techniques are not interchangeable. It will be understood that converting a system that relies on spectral domain processing to one that relies on wavelet space processing would require significant and fundamental modifications to the system in order to accommodate the wavelet space processing (*e.g.*, to derive a representative energy value for a signal or part of a signal requires integrating twice, across time and scale, in the wavelet domain while, conversely, one integration across frequency is required to derive a representative energy value from a spectral domain). As a further example, to reconstruct a temporal signal requires integrating twice, across time and scale, in the wavelet domain while, conversely, one integration across frequency is required to derive a temporal signal from a spectral domain. It is well known in the art that, in addition to or as an alternative to amplitude, parameters such as energy density, modulus, phase, among others may all be generated using such transforms and that these parameters have distinctly different contexts and meanings when defined in a two-dimensional frequency coordinate system rather than a three-dimensional wavelet coordinate system. For example, the phase of a Fourier system is calculated with respect to a single origin for all frequencies while the phase for a wavelet system is unfolded into two dimensions with respect to a wavelet's location (often in time) and scale.

The energy density function of the wavelet transform, the scalogram, is defined as

$$S(a,b) = |T(a,b)|^2 \qquad (10)$$

where '||' is the modulus operator. The scalogram may be rescaled for useful purposes. One common rescaling is defined as

$$S_R(a,b) = \frac{|T(a,b)|^2}{a} \qquad (11)$$

and is useful for defining ridges in wavelet space when, for example, the Morlet wavelet is used. Ridges are defined as the locus of points of local maxima in the plane. Any reasonable definition of a ridge may be employed in the method. Also included as a definition of a ridge herein are paths displaced from the locus of the local maxima. A ridge associated with only the locus of points of local maxima in the plane are labeled a "maxima ridge".

For implementations requiring fast numerical computation, the wavelet transform may be expressed as an approximation using Fourier transforms. Pursuant to the convolution theorem, because the wavelet transform is the cross-correlation of the signal with the wavelet function, the wavelet transform may be approximated in terms of an inverse FFT of the product of the Fourier transform of the signal and the Fourier transform of the wavelet for each required a scale and then multiplying the result by $\sqrt{a}$.

In the discussion of the technology which follows herein, the "scalogram" may be taken to include all suitable forms of rescaling including, but not limited to, the original unscaled wavelet representation, linear rescaling, any power of the modulus of the wavelet transform, or any other suitable rescaling. In addition, for purposes of clarity and conciseness, the term "scalogram" shall be taken to mean the wavelet transform, T(a,b) itself, or any part thereof. For example, the real part of the wavelet transform, the imaginary part of the wavelet transform, the phase of the wavelet transform, any other suitable part of the wavelet transform, or any combination thereof is intended to be conveyed by the term "scalogram".

A scale, which may be interpreted as a representative temporal period, may be converted to a characteristic frequency of the wavelet function. The characteristic frequency associated with a wavelet of arbitrary a scale is given by

$$f = \frac{f_c}{a} \tag{12}$$

where f_c, the characteristic frequency of the mother wavelet (*i.e.*, at a=1), becomes a scaling constant and f is the representative or characteristic frequency for the wavelet at arbitrary scale a.

Any suitable wavelet function may be used in connection with the present disclosure. One of the most commonly used complex wavelets, the Morlet wavelet, is defined as:

$$\psi(t) = \pi^{-1/4}(e^{i2\pi f_0 t} - e^{-(2\pi f_0)^2/2})e^{-t^2/2} \tag{13}$$

where f_0 is the central frequency of the mother wavelet. The second term in the parenthesis is known as the correction term, as it corrects for the non-zero mean of the complex sinusoid within the Gaussian window. In practice, it becomes negligible for values of f_0>>0 and can be ignored, in which case, the Morlet wavelet can be written in a simpler form as

$$\psi(t) = \frac{1}{\pi^{1/4}} e^{i2\pi f_0 t} e^{-t^2/2} \tag{14}$$

This wavelet is a complex wave within a scaled Gaussian envelope. While both definitions of the Morlet wavelet are included herein, the function of equation (14) is not strictly a wavelet as it has a non-zero mean (*i.e.*, the zero frequency term of its corresponding energy spectrum is non-zero). However, it will be recognized by those skilled in the art that equation (14) may be used in practice with f_0>>0 with minimal error and is included (as well as other similar near wavelet functions) in the definition of a wavelet herein. A more detailed overview of the underlying wavelet theory, including the definition of a wavelet function, can be found in the general literature. Discussed herein is how wavelet transform features may be extracted from the wavelet decomposition of signals. For example, wavelet decomposition of PPG signals may be used to provide clinically useful information within a medical device.

Pertinent repeating features in a signal give rise to a time-scale band in wavelet space or a rescaled wavelet space. For example, the pulse component of a PPG signal produces a dominant band in wavelet space at or around the pulse frequency. **FIGS. 3(a)** and **(b)** show two views of an illustrative scalogram derived from a PPG signal, according to an embodiment. The figures show an example of the band caused by the pulse component in such a signal. The pulse band is located between the dashed lines in the plot of **FIG. 3(a)**. The band is formed from a series of dominant coalescing features across the scalogram. This can be clearly seen as a raised band across the transform surface in **FIG. 3(b)** located within the region of scales indicated by the arrow in the plot (corresponding to 60 beats per minute). The maxima of this band with respect to scale is the ridge. The locus of the ridge is shown as a black curve on top of the band in **FIG. 3(b)**. By employing a suitable rescaling of the scalogram, such as that given in equation (11), the ridges found in wavelet space may be related to the instantaneous frequency of the signal. In this way, the pulse rate may be obtained from the PPG signal. Instead of rescaling the scalogram, a suitable predefined relationship between the scale obtained from the ridge on the wavelet surface and the actual pulse rate may also be used to determine the pulse rate.

By mapping the time-scale coordinates of the pulse ridge onto the wavelet phase information gained through the wavelet transform, individual pulses may be captured. In this way, both times between individual pulses and the timing of components within each pulse may be monitored and used to detect heart beat anomalies, measure arterial system compliance, or perform any other suitable calculations or diagnostics. Alternative definitions of a ridge may be employed. Alternative relationships between the ridge and the pulse frequency of occurrence may be employed.

As discussed above, pertinent repeating features in the signal give rise to a time-scale band in wavelet space or a rescaled wavelet space. For a periodic signal, this band remains at a constant scale in the time-scale plane. For many real signals, especially biological signals, the band may be non-stationary; varying in scale, amplitude, or both over time. **FIG. 3(c)** shows an illustrative schematic of a wavelet transform of a signal containing two pertinent components leading to two bands in the transform space, according to an embodiment. These bands are labeled band A and band B on the three-dimensional schematic of the wavelet surface. In this embodiment, the band ridge is defined as the locus of the peak values of these bands with respect to scale. For purposes of discussion, it may be assumed that band B contains the signal information of interest. This will be referred to as the "primary band". In addition, it may be assumed that the system from which the signal originates, and from which the transform is subsequently derived, exhibits some form of coupling between the signal components in band A and band B. When noise or other erroneous features are present in the signal with similar spectral characteristics of the features of band B then the information within band B can become ambiguous (*i.e.*, obscured, fragmented or missing). In this case, the ridge of band A may be followed in wavelet space and extracted either as an amplitude signal or a scale signal which will be referred to as the "ridge amplitude perturbation" (RAP) signal and the "ridge scale perturbation" (RSP) signal, respectively. The RAP and RSP signals may be extracted by projecting the ridge onto the time-amplitude or time-scale planes, respectively. The top plots of **FIG. 3(d)** show a schematic of the RAP and RSP signals associated with ridge A in **FIG. 3(c)**. Below these RAP and RSP signals are schematics of a further wavelet decomposition of these newly derived signals. This secondary wavelet decomposition allows for information in the region of band B in **FIG. 3(c)** to be made available as band C and band D. The ridges of bands C and D may serve as instantaneous time-scale characteristic measures of the signal components causing bands C and D. This technique, which will be referred to herein as secondary wavelet feature decoupling (SWFD), may allow information concerning the nature of the signal components associated with the underlying physical process causing the primary band B (**FIG. 3(c)**) to be extracted when band B itself is obscured in the presence of noise or other erroneous signal features.

In some instances, an inverse continuous wavelet transform may be desired, such as when modifications to a scalogram (or modifications to the coefficients of a transformed signal) have been made in order to, for example, remove artifacts. In one embodiment, there is an inverse continuous wavelet transform which allows the original signal to be recovered from its wavelet transform by integrating over all scales and locations, *a* and *b*:

$$x(t) = \frac{1}{C_g} \int_{-\infty}^{\infty} \int_{0}^{\infty} T(a,b) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \frac{\mathrm{d}a\mathrm{d}b}{a^2} \qquad (15)$$

which may also be written as:

$$x(t) = \frac{1}{C_g} \int_{-\infty}^{\infty} \int_{0}^{\infty} T(a,b) \psi_{a,b}(t) \frac{\mathrm{d}a\mathrm{d}b}{a^2} \qquad (16)$$

where C_g is a scalar value known as the admissibility constant. It is wavelet type dependent and may be calculated from:

$$C_g = \int_0^{\infty} \frac{|\hat{\psi}(f)|^2}{f} \mathrm{d}f \tag{17}$$

FIG. 3(e) is a flow chart of illustrative steps that may be taken to perform an inverse continuous wavelet transform in accordance with the above discussion. An approximation to the inverse transform may be made by considering equation (15) to be a series of convolutions across scales. It shall be understood that there is no complex conjugate here, unlike for the cross correlations of the forward transform. As well as integrating over all of a and b for each time t, this equation may also take advantage of the convolution theorem which allows the inverse wavelet transform to be executed using a series of multiplications. **FIG. 3(f)** is a flow chart of illustrative steps that may be taken to perform an approximation of an inverse continuous wavelet transform. It will be understood that any other suitable technique for performing an inverse continuous wavelet transform may be used in accordance with the present disclosure.

FIG. 4 is an illustrative continuous wavelet processing system **400** in accordance with an embodiment. In this embodiment, input signal generator **410** generates an input signal **416**. As illustrated, input signal generator **410** may include oximeter **420** coupled to sensor **418**, which may provide as input signal **416**, a PPG signal. It will be understood that input signal generator **410** may include any suitable signal source, signal generating data, signal generating equipment, or any combination thereof to produce signal **416**. Signal **416** may be any suitable signal or signals, such as, for example, biosignals (*e.g.*, electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal), dynamic signals, non-destructive testing signals, condition monitoring signals, fluid signals, geophysical signals, astronomical signals, electrical signals, financial signals including financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, and/or any other suitable signal, and/or any combination thereof.

In this embodiment, signal **416** may be coupled to processor **412**. Processor **412** may be any suitable software, firmware, and/or hardware, and/or combinations thereof for processing signal **416**. For example, processor **412** may include one or more hardware processors (*e.g.*, integrated circuits), one or more software modules, computer-readable media such as memory, firmware, or any combination thereof. Processor **412** may, for example, be a computer or may be one or more chips (*i.e.*, integrated circuits). Processor **412** may perform the calculations associated with the continuous wavelet transforms of the present disclosure as well as the calculations associated with any suitable interrogations of the transforms. Processor **412** may perform any suitable signal processing of signal **416** to filter signal **416**, such as any suitable band-pass filtering, adaptive filtering, closed-loop filtering, and/or any other suitable filtering, and/or any combination thereof.

Processor **412** may be coupled to one or more memory devices (not shown) or incorporate one or more memory devices such as any suitable volatile memory device (*e.g.*, RAM, registers, *etc.*), non-volatile memory device (*e.g.*, ROM, EPROM, magnetic storage device, optical storage device, flash memory, *etc.*), or both. The memory may be used by processor **412** to, for example, store data corresponding to a continuous wavelet transform of input signal **416,** such as data representing a scalogram. In one embodiment, data representing a scalogram may be stored in RAM or memory internal to processor **412** as any suitable three-dimensional data structure such as a three-dimensional array that represents the scalogram as energy levels in a time-scale plane. Any other suitable data structure may be used to store data representing a scalogram.

Processor **412** may be coupled to output **414**. Output **414** may be any suitable output device such as, for example, one or more medical devices (e.g., a medical monitor that displays various physiological parameters, a medical alarm, or any other suitable medical device that either displays physiological parameters or uses the output of processor **412** as an input), one or more display devices (*e.g.*, monitor, PDA, mobile phone, any other suitable display device, or any combination thereof), one or more audio devices, one or more memory devices (*e.g.*, hard disk drive, flash memory, RAM, optical disk, any other suitable memory device, or any combination thereof), one or more printing devices, any other suitable output device, or any combination thereof.

It will be understood that system **400** may be incorporated into system **10** (**FIGS. 1** and **2**) in which, for example, input signal generator **410** may be implemented as parts of sensor **12** and monitor **14** and processor **412** may be implemented as part of monitor **14**.

The continuous wavelet processing of the present disclosure will now be discussed in reference to **FIGS. 5-9**.

FIG. 5 is a flowchart of an illustrative process for selecting and mirroring portions of a signal to create a new signal for further analysis in accordance with an embodiment of the disclosure. Process **300** may begin at step **302**. At step **304**, a first portion of an original signal may be selected. The original signal may include a signal from any suitable source and may contain one or more repetitive components. For example, the original signal may be a PPG signal. The first portion may be selected using any suitable method based on characteristics of the signal (*e.g.*, using local maximum and minimum values, or using second derivatives to find one or more turning points, of the original signal). The selected portion may correspond to a repetitive portion of the signal. For example, the selected portion may correspond to the up stroke or the down stroke of a PPG signal corresponding to a heartbeat. At step **306**, the first portion may be mirrored about any suitable first vertical axis, such as a vertical axis located at the beginning or end of the selected segment, to create a mirrored first portion. By "mirroring," it is meant that the first portion is reflected about any suitable axis to create a mirrored first portion that contains both the original first portion of the signal and the mirrored, or reflected, portion. By mirroring the first portion about the first vertical axis, a pulse may be created that is symmetrical about the first vertical axis. Process **300** may advance to step **308**, in which a second portion may be selected from the original signal. The second portion may be the same as, similar to, or different from the first portion, and may be selected using any suitable method. For example, the second portion may correspond to characteristics of the signal that occur subsequent in time to the first portion. At step **310**, the second portion of the original signal may be mirrored about any suitable second vertical axis to create a mirrored second portion. By mirroring the second portion about the second vertical axis, a pulse may be created that is symmetrical about the second vertical axis. In an embodiment, process **300** may advance to step **312**, in which the mirrored first portion and the mirrored second portion may be combined to create a new signal. In an embodiment, process **300** may create two new signals: one from the mirrored first portion and one from the mirrored second portion. In this manner, one or more new signals may be created. These new signal may be analyzed further in step **314** using any suitable method. Process **300** may advance to step **316** and end.

The foregoing steps of the flowchart are merely illustrative and any suitable modifications may be made. For example, additional portions of the signal may be selected, mirrored (*e.g.* reflected about any suitable axis to create a pulse that is symmetrical about that axis), and added to the new signal. The process may be performed in real time as the signal is being received or may be performed after a signal has been received. The new signal may be analyzed using a wavelet transform such as a continuous wavelet transform.

FIG. 6 is a schematic of an illustrative process for reconstructing an up stroke signal and a down stroke signal from an original PPG signal in accordance with an embodiment of the disclosure. Process **6400** may be performed by processor **412** (**FIG.** 4) or microprocessor **48** (**FIG. 2**) in real time using a PPG signal obtained by sensor **12** (**FIG. 2**) or input signal generator **410** (**FIG. 4**), which may be coupled to patient **40**, using a time window smaller than the entire time window over which the PPG signal may be collected. Alternatively, process **6400** may be performed offline on PPG signal samples from QSM **72** (**FIG. 2**) or from PPG signal samples stored in RAM **54** or ROM **52** (**FIG. 2**)., using the entire time window of data over which the PPG signal was collected.

Process **6400** may begin at step **6410**, in which a PPG signal **6405** may be collected by sensor **12** or input signal generator **410** over any suitable time period **t** to reconstruct an up stroke signal **6463** and/or a down stroke signal **6465**. The portion of PPG signal **6405** used to reconstruct up signal **6463** and down signal **6465** may be selected using any suitable approach. For example, the up stroke and the down stroke of PPG signal **6405** may be selected based upon maximum and minimum values of PPG signal **6405**. Alternatively, a portion of PPG signal **6405** having an up stroke and a down stroke may be located using second derivatives to find one or more turning points of PPG signal **6405**. In an embodiment, processor **412** or microprocessor **48** may include any suitable software, firmware, and/or hardware, and/or combinations thereof for identifying maximum and minimum values of PPG signal **6405** and second derivatives of PPG signal **6405**, selecting a portion of PPG signal **6405**, and separating one or more up strokes in the portion of PPG signal **6405** from one or more down strokes. The local minimum turning points of PPG signal **6405** are shown in step **6410** using circles. In step **6420**, the up stroke and the down stroke may occur between two selected turning points, and the up stroke "**U**" may be distinguished from the down stroke "**D**" using a dotted line representing the local maximum value of PPG signal **6405** between and perpendicular to the two turning points of the original baseline **B** of PPG signal **6405**. In one suitable embodiment, the up stroke and the down stroke may be selected after filtering the PPG signal **6405** using, for example, a bandpass filter or low pass filter **68** to filter out frequencies higher and lower than the range of typical heart rates. In another suitable embodiment, the up and down strokes may be detected using techniques described in Watson, U.S. Provisional Application No. 61/077,092, filed June 30, 2008, entitled "Systems and Method for Detecting Pulses," which is incorporated by reference herein in its entirety. Those skilled in the art will appreciate that any suitable method may be employed for the detection and/or selection of salient portions of the trace including but not limited to pattern matching methods (such as summation of differences or nearest neighbor techniques), syntactic processing methods (such as predicate calculus grammars), and adaptive methods (such as non-monotonic logic inference or artificial neural networks).

In **FIG. 6**, the original baseline **B** of PPG signal **6405** is shown as a sinusoidal-like dotted line, according to an embodiment. The baseline **B** may fluctuate due to the breathing of patient **40**, which may cause the PPG signal to oscillate, or twist, in the time plane. For example, PPG signal **6405** may experience amplitude modulation that may be related to dilation of the patient's vessels in correspondence with the patient's respiration. PPG signal **6405** may also include a carrier wave that may be based at least in part on the pressure in the patient's venous bed. PPG signal **6405** may also experience frequency modulation that may be based at least in part on a respiratory sinus arrhythmia of the patient. Process **6400** may remove the carrier wave of a PPG signal, the removal of which may be reflected at least in part in the amplitude modulation of the reconstructed up stroke signal and down stroke signal.

Process **6400** may advance to step **6420**, in which one up stroke and one down stroke of PPG signal **6405** may be selected by processor **412** or microprocessor **48** using any suitable method. In step **6420**, the up stroke and the down stroke may occur between two selected turning points, and the up stroke "**U**" may be distinguished from the down stroke "**D**" using a dotted line representing the local maximum value of PPG signal **6405** between and perpendicular to the two turning points. Any other suitable technique may be used to distinguish the up stroke and the down stroke. In an embodiment of the disclosure, up strokes of PPG signal **6405** may be selected for further processing by processor **412** or microprocessor **48** without also selecting down strokes from PPG signal **6405**. Similarly, down strokes of PPG signal **6405** may be selected for further processing without also selecting up strokes from PPG signal **6405**.

Process **6400** may advance to step **6430**, in which the up stroke selected at step **6420** may be separated from the selected down stroke by processor **412** or microprocessor **48** for further processing using any suitable method. For example, the up stroke may be separated from the down stroke at the point where the dotted line, representing the local maximum perpendicular to the two turning points, may intersect the selected portion of PPG signal **6405**.

Process **6400** may advance to step **6440**, in which each of the selected up stroke "**U**" and the selected down stroke "**D**" may be mirrored by processor **412** or microprocessor **48** about any suitable vertical axis. By mirroring each of the selected up stroke "**U**" and the selected down stroke "**D**" about a vertical axis, a mirrored up pulse **6443** and a mirrored down pulse **6445** may be created. The mirrored up pulse **6443** and the mirrored down pulse **6445** may each be symmetrical about the respective vertical axis that was used to reflect the selected up stroke "**U**" and the selected down stroke "**D**." The shape of mirrored up pulse **6443** and mirrored down pulse **6445** may depend on which portion of PPG signal **6405** was selected. Because baseline **B** of PPG signal **6405** may fluctuate, an up stroke and down stroke combination selected from one portion of PPG signal **6405** may have a different amplitude and/or a different frequency than a similar up stroke and down stroke combination from another portion of PPG signal **6405**. For example, if a portion of PPG signal **6405** was selected from step **6410** in which the original baseline **B** was trending downwards, then the up stroke "**U**" and the resulting mirrored up signal may form a wider, flatter pulse while the down stroke "**D**" and the resulting mirrored down signal may form a narrower and taller pulse.

Process **6400** may advance to step **6450**, in which each of the mirrored up pulse **6443** and mirrored down pulse **6445** may be added to additional multiple pulses formed from the selection and mirroring of additional up strokes and down strokes from PPG signal **6405** to form mirrored up signal **6453** and mirrored down signal **6455**. Alternatively, mirrored up pulse **6443** and mirrored down pulse **6445** may each remain as an individual signal pulse and may be further analyzed by processor **412** or microprocessor **48** as described below with respect to **FIG. 7**. Each of the pulses in mirrored up signal **6453** and mirrored down signal **6455** may vary in their amplitude and/or their time period, reflecting the amplitude and/or frequency oscillation of PPG signal **6405** in the time plane. Alternatively, each of the mirrored signals could be replicated to form a signal within a desired temporal window instead of forming a signal with a desired number of pulses.

Process **6400** may advance to step **6460**, in which each of mirrored up signal **6453** and mirrored down signal **6455** may be further manipulated by processor **412** or microprocessor **48** prior to further analysis, such as by being stretched or compressed to any desired size. Each pulse of the mirrored signals **6453** and **6455** may be expanded or shortened independently of the other pulses in the mirrored signals. For example, each of the pulses in the mirrored signals **6453** and **6455** may be stretched or compressed to make the time period for each pulse equal in size, where all of the time periods together equal the time period t over which PPG signal **6405** was collected or is being analyzed. Alternatively, each pulse of mirrored up signal **6453** and mirrored down signal **6455** may not be stretched to match time period t, but may instead be stretched or compressed to any desired size based at least in part on another time period of PPG signal **6405** or based at least in part on an individual or predetermined number of signal pulses. In an embodiment, each mirrored up pulse may be stretched or compressed to match the size of the up stroke used in the mirroring combined with its corresponding down stroke. The same process may be performed on each mirrored down pulse. In an embodiment, the mirrored pulses in mirrored signals **6453** and **6455** may be equally stretched or compressed to match the time period t over which the PPG signal **6405** was collected or is being analyzed.

The frequency modulation that occurs when one or more of the pulses in mirrored signals **6453** and **6455** is stretched or compressed may be converted into amplitude modulation by processor **412** or microprocessor **48** at step **6460** by increasing or decreasing the amplitude of each of the pulses in the mirrored signals **6453** and **6455** in relation to the amount of individual stretching or compressing described above. This may increase the amplitude modulation that may already exist in the mirrored pulses due to baseline changes in the original PPG signal **6405**. Translating the effect of the frequency modulation into amplitude modulation within the mirrored signals **6453** and **6455** may reduce the effect of respiratory sinus arrhythmia of patient **40** on further analysis of PPG signal **6405**. The amplitude of the pulses in reconstructed up signal **6463** and/or reconstructed down signal **6465** may be modulated or augmented if each of the pulses was stretched or compressed independently of each other (*e.g.*, to match the time period t over which PPG signal **6405** was collected and to match the period of each other pulse). Alternatively, the amplitude of each of the pulses in reconstructed up signal **6463** or reconstructed down signal **6465** may be the same (not shown) if the frequency modulation applied to the reconstructed signal stretched or compressed each pulse individually to create reconstructed signals with uniform amplitude. In an embodiment, reconstructed up signal **6463** and/or reconstructed down signal **6465** may include pulses that may vary in amplitude and frequency.

In an embodiment of the disclosure, an up stroke, but not a down stroke, may be selected in step **6420**, mirrored about a vertical axis in step **6440**, replicated in step **6450**, and stretched (or compressed) in step **6460**. Once the processing (e.g., selecting an up stroke and/or a down stroke, mirroring the strokes, replicating the mirrored pulses, and stretching or compressing the mirrored signals) of mirrored up signal **6453** and mirrored down signal **6455** is completed, then reconstructed up signal **6463** and reconstructed down stroke signal **6465** may be used in further processing by processor **412** or microprocessor **48** as described below with respect to **FIG. 7**.

FIG. 7 is a flowchart of an illustrative process for analyzing the reconstructed signals of, for example, **FIG. 6**, using secondary wavelet feature decoupling in accordance with an embodiment of the disclosure. Process **500** may begin at step **530**, in which up signal **533** and down signal **535**, which may be the same as, and may include some or all of the features of, reconstructed up signal **6463** and reconstructed down signal **6465**, respectively, may be generated from any original signal (*e.g.*, a PPG signal) using any suitable method. In an embodiment of the disclosure, only one reconstructed signal (*e.g.*, up signal **533**), instead of both reconstructed signals, may be analyzed by process **500**.

Process **500** may advance to step **540**, in which a primary up scalogram **543** and a primary down scalogram **545** may be derived at least in part from up signal **533** and down signal **535** using any suitable method. For example, up scalogram **543** and down scalogram **545** may be derived using the same method (*e.g.*, using continuous wavelet transforms) that was used to derive the scalograms shown in **FIGS. 3(a)**, **3(b)**, and **3(c)**. In an embodiment, processor **412** or microprocessor **48** may perform the calculations associated with the continuous wavelet transforms of up signal **533** and down signal **535**. Up scalogram **543** and down scalogram **545** may be derived using a mother wavelet of any suitable characteristic frequency or form such as the Morlet wavelet where f_0 (which is related to its oscillatory nature) may take a value equal to $(5.5/2\pi)$ Hz, or any other suitable value.

Up scalogram **543** and down scalogram **545** also may be derived over any suitable range of scales. For example, up scalogram **543** and down scalogram **545** may be derived using wavelets within a range of scales whose characteristic frequencies span, for example, approximately 0.8 Hz on either side of the scale corresponding to band **A** as shown in **FIG. 3(c)**. A narrower range of scales may be used to derive up scalogram **543** and down scalogram **545** to eliminate the inclusion of other artifacts (*e.g.*, noise), to focus on the component of interest within the PPG signal (*e.g.*, the pulse component), and to minimize the number of computations that processor **412** or microprocessor **48** would need to perform. The resultant up scalogram **543** and down scalogram **545** may include ridges corresponding to at least one area of increased energy, such as band **A** that may be analyzed further using any suitable method, for example using secondary wavelet feature decoupling.

Process **500** may advance to step **550**, in which an up ridge **553** and a down ridge **555** may be extracted by processor **412** or microprocessor **48** from up scalogram **543** and down scalogram **545**, respectively, using any suitable method. For example, up ridge **553** and down ridge **555** may represent that at a particular scale value, the PPG signal may contain high amplitudes corresponding to the characteristic frequency of that scale. The amplitude and/or scale modulation observed in band **A** may be the result of the effect of one component of the PPG signal (*e.g.*, a patient's respiration, as shown by breathing band **B** in **FIG. 3(c)**) on another component (*e.g.*, a patient's pulse rate, as shown by pulse band **A**). By extracting and further analyzing up ridge **553** and/or down ridge **555** with respect to band **A**, information concerning the nature of the signal component associated with the underlying physical process causing the primary band **B** (**FIG. 3(c)**) may also be extracted when band **B** itself is, for example, obscured in the presence of noise or other erroneous signal features.

Process **500** may advance to step **560**, in which each of up ridge **553** and down ridge **555** may be transformed further into a secondary up scalogram **563** and a secondary down scalogram **565**, respectively, using any suitable method. In an embodiment, processor **412** or microprocessor **48** may perform the calculations associated with any suitable interrogations of the continuous wavelet transforms, including further transforming up ridge **553** and down ridge **555**. For example, secondary wavelet feature decoupling may be applied by processor **412** or microprocessor **48** to each of up ridge **553** and down ridge **555** to derive secondary up scalogram **563** and secondary down scalogram **565**. The secondary wavelet feature decoupling technique may provide desired information about the primary band **B** in **FIG. 3(c)** by examining the amplitude modulation of band **A**, such amplitude modulation being based at least in part on the presence of the signal component in the PPG signal that may be related to primary band **B**.

Up ridge **553** or down ridge **555** may be followed in wavelet space and extracted either as an amplitude signal (*e.g.*, the RAP signal as shown in **FIG. 3(d)**) and/or a scale signal (*e.g.*, the RSP signal as shown in **FIG. 3(d)**). In an embodiment, an "off-ridge" technique may be employed, in which a path near up ridge **553** or down ridge **555**, but not the maxima ridge itself, may be followed in wavelet space. The off-ridge technique may also be used to obtain amplitude modulation in the RAP signal.

The RAP and/or the RSP signal may be extracted by projecting up ridge **553** or down ridge **555** onto the time-amplitude plane. This secondary wavelet decomposition of up ridge **553** and down ridge **555** allows for information concerning the band of interest (*e.g.*, band **B** in **FIG. 3(c)**) to be made available as secondary bands (*e.g.*, band **C** and band **D** in **FIG. 3(d)**) for each of secondary up scalogram **563** and secondary down scalogram **565**. The ridges of the secondary bands may serve as instantaneous time-scale characteristic measures of the underlying signal components causing the secondary bands, which may be useful in analyzing the signal component associated with the underlying physical process causing the primary band of interest (*e.g.*, the breathing band **B**) when band **B** itself may be obscured.

In an embodiment, secondary up scalogram **563** and secondary down scalogram **565** may be derived by processor **412** or microprocessor **48** within a different window of scales than was used to derive up scalogram **543** and down scalogram **545**. Secondary up scalogram **563** and secondary down scalogram **565** may be derived using wavelets within a range of scales from any suitable minimum value, such as a scale whose characteristic frequency is approximately 0.07 Hz, up to any suitable maximum value, such as a scale at which the ridge of band **A** in **FIG. 3(c)** may be present. For example, using a window between a suitable minimum scale value and a scale value at which band **A** may be primarily located allows other signal components of the PPG signal (e.g., the breathing band represented by band **B**) to be analyzed. The window of scale values may still be chosen to eliminate the inclusion of other artifacts (e.g., noise) within the PPG signal.

Secondary up scalogram **563** and secondary down scalogram **565** may be derived by processor **412** or microprocessor **48** using any suitable value for scaling factor f_c for the wavelet. For example, the value of f_c may be lower than the value of f_c used to derive up scalogram **543** and down scalogram **545** to reduce the formation of continuous ridge paths in secondary up scalogram **563** and secondary down scalogram **565**. A lower value of f_c may decrease the oscillatory nature of a wavelet.

Process **500** may advance to step **567**, which may be a repetition of step **560** at a different value of f_c. The value of f_c may be lower than the value used in step **560** so as to break up false ridges within the scalograms of step **567**. The ridge fragments formed within the repeated scalograms of step **567** may be used to identify stable regions within secondary up scalogram **563** and secondary down scalogram **565**.

Process **500** may advance to step **570**, in which the ridge fragments formed within the scalograms of step **560** and the repeated scalograms of step **567** may be analyzed by processor **412** or microprocessor **48** to select one or more desired ridges, using any suitable method. The one or more ridges may be selected, for example, using the techniques described in Watson, et al., U.S. Application No. 61/077,029, filed June 30, 2008, entitled "Systems and Methods for Ridge Selection in Scalograms of Signals," which is incorporated by reference herein in its entirety. For example, to analyze the ridge fragments, a time window that may vary both in width and in start position (e.g., start time) may be slid across the one or more up repeated scalograms and the one or more down repeated scalogram derived in each of steps **560** and **567**. The ridge fragments within the time window may be parameterized in terms of a weighting of the standard deviation of the path that the particular ridge fragment may take, in units of scale, the length of the ridge fragment, the proximity of the ridge fragment to other ridge fragments, and/or any other suitable weighting characteristics. The ridge having the highest weighting may be chosen for further processing by processor **412** or microprocessor **48**. In an embodiment, the ridge having the highest weighting may be used to identify and select a stable region within one of the generated scalograms.

Process **500** may advance to step **580**, in which a sum along amplitudes technique may be applied by processor **412** or microprocessor **48** to at least a portion of the band corresponding to the selected ridge or at least a portion (e.g., the identified stable region) of the selected secondary scalogram from step **570** using any suitable method. The sum along amplitudes technique may sum, for each scale increment within a range of scales, the amplitude (*e.g.*, the energy) of a selected portion of the secondary scalogram across any suitable time window (*e.g.*, the time window from step **570** with the minimum parameterization value). The resulting sum may thereafter be represented in any suitable manner, such as by plotting the sum for each scale value as a function of scale value. In an embodiment, processor **412** or microprocessor **48** may include any suitable software, firmware, and/or hardware, and/or combinations thereof for generating a sum along amplitudes vector and applying it to the selected secondary scalogram. The technique of applying a sum along amplitudes may be applied to any secondary wavelet feature decoupling method of any suitable original signal. For example, if the ridge fragment selected from step **570** was a ridge fragment of the up repeated scalogram derived in step **567**, then the sum along amplitudes technique may be applied to at least a portion of secondary up scalogram **563** containing the selected ridge fragment. Similarly, if the ridge fragment selected from step **570** was a ridge fragment of the down repeated scalogram derived in step **567**, then the sum along amplitudes may be applied to at least a portion of secondary down scalogram **565** containing the selected ridge fragment. Alternatively, the sum along amplitudes technique may be applied to the entire secondary up scalogram **563** or secondary down scalogram **565**. The sum along amplitudes technique also may be applied to any continuous wavelet transform of any suitable signal, such as a wavelet transform of the original PPG signal **6405** in **FIG. 6**. In an embodiment, the sum along amplitudes technique may be applied to a scalogram composite, or a superposition formed from the secondary scalograms derived in steps **560** and **567**.

Process **500** may then advance to step **590**, in which the sum along amplitudes function may be plotted as a function of scale value by processor **412** or microprocessor **48**. For example, the amplitude (*e.g.*, energy) of at least a portion of either secondary up scalogram **563** or secondary down scalogram **565** may be summed across time for each scale value increment. In an embodiment, the plot generated at step **590** may be displayed in any suitable manner, including for example, on display **20** (**FIG. 2**), display

28 (**FIG. 2**), or output **414** (**FIG. 4**) for review and analysis by a user of system **10** (**FIG. 1**) or system **400** (**FIG. 4**). From the plot, the first peak or edge moving from a direction of decreasing scale along the sum of amplitudes may be identified, either by processor **412** or microprocessor **48** or by a user of system **10** or system **400**. The first peak or edge may have analytical value in relation to the original signal from which the secondary wavelet transforms were derived. If secondary up scalogram **563** and secondary down scalogram **565** were derived from a PPG signal, then the first peak or edge of the plot in step **590** may represent the respiration rate of patient **40**.

It is to be understood that process **500** may use one or more secondary up scalograms **563**, one or more secondary down scalograms **565**, or a superposition formed from two or more secondary scalograms, to locate the desired information. Each of up scalogram **543** and down scalogram **545** may be used to generate the amplitude-modulated up ridge **553** and down ridge **555**. Up ridge **553** and down ridge **555** may be transformed again, however, before the desired information (e.g., the respiration rate) may be obtained.

Process **500** may be applied to a PPG signal obtained from patient **40** in any suitable manner. In an embodiment, process **500** may take the form of a computer algorithm that may be installed as part of system **10** or system **400**. The algorithm may be applied by processor **412** or microprocessor **48** to the PPG signal data in real time as the PPG signal is detected using sensor **12** or using input signal generator **410**. In an embodiment, the algorithm may be applied offline to PPG signal samples from QSM **72** or from PPG signal samples stored in RAM **54** or ROM **52**. The output of the algorithm, which may be displayed in any suitable manner (*e.g.*, using display **20**, display **28** , or output **414**) may include the respiration rate of patient **40**, which may be used by a user of system **10** or system **400** for any suitable purpose (*e.g.*, assessing the respiratory health of patient **40**). In an embodiment, the algorithm may provide several benefits in calculating the respiration rate of patient **40**. The algorithm uses forced symmetry in that a selected up stroke or down stroke is mirrored about a desired axis to create a pulse that is symmetrical about that desired axis, and a new signal (*e.g.*, up signal **533** or down signal **535**) may be created using any suitable number of symmetrical pulses. The forced symmetry may improve the accuracy of the respiration rate determination by permitting a more accurate derivation of scalograms **543** and **545** from up signal **533** and down signal **535**, and a more accurate extraction of up ridge **553** and down ridge **555**. The process **500** algorithm may also significantly improve the number of samples, or the percentage of patient data, that may be used to determine the patient's respiration rate effectively. Using the process **500** algorithm may further improve the standard deviation of the differences observed between computing the respiration rate using the mirroring algorithm and computing the respiration rate using another method (*e.g.*, by counting one or more respiration features in a patient's nasal thermistor signal). A tradeoff to using the process **500** algorithm, however, may include an increase (*e.g.*, on the order of 7%) in the amount of patient data classified as invalid and therefore unable to be used to determine the respiration rate of patient **40**.

FIG. 8(a) shows a plot of a signal **800**, such as a raw absorbance PPG signal, and an illustrative scalogram **810** derived from signal **800** in accordance with an embodiment of the disclosure. Signal **800** may include a red light signal or an infrared light signal obtained from a pulse oximeter sensor attached to a patient as described above. Signal **800** may be plotted as shown in **FIG. 8(a)** after passing through a portion of the patient's blood perfused tissue (e.g., a fingertip, a toe, a foot). The pulse oximeter sensor may transmit signal **800** to any suitable processing unit (*e.g.*, processor **412** in **FIG. 4** or microprocessor **48** in **FIG. 2**) for further analysis.

Scalogram **810** may be derived from signal **800** by processor **412** or microprocessor **48**. Scalogram **810** may include any suitable features, including bands that may relate to clinical parameters of interest, such as a patient's pulse rate (related to pulse band **P**) or a patient's breathing rate (related to breathing band **B**), as well as any other artifact that was present in signal **800** (*e.g.* artifact **A**). It is to be understood with respect to scalograms **810**, **840** (**FIG. 8(b)**), and **880** (**FIG. 8(c)**) that the grayscale shown may correspond to high energy components being shaded with a lighter tone and the lower energy components being shaded with a darker tone. The shading may be automatically scaled such that black and white tones may correspond to the lowest and highest energy in each scalogram, respectively. It is to be further understood that the shading used in scalograms **810**, **840**, and **880** does not necessarily correspond to the same absolute values within each scalogram.

FIG 8(b) shows an up stroke signal **830** reconstructed from raw absorbance PPG signal **800** and an illustrative scalogram **840** derived from up stroke signal **830** in accordance with an embodiment of the disclosure. Similarly, **FIG 8(c)** shows a down stroke signal **870** reconstructed from raw absorbance PPG signal **800** and an illustrative scalogram **880** derived from down stroke signal **870** in accordance with an embodiment of the disclosure. Up stroke signal **830** and down stroke signal **870** may be reconstructed using any suitable methods, including the methods described with respect to **FIGS. 5** and **6**. Scalogram **840** and scalogram **880** may be derived using any suitable methods, including the method described with respect to **FIG. 7**. Scalograms **840** and **880** may be derived using a narrower range of scales to eliminate the inclusion of artifacts (*e.g.*, artifact **A** in scalogram **810**), to focus on the component of interest (*e.g.* pulse band **P**, which appears lighter in tone and thereby higher in energy in both scalograms **840** and **880** than in scalogram **810**), and to minimize the number of computations that processor **412** or microprocessor **48** would need to perform. Scalograms **840** and **880** may include ridges corresponding to at least one area of increased energy, such as band **P**, that may be analyzed further using any suitable method, for example using secondary wavelet feature decoupling. By extracting and further analyzing the ridges with respect to band **P**, information concerning the nature of the signal component associated with the underlying physical process causing the breathing band **B** in scalogram **810** may also be extracted when band **B** itself is, for example, obscured in the presence of noise or other erroneous signal features.

The sum along amplitudes technique, as described in **FIG. 7**, may be applied to any suitable signal that has been transformed using continuous wavelet transforms. **FIG. 9** is a flowchart of an illustrative process for applying a sum along amplitudes to a scalogram in accordance with an embodiment of the disclosure. Process **900** may begin at step **902**. At step **904**, a signal may be obtained. For example, the signal may include a PPG signal obtained from patient **40** using sensor **12** in system **10** or input signal generator **410** in system **400**.

Process **900** may advance to step **906**, where the signal may be transformed using any suitable method. For example, the PPG signal may be transformed using a continuous wavelet transform as described above using equation (9). At step **908**, a scalogram may be generated in any suitable manner and based at least in part on the transformed signal from step **906**. For example, the scalogram may be generated using the energy density function equation (10) and may include some or all of the features described above with respect to **FIGS. 3(a)**, **3(b)**, and **3(c)**. In an embodiment, the scalogram of the PPG signal may include any suitable number of bands containing pulse information and respiration information, and each band may include a ridge. The ridge may be continuous or may include any suitable number of ridge fragments.

Process **900** may advance to step **910**, where any suitable region of the scalogram may be selected. For example, a portion of the scalogram containing a ridge fragment may be selected. Alternatively, the entire scalogram may be selected. Process **900** may advance to step **912**, where, for each scale within the selected region, a sum of the amplitudes (*e.g.*, the energy) across time at that scale may be obtained. Thus, for a region of the scalogram, any suitable number of sums may be calculated within a given time window. The technique may be applied by processor **412** or microprocessor **48** to at least a portion of the band corresponding to the selected ridge or at least a portion of the scalogram. In an embodiment, processor **412** or microprocessor **48** may include any suitable software, firmware, and/or hardware, and/or combinations thereof for generating a sum along amplitudes vector and applying it to the selected region. In an embodiment (not shown), if more than one scalogram was generated at step **908** (*e.g.*, two scalograms may be generated from transforming two PPG signals), then the sum along amplitudes technique may be applied to a scalogram composite, or a superposition formed from the scalograms. In an embodiment (not shown), the sum along amplitudes function (*e.g.*, the sum obtained for each scale value) may be plotted as a function of scale value using any suitable approach. For example, the plot may be generated by processor **412** or microprocessor **48** and may be displayed on display **20** (**FIG. 2**), display **28** (**FIG. 2**), or output **414** (**FIG. 4**) for review and analysis by a user of system **10** (**FIG. 1**) or system **400** (**FIG. 4**).

Process **900** may then advance to step **914**,where a maximum may be identified (*e.g.*, using processor **412** or microprocessor **48**). In an embodiment, the maximum may be identified from a plot by processor **412** or microprocessor **48** or by a user of system **10** or system **400**. In an embodiment, the maximum may be the first peak or edge moving from a direction of decreasing scale along the sum of amplitudes. The first peak or edge may have analytical value in relation to a PPG signal from which the scalogram or scalograms may have been generated.

Process **900** may advance to step **916**, where a desired scale value that may be associated with the maximum identified in step **914** may be selected. For example, if the original signal was a PPG signal, then the first peak or edge in step **914** may relate to a scale value at that maximum. The scale value may represent the respiration rate of patient **40**. Process **900** may then advance to step **918** and end.

It will be understood that the foregoing is only illustrative of the principles of the disclosure, and that the disclosure can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation.

What is Claimed is:

1. A signal processing method comprising:

selecting a first portion of an original signal;

mirroring the first portion of the original signal about a first vertical axis to create a mirrored first portion; and

analyzing the mirrored first portion.

2. The method of claim 1, wherein selecting the first portion of the original signal comprises:

identifying a first local minimum value of the original signal;

identifying a subsequent first local maximum value of the original signal; and

selecting the first portion to be the portion of the original signal between the first local minimum value of the original signal and the subsequent first local maximum of the original signal.

3. The method of claim 1, further comprising selecting a subsequent second portion of the original signal;

mirroring the second portion of the original signal about a second vertical axis to create a mirrored second portion; and

analyzing the mirrored second portion.

4. The method of claim 3, wherein selecting the second portion of the original signal comprises:

identifying a second local minimum value of the original signal, wherein the second local minimum value is subsequent to the first local minimum value of the original signal;

identifying a subsequent second local maximum value of the original signal; and

selecting the second portion to be the portion of the original signal between the second local minimum value of the original signal and the subsequent second local maximum of the original signal.

5. The method of claim 3, further comprising combining the mirrored first portion and the mirrored second portion to create a new signal, and analyzing the new signal.

6. The method of claim 5, wherein the first portion of the original signal is selected from a larger first segment of the original signal, wherein the second portion of the original signal is selected from a larger second segment of the original signal, and wherein the first and the second segments are consecutive segments, the method further comprising:

adjusting the length of the new signal by stretching or compressing the new signal to be substantially identical to a combined length of the first and the second segments.

7. The method of claim 5, wherein the first portion of the original signal is selected from a larger first segment of the original signal and wherein the second portion of the original signal is selected from a larger second segment of the original signal, the method further comprising:

adjusting the length of the mirrored first portion by stretching or compressing the mirrored first portion to be a first size; and

adjusting the length of the mirrored second portion by stretching or compressing the mirrored second portion to be a second size.

8. The method of claim 7, further comprising:

adjusting the amplitude of the mirrored first portion based at least in part on the length adjustment of the mirrored first portion; and

adjusting the amplitude of the mirrored second portion based at least in part on the length adjustment of the mirrored second portion.

9. The method of claim 7, wherein the first portion and the second portion of the original signal are selected based at least in part on a second derivative of the original signal.

10. The method of claim 7, wherein analyzing the new signal comprises transforming the new signal into a transformed signal using a wavelet transform.

11. The method of claim 10, further comprising generating a scalogram based at least in part on the transformed signal.

12. The method of claim 11, wherein the original signal is a photoplethysmograph signal from a user, the method further comprising analyzing the scalogram to obtain respiration information of the user.

13. The method of claim 11, wherein the first portion of the original signal and the second portion of the original signal are up strokes of the photoplethysmograph signal.

14. The method of claim 11, wherein the first portion of the original signal and the second portion of the original signal are down strokes of the photoplethysmograph signal.

15. A system for processing a signal, the system comprising:

an input signal generator for generating the signal;

a processor coupled to the input signal generator, wherein the processor is configured to select a first portion of an original signal, mirror the first portion of the original signal about a first vertical axis to create a mirrored first portion, select a subsequent second portion of the original signal, mirror the second portion of the original signal about a second vertical axis to create a mirrored second portion, combine the mirrored first portion and the mirrored second portion to create a new signal, and analyze the new signal; and

an output coupled to the processor, wherein the output is configured to display the new signal analyzed by the processor.

16. The system of claim 15, wherein the input signal generator is a pulse oximeter coupled to a sensor.

17. The system of claim 15, wherein the processor is further configured to adjust an amplitude of the mirrored first portion based at least in part on a length adjustment of the mirrored first portion, and adjust an amplitude of the mirrored second portion based at least in part on a length adjustment of the mirrored second portion.

18. The system of claim 15, wherein analyzing the new signal comprises transforming the new signal into a transformed signal using a wavelet transform.

19. The system of claim 15, wherein the processor is further configured to generate a scalogram based at least in part on the transformed signal.

20. The system of claim 19, wherein the original signal is a photoplethysmograph signal from a user, the processor further configured to analyze the scalogram to obtain respiration information of the user.

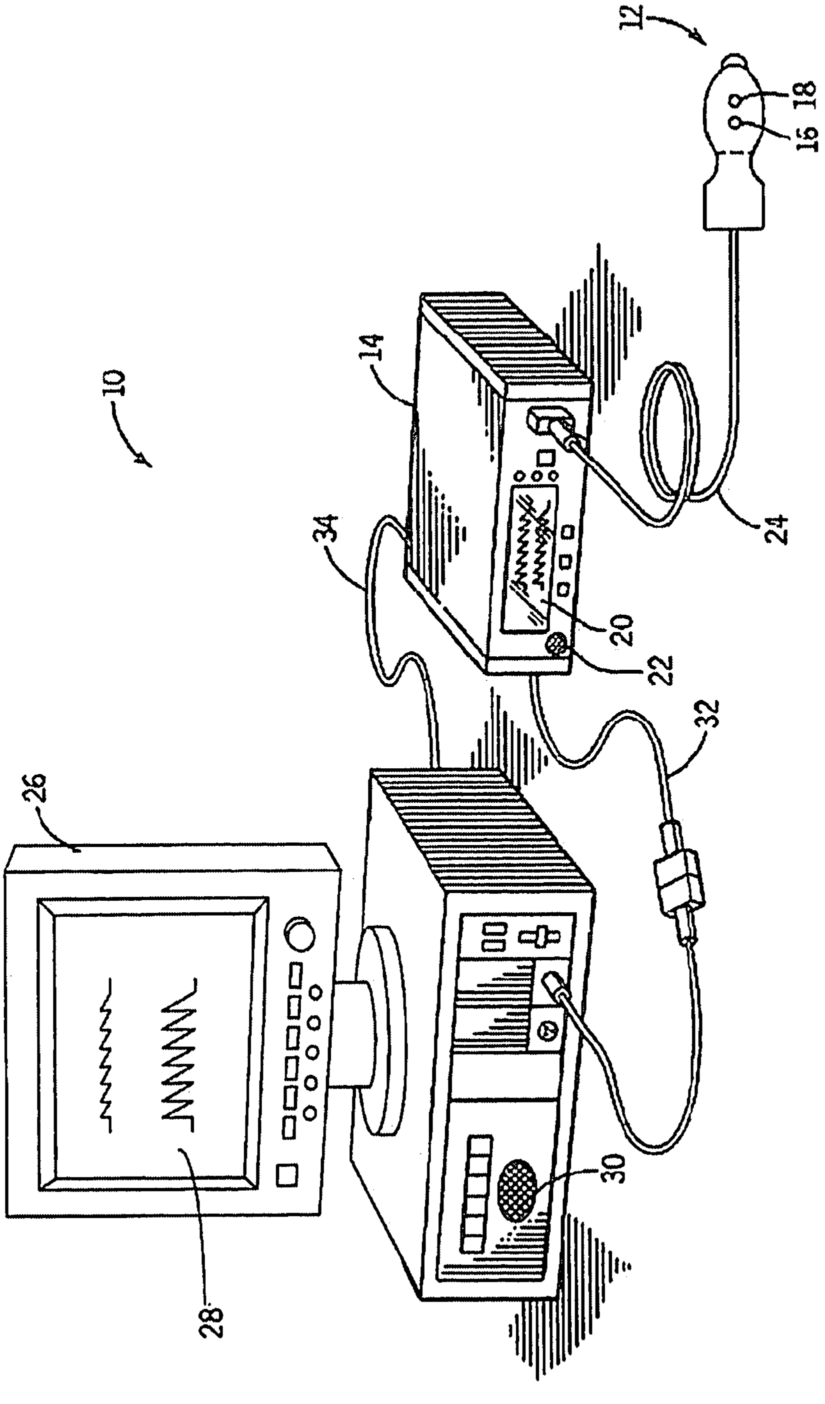

FIG.1

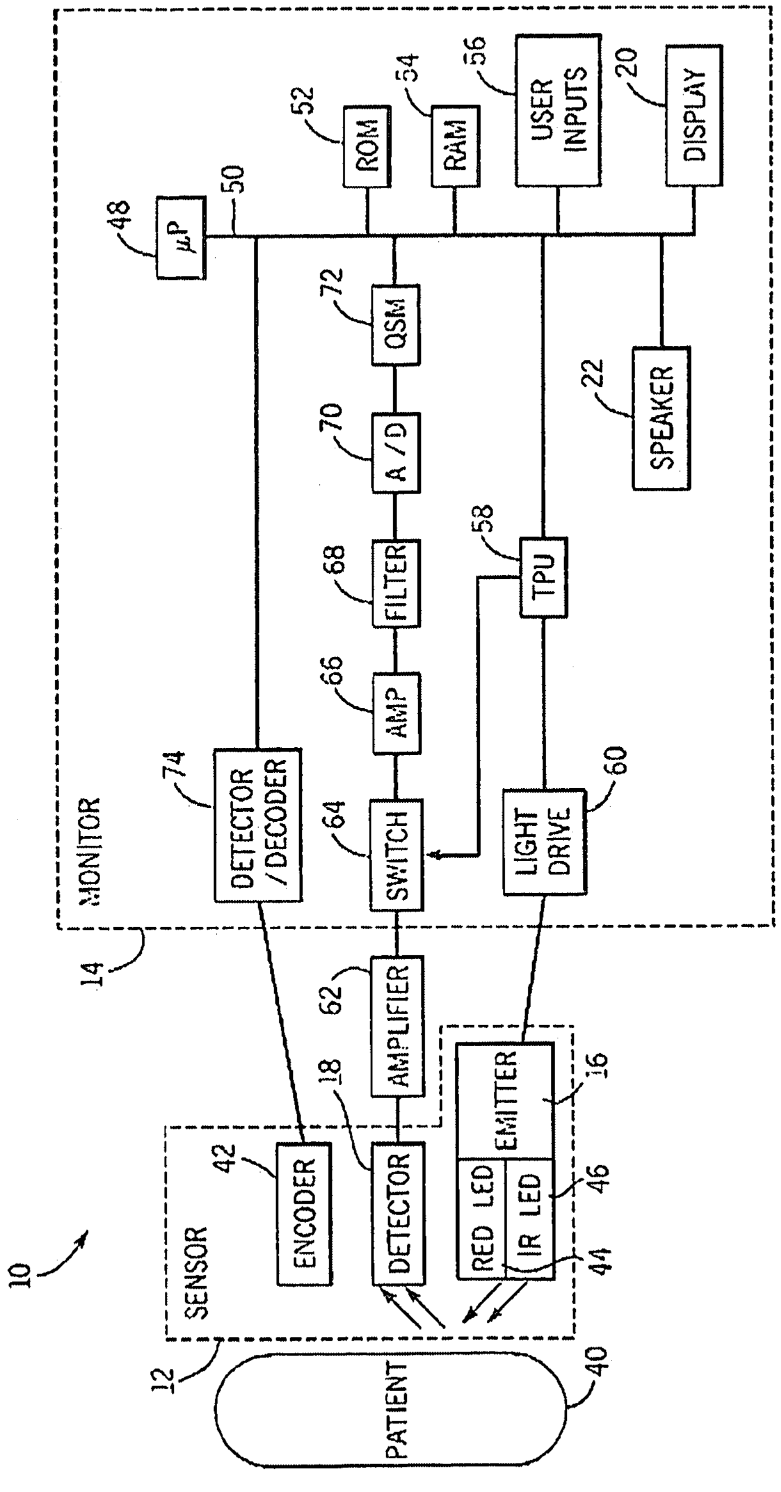
10
MONITOR
14
μP
48
50
ROM
52
RAM
54
USER INPUTS
56
DISPLAY
20
QSM
72
A / D
70
FILTER
68
AMP
66
SWITCH
64
DETECTOR / DECODER
74
TPU
58
LIGHT DRIVE
60
SPEAKER
22
AMPLIFIER
62
SENSOR
12
ENCODER
42
DETECTOR
18
EMITTER
16
RED LED
44
IR LED
46
PATIENT
40

FIG. 2

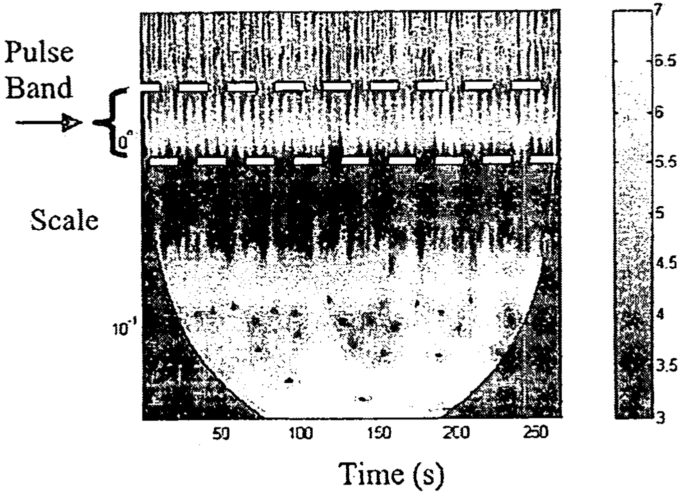
Pulse
Band
10^0
Scale
10^-1
50
100
150
200
250
Time (s)
7
6.5
6
5.5
5
4.5
4
3.5
3

FIG. 3(a)

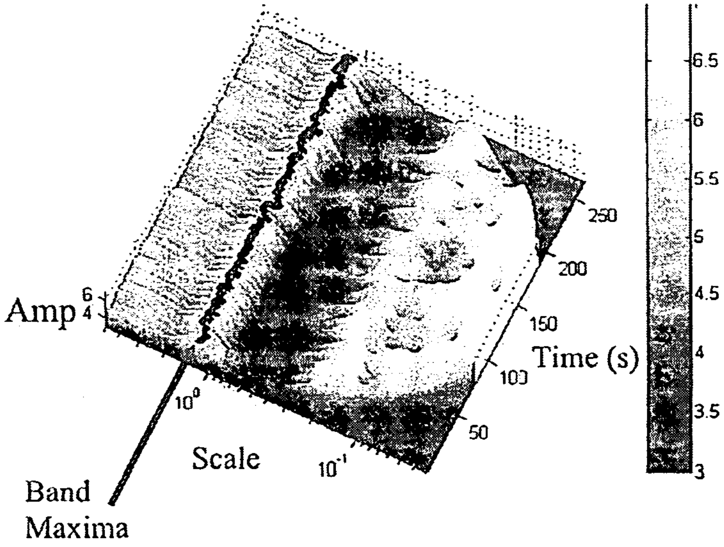
Amp
6
4
Band
Maxima
10^0
Scale
10^-1
50
100
150
200
250
Time (s)
6.5
6
5.5
5
4.5
4
3.5
3

FIG. 3(b)

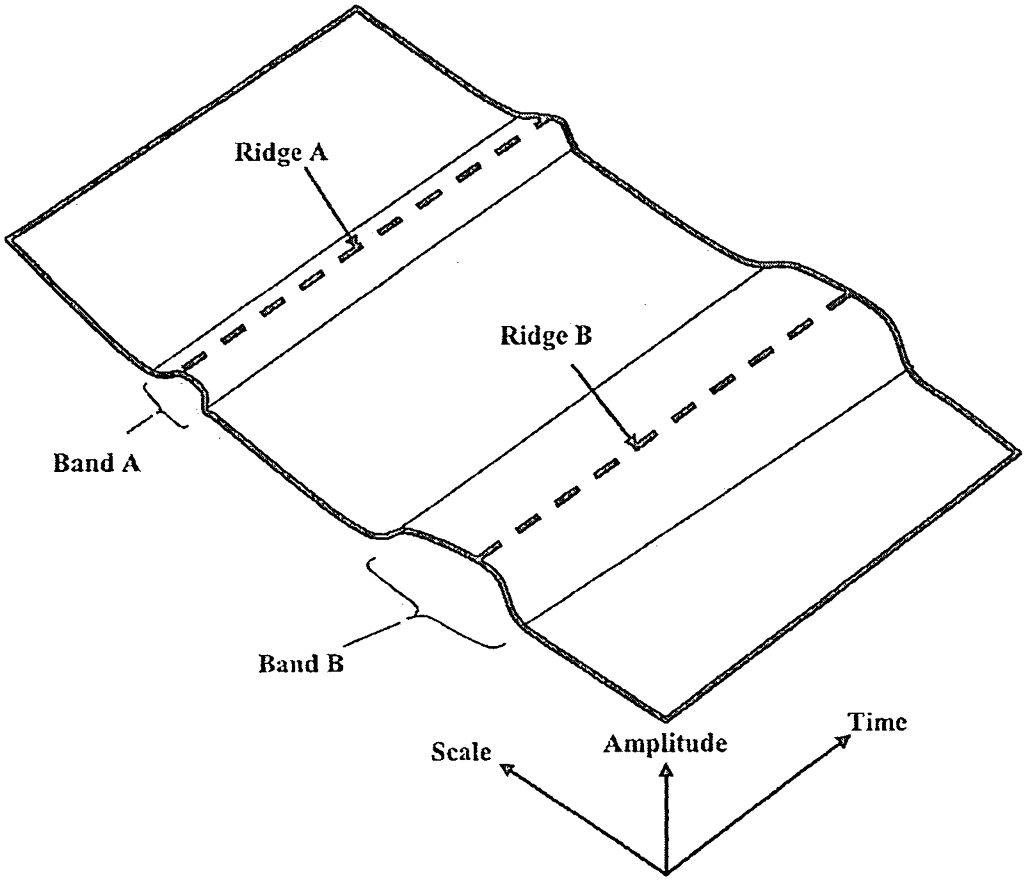

FIG. 3(c)

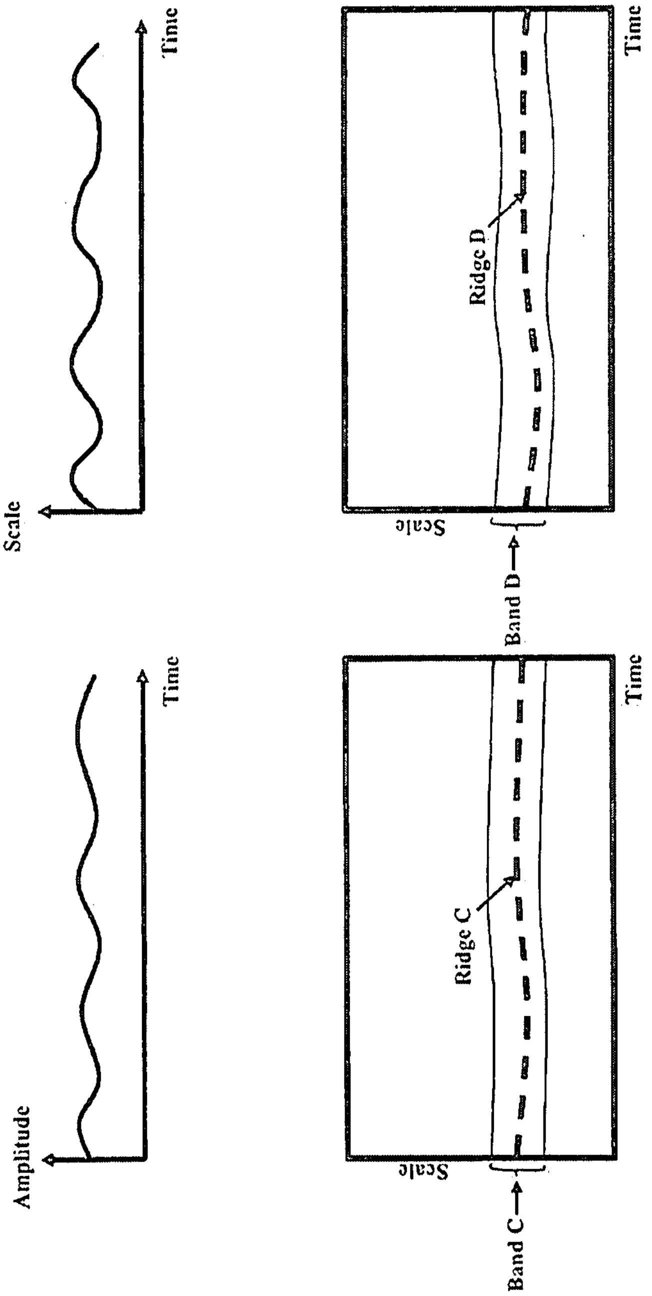
Amplitude
Time
Scale
Time
Scale
Time
Ridge C
Band C
Scale
Time
Ridge D
Band D

FIG. 3(d)

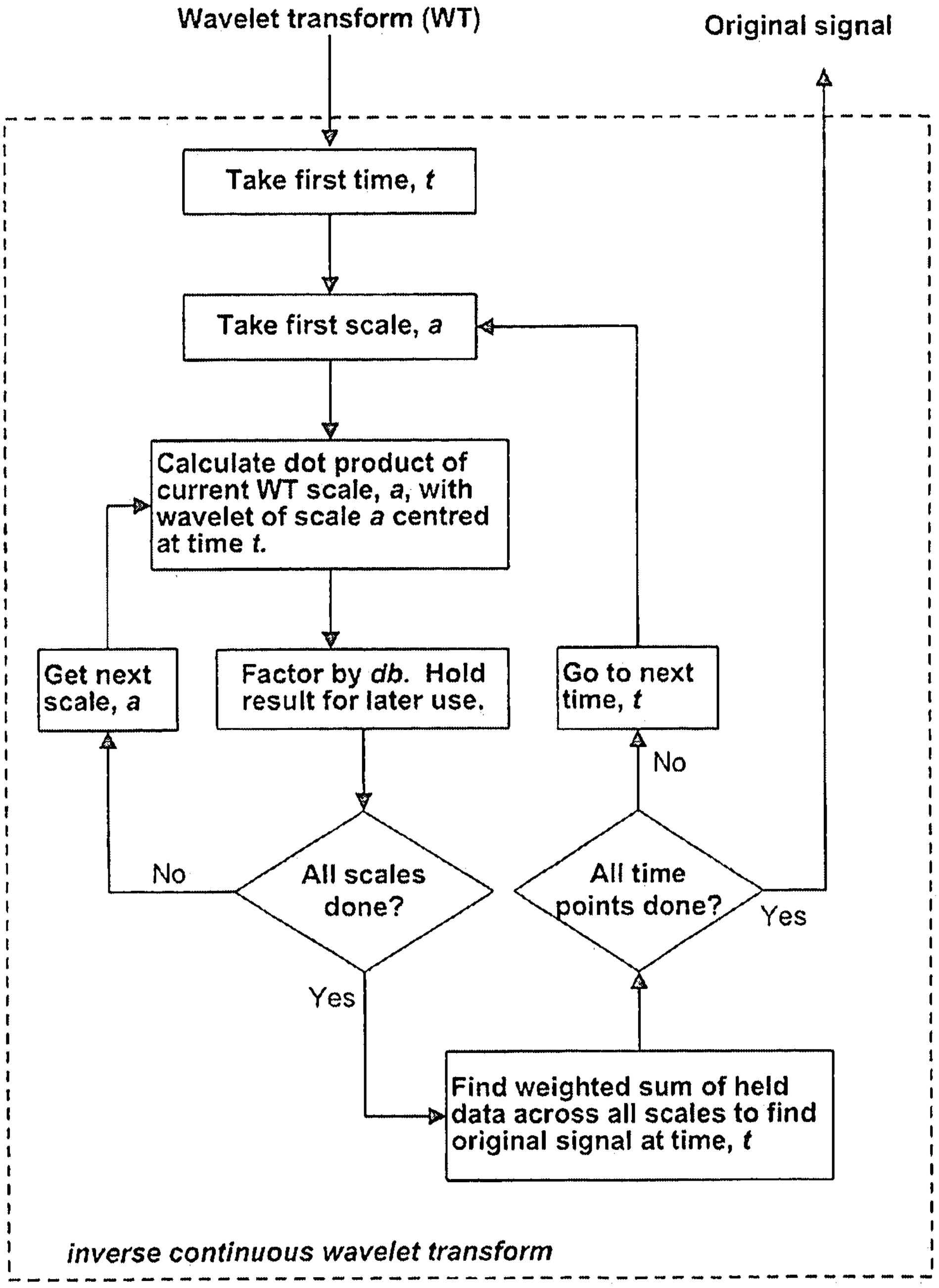
Wavelet transform (WT)
Original signal
Take first time, *t*
Take first scale, *a*
Calculate dot product of current WT scale, *a*, with wavelet of scale *a* centred at time *t*.
Get next scale, *a*
Factor by *db*. Hold result for later use.
Go to next time, *t*
No
All scales done?
No
Yes
All time points done?
Yes
Find weighted sum of held data across all scales to find original signal at time, *t*
inverse continuous wavelet transform

FIG. 3(e)

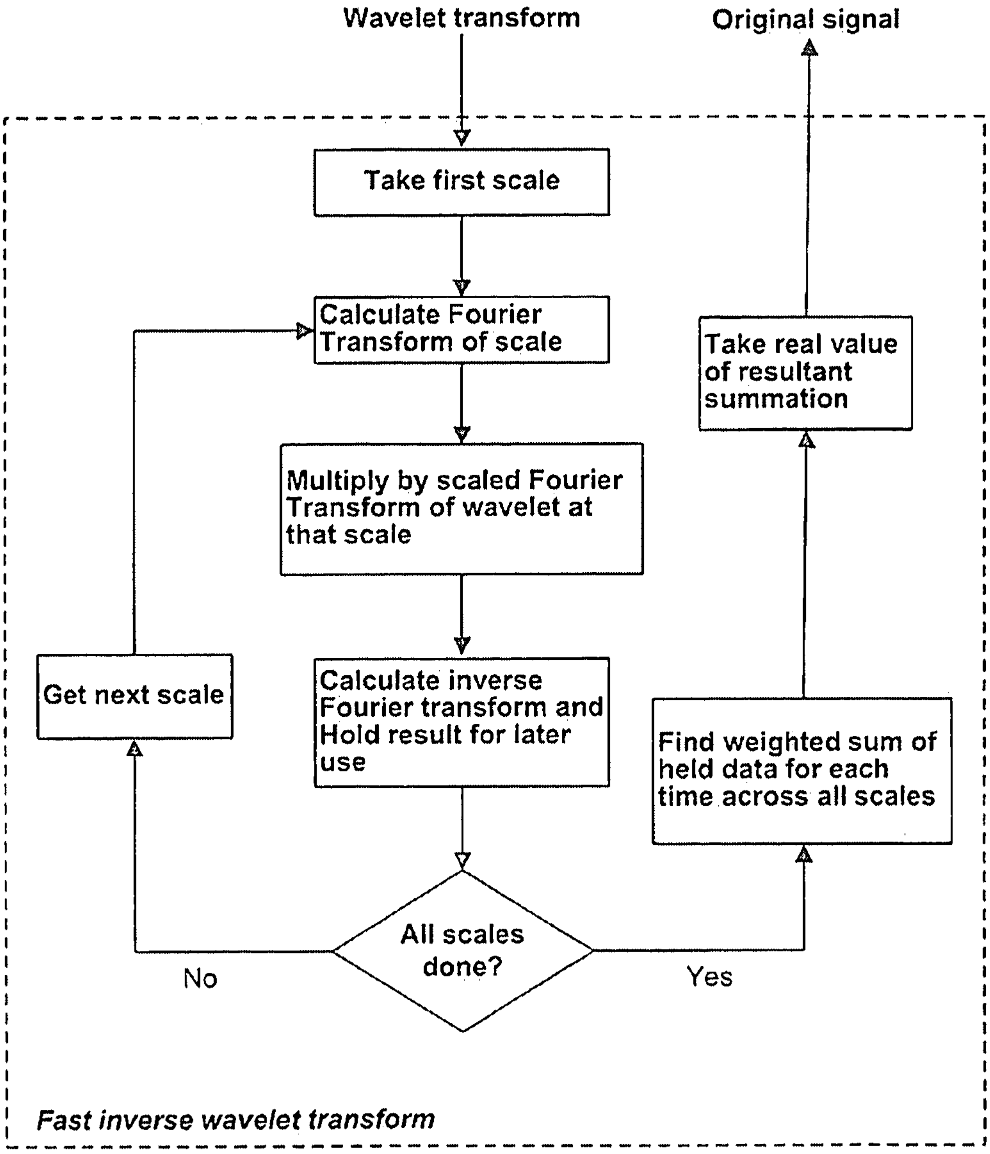
Wavelet transform
Original signal
Take first scale
Calculate Fourier Transform of scale
Multiply by scaled Fourier Transform of wavelet at that scale
Calculate inverse Fourier transform and Hold result for later use
All scales done?
No
Yes
Get next scale
Find weighted sum of held data for each time across all scales
Take real value of resultant summation
Fast inverse wavelet transform

FIG. 3(f)

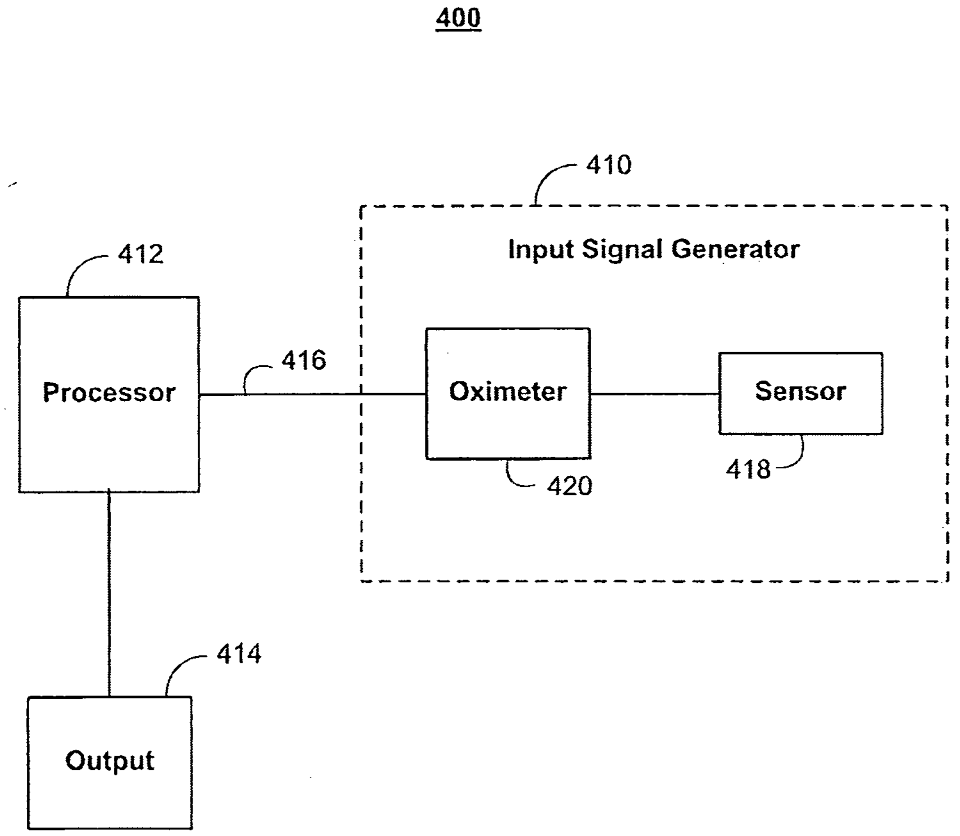
400
410
Input Signal Generator
412
Processor
416
Oximeter
Sensor
420
418
414
Output

FIG. 4

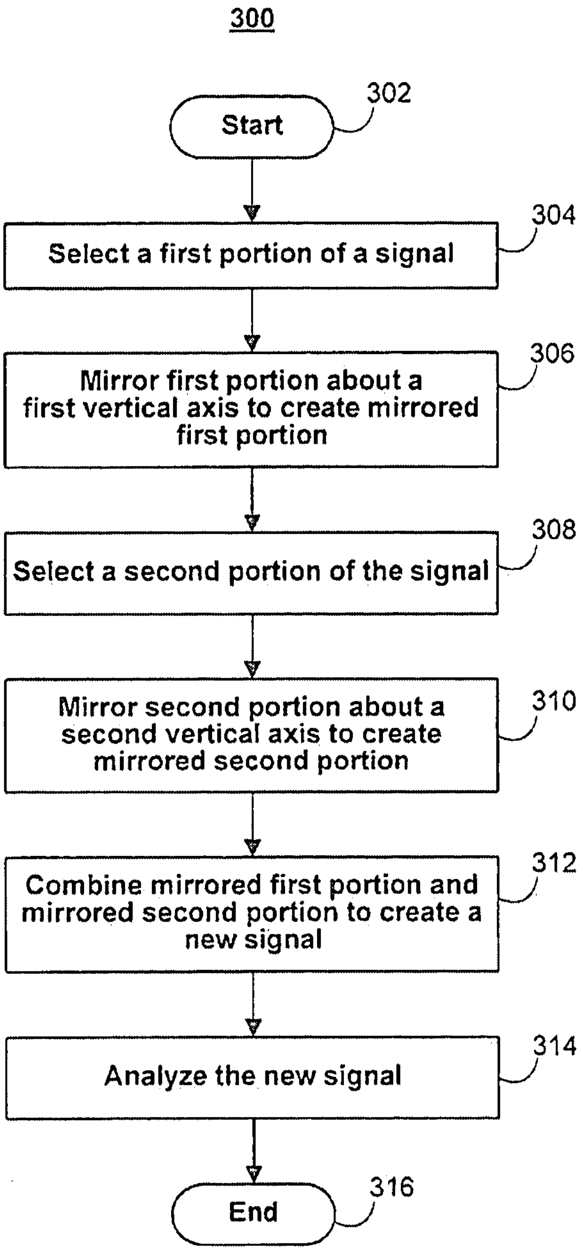
300
Start
302
Select a first portion of a signal
304
Mirror first portion about a first vertical axis to create mirrored first portion
306
Select a second portion of the signal
308
Mirror second portion about a second vertical axis to create mirrored second portion
310
Combine mirrored first portion and mirrored second portion to create a new signal
312
Analyze the new signal
314
End
316

FIG. 5

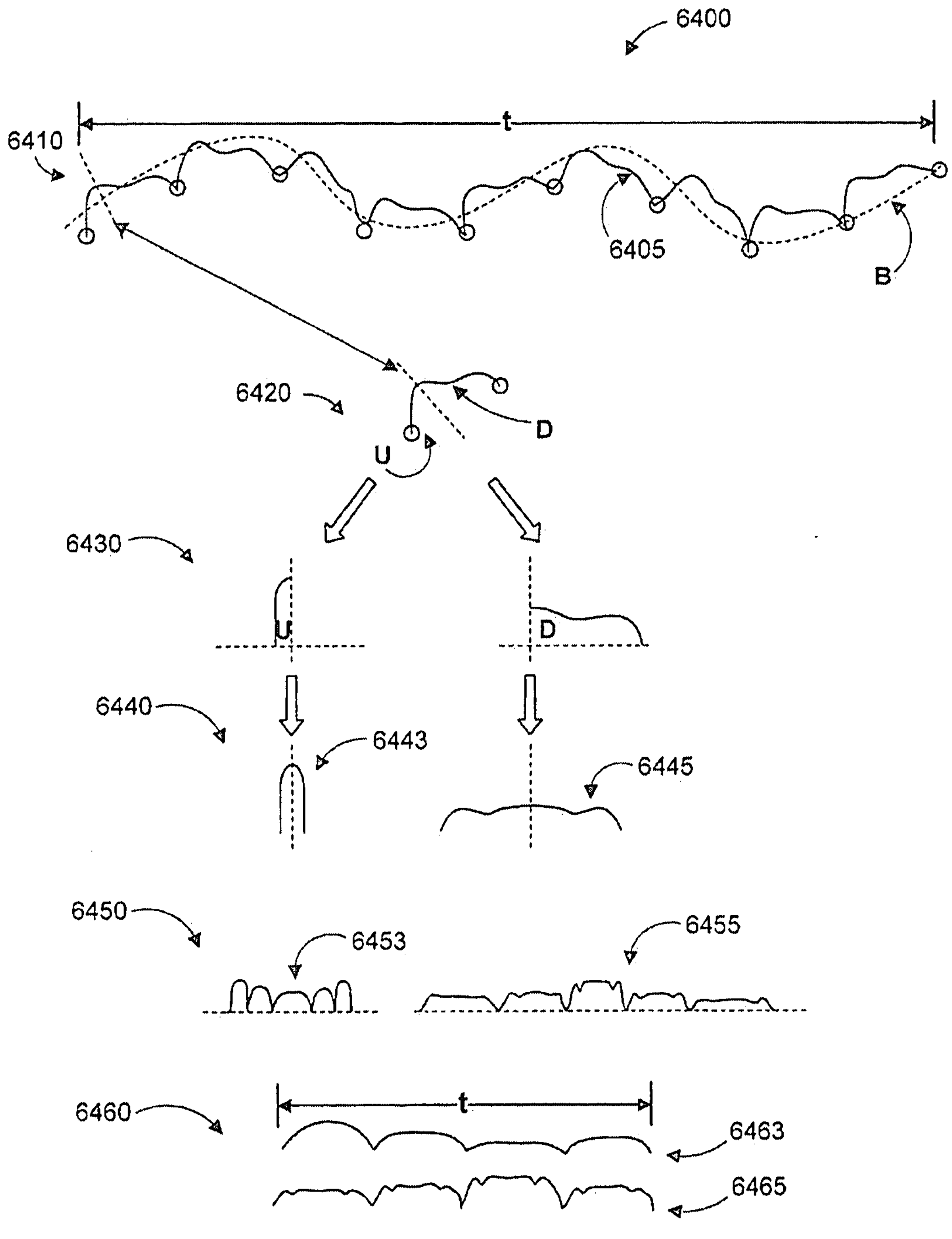
6400
t
6410
6405
B
6420
D
U
6430
U
D
6440
6443
6445
6450
6453
6455
6460
t
6463
6465

FIG. 6

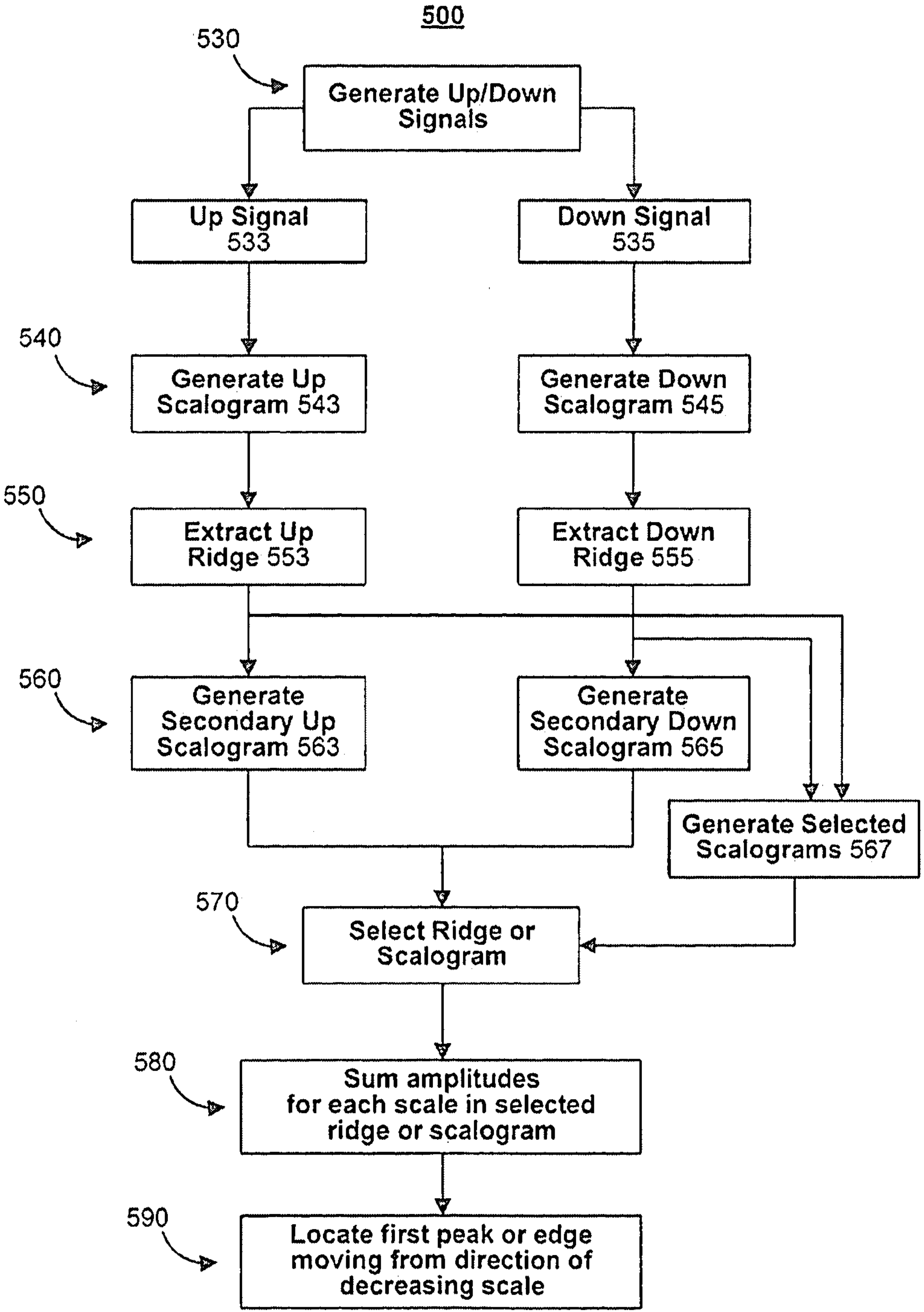
500
530
Generate Up/Down Signals
Up Signal 533
Down Signal 535
540
Generate Up Scalogram 543
Generate Down Scalogram 545
550
Extract Up Ridge 553
Extract Down Ridge 555
560
Generate Secondary Up Scalogram 563
Generate Secondary Down Scalogram 565
Generate Selected Scalograms 567
570
Select Ridge or Scalogram
580
Sum amplitudes for each scale in selected ridge or scalogram
590
Locate first peak or edge moving from direction of decreasing scale

FIG. 7

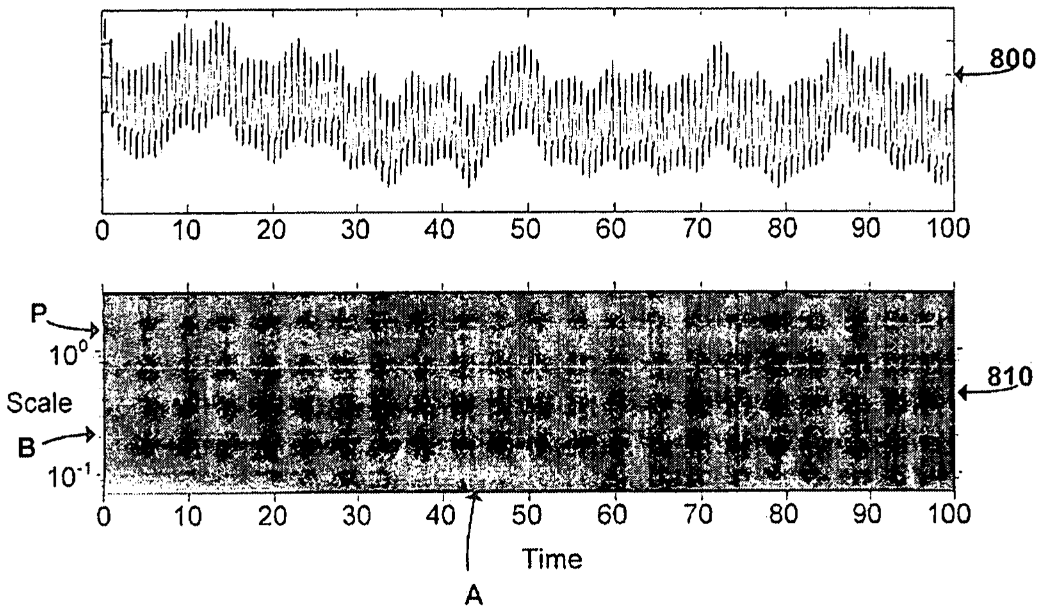
800
0
10
20
30
40
50
60
70
80
90
100
P
10^0
Scale
B
10^{-1}
810
0
10
20
30
40
50
60
70
80
90
100
Time
A

FIG. 8(a)

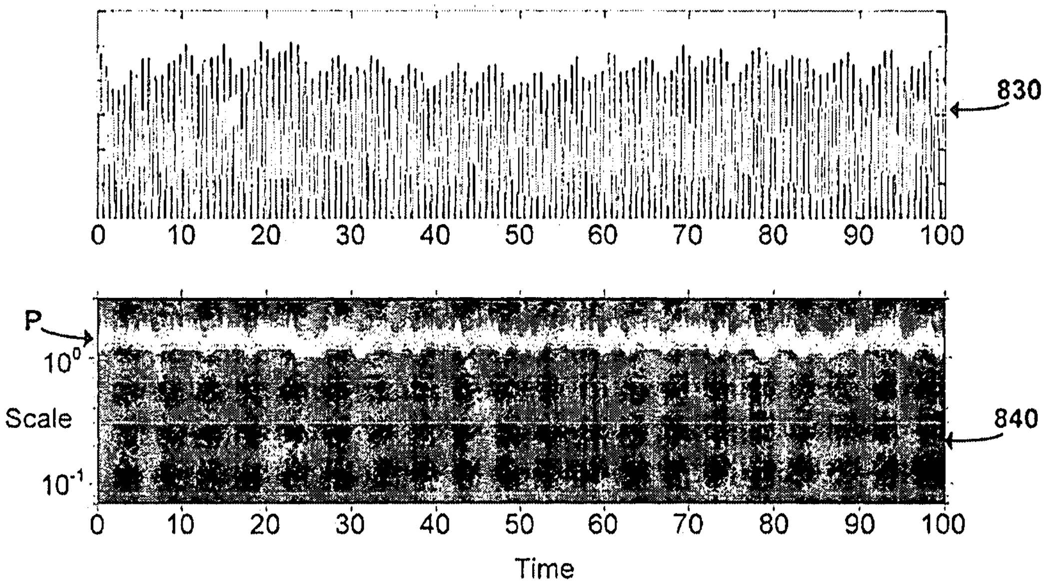
830
0
10
20
30
40
50
60
70
80
90
100
P
10^0
Scale
10^{-1}
840
0
10
20
30
40
50
60
70
80
90
100
Time

FIG. 8(b)

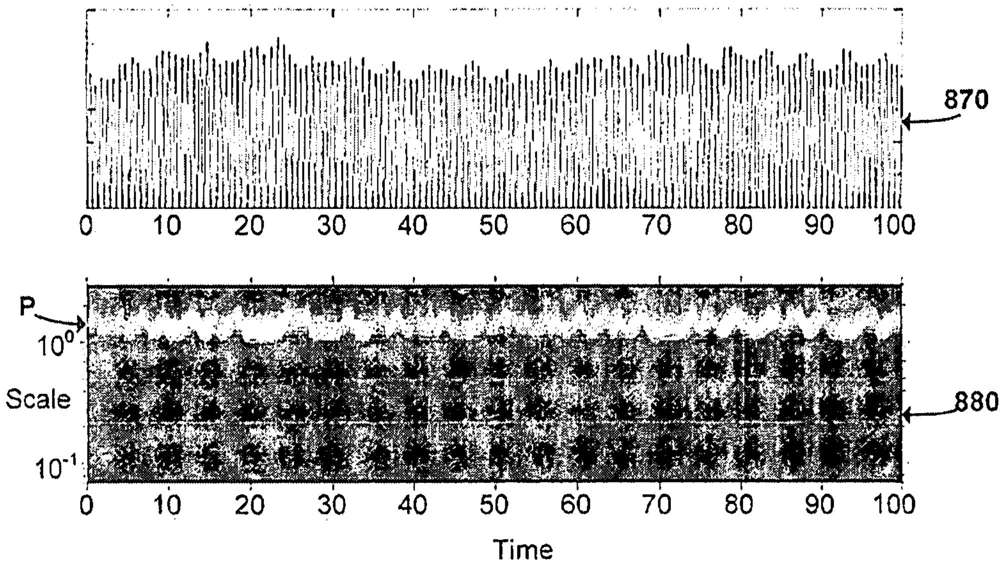
870
0
10
20
30
40
50
60
70
80
90
100
P
10^0
Scale
10^{-1}
880
0
10
20
30
40
50
60
70
80
90
100
Time

FIG. 8(c)

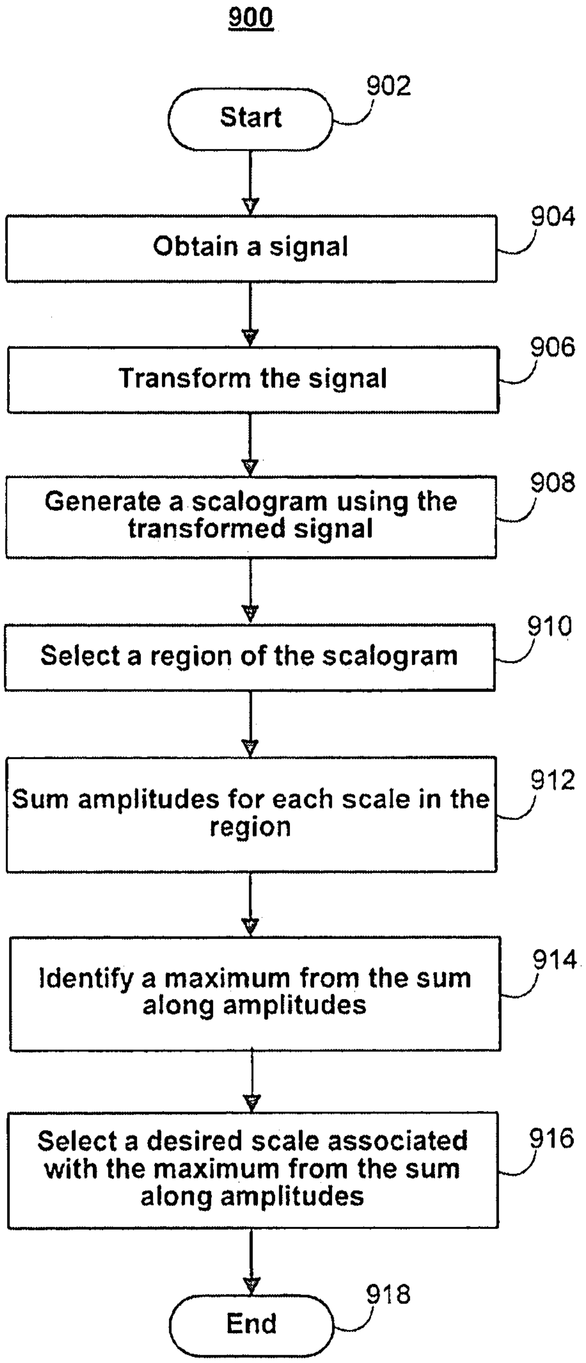
900
Start
902
Obtain a signal
904
Transform the signal
906
Generate a scalogram using the transformed signal
908
Select a region of the scalogram
910
Sum amplitudes for each scale in the region
912
Identify a maximum from the sum along amplitudes
914
Select a desired scale associated with the maximum from the sum along amplitudes
916
End
918

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/006153

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2005/044102 A (PSI HEARTSIGNALS LTD [GB]; HUNT ANTHONY CHARLES [GB]) 19 May 2005 (2005-05-19) page 9, line 18 - page 12, line 21 figures 1-7	1,15
A	US 2006/258921 A1 (ADDISON PAUL S [GB] ET AL) 16 November 2006 (2006-11-16) the whole document	1-20
A	US 2005/070774 A1 (ADDISON PAUL STANLEY [GB] ET AL) 31 March 2005 (2005-03-31) the whole document	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search 15 October 2009	Date of mailing of the international search report 26/10/2009
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Abraham, Volkhard

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/006153

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2005044102 A	19-05-2005	AT 415124 T	15-12-2008
		AU 2003269280 A1	26-05-2005
		EP 1677672 A1	12-07-2006
		ES 2318154 T3	01-05-2009
		US 2008262366 A1	23-10-2008
US 2006258921 A1	16-11-2006	EP 1628571 A2	01-03-2006
		WO 2004075746 A2	10-09-2004
		JP 2007515977 T	21-06-2007
US 2005070774 A1	31-03-2005	AT 424139 T	15-03-2009
		EP 1399056 A1	24-03-2004
		EP 2067437 A1	10-06-2009
		ES 2321282 T3	04-06-2009
		WO 03000125 A1	03-01-2003
		JP 4278048 B2	10-06-2009
		JP 2005500876 T	13-01-2005
		JP 2008212745 A	18-09-2008