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(54) Title: SYSTEMS AND METHODS FOR DETERMINING EFFORT

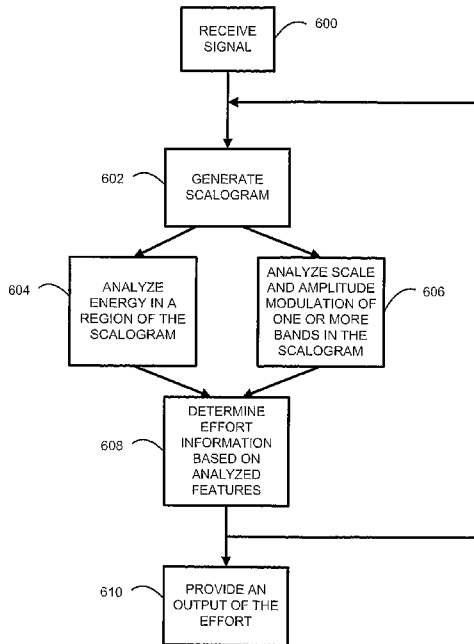


FIG. 6

(57) Abstract: According to embodiments, methods and systems for determining effort is disclosed. Effort may relate to a measure of strength of at least one repetitive feature in a signal. Effort may also relate to physical effort or work of a process (e.g., respiratory effort) that may affect the signal (e.g., a PPG signal). Effort may be determined through feature analysis of a transformed signal that has been transformed via a continuous wavelet transform. For example, respiratory effort may be determined using a scalogram generated based at least in part on a wavelet transform of a physiological signal and analyzing features of the scalogram.

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## SYSTEMS AND METHODS FOR DETERMINING EFFORT

### Cross-Reference to Related Applications

This claims the benefit of United States Provisional Application No. 61/077,097, filed June 30, 2008 and United States Provisional Application No. 61/077,130, filed June 30, 2008, which are hereby incorporated by reference herein in their entireties.

### Summary of the Disclosure

The present disclosure relates to signal processing and, more particularly, the present disclosure relates to using continuous wavelet transforms for processing, for example, a photoplethysmograph (PPG) signal, to determine effort, such as respiratory effort of a patient.

Systems and methods to analyze the suitable signal domain representation in order to determine effort are disclosed herein. In one embodiment, effort may relate to a measure of strength of at least one repetitive feature in a signal. In another embodiment, effort may relate to physical effort of a process that may affect the signal (*e.g.* effort may relate to work of a process).

In some embodiments, the use of a transform may allow a signal to be represented in a suitable domain such as, for example, a scalogram (in a time-scale domain) or a spectrogram (in a time-frequency domain). A type of effort which may be determined by analyzing the signal representation may be, for example, breathing effort of a patient. The breathing effort of the patient may be determined by analyzing a scalogram with the processes presented in this disclosure.

The determination of effort from a scalogram or any other signal representation is possible because changes in effort induce or change various features of the signal used to generate the scalogram. For example, the act of breathing may cause a breathing band to become present in a scalogram that was derived from a PPG signal. This band may occur at or about the scale having a characteristic frequency that corresponds to the breathing frequency. Furthermore, the features within this band or other bands on the scalogram (*e.g.*, energy, amplitude, phase, or modulation) may result from changes in

breathing and/or breathing effort and therefore may be correlated with the patient's breathing effort.

The effort determined by the methods and systems described herein may be represented in any suitable way. For example, breathing effort may be represented graphically in which changes in features of the breathing band and of neighboring bands are represented by changes in color or pattern.

Alternatively, or in combination with the graphical representation, a quantitative value indicative of the relative change in effort or of an absolute value of effort may be calculated according to any suitable metric.

In addition, thresholds may be set to trigger alarms if effort increases (*e.g.*, by percent change or absolute value) over the threshold.

In one embodiment, the present disclosure may be used in the context of a sleep study environment to detect and/or differentiate apneic events. In an embodiment, the present disclosure may be used to monitor the effect of therapeutic intervention.

### **Brief Description of the Drawings**

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

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 effort system in accordance with an embodiment;

**FIG. 2** is a block diagram of the illustrative effort 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 some embodiments;

5 **FIG. 5** is an illustrative scalogram showing the manifestation of a plurality of bands and an increase in effort in accordance with some embodiments; and

**FIG. 6** is an illustrative flow chart depicting the steps used to determine effort in accordance with some embodiments.

## 10 Detailed Description

An oximeter is a medical device that may determine the oxygen saturation of the blood. One common type of oximeter is a pulse oximeter, which 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  
15 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. Pulse oximeters may also be used to determine respiratory effort in accordance with the present disclosure.

20 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  
25 time. A signal representing light intensity versus time or a mathematical manipulation of this signal (*e.g.*, a scaled version thereof, a log taken thereof, a scaled version of a log taken thereof, *etc.*) may be referred to as the photoplethysmograph (PPG) signal. In addition, the term "PPG signal," as used herein, may also refer to an absorption signal (*i.e.*, representing the amount of light absorbed by the tissue) or any suitable  
30 mathematical manipulation thereof. 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  
 5 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.

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

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

where:

15  $\lambda$ =wavelength;

$t$ =time;

$I$ =intensity of light detected;

$I_o$ =intensity of light transmitted;

$s$ =oxygen saturation;

20  $\beta_o, \beta_r$ =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  
 25 follows.

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

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

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

30 
$$\frac{d \log I}{dt} = -(s\beta_o + (1-s)\beta_r) \frac{dl}{dt} \quad (3)$$

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

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

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

$$5 \quad \frac{d \log I(\lambda, t)}{dt} \approx \log I(\lambda, t_2) - \log I(\lambda, t_1)$$

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

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

10 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

$$15 \quad \frac{d \log I}{dt} = \frac{dI / dt}{I} \quad (6)$$

now (5) becomes

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

$$= R \quad (7)$$

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

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

**FIG. 1** is a perspective view of an embodiment of an effort system **10**. In an  
 5 embodiment, effort system **10** is implemented as part of a pulse oximetry system. System **10** may include a sensor **12** and a 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.

10 Sensor **12** or monitor **14** may further include, but are not limited to software modules that calculate respiration rate, airflow sensors (*e.g.*, nasal thermistor), ventilators, chest straps, transthoracic sensors (*e.g.*, sensors that measure transthoracic impedance).

According to another embodiment and as will be described, system **10** may  
 15 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  
 20 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  
 25 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  
 30 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 effort or oximetry reading may be passed to monitor **14**.

5 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.

10 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, effort system **10** may also include a multi-  
15 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  
20 (not shown). For example, multiparameter patient monitor **26** may be configured to display an estimate of a patient's respiratory effort or blood oxygen saturation (referred to as an "SpO<sub>2</sub>" measurement) generated by monitor **14**, 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  
25 **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  
30 outlet.

**FIG. 2** is a block diagram of an effort system, such as effort 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 one or more wavelengths of light (*e.g.*, *RED* and/or *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/or 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**.

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 wavelength or 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  
5 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  
10 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  
15 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 effort, SpO<sub>2</sub>, 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  
20 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  
25 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**.

30 The optical signal through the tissue can be degraded by noise, 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 probe is attached.

Noise (e.g., from patient movement) 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 effort and 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

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

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  
5 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.

10 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  
15 transforms allow for the use of a range of wavelets with scales spanning the scales of interest of a signal such that small scale signal components correlate well with the smaller scale wavelets and thus manifest at high energies at smaller scales in the transform. Likewise, large scale signal components correlate well with the larger scale wavelets and thus manifest at high energies at larger scales in the transform. Thus,  
20 components at different scales may be separated and extracted in the wavelet transform domain. Moreover, the use of a continuous range of wavelets in scale and time position allows for a higher resolution transform than is possible 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  
25 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  
30 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

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

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

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

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  
 5 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  
 10 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  
 15 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  
 20 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

$$25 \quad f = \frac{f_c}{a} \quad (12)$$

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  
 30 disclosure. One of the most commonly used complex wavelets, the Morlet wavelet, is defined as:

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



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  $f_0 \gg 0$  and can be ignored, in which case, the Morlet wavelet can be written in a simpler form as

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

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  $f_0 \gg 0$  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 an 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  
 5 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  
 10 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  $b$ :

$$15 \quad x(t) = \frac{1}{C_g} \int_{-\infty}^{\infty} \int T(a,b) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \frac{da db}{a^2} \quad (15)$$

which may also be written as:

$$20 \quad x(t) = \frac{1}{C_g} \int_{-\infty}^{\infty} \int T(a,b) \psi_{a,b}(t) \frac{da db}{a^2} \quad (16)$$

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

$$25 \quad C_g = \int \frac{|\hat{\psi}(f)|^2}{f} df \quad (17)$$

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  
 30 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  
5 will be understood that any other suitable technique for performing an inverse continuous wavelet transform may be used in accordance with the present disclosure.

The present disclosure relates to methods and systems for processing a signal using the above mentioned techniques and analyzing the results of the techniques to determine effort. In one embodiment, effort may relate to a measure of strength of at  
10 least one repetitive feature in a signal. In another embodiment, effort may relate to physical effort of a process that may affect the signal (*e.g.* effort may relate to work of a process). For example, effort calculated from a PPG signal may relate to the respiratory effort of a patient. Respiratory effort may increase, for example, if a patient's respiratory pathway becomes restricted or blocked. Conversely, respiratory effort may decrease as a  
15 patient's respiratory pathway becomes unrestricted or unblocked. The effort of a signal may be determined, for example, by transforming the signal using a wavelet transform and analyzing features of a scalogram derived from the wavelet transform. In particular, changes in the features of the pulse band and breathing band in the scalogram may be correlated to a change in breathing effort.

As an additional example, the methods and systems disclosed herein may be used  
20 to determine effort in a mechanical engine. Over time, a mechanical engine may become less efficient because of wear of the mechanical parts and/or insufficient lubrication. This may cause extra strain on the engine parts and, in particular, cause the engine to exert more effort, work, or force to complete a process. Engine function may be  
25 monitored and represented using signals. These signals may be transformed and analyzed to determine effort using the techniques described herein. For example, an engine may oscillate in a particular manner. This oscillation may produce a band or bands within a scalogram. Features of this band or bands may change as the engine exerts more or less effort. The change in the features may then be correlated to effort.

It will be understood that the present disclosure is applicable to any suitable  
30 signals and that PPG signals or mechanical monitoring 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  
5 financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, and/or any other suitable signal, and/or any combination thereof.

The methods for determining effort described in this disclosure may be implemented on a multitude of different systems and apparatuses through the use of  
10 human-readable or machine-readable information. For example, the methods described herein maybe implemented using machine-readable computer code and executed on a computer system that is capable of reading the computer code. An exemplary system that is capable of determining effort is depicted in **FIG. 4**.

**FIG. 4** is an illustrative continuous wavelet processing system in accordance with  
15 an embodiment. In an 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**.  
20 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  
25 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 an embodiment, signal **416** may be coupled to processor **412**. Processor **412** may be any suitable software, firmware, and/or hardware, and/or combinations thereof  
30 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**.

In some embodiments, in order to determine effort, processor **412** may first transform the signal into any suitable domain, for example, a Fourier, wavelet, spectral, scale, time, time-spectral, time-scale domains, or any transform space. Processor **412**

may further transform the original and/or transformed signals into any of the suitable domains as necessary.

Processor **412** may represent the original or transformed signals in any suitable way, for example, through a two-dimensional representation or three-dimensional  
5 representation, such as a spectrogram or scalogram.

After processor **412** represents the signals in a suitable fashion, processor **412** may then find and analyze selected features in the signal representation of signal 416 to determine effort. Selected features may include the value, weighted value, or change in values with regard to energy, amplitude, frequency modulation, amplitude modulation,  
10 scale modulation, differences between features (*e.g.*, distances between ridge amplitude peaks within a time-scale band).

For example, selected features may include features in a time-scale band in wavelet space or a rescaled wavelet space described above. As an illustrative example, the amplitude or energy of the band may be indicative of the breathing effort of a patient  
15 when the band is the patient's breathing band. Furthermore, changes in the amplitude or energy of the band may be indicative of a change in breathing effort of a patient. Other time-scale bands may also provide information indicative of breathing effort. For example, amplitude modulation, or scale modulation of a patient's pulse band may also be indicative of breathing effort. Effort may be correlated with any of the above selected  
20 features, other suitable features, or any combination thereof.

The selected features may be localized, repetitive, or continuous within one or more regions of the suitable domain space representation of signal **416**. The selected features may not necessarily be localized in a band, but may potentially be present in any region within a signal representation. For example, the selected features may be  
25 localized, repetitive, or continuous in scale or time within a wavelet transform surface. A region of a particular size and shape may be used to analyze selected features in the domain space representation of signal **416**. The region's size and shape may be selected based at least in part on the particular feature to be analyzed. As an illustrative example, in order to analyze a patient's breathing band for one or more selected features, the  
30 region may be selected to have an upper and lower scale value in the time-scale domain such that the region covers a portion of the band, the entire band, or the entire band plus additional portions of the time-scale domain. The region may also have a selected time window width.

The bounds of the region may be selected based at least in part on expected locations of the features. For example, the expected locations may be based at least in part on empirical data of a plurality of patients. The region may also be selected based at least in part on patient classification. For example, an adult's breathing band location generally differs from the location of a neonatal patient's breathing band. Thus, the region selected for an adult may be different than the region selected for a neonate.

In some embodiments, the region may be selected based at least in part on features within a scalogram. For example, the scalogram for a patient may be analyzed to determine the location of the breathing band and its corresponding ridge. The breathing band ridge may be located using standard ridge detection techniques. Ridges may also be detected using the techniques described in Watson et al., U.S. Application No. 12/245,326 (Attorney Docket No. H-RM-01197-1 (COV-2-01)), filed October 3, 2008, entitled "Systems and Method for Ridge Selection in Scalograms of Signals," which is incorporated by reference herein in its entirety. As an illustrative example, if the ridge of a band were found to be at location X, the region may be selected to extend a predetermined distance above and below location X. Alternatively, the band itself may be analyzed to determine its size. The upper and lower bounds of the band may be determined using one or more predetermined or adaptive threshold values. For example, the upper and lower bounds of the band may be determined to be the location where the band crosses below a threshold. The width of the region may be a predetermined amount of time or it may vary based at least in part on the characteristics of the original signal or the scalogram. For example, if noise is detected, the width of the region may be increased or portions of the region may be ignored.

In some embodiments, the region may be determined based at least in part on the repetitive nature of the selected features. For example, a band may have a periodic feature. The period of the feature may be used to determine bounds of the region in time and/or scale.

The size, shape, and location of the one or more regions may also be adaptively manipulated using signal analysis. The adaptation may be based at least in part on changing characteristics of the signal or features within the various domain spaces.

As a signal is being processed, for example by processor **412**, the region may be moved over the signal in any suitable domain space over any suitable parameter in order to determine the value or change in value of the selected features. The processing may



be performed in real-time or via a previously recorded signal. For example, a region may move over the breathing band in the time-scale domain over time. When the selected features have been analyzed, they may be correlated with effort over time, and hence show the value or change in value of effort over time.

5           In some embodiments, the determined effort may be provided as a quantitative or qualitative value indicative of effort. The quantitative or qualitative value may be determined using the value or change in values in one or more suitable metrics of relevant information, such as the selected features mentioned above. The quantitative or qualitative values may be based on an absolute difference from a baseline or a calibrated  
10 value of the features. For example, breathing effort of a patient may be calibrated upon initial setup. Alternatively, the values may be indicative of a relative change in the features such as the change in distance between peaks in amplitude, changes in magnitude, changes in energy level, or changes in the modulation of features.

The quantitative or qualitative value of effort may be provided to be displayed on  
15 a display, for example on display **28**. Effort may be displayed graphically on a display by depicting values or changes in values of the determined effort or of the selected features described above. The graphical representation may be displayed in one, two, or more dimensions and may be fixed or change with time. The graphical representation may be further enhanced by changes in color, pattern, or any other visual representation.

20           The depiction of effort through a graphical, quantitative, qualitative representation, or combination of representations may be presented on output **414** and may be controlled by processor **412**.

In some embodiments, a display and/or speaker on output **414** may be configured to produce visual and audible alerts, respectively, when effort rises above or falls below  
25 some quantitative or qualitative threshold value. Visual alerts may be displayed on, for example, display **28** and audible alerts may be produced on, for example, speaker **22**. The threshold value may be based at least in part on empirical data, baseline readings, average readings, or a combination of data. The threshold value may be configured at the start of operation or configured during operation. In some embodiments,  
30 processor **412** may determine whether or not to produce visual, audible, or combination of alerts. The alerts may be triggered if effort rises above or falls below the threshold value by a particular percentage change or absolute value change.

The analysis performed above that leads to a value of determined effort and/or an alert may also be used to detect events based at least in part on determined effort and/or other detected features. For example, this process may be used in connection with sleep studies. Increased effort may be used to detect and/or differentiate apneic events from  
5 other events. For example, reduced effort may indicate a central apnea and increased effort may indicate an obstructive apnea. In an embodiment, respiration effort from a PPG signal may be used in combination with other signals typically used in sleep studies. In one embodiment, the present disclosure may be used to monitor the effect of therapeutic intervention, for example, to monitor the effect of asthmatic drugs on a  
10 patient's respiratory effort. For example, a patient's respiratory effort may be monitored to determine how quickly the patient's respiratory effort reduces over time, if at all, after the patient receives a drug to relieve the symptoms of asthma.

**FIG. 5** shows an illustrative scalogram of a PPG signal that may be analyzed in accordance with an embodiment of the disclosure. The scalogram may be produced by  
15 system 10 of FIGS. 1 and 2 or system 400 of **FIG. 4** as described above. The scalogram as shown includes breathing band **502** and pulse band **504**. These bands may be found and analyzed for features that may be indicative of breathing effort.

**FIG. 5** shows an increased respiratory effort beginning at time **506**, which may be caused by a patient experiencing increased breathing resistance. In order to detect this  
20 change in respiration effort, regions **508** and **510** may be used. Region **508** is generally located over a portion of pulse band **504** and region **510** is generally located over a portion of breathing band **502**. Regions **508** and **510** may be shifted across the scalogram over time, allowing the features within the regions to be analyzed over time. The size, shape, and locations of regions **508** and **510** are merely illustrative. The  
25 features of the regions may be changed as they are shifted and any other suitable size, shape, and location may be used as described above.

At time **506**, it may be observed that the modulation of the amplitude and scale of pulse band **504** may begin to increase (*e.g.*, within region **508**). Analysis of this modulation or change of this modulation, as described above, may be correlated to the  
30 patient's breathing effort because increased respiration effort may lead to this increase in amplitude and scale modulation of the pulse band. The modulation may be determined by analyzing, for example, the modulation of the ridge of the pulse band.

Increased respiration effort may also lead to increased amplitude and energy of the breathing band **502**. The increase in amplitude and energy can be seen within region **510** at time **506**. The amplitude may be determined by analyzing the ridge of the respiration band. The energy may be determined by analyzing the average or median  
5 energy within region **510**. Analysis of the amplitude and/or energy or change in amplitude and/or energy within region **510** may also be correlated to the patient's breathing effort.

The patient's breathing effort may be determined based at least in part on the amplitude modulation, scale modulation, the amplitude, or the energy of the respiration  
10 band or the pulse band, or changes in those features, or any suitable combination thereof.

It will be understood that the above techniques for analyzing a patient's breathing effort can be used to determine any kind of effort. For example, these techniques can be used to determine the effort associated with any biological process, mechanical process, electrical process, financial process, geophysical process, astronomical process, chemical  
15 process, physical process, fluid process, speech process, audible process, meteorological process, and/or any other suitable process, and/or any combination thereof.

As an additional example, the above techniques may be used to determine effort in a mechanical engine. Engine function may be monitored and represented using signals. These signals may be transformed and represented by, for example, a  
20 scalogram. Normal engine function may produce a band or bands within the scalogram. Features of this band or bands may change or become apparent as the engine exerts more or less effort. These features may include changes in the amplitude modulation, scale modulation, the amplitude, or energy of the bands. These features may also change or become apparent in other regions of the scalogram. The appearance or change in these  
25 features may then be correlated to effort or change in effort exerted by the engine.

It will also be understood that the above techniques may be implemented using any human-readable or machine-readable instructions on any suitable system or apparatus, such as those described herein.

**FIG. 6** is an illustrative flow chart depicting the steps that may be used to  
30 determine effort. In step **600**, one or more signals may be received, including, for example, one or more biosignals (*e.g.*, electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal), physiological signals, dynamic signals, non-destructive

testing signals, condition monitoring signals, fluid signals, geophysical signals, physical signals, astronomical signals, electrical signals, electromagnetic signals, mechanical signals, financial signals including financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, and/or any other suitable  
5 signal, and/or any combination thereof. As an illustrative example, the input signal may be a PPG signal.

In step **602**, the received signal(s) may be transformed into any suitable domain, such as a Fourier, wavelet, spectral, scale, time, time-spectral, or time-scale domain. For example, the signal(s) may be transformed into a time-scale domain using a wavelet  
10 transform such as a continuous wavelet transform. Once the signal is transformed into a suitable domain, it may be depicted by a suitable representation. Suitable representations may include two-dimensional or three-dimensional representations. As an illustrative example, the signal transformed into the time-scale domain and then may be represented by a scalogram.

Once the signal is transformed and represented by a suitable representation, one  
15 or more features may be analyzed within the signal representation as shown in steps **604** and **606**.

In steps 604 and 606, one or more regions within the signal representation may be chosen for inspection. These regions may be similar to region 508 and region 510. As  
20 stated above with respect to region 508 and region 510, the regions may be comprised of any suitable size, shape, and location. They also may be shifted across the scalogram over time, allowing features within the regions to be analyzed over time. For example, the regions may cover bands within a scalogram such as a pulse band or a respiration band. The regions may also cover any other suitable bands or features within the signal  
25 representation.

In step **604**, the features analyzed within a region may include amplitude or energy. In step **606**, amplitude modulation, scale or frequency modulation, distances between peaks, and/or any other suitable features and/or combination of features may be analyzed.

In step **608**, effort information may be determined based at least in part on the  
30 analysis of the features in steps **604** and **608**. As described above with respect to **FIG. 5**, effort may be correlated with changes or the appearance of the features found and analyzed in steps **604** and **606**. For example, breathing effort may be correlated with a

change or weighted change in amplitude, energy, amplitude modulation, frequency modulation, and/or scale modulation in the breathing and/or pulse bands. The correlation between effort and the analyzed features may be used to determine quantitative or qualitative values associated with effort. The determined values may, for example, indicate effort or a change of effort. The values may be determined based at least in part on an absolute or percentage difference from a baseline or calibrated value of effort. Furthermore, the values may be determined based at least in part on changes or appearance of the analyzed features within the signal representation.

The analysis performed in step **608** may also determine whether the determined effort has risen above or fallen below a threshold value. The threshold value may be based at least in part on empirical data, baseline readings, average readings, or a combination of data. The threshold value may be configured based at least in part on effort or features at the start of operation or may be adjusted during operation. If effort crosses a threshold value, an alert may be issued. In some embodiments, the alert may be triggered if effort rises above or falls below a threshold value by a particular percentage change, absolute value change, or if the determined effort value crosses the threshold value.

The analysis performed in step **608** may also detect events based at least in part on determined effort and/or other detected features. For example, this process may be used in connection with sleep studies. Increased effort may be used to detect and/or differentiate apneic events from other events. If such an apneic event occurs, an additional notification may be generated. In an embodiment, respiration effort from a PPG signal may be used in combination with other signals typically used in sleep studies.

In step **610**, the signal analysis and determined effort may be output along with a possible alert if an alert has been triggered. The output may be displayed on a display, such as display **28** shown in **FIG. 1**. A graphical display may be generated based at least in part on the determined qualitative or quantitative values representing effort or changes in effort. The graphical representation may be displayed in one, two, or more dimensions and may be fixed or change with time. The graphical representation may be further enhanced by changes in color, pattern, or any other visual representation. Additionally, the alert may be made visual by being displayed on a display, for example display **28**, or may be made through an audible sound on a speaker, for example speaker **22**.

As the signal analysis and determined effort are being output in step **610**, the whole process may repeat. Either a new signal may be received, or the effort determination may continue on another portion of the received signal(s). The process may repeat indefinitely, until there is a command to stop the effort determination, and/or  
5 until some detected event occurs that is designated to halt the effort determination process. For example, it may be desirable to halt effort determination after a sharp increase in breathing effort is detected.

It will also be understood that the above method may be implemented using any human-readable or machine-readable instructions on any suitable system or apparatus,  
10 such as those described herein.

The foregoing is merely illustrative of the principles of this disclosure and various modifications can be made by those skilled in the art without departing from the scope and spirit of the disclosure. The following claims may also describe various aspects of this disclosure.

What is Claimed is:

1. A method for determining effort, comprising:  
transforming a signal to generate a transformed signal;  
generating a scalogram based at least in part on the transformed  
signal;  
analyzing one or more features within the scalogram;  
determining effort information based at least in part on the one or  
more analyzed features; and  
providing the effort information.
2. The method of claim 1, wherein transforming the signal comprises  
transforming the signal using a continuous wavelet transform.
3. The method of claim 1, wherein at least one of the one or more  
features within the scalogram is located in one or more bands within the scalogram.
4. The method of claim 3, wherein the signal is a  
photoplethysmograph signal, wherein the effort information is breathing effort  
information, and wherein one of the one or more bands within the scalogram is a  
breathing band or a pulse band.
5. The method of claim 1, wherein analyzing the one or more  
features comprises:  
calculating an energy parameter within a selected region; and  
calculating a second energy parameter from a second selected  
region, wherein the selected region and the second selected region are different regions,  
and wherein determining breathing effort information comprises determining a change in  
breathing effort.
6. The method of claim 5, wherein the selected region and the second  
selected region are the same size and wherein the second region is shifted in time from  
the first region.

7. The method of claim 1, wherein the one or more features are selected from the group consisting of:
- amplitude;
  - energy;
  - amplitude modulation; and
  - scale modulation.
8. A system for determining effort, comprising:
- a sensor capable of generating a signal;
  - a processor capable of:
    - transforming the signal;
    - generating a scalogram based at least in part on the transformed signal;
    - analyzing one or more features within the scalogram;
    - determining effort information based at least in part on the one or more analyzing features; and
    - providing the effort information.
9. The system of claim 8, wherein transforming the signal comprises transforming the signal using a continuous wavelet transform.
10. The system of claim 8, wherein at least one of the one or more features within the scalogram is located in one or more bands within the scalogram.
11. The system of claim 10, wherein the signal is a photoplethysmograph signal, wherein the effort information is breathing effort information, and wherein one of the one or more bands within the scalogram is a breathing band or a pulse band.
12. The system of claim 8, wherein analyzing the one or more features comprises:
- calculating an energy parameter within a selected region; and
  - calculating a second energy parameter from a second selected region, wherein the selected region and the second selected region are different regions,



and wherein determining breathing effort information comprises determining a change in breathing effort.

13. The system of claim 12, wherein the selected region and the second selected region are the same size and wherein the second region is shifted in time from the first region.

14. The system of claim 8, wherein the one or more features are selected from the group consisting of:

amplitude;  
energy;  
amplitude modulation; and  
scale modulation.

15. A computer-readable medium for determining effort, the computer-readable medium having computer program instructions recorded thereon for:

transforming a signal to generate a transformed signal;  
generating a scalogram based at least in part on the transformed signal;  
analyzing one or more features within the scalogram;  
determining effort information based at least in part on the one or more analyzed features; and  
providing the effort information.

16. The computer-readable medium of claim 15, wherein transforming the signal comprises transforming the signal using a continuous wavelet transform.

17. The computer-readable medium of claim 15, wherein at least one of the one or more features within the scalogram is located in one or more bands within the scalogram.

18. The computer-readable medium of claim 17, wherein the signal is a photoplethysmograph signal, wherein the effort information is breathing effort information, and wherein one of the one or more bands within the scalogram is a breathing band or a pulse band.

19. The computer-readable medium of claim 15, wherein analyzing the one or more features comprises:

calculating an energy parameter within a selected region; and  
calculating a second energy parameter from a second selected region, wherein the selected region and the second selected region are different regions, and wherein determining breathing effort information comprises determining a change in breathing effort.

20. The computer-readable medium of claim 19, wherein the selected region and the second selected region are the same size and wherein the second region is shifted in time from the first region.

21. The computer-readable medium of claim 1, wherein the one or more features are selected from the group consisting of:

amplitude;

energy;

amplitude modulation;

scale modulation; and

distances between amplitude peaks of a band.

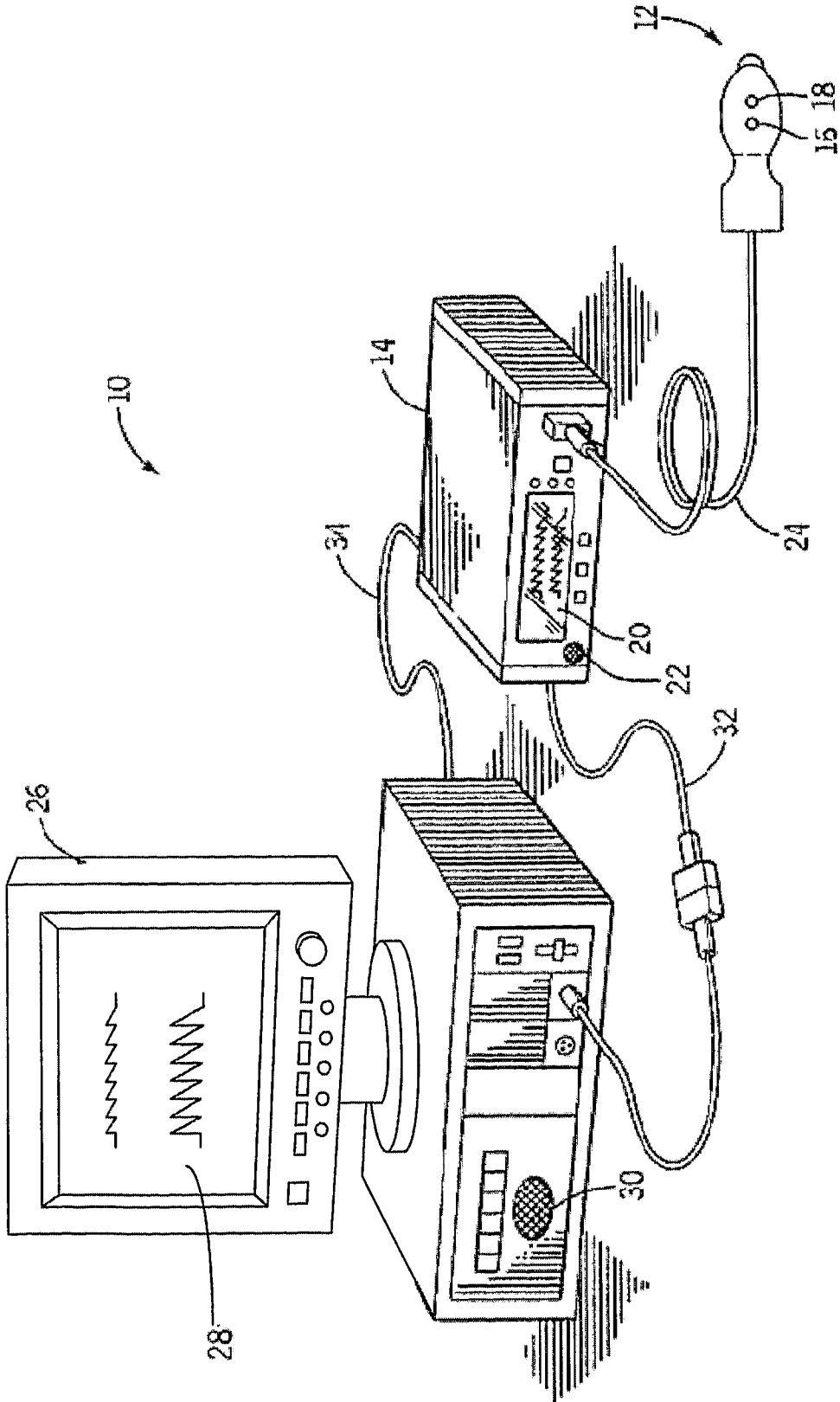


FIG.1

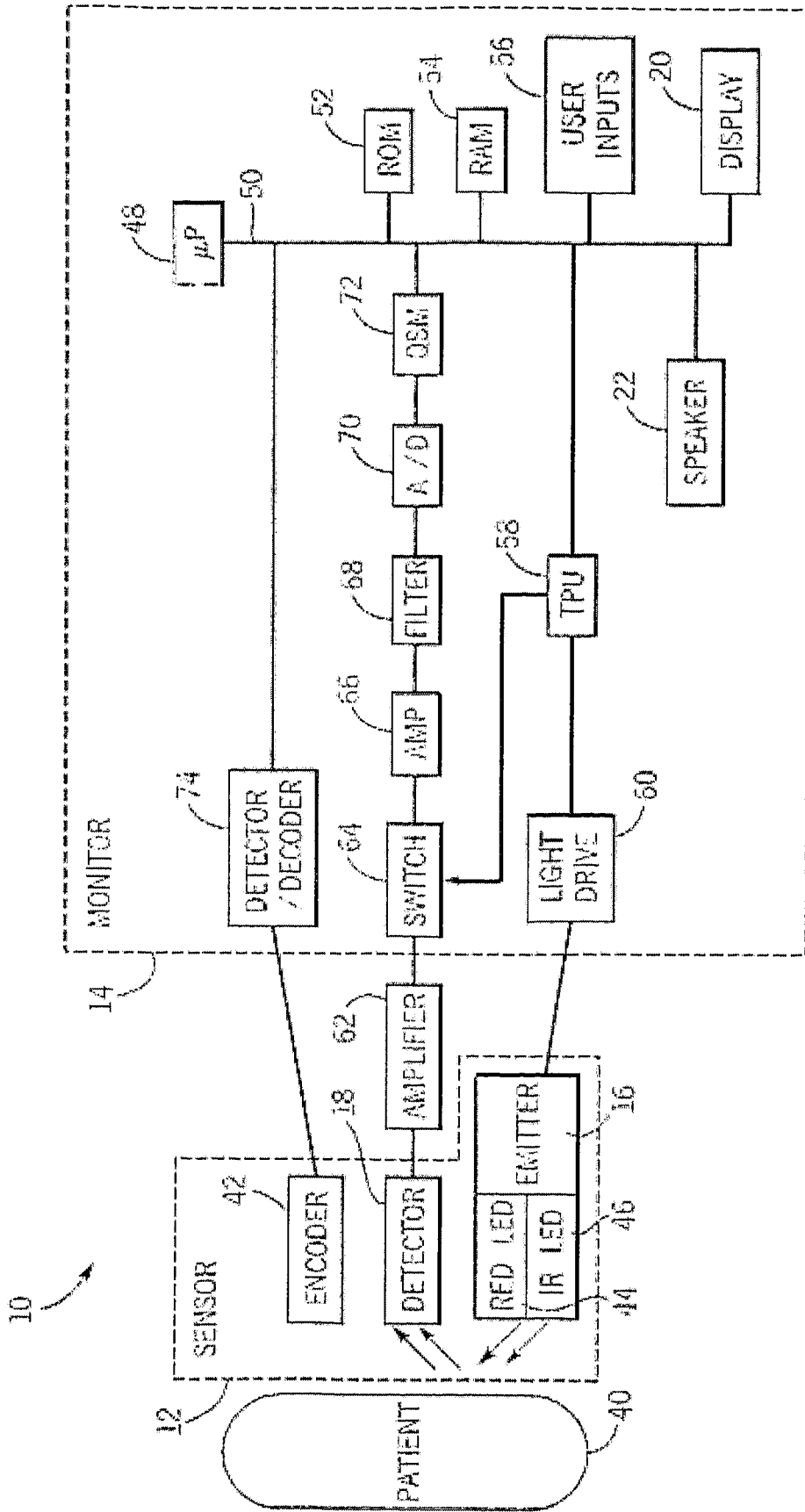


FIG. 2

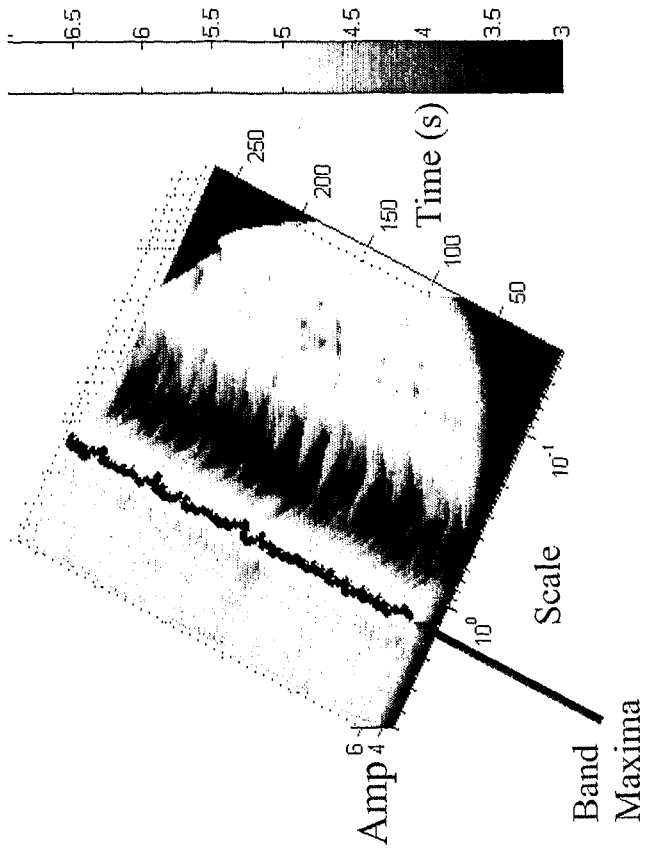


FIG. 3(b)

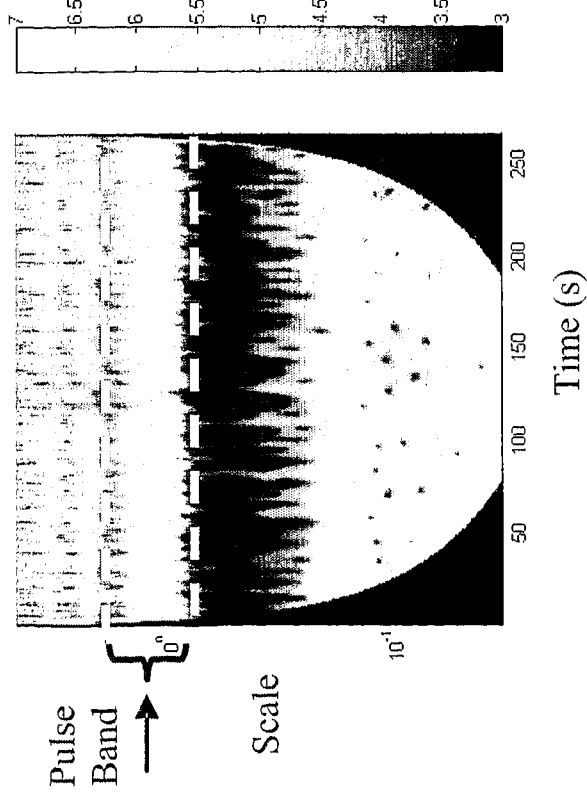


FIG. 3(a)

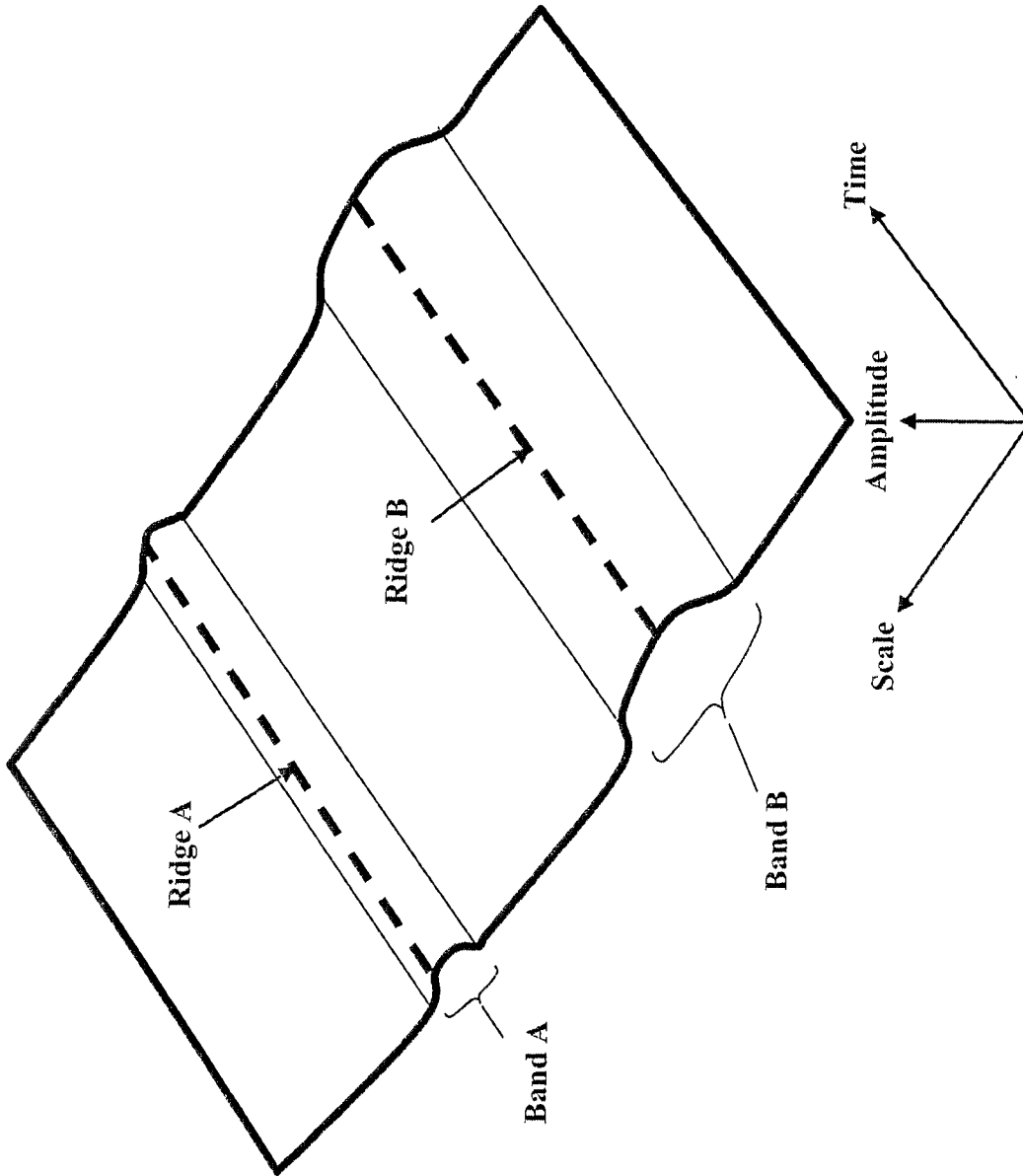


FIG. 3(c)

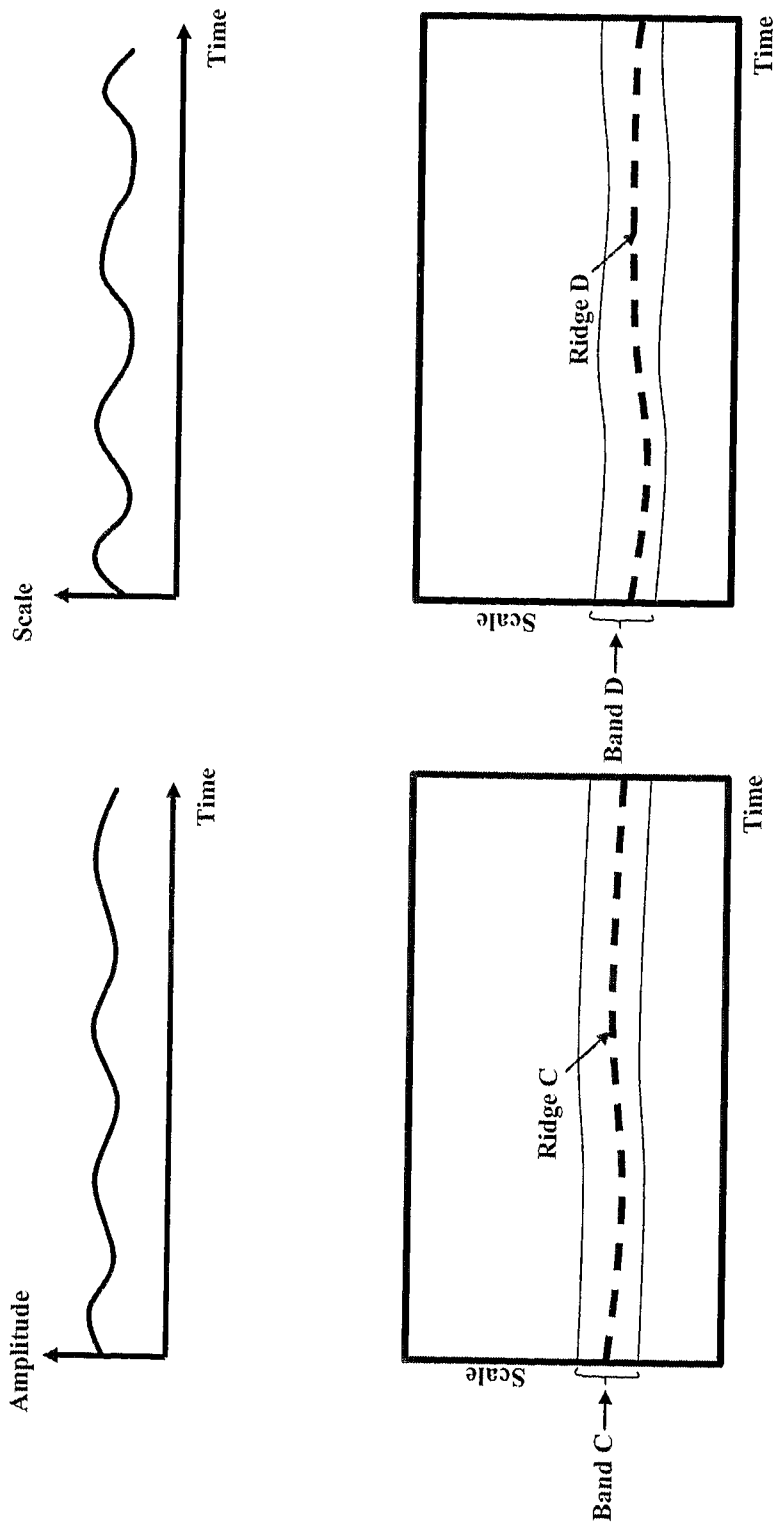


FIG. 3(d)

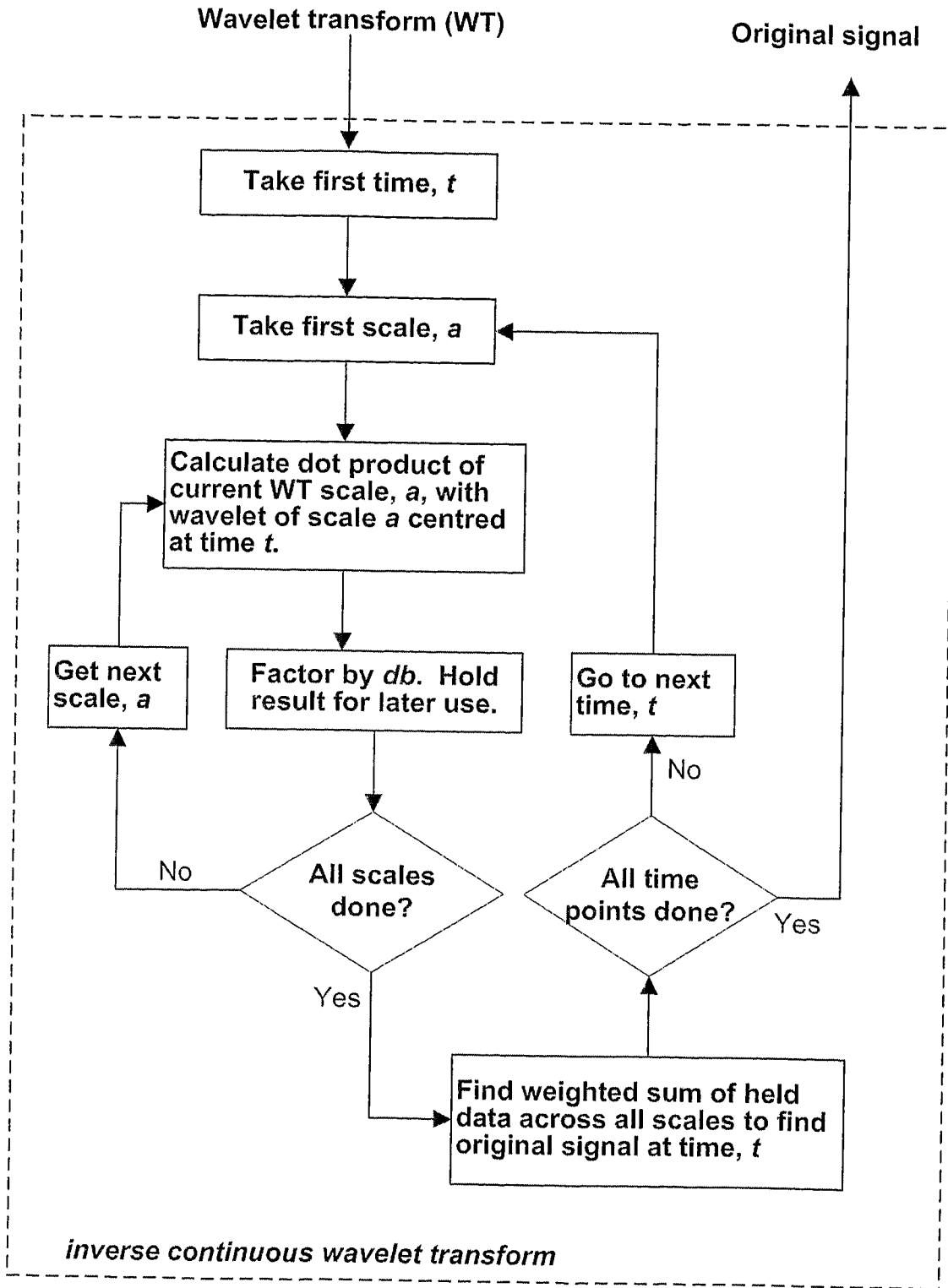


FIG. 3(e)



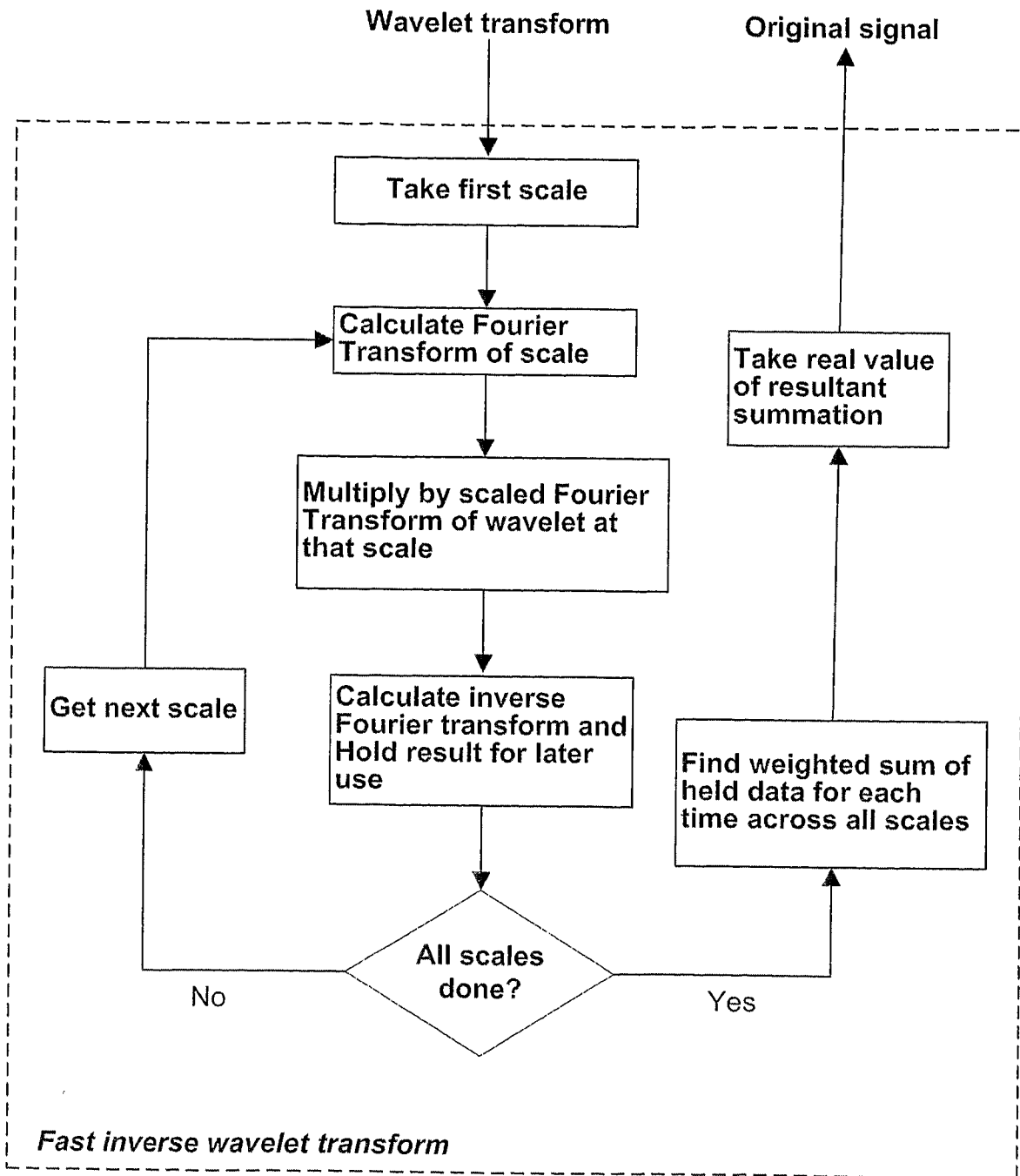
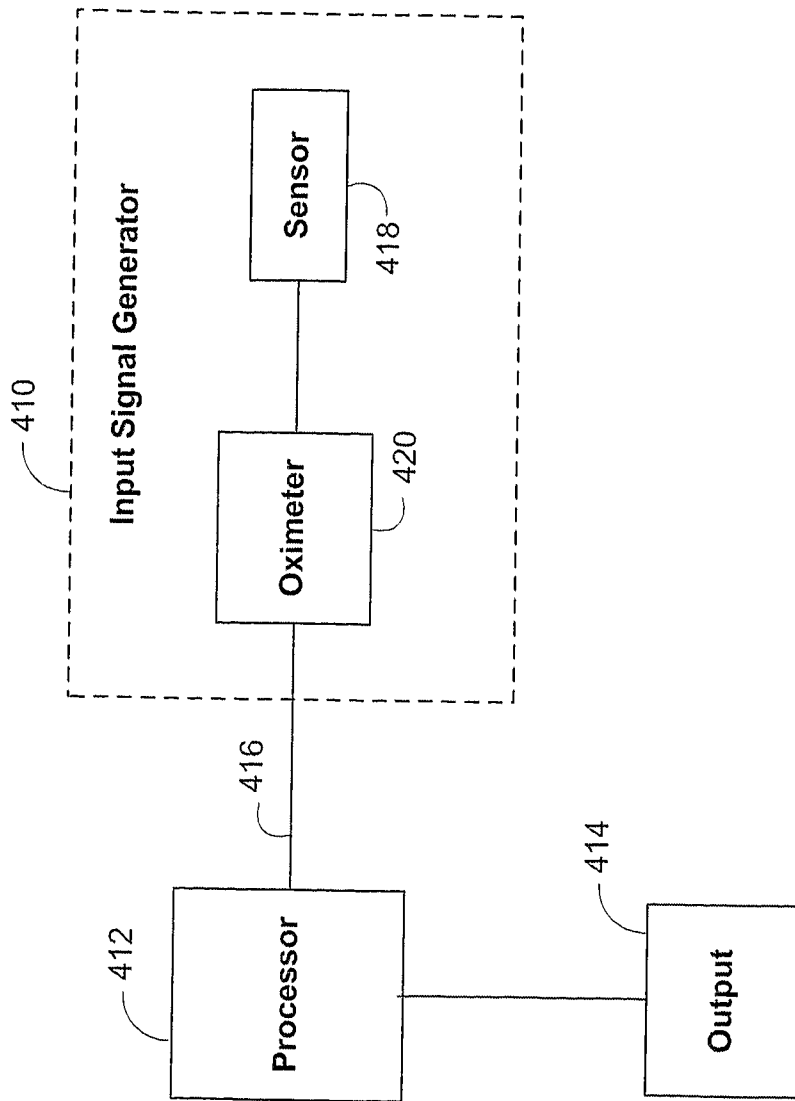


FIG. 3(f)

400



**FIG. 4**

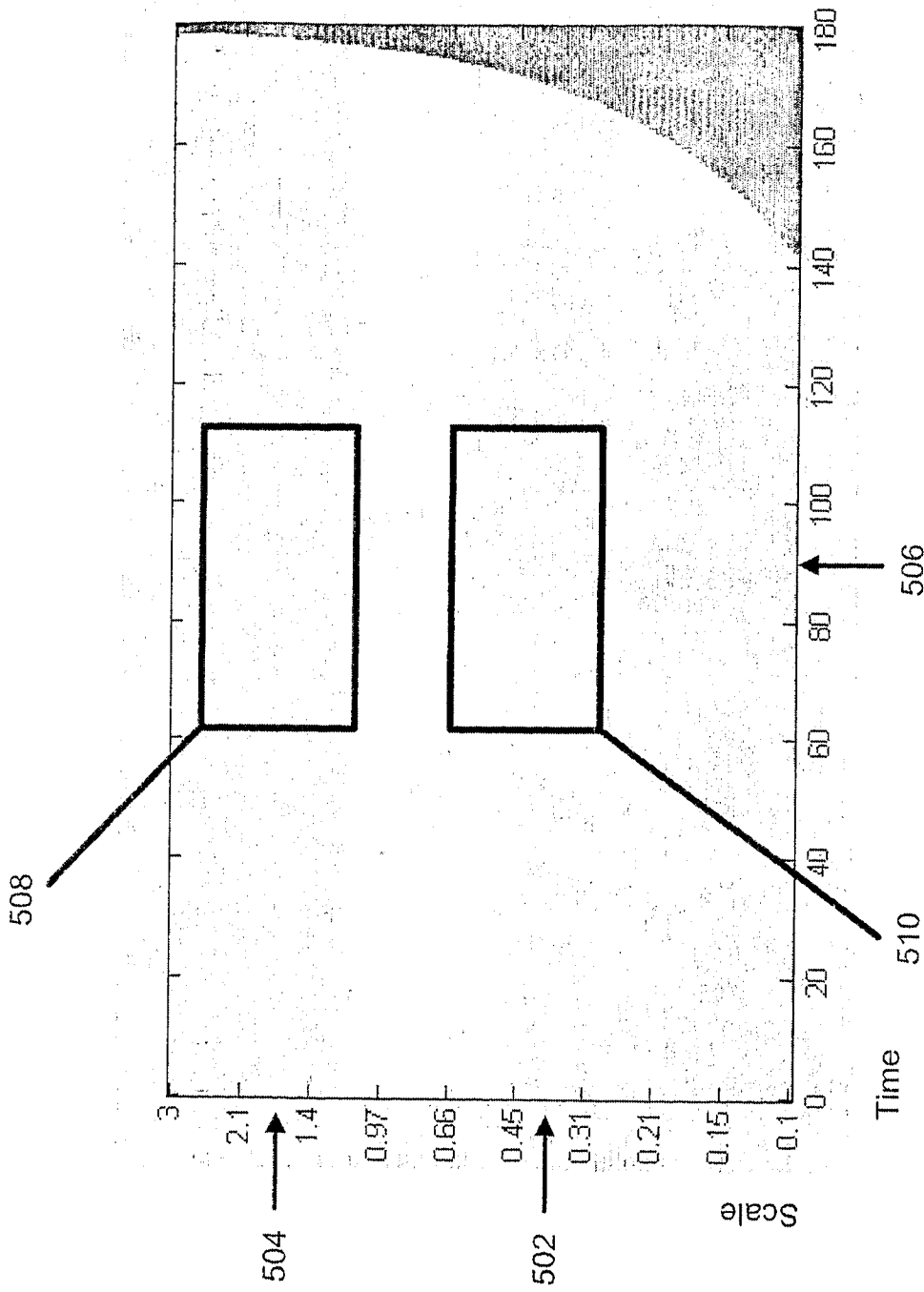


FIG. 5

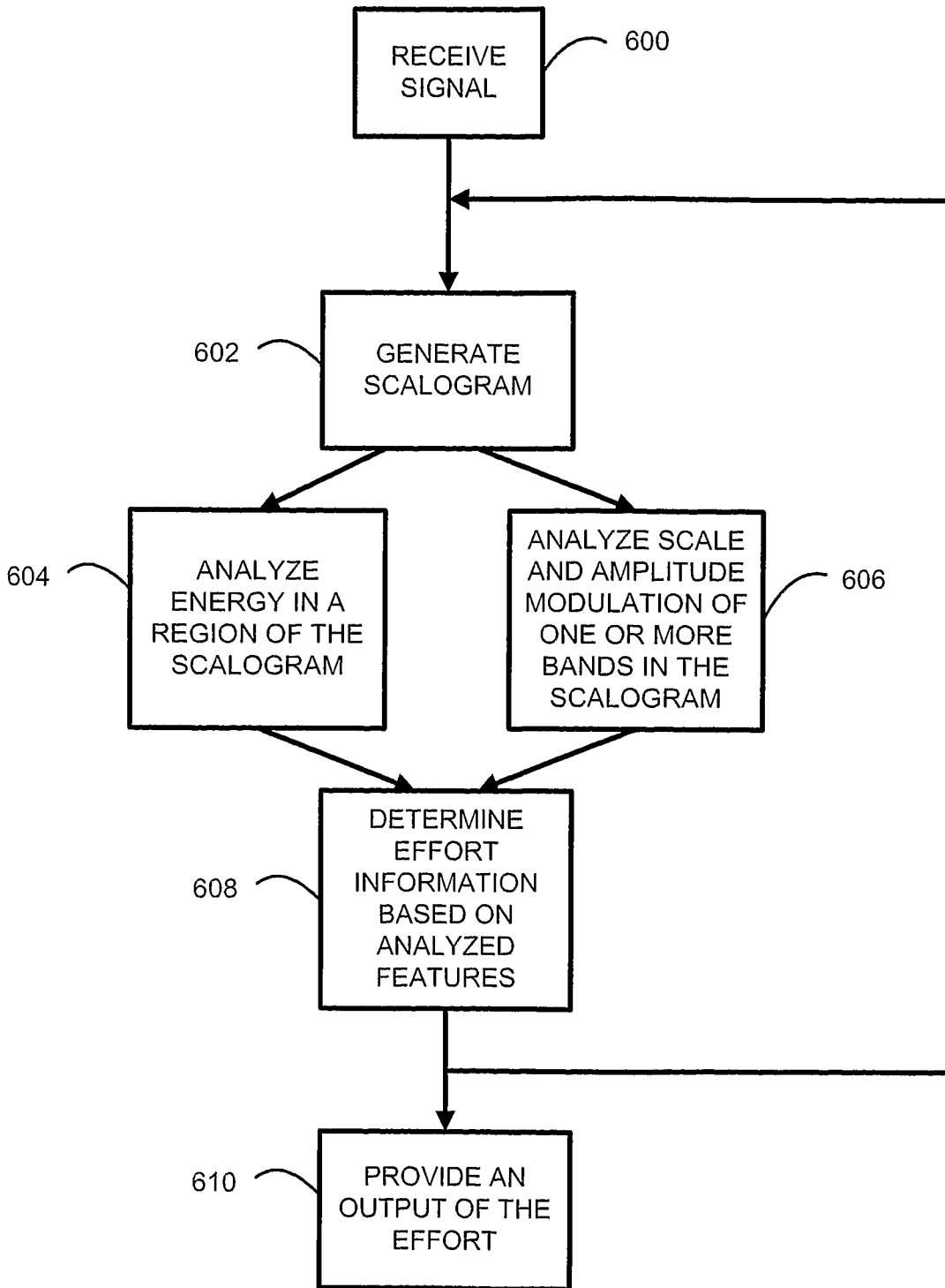


FIG. 6

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/IB2009/006135

**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, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2005/070774 A1 (ADDISON PAUL STANLEY [GB] ET AL) 31 March 2005 (2005-03-31) the whole document -----	1-21
A	US 2006/258921 A1 (ADDISON PAUL S [GB] ET AL) 16 November 2006 (2006-11-16) the whole document -----	1-21
A	WO 2005/096170 A (CARDIODIGITAL LTD [GB]; ADDISON PAUL STANLEY [GB]; WATSON JAMES NICHOL) 13 October 2005 (2005-10-13) page 4, line 1 - page 10, line 6 page 12, line 6 - page 16, line 24 figures 1-6 -----	1-21

Further documents are listed in the continuation of Box C.

See patent family annex

\* Special categories of cited documents:

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the international filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*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

18 September 2009

Date of mailing of the international search report

06/10/2009

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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2009/006135

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